INTERNATIONAL SYMPOSIUM

# Aquifer Thermal Energy Storage

November 14-15, 1994

The University of Alabama
Paul W. Bryant Conference Center
Tuscaloosa, Alabama, USA

PROCEEDINGS

Sponsored by

- **U.S. Department of Energy**
  through Pacific Northwest Laboratory
- **The University of Alabama**
  Bureau of Engineering Research
  School of Mines and Energy Development
  College of Continuing Studies
- **Oak Ridge Associated Universities**

# ABOUT AQUIFER THERMAL ENERGY STORAGE

Aquifer thermal energy storage (ATES), a promising new technology, utilizes the insulating properties of natural earth materials insitu, together with the storage and retrieval properties of water, in order to economically store either heat or chill for climate control systems and other heating or cooling applications. Many countries have geohydrologic and climatic conditions suitable for deployment of this technology. In the U.S., it is estimated that approximately 70 percent of the population is located in areas where aquifers are available for energy storage.

The U.S. Department of Energy has actively sponsored R&D in the area of aquifer thermal energy storage for more than fifteen years. The University of Alabama has been recognized as a leader in aquifer thermal energy storage R&D since the early 1980s. University of Alabama researchers have played a key role in implementing and improving the technology locally. Current research suggests that ATES systems, which are typically 100-ton (350kW, thermal) capacity or greater, may require up to 80 percent less electricity than conventional systems. Also of significance, ATES systems shift peak loads from summer to winter, and they eliminate problems with human pathogens such as Legionnaire's Disease. Wide deployment of such systems would have significant positive economic and environmental ramifications.

The purpose of this symposium is to foster communication among international researchers, further advance the technology, and introduce ATES to a wider audience of researchers, research managers, and potential users especially in the North American HVAC marketplace.

## DISCLAIMER

# TABLE OF CONTENTS

VOLUME I

## Technical Session II

## Technical Session III

## Technical Session IV

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# ATES–Energy Efficiency, Economics and the Environment

• Edward L. Morofsky
Senior Energy Technology Research Engineer
Public Works and Government Services
Ottawa, Ontario, Canada


## ABSTRACT

Aquifers have been used to store large quantities of thermal energy to supply process cooling, space cooling, space heating, and ventilation air preheating, and can be used with or without heat pumps. Aquifers are used as energy sinks and sources when supply and demand for energy do not coincide. Aquifer thermal energy storage may be used on a short-term or long-term basis; as the sole source of energy or as a partial storage; at a temperature useful for direct application or needing upgrade. The sources of energy used for aquifer storage are ambient air, usually cold winter air; waste or by-product energy; and renewable energy such as solar. The present technical, financial and environmental status of ATES is promising. Numerous projects are operating and under development in several countries. These projects are listed and results from Canada and elsewhere are used to illustrate the present status of ATES. Technical obstacles have been addressed and have largely been overcome. Cold storage in aquifers can be seen as a standard design option in the near future as it presently is in some countries. The cost-effectiveness of aquifer thermal energy storage is based on the capital cost avoidance of conventional chilling equipment and energy savings. ATES is one of many developments in energy efficient building technology and its success depends on relating it to important building market and environmental trends. This paper attempts to provide guidance for the future implementation of ATES.


## INTRODUCTION

Aquifers can be used to store large quantities of thermal energy to meet large cooling and heating demands. Aquifers are underground, water-yielding geological formations, either unconsolidated (gravel and sand) or consolidated (rocks). The natural aquifer water temperature is close to, but slightly warmer than, the local mean annual air temperature. Aquifers are either unconfined, occurring as surficial alluvial, colluvial, or glacial deposits, or confined, occurring at depths ranging from tens to hundreds of meters below ground surface.

Aquifer thermal energy storage has been used for process cooling, space cooling, space heating, and ventilation air preheating, and can be used with or without heat pumps [1]. Aquifers are used as thermal energy sinks or sources and to store energy from ambient winter air and sunlight. Although aquifer thermal energy storage is associated with large energy demands, groundwater source heat pumps for heating and cooling are routinely used for single family residences and cottages, especially when existing wells can be used.

Two separate wells, hydraulically-coupled, are normally used to separate water supply from storage. Aquifer thickness, porosity and the number of wells determine the storage volume. A minimum separation distance between supply and storage wells is 30 meters and distances of 100 to 200 meters are common for commercial building applications. Single well applications have also been employed using vertical separation of hot and cold groundwater. A well pair may be pumped constantly in one direction or alternatively, from one well to the other, especially when heating and cooling are both being provided. It is recommended to design injection wells with a backflush capability, because this is a good method of minimizing well plugging with sediment. All wells should therefore be equipped with pumps [2].

Injection of water into a well at high rates requires design consideration. A simple rule-of-thumb is that a well in an unconsolidated aquifer should not be expected to accept more than 66% of the water that it can produce [3]. In consolidated aquifers the opposite occurs, fractures open up under the injection pressure.

Chemical changes in groundwater caused by the temperature and pressure variations associated with aquifer thermal energy storage may result in operational and maintenance problems. The precipitation of minerals in heat exchangers and well screens is an example. Some groundwaters are naturally corrosive to common materials used in heat exchangers, pumps and pipes. Additionally, the aquifer may become clogged by precipitation of minerals. Fortunately, these problems are avoidable and manageable within the operating range of most common applications. Guidelines are now available that allow such problems to be avoided by proper design, materials selection and operation [4].

The length of storage depends on the local climate and the type of building or process being supplied with cooling or heating. Aquifer thermal energy storage may be used on a short-term or long-term basis; as the sole source of energy or as a partial storage; at a temperature useful for direct application or needing upgrade; and in combination with a dehumidification system such as desiccant cooling.

The cost-effectiveness of aquifer thermal energy storage is based on the capital cost avoidance of conventional chilling equipment and energy savings. Heat rejection equipment, such as cooling towers, may be avoided if the aquifer is used as a heat sink.

Aquifer thermal energy storage may be 'closed' with a heat exchanger between the well to well piping or 'open' with groundwater circulating through the building. The latter is suited to process cooling applications and in low-rise commercial buildings when the storage temperatures are just sufficient for space cooling or dehumidification purposes. Closed, pressurized systems that separate the groundwater from the building HVAC system by using a heat exchanger are preferred when undesirable groundwater interaction with oxygen might be a concern.

Cold storage temperatures injected are normally 2° C to 5° C with cooling power typically ranging from 200 kW thermal to 20 MW thermal and with the stored cooling energy extending to 20 GWh. A typical single well flow rate for a small application is 3 L/s and 30 L/s for large applications. Cost-effectiveness is enhanced when both heating and cooling energy are supplied.

The incorporation of aquifer thermal energy storage into a building system may be accomplished in a variety of ways depending on the other components present and the intentions of the designer [5] [6]. If the storage is closed, the cold and hot wells are connected in series with connection to the building by uncoupled circuits sharing a heat exchanger. The heat pump may then be connected in series or parallel depending on whether the store can be used for direct heating or cooling. Control is simplified by the existence of separate hot and cold wells that operate on the principle of 'last water in, first water out'. This ensures that the hottest or coldest water is always available for discharge when needed.

Aquifer thermal energy storage systems can be distinguished by whether they store energy that is actively gathered (e.g., the University building in Tuscaloosa, Alabama, where the cooling tower is used in winter as a collector of chilled water) or whether they store waste or by-product energy (e.g., groundwater heat pump projects that store the by-product chilled water from the heating season). In the former type, the various designs are often compared on the basis of COP. In the latter case, energy that would otherwise be wasted is stored. These double effect storage projects are more likely to be economical, but the judgement of overall efficiency must be made at a system level. A comprehensive procedure that evaluates the relative efficiency of such schemes taking into account the storage time, temperature levels, and application requirements remains to be developed.

The natural groundwater flow velocity (1 to 100 m per year) can either be an obstacle in keeping a plug of stored energy in place or be of help in dispersing waste heat, such as in a cooling application where the aquifer serves as a heat sink.

## HISTORY

Aquifer thermal energy storage has a history of about 30 years. It began at industrial sites originally dependent on direct groundwater cooling. Environmental impacts related to aquifer warming and ground subsidence when water was not recharged led to the recharge of aquifers with chilled water. The natural groundwater temperature may be suitable for direct cooling, for example in Winnipeg, Manitoba where the temperature is 6° C or less. Here, aquifer thermal energy storage is used to avoid the gradual warming of the aquifer. In locations such as Alabama, where the natural groundwater temperature (about 18° C) is too high for direct cooling, aquifer thermal energy storage is used to store a sufficient volume of chilled water produced during the winter months.

More recently, the increasing use of groundwater source heat pumps for heating and cooling of residential and commercial buildings has stimulated aquifer thermal energy storage applications with heat pumps. Such facilities may have roughly equal heating and cooling energy requirements depending on the local climate. A groundwater source heat pump connected to a cold well and a warm well is a rudimentary aquifer thermal energy storage system. The warm well can be used as a heat source for the heat pump evaporator in the heating season with the by-product chilled water stored in the cold well. The chilled water is stored until the cooling season when it can be used directly for space and process cooling.

Hot wells have successfully stored water up to a temperature of 90° C (waste heat from cogeneration during summer is stored to supply direct heating to the Utrecht University campus in the Netherlands and an experimental field test facility at the University of Minnesota in Minneapolis). Attempts to store heat at temperatures of 250° C have not been successful due to adverse geochemical interactions.

Seasonal storage has a large energy savings potential and began as an environmentally sensitive improvement on the large-scale mining of groundwater [7]. The reinjection of all pumped water along with an attempt at annual thermal balancing is the modern approach along with minimal water treatment [2] [5] [6] [8]. The recent research directed to community-based and aquifer-based implementation of aquifer thermal energy storage, perhaps integrated with other community services such as drinking water supply or aquifer remediation, promises large-scale storage implementation.

The Chinese Experience

There were three interrelated problems in Shanghai that led to the development of aquifer thermal energy storage - ground subsidence, groundwater pollution, and the lack of summer cooling in factories. Restrictions on groundwater extraction aimed to solve subsidence and pollution. However, large-scale year round injection made the groundwater temperature unsuitable for cooling.

In 1965, cold water injection during winter started for summer cooling and has continued since giving thirty years of experience. Heated water is also injected for winter heating. Experience with heat storage is also extensive with the water volume injected being about 30% of the cold storage volume.

By 1984 there were 492 cold storage wells in Shanghai accepting 29 million cubic meters of water annually. Of these wells, 90% were used for both injection and extraction. These cold storage wells supplied textile mills, chemical works and other industrial plants, but also commercial buildings such as the Shanghai Exhibition Hall where there are 5 injection wells and 1 extraction well. Most of these cold storage wells are 10 to 12 inches in diameter. The total annual cooling energy stored in Shanghai is about 1 100 TJ. Hot water storage of waste heat is practiced with injection temperatures as high as 40° C. Recovery temperatures in winter can be as high as 38° C.

## REVIEW OF COLD STORAGE PROJECTS

The objectives of the International Energy Agency, Energy Storage Implementing Agreement Annex 7 were to:

- Demonstrate and document innovative, energy efficient and cost-effective cold storage designs for a variety of building types and industrial applications to encourage the adoption of seasonal cold storage as a standard design option.
- Evaluate the potential application of combined hot and cold storage for increased energy efficiency and cost-effectiveness.
- Document the total energy savings and peak demand reductions from the evaluated systems in the context of national market studies. Identify the source fuel types of energy saved to permit an assessment of the associated environmental benefits.

State-of-the-Art Reviews

The first activity of Annex 7 was the state of the art reviews.

- Prepare national reports of the state of the art of appropriate storage technologies for building and industrial applications, design models for application of these technologies, and methods of predicting subsoil characteristics.
- Prepare national reviews of existing projects and feasibility studies of appropriate seasonal cold storage applications identifying costs and energy use, advantages and disadvantages, and technical and non-technical constraints to implementation.

Characteristics

Seasonal cold storage system concepts can be differentiated according to the following characteristics:

- Cold storage medium and duration of storage;
- Source of (cooling) energy; and
- System for meeting cooling load.

The basic system classification structure developed in Annex 7 is shown below. To focus the work of the Annex, emphasis was given to seasonal applications (defined as having at least three months of storage) which have a charging cycle (for cooling), and which are cost-effective as compared with conventional system design.

The source of cooling is divided into systems which use heat pumps for cold production and systems which do not use heat pumps (e.g., dry coolers, cooling towers). In meeting the cooling load, systems are differentiated by whether the storage meets the entire load or whether any other supplementary cooling is required (e.g., free cooling, surface water).

**System Classification**

**Qualification for Annex 7**

| | |
|---|---|
| Cold Storage: | Must be charged with cold for purpose of cooling |
| Seasonal Storage: | Discharging at least three months after charging |
| Cost-effective: | Better SPF than conventional reference system. |
| **Classification:** | Each system must fit into either Column 2 or Column 3 below for each characteristic identified in Column 1. |

| | | |
|---|---|---|
| **Application:** | Cooling only | Heating and cooling |
| **Storage technology:** | Open | Closed |
| **Cold source:** | Air | HP or HX |
| **Load:** | Building | Industrial Process |
| **Size of Storage:** | Meets entire load | Additional cooling required |

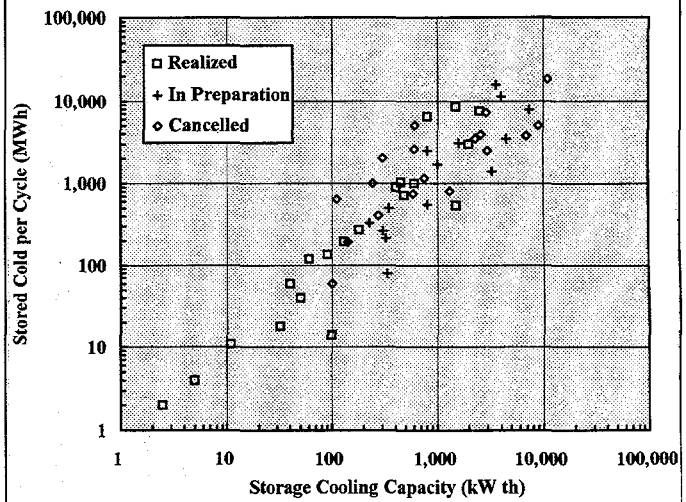
Project Data

Data for 55 cold storage projects from Canada, Germany, the Netherlands, and Sweden that are either realized, in preparation, or cancelled are summarized. The data include estimates from feasibility studies and detailed designs, and actual measurements [1].

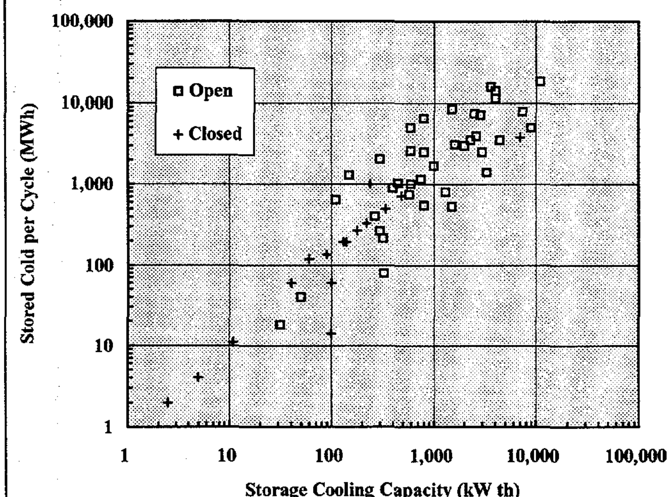
The amount of cold energy that is stored per cycle is plotted against the maximum cooling capacity as shown is the following three charts. The three charts identify firstly, the project status as of May 1991; secondly, the storage type; and thirdly, the country location. As expected, there is a close correlation between the amount of energy that is stored per cycle and the storage cooling capacity. The size of the projects varies widely from over 10 MW (20 000 MWh) down to 10 kW (10 MWh) and even smaller. The median size is approximately 1 000 kW (1 500 MWh).

For the projects identified, aquifers are by far the dominant storage medium in Canada, Sweden, and the Netherlands; but soil is the prevalent storage medium in Germany. The type of storage is indicated in the chart below (open = aquifer and closed = ground). Projects with open storage media tend to have higher cooling capacities and cold stored per cycle.

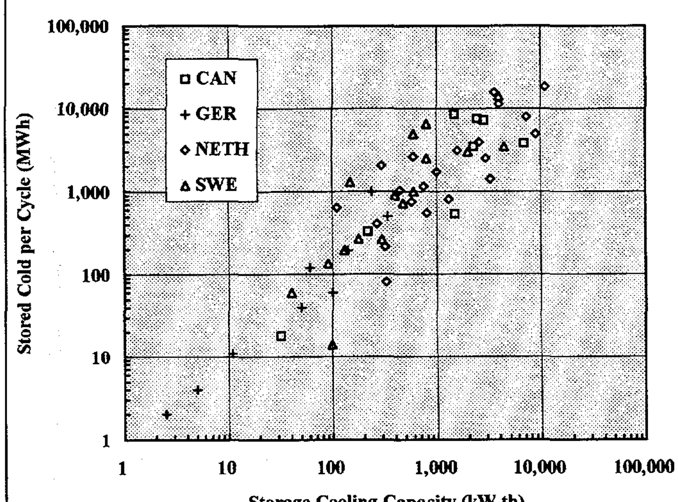
**Stored Cold by Cooling Capacity IEA Annex 7 Projects (Project Status)**




**Stored Cold by Cooling Capacity IEA Annex 7 Projects (Storage Type)**




**Stored Cold by Cooling Capacity IEA Annex 7 Projects (Country)**



Payback

The three figures following below show the simple payback of the investment against the storage cooling capacities of the systems for project status, storage type and country. The payback refers to the additional costs of the application of seasonal cold storage over that of a conventional system.

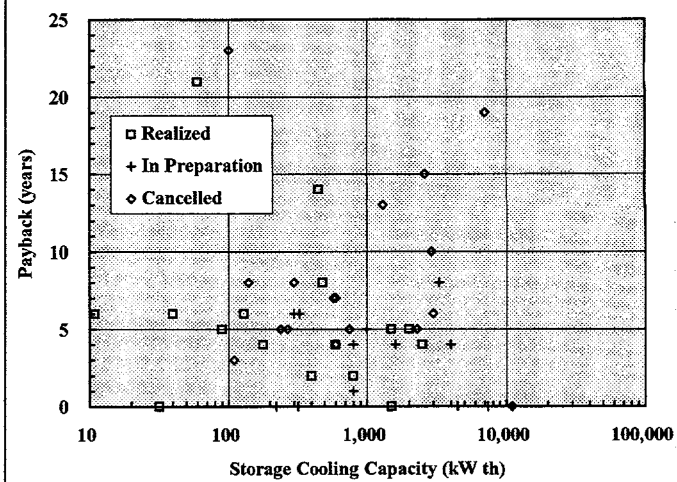
The findings from the system designs, energy simulations and economic analyses are based on comparisons of storage systems designs with conventional system designs. These comparisons have been made based on typical design practice in each of the four participating countries. Two climate regimes (extreme and moderate) have been analyzed. For building applications, both new and retrofit cases have been examined. For the process cooling load case, only new system designs were analyzed.

For the building applications (new and retrofit, moderate and extreme climate):

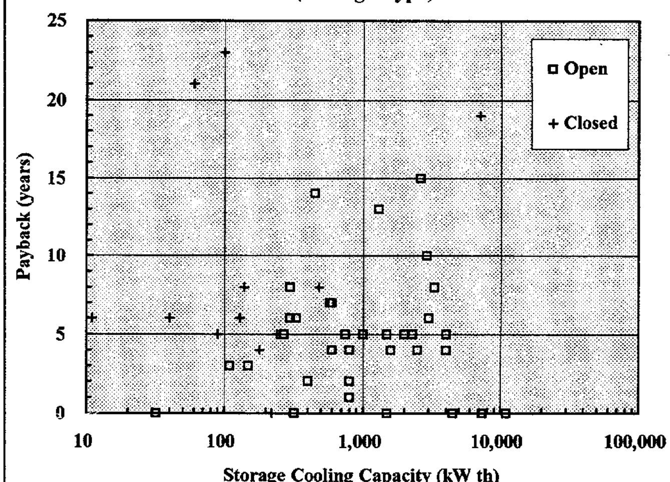
- Total energy cost of the storage design is less than that for the conventional design in all cases;
- Electrical energy consumption is higher (than the conventional design) for the storage design cases which included (electrical) heat pumps, but significantly lower for storage designs without heat pumps;
- Thermal energy consumption is lower (than the conventional design) for the storage with heat pump cases, but is generally about the same in the designs without heat pumps;
- Capital cost is higher (than the conventional design) for the heat pump cases but generally lower in the designs without heat pumps; and
- Total (energy and annualized capital) cost is higher (than the conventional design) for the designs with heat pumps but lower for the designs without heat pumps.

In the building applications analyzed, the relative difference between new and retrofit applications (as compared to conventional) is negligible, as is the relative difference due to the two climates.

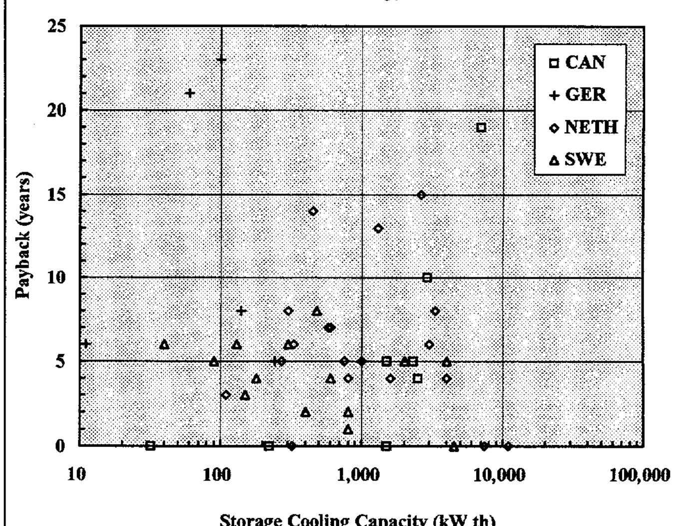
**Payback by Cooling Capacity IEA Annex 7 Projects (Project Status)**




**Payback by Cooling Capacity IEA Annex 7 Projects (Storage Type)**




**Payback by Cooling Capacity IEA Annex 7 Projects (Country)**

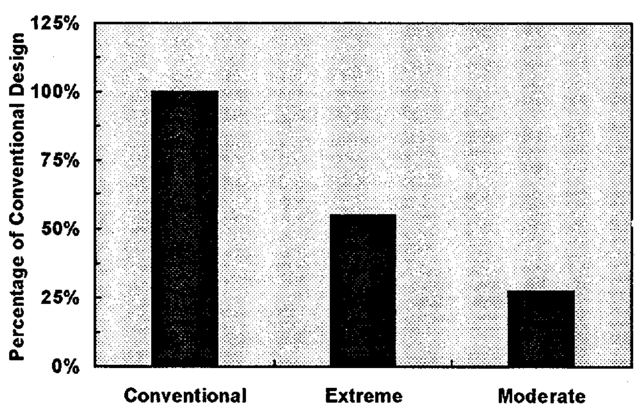


### Process Cooling

For the process cooling load application:

- Electrical energy consumption (and cost) are significantly reduced in the storage design as compared to the conventional design;
- Capital costs are slightly higher (than the conventional design) for the storage design, but total costs are significantly lower;
- There are significant differences between the moderate climate and the extreme climate simulations due to the level of "free cooling" that is available in each climate--free cooling satisfies more of the cooling demand in the extreme climate so that the energy savings possible from eliminating the chiller in the extreme climate is more limited.

**Annual Energy Costs Relative to a Conventional Design for Process Cooling**

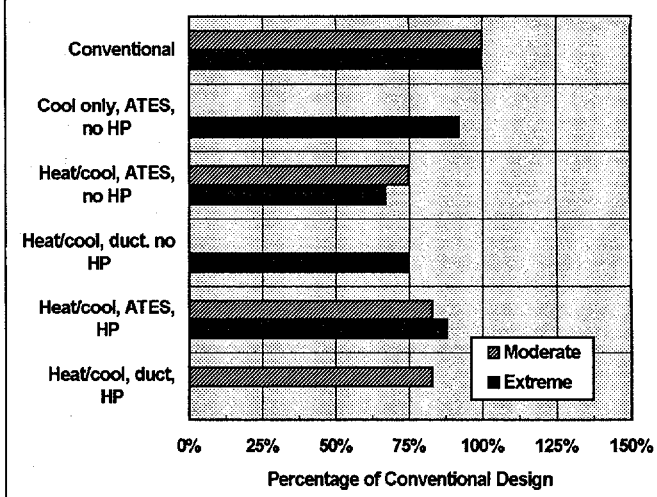



### Process Cooling, Example of the Winpak Plant

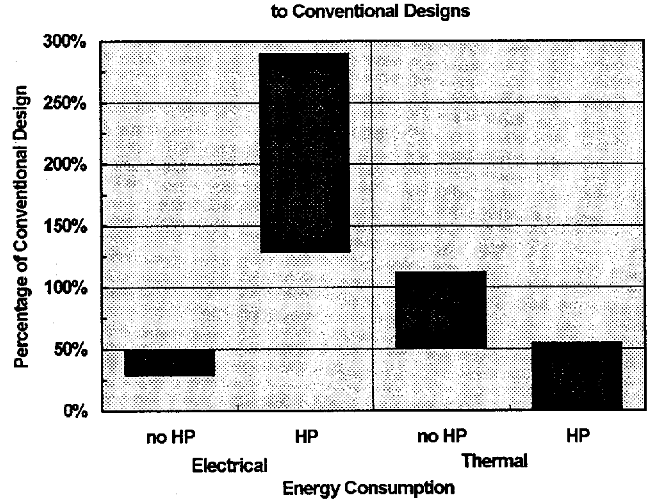
Winpak Limited of Winnipeg, Manitoba, is a manufacturer of high barrier polyethylene laminates for packaging of food products. Like many other businesses and institutions in Winnipeg, Winpak has found it profitable to rely on groundwater for cooling and heating at its offices and manufacturing facilities.

The original plant, constructed in 1975, included a well water system tapping into the extensive aquifers underlying the city of Winnipeg and much of Southern Manitoba. A 1986 expansion doubled the manufacturing capacity and added 7 000 $m^2$ of floor area, bringing the total to 23 000 $m^2$. The increased process cooling demand was met very economically by increasing the capacity of the existing groundwater system, instead of adding mechanical cooling. The groundwater system avoided investment in 350 tons of mechanical space cooling capacity costing $420 000, and 72 tons of mechanical process cooling capacity costing $87 000.

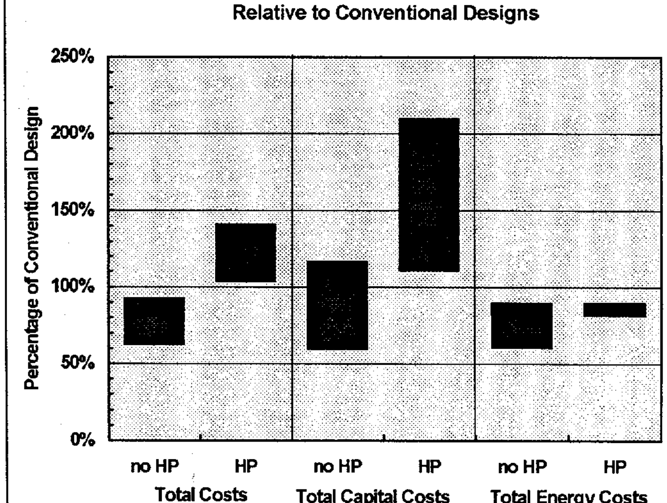
**Annual Energy Costs (Retrofit Buildings) All Cases, with Country Locations**




**Energy Performance Ranges for Storage Configurations Relative to Conventional Designs**




**Cost Peformance Ranges for Storage Configurations Relative to Conventional Designs**



The system does not require a heat pump. Process and space cooling loads are met directly at the aquifer supply temperature, while space preheating is provided in winter heat recovery mode, with main space heating provided by an existing gas-fired boiler. This system is applicable to most commercial, industrial, and institutional facilities that have a suitable supply of groundwater.

Annual savings in energy and utility demand charges of this system are approximately $45 000. Since the best alternative system was more expensive by $398 600, the payback was immediate. Potential users should note that these dramatic savings are evidence that combining cooling with preheating using groundwater heat recovery is cost-effective. This could well be the best way of meeting expanding demands in existing facilities. Even retrofit of existing mechanical systems would seem to offer attractive paybacks of less than three years.

An important benefit of winter heat recovery is that it lowers aquifer temperatures, thus balancing summer cooling use to a greater or lesser extent. This will slow down or stop the gradual temperature rise of an aquifer used only for cooling, allowing the aquifer to be used as a renewable resource on a permanent basis.

The system has performed admirably with nothing more than routine pump seal and bearing maintenance. The absence of mechanical chillers and cooling towers means that maintenance and repair costs are reduced. Once a year, a one-day shutdown takes place to allow heat exchanger service with high pressure cleansing solution.

Process cooling is done with a conventional heat exchanger, while space cooling makes use of groundwater directly in the ventilation system cooling coils. A glycol heat exchange loop transfers heat to the preheating coils. This allows groundwater return temperatures to be precisely maintained within a few degrees above freezing, and provides preheating in very cold weather without danger of coil freezeup. Using this glycol loop, Winpak's winter return water temperature has been reduced from 14 °C to as low as 2 °C.

On an annual basis more heat is injected into the aquifer than is drawn out. In nine years of process cooling at Winpak, a steady temperature rise in the aquifer supply temperature from 5.6 °C to 9.0 °C had been observed. This temperature rise was due to the use of the water for cooling by Winpak and by neighbouring plants and buildings using aquifer water for cooling. Over the past few years many users in the city of Winnipeg have reported higher aquifer source temperatures.

After the startup of the increased capacity system with winter heat recovery, the supply temperature has dropped back by 1 °C and is now holding at that level. This indicates that the aquifer's life as a useful sink of waste heat from process and space cooling may be indefinitely extended as a result of the winter heat recovery.

| **Groundwater System Costs** | **WINPAK** |
|---|---|
| ***Interior System*** | |
| heat exchangers | $16 000 |
| pumps and controls | $ 6 000 |
| piping and installation | $10 000 |
| equipment installation | $ 4 000 |
| **Total Interior** | **$36 000** |
| ***Exterior System*** | |
| wells and pumps | $78 000 |
| service lines | $15 000 |
| **Total Exterior** | **$93 000** |
| ***Total System Cost*** | ***$129 000*** |

| **Groundwater Savings** | **WINPAK** |
|---|---|
| ***Cooling Savings:*** | |
| equipment cost avoidance | $398 600 |
| annual demand charge avoided | $ 14 800 |
| annual consumption avoided | $ 14 425 |
| ***Heating Savings:*** | |
| annual gas consumption avoided | $ 15 600 |
| ***Overall Savings:*** | |
| equipment investment avoidance | **$398 600** |
| annual operating cost avoidance | **$ 44 825** |

## Environmental Aspects

Environmental emission levels were calculated for the building applications based on differences in energy consumption between the conventional designs and the storage designs. Emissions were estimated using national average emissions per unit of energy used (electricity, oil, gas, district heating).

Generally emission levels of $CO_2$, $SO_2$ and $NO_x$ are significantly lower for the storage design cases as compared to the conventional designs. One design (heating and cooling, with duct storage and no heat pump) in Sweden exhibited higher emissions because the storage design required higher levels of thermal energy. Storage designs without heat pumps also have the environmental advantage that CFCs in the chillers of the conventional design are eliminated.

Based on the analyses of these cases, it is concluded that seasonal thermal energy storage (STES) for cooling only, and for heating and cooling applications of buildings, is attractive as compared to conventional system designs especially for storage designs without heat pumps. For a continuous cooling load such as an industrial process, the application of STES designs in very attractive as compared to conventional designs based on the use of chillers [1] [8] [9].

## CONCLUSIONS

Thermal energy cold storage projects have aquifers as the dominant storage medium, but soil is also used. Projects with aquifer storage tend to have higher cooling capacities and cold stored per cycle.

For the building applications studied the total energy cost of the storage design is less than that for the conventional design in all cases. Electrical energy consumption is higher for the storage design cases which include heat pumps, but significantly lower for storage designs without heat pumps. Thermal energy consumption is lower for the storage with heat pump cases, but is generally about the same in the designs without heat pumps.

Capital cost is higher for the heat pump cases but generally lower in the designs without heat pumps. Total (energy and annualized capital) cost is higher for the designs with heat pumps, but lower for the designs without heat pumps. In the building applications analyzed, the relative difference between new and retrofit applications is negligible, as is the relative difference due to the two climates. Paybacks of recent realized and planned projects are often at five years or less.

For the process cooling load application electrical energy consumption (and cost) are significantly reduced in the storage design as compared to the conventional design. Capital costs are slightly higher for the storage design, but total costs are significantly lower. There are significant differences between the moderate climate and the extreme climate simulations due to the level of "free cooling" that is available in each climate--free cooling satisfies more of the cooling demand in the extreme climate so that the energy savings possible from eliminating the chiller in the extreme climate is more limited.

Emission levels of $CO_2$, $SO_2$ and $NO_x$ are significantly lower for the storage design cases. Storage designs without heat pumps also have the environmental advantage that CFCs in the chillers of the conventional design are eliminated. The source of the electricity (nuclear, hydro or thermal) is a significant factor in comparing storage with and without heat pumps.

It is concluded that seasonal thermal energy storage (STES) for cooling only, and for heating and cooling applications of buildings, is attractive as compared to conventional system designs especially for storage designs without heat pumps. For a continuous cooling load such as an industrial process, the application of STES designs is very attractive as compared to conventional designs based on the use of chillers.

## REFERENCES

[1]. Innovative and Cost-effective Seasonal Cold Storage Applications, Summary of National State-of-the-Art Reviews, International Energy Agency, Energy Conservation Through Energy Storage Implementing Agreement (Annex 7), Public Works Canada, PWC/RDD/96E, Ottawa K1A 0M2, June 1992, 41 p.

[2]. Procedures for the Environmental Impact Assessment of Aquifer Thermal Energy Storage, Environment Canada and Public Works and Government Services Canada, E. Morofsky (Ed.), PWC/RDD/106E, 75 p., Ottawa K1A 0M2, 1994.

[3]. Proceedings of Workshop on Design and Construction of Water Wells for ATES, C. Mirza (Ed.), International Energy Agency, Energy Conservation Through Energy Storage Implementing Agreement (Annex 6 - Environmental and chemical aspects of thermal energy storage in aquifers and research and development of water treatment methods), Report 41-E, August 1992, 184 p, the Netherlands.

[4]. Scaling and Corrosion, International Energy Agency, Energy Conservation Through Energy Storage Implementing Agreement (Annex 6 - Environmental and chemical aspects of thermal energy storage in aquifers and research and development of water treatment methods), Olof Andersson (Ed.) Report 38-E, 102 p, 1993.

[5]. Workshop on Generic Configurations of Seasonal Cold Storage Applications, International Energy Agency, Energy Conservation Through Energy Storage Implementing Agreement (Annex 7), Public Works Canada, PWC/RDD/89E, Ottawa K1A 0M2, September 1991, 89 p.

[6]. Design and Construction of Earth Energy Heat Pump Systems for Commercial and Institutional Buildings, Canadian Standards Association, C447-93, Rexdale, Ontario.

[7]. Environmental Risk Assessment for Aquifer Thermal Energy Storage, S. H. Hall, Pacific Northwest Laboratory, PNL-8365, Richland WA, January 1993.

[8]. Groundwater Heat exchange for Heating and Cooling in an Industrial Plant, Winnipeg Manitoba, STES Newsletter April 1990, Vol. XI, No. 4, E. Morofsky (Editor), 1-2.

[9]. Calorstock'94 Proceedings (2 volumes) available from the Helsinki University of Technology, Department of Technical Physics, FIN-02150 Espoo Finland; Fax: +358-0-451 3195: CALORSTOCK'94; THERMAL ENERGY STORAGE Better Economy, Environment, Technology; 6th International Conference on Thermal Energy Storage; ISBN 951-22-2223-X, Helsinki, Editors M. T. Kangas and P. D. Lund.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# Optimizing the Design and Operation of ATES Systems


• Lance W. Vail
Pacific Northwest Laboratory
Richland, Washington, USA
• Everett A. Jenne
Pacific Northwest Laboratory
Richland, Washington, USA



ABSTRACT

The design of Aquifer Thermal Energy Storage (ATES) systems is complicated by significant uncertainties in our ability to reliably predict the response of the aquifer to fluid and thermal fluxes. Overdesigning the system, to compensate for these uncertainties, reduces the potential economic and energy benefits of an ATES system. Underdesigning the system results in systems that fail to meet design targets. Unfortunately, standard aquifer characterization methods and hydrologic models do not provide adequate information to overcome these uncertainties. Thus, expensive full-scale tests are generally recommended to develop an adequate understanding of the systems' response. However, the standard engineering "design-build-operate" process is not appropriate for ATES systems because an optimal design cannot be completed without some operational experience, i.e., field tests. A more adaptive engineering process is required. This engineering process should be flexible enough to allow the design to be adjusted during the operation, as monitoring data become available and as an understanding of the system response increases. Engineering approaches being developed for environmental restoration of contaminated soil and groundwater can be adapted to optimally design and operate ATES systems.


INTRODUCTION

Aquifer Thermal Energy Storage (ATES) was proposed in the early 1970s [1,2]. Early estimates suggested that ATES could have a significant impact on the United States energy consumption. However, although several million dollars have been spent in ATES research, only one ATES system is currently in operation in the United States. The negligible penetration of ATES into the United States energy market resulted from relatively low energy prices and the unwillingness of the building energy technical community to accept the real risk of ATES systems failing to meet design goals. To reduce this risk, methods for dealing with the uncertainty of an ATES system's response must be employed.

Early assessments of ATES systematically overestimated the performance of ATES systems by neglecting to thoroughly address the variety of uncertainties that impact both the performance of the aquifer and the associated delivery/supply system. Uncertainties in aquifer response to thermal and fluid loads include:

- hydraulic conductivity
- porosity
- aquifer/strata thickness(es), and
- boundary conditions, such as recharge rates, transient piezometric heads.

For instance, early assessments were based on model simulations in which the aquifer was assumed to be homogeneous. Field experiments quickly showed that the level of stratification common to most shallow alluvial aquifers has a significant impact on the aquifer's thermal performance. Subsequent modeling studies confirmed this finding [3]. Early modeling studies also underestimated the impact of regional groundwater flow of many of the most readily accessible aquifers (i.e., shallow unconfined aquifers) on thermal recovery efficiency.

Uncertainty in the delivery and supply system performance also impacts the system design. Such uncertainties include:

- chemical treatment requirements
- transient nature of energy supply
- transient nature of energy demand
- transient nature of the recovery temperature.

Many of the early evaluations of ATES designs assumed that a constant recovery temperature would be servicing a steady demand. Such an assumption clearly overestimated the system's performance. Designers aware of these assumptions were obligated to overdesign the system. Overdesigning often resulted in systems that were no longer economically justified.

An alternative to overdesigning the system to compensate for uncertainties in the aquifer system's response is to further characterize the aquifer (e.g., pump tests, geophysical logging). However, even after extensive characterization, the ability to predict the aquifer's response is still limited. A characterization effort of sufficient magnitude to reduce the need for overdesign is likely to result in overcharacterization, hence in unnecessary cost. Characterization should be limited to the amount that can be expected to provide increased return on investment (i.e., the cost-benefit ratio of reduced risk of system failure) that is greater than the cost of the characterization itself.

The uncertainties mentioned above make the cost-effective design of an ATES system difficult. The design process must provide enough flexibility to allow the operating strategy, and any subsequent design opportunities, to be adapted to new knowledge gathered during the operation. Most of the uncertainties in aquifer response, as well as many demand or supply uncertainties, are commonly encountered in other fields, as discussed below.

## RELATED DESIGN EXPERIENCE

Approaches originally designed to reduce costs while meeting design criteria for foundation stability have undergone major development for the design and operation of systems to cleanup contaminated aquifers. These approaches (discussed below) and tools (e.g., models) are readily adapted to the design and operation of ATES systems. The techniques discussed here explicitly consider the impact of uncertainty on the design process.

### Observational Approach

The Observational Approach was put forward by Karl Terzaghi and further developed by Peck [4] as a means of balancing characterization costs and the residual characterization uncertainty relative to the stability of foundations and earthen works. This approach has been applied to groundwater monitoring problems [5] and to environmental restoration problems [6]. The National Research Council, the U.S. Department of Energy (DOE), and the U.S. Environmental Protection Agency (EPA) have encouraged application of this method to subsurface remediation. It provides a framework for managing uncertainty and planning decision-making on an iterative basis throughout the life of a project. The merit of the observational approach lies in two cost reduction aspects. First, the approach explicitly recognizes that it is cost-effective to postpone some decisions until after portions of the construction have been completed, using the information gained to increase understanding of the environment. Second, uncertainty in earth material properties is managed in a cost-effective manner by planning alternatives that are allowed for in the original construction and are only implemented when, and if, required.

The Observational Approach applied to ATES involves collecting and reviewing available regional records of wells drilled in the same formation(s) to determine the range in variables of interest, e.g., thickness of strata, frequency of occurrence of high and low porosity and permeability layers, ranges and distribution of hydraulic conductivity and porosity, and water chemistry. This information is used to derive a conceptual model of the aquifer system including fluid, energy, and geochemical aspects. A mathematical model of groundwater flow and energy transport can be used to estimate unmeasured parameters (e.g., head, velocity) for numerous equally-feasible realizations of the subsurface environment once adequate characterization data is available. These results can also help define future characterization data needs. The conceptual model will include recharge and discharge locations and processes, the relative importance of different zones, and any important water chemistry interactions (such as clay dispersal if Na-exchange is to be used to avoid carbonate scaling). Conceptual model development is followed by limited initial site characterization if information from wells drilled locally is unavailable or is clearly insufficient. This characterization will use information derived from wells that are intended for subsequent use for monitoring, injection, or recovery. The conceptual groundwater model is iteratively refined as characterization information is acquired.

An important aspect of the Observational Approach, as developed by Terzaghi and used in environmental restoration, is the formulation of alternatives in the design stage as opposed to after the low-probability failure has occurred. Design decisions are made with the full intent to modify them as characterization and monitoring information becomes available as construction and installation proceeds. As D'Appolonia [5] pointed out, "The essential ingredient, without which all the others may lead to nothing, is the visualization of all possible eventualities and the preparation in advance of courses of action to meet whatever situation develops."

A relatively direct application of the Observational Approach to ATES would involve the development of risk identification and risk management matrices. Table 1 shows an example of such a matrix. The objective of this matrix is to identify all significant risks and their respective likelihood; of occurring. This is followed by the development of a risk management matrix (Table 2). This matrix clearly identifies the contingent actions that are triggered when a specific event has occurred. It also defines the preventive actions that reduce the likelihood that the risk will occur. Table 3 identifies some of the risks and possible preventive actions and design contingencies to mitigate identified risks.

### Data Quality Objectives

The Data Quality Objectives (DQO) approach establishes the quality and quantity of data required for resolving a given problem by formalizing the linkage between data collection and decision-making. The purpose of Data Quality Objectives is to "Specify the decision maker's acceptable limits on decision errors, which are used to establish appropriate performance goals for limiting uncertainty in the data." [7]. The EPA [7] defines five steps to accomplish this purpose:

- determine the possible range of the parameter of concern
- identify the potential consequences of error of hypothesis testing
- specify a range of possible parameter values over which the consequences of decision errors are relatively minor
- assign probability values to points above and below the action level that reflect the acceptable probability for the occurrence of decision errors
- check the limits on decision errors to ensure that they accurately reflect the decision maker's concern about the relative consequences for each type of decision error.

These activities follow the development of a decision rule. To limit both costs and the likelihood of making decision errors, the acceptable probabilities of decision errors are defined. This allows the design to be optimized with iteration between decision error probability definition and design optimization.

Data Quality Objectives can provide guidance on the quantity and frequency of characterization data required to provide statistically valid data on which to base ATES design decisions. For instance, one could define the number of ambient water chemistry samples required to design a water treatment system for an ATES facility. Whereas Data Quality Objectives focus on overcoming analytical measurement errors, the focus would shift to sampling and modeling errors for ATES systems.

## Streamlined Approach for Environmental Restoration

A Streamlined Approach for Environmental Restoration (SAFER) was developed in response to the DOE's recognition of the need for increased speed and cost-effectiveness of environmental restoration. It is a methodology that integrates the quantitative tools of the Data Quality Objectives with the qualitative philosophy implicit in the Observational Approach [6]. SAFER explicitly recognizes the inherent uncertainty of groundwater flow and composition. An important concept of SAFER is an emphasis on quantitatively defining the adequacy of site characterization data by means of a decision rule. The rationale for the decision rule is that it specifies the level of data adequacy that will reduce the residual uncertainty to some acceptable level for decision-making. The intent is to link the hydrologic uncertainty and the objective function to data requirements. This must be done iteratively as data availability increases and the conceptual model is refined. Probable conditions are identified, and the level of certainty is determined by the decision rule. The acceptable uncertainty is viewed as deviations from the probable conditions and contingency plans are developed to deal with deviations from the probable conditions.

## Adaptive Management

Another relevant approach called Adaptive Management comes from the field of ecosystem management. Adaptive Management was developed by a team of biologists and systems analysts in the 1970s [8]. Adaptive management employs deliberate experimentation to improve the understanding of the ecosystem behavior while attempting to avoid adversely effecting the ecosystem. A similar approach called 'dual control' has been developed in the field of electrical engineering.

In the design of ATES systems, Adaptive Management encourages the ATES designer to proceed with deliberate experimentation (e.g., field tests) that improve knowledge of aquifer response with minimum adverse effects (e.g., poor thermal efficiency, high costs) on the performance of the system. This requires balancing a potential decrease in efficiency with the need to gain knowledge of the system.

## Integrated Environmental Monitoring

The Integrated Environmental Monitoring Initiative is a current Pacific Northwest Laboratory initiative to develop an integrated framework for the design of monitoring systems. The framework (Figure 1) identifies the process involved in defining the tradeoffs between multiple objectives. The ATES system designer selects optimized designs once the design objectives are established. The optimized designs are flexible and adjust to the results of the deliberate experiments included in the design. Integrated Environmental Monitoring provides a formal and quantitative framework consistent with the Observational Approach, Data Quality Objectives, SAFER, and Adaptive Management.

The Integrated Environmental Monitoring framework includes the requirement specifications for a variety of software tools including physically based models, optimization methods (e.g., genetic algorithms, dynamic programming), uncertainty assessment tools (e.g., geostatistical software), database management systems, and visualization tools. A model of uncertainty is a critical element of the Integrated Environmental Monitoring framework. Such a model of uncertainty embeds both expert judgment and the results of probabilistic and statistical analyses. Integrated Environmental Monitoring provides a framework to evaluate the worth of additional data by relating the reduction of uncertainty to expected changes in each of the objectives. Relevant uncertainty models for ATES need to be developed.

## Aquifer Thermal Energy Storage System Simulator

The Aquifer Thermal Energy Storage System Simulator [9, 10] provides ATES designers with a user-friendly, interactive model using a simple aquifer and aboveground heat transfer compartments. It is intended to evaluate energy recovery as a function of interrelationships among design specifications, operational strategies, and variable energy usage rates. The aboveground compartment exchanges heat between the aquifer and distribution fluid and includes energy demand loads. The aquifer compartment assumes perfect stratification (e.g., it does not consider buoyancy, thus large-scale convective mixing is not simulated) and transfers heat by horizontal convection and vertical conduction within the storage layer(s). The three-dimensional flow is conceptualized as a set of two-dimensional streamline planes, i.e., a vertical projection of a fluid volume moving away perpendicular to a storage well. Diffusion (or dispersion) coefficients need not be estimated; the dispersive effects indicated in model results arise primarily from the variability in the hydraulic conductivity values. The consequences to energy recovery of the number of aquifer layers in which thermally altered water is stored can be readily examined with this model. Stochastic generators (crude uncertainty models) for system inputs (energy for storage) and outputs (demand for energy), available in earlier versions of the model, have been removed until better uncertainty models become available. This simulator does not consider the uncertainty in aquifer parameters (e.g., hydraulic conductivity, porosity).

## CONCLUSIONS

ATES is a technology whose cost-effectiveness is increased by deploying it in steps that are consistent with monitoring and deliberate experimentation. An expansion of ATES capacity in steps provides an opportunity to adapt to the improved understanding that occurs during operation and probing of the system before the capacity expansion phase and additional characterization that results from it.

Development of an ATES system in steps is not always consistent with the demand that the system it is intended to supply. In many facilities, the building energy infrastructure is considered a one-time capital investment. If it is not feasible for the demand to increase in steps as the ATES capacity is expanded, temporary backup energy sources must be included in the design. Typical periods of expected return on investment are too short to justify investing in the required temporary capacity. Energy system opportunities that are amenable to capacity expansion in steps should be targeted to facilitate the penetration of the energy market by ATES systems.

## ACKNOWLEDGMENT

Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

## REFERENCES

1. C.F. Meyer, and D.K. Todd, 1973, "Conserving Energy with Heat Storage Wells, Environmental Science and Technology, Vol. 7, No. 6, p. 512-516.

2. R.G. Kazmann, 1971,"Exotic Uses of Aquifers" American Society of Civil Engineers Journal of the Irrigation and Drainage Division Vol. 97, No IR3, p. 515-522.

3. L.D. Kannberg and L.W. Vail, 1987, "Effects of Stratification on Thermal Energy Storage" in Proceedings of the 22nd Intersociety Energy Conversion Engineering Conference, p. 1288-1292, American Institute of Aeronautics and Astronautics, New York.

4. R.B. Peck, 1969, "Advantages and Limitations of Observational Method in Applied Soil Mechanics", Geotechnique, Vol. 19 p. 171-187.

5. E. D'Appolonia, 1990, "Monitored Decisions", Journal of Geotechnical Engineering, Vol. 116, p. 4-34.

6. J.D. Symth, J.P Amaya, and M.S. Peffers, 1992, "DOE Developments: Observational Approach Implementation at DOE Facilities", Federal Facilities Environmental Journal, p. 345-355.

7. United States Environmental Protection Agency, 1993, EPA/540/G-93/071.

8. C.S. Holling, 1978, Adaptive Environmental Management. John Wiley and Sons., New York.

9. L.W. Vail, L.D. Kannberg, and C.T. Kincaid, 1985, "A Computer Code for Analyzing the Performance of Aquifer Thermal Energy Storage Systems", in Proceedings of the International Conference on Energy Storage for Building Heating and Cooling, ENERSTOCK 85, p. 144-148, Public Works Canada, Toronto, Canada.

10. L.W. Vail, 1989, "ATES/Heat Pump Simulations Performed with the ATESSS Code" in Proceedings of the Third Workshop on Solar-Assisted Heat Pumps with Ground-Coupled Storage, Gotenberg, Sweden.

Table 1. Risk Identification Matrix

| Identified Risk | Likelihood of Occurrence | Difficulty of Timely Detection | Potential Impact | Overall Risk to Project |
|---|---|---|---|---|
| | | | | |
| | | | | |

Table 2. Risk Management Matrix

| Identified Risk | Preventive Action | Contingency Action | Trigger |
|---|---|---|---|
| | | | |
| | | | |

Table 3. Examples of Risks and Preventive/Contingency Designs/Plans

| Risk | Preventive/Contingency Design |
|---|---|
| Improper well field design | Flexible piping design (capability to use any specific well for storage or injection during any period) |
| Higher than expected regional flow | Flexible piping, New wells |
| Lower than expected recovery temperature | Backup units, Selective withdrawal |
| Underdesigned for peak capacity | Short-term storage |

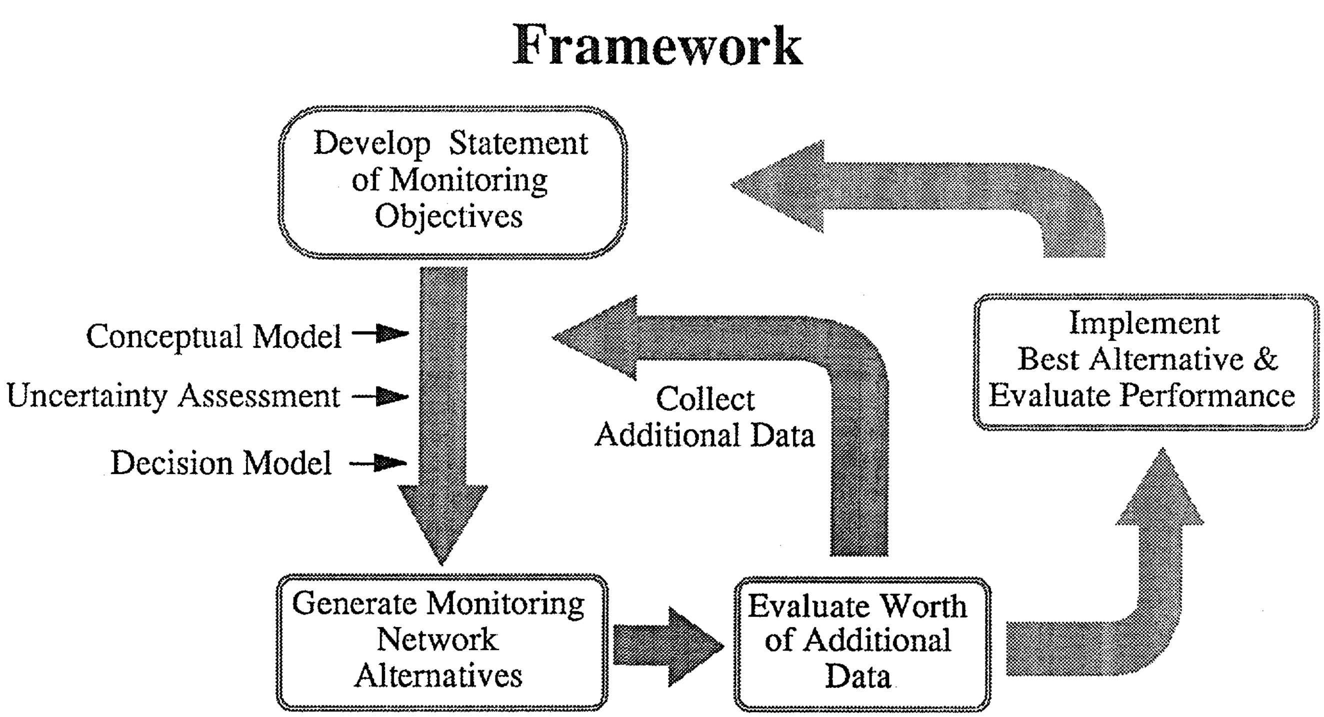



Figure 1. Integrated Environmental Monitoring Components

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Design and System Integration of Groundwater Heating and Cooling Plants

• Jan Reffstrup
Laboratory for Energetics
Technical University of Denmark
Lyngby, Denmark
• Stig N. Sørensen
Energy and Environmental Consulting
Gentofte, Denmark
• Bjørn Qvale
Laboratory for Energetics
Technical University of Denmark
Lyngby, Denmark

## ABSTRACT

Groundwater reservoirs are being used more and more frequently as a component in energy supply systems, e.g. as a storage unit for warm or chilled water or as a direct source in heat-pump plants and cooling systems.

An optimal design of systems utilizing groundwater reservoirs as a system unit is important from both an economic and environmental point of view.

When using the aquifer as a storage unit in the energy system, the objective is to minimize the energy exchange with the surroundings to optimize the storage efficiency.

When used as a direct source in connection with heat-pumps or cooling systems, energy is withdrawn from the aquifer and the objective in the design phase is to ensure efficient energy recharge by energy inflow from the surroundings.

This paper focuses on the design criteria for energy systems using groundwater as a direct source, i.e. heating systems based on the application of heat-pumps and cooling systems using groundwater as cooling media. Examples of system integration of aquifers with heat-pumps and cooling units are discussed.

Furthermore, simplified models to predict the thermal behavior of the aquifer as a system unit are presented including models for both the double-well system with pumping from one well and reinjection through a second well, and for single well systems where groundwater is pumped and reinjected at different levels in the same well. The model for the double-well configuration describes the transient development of the temperature of the produced groundwater, whereas the model for the single-well configuration can be used to calculate the steady-state operational conditions for the plant.

The determination of the horizontal to vertical permeability in the reservoir is essential for predicting the long-term operation conditions of the single-well configuration and a simple flow model which has been developed particularly for this use is described in the paper.

Likewise, the heat exchange with the surroundings is very important for the prediction of the long-term operation of the double-well configuration, and a simplified approach to estimate long term operational conditions is described.

The paper gives a comparison between experimental results obtained from field experiments and data obtained from model calculations and summarizes the conclusions from Danish experiences from more than 200 groundwater heat-pumps and experimental results from the groundwater heat-pump test facility at the Technical University of Denmark.

Finally, the results from a feasibility study of the integration of a groundwater cooling system in a plastic factory are presented.

## INTRODUCTION

The use of aquifers for thermal energy (heat) storage (ATES) and cold storage has been investigated intensively over the last two decades and the technology is now ready for commercial use.

In many respects energy systems based on the use of aquifers represent a promising alternative to traditional commercial energy systems for heating and cooling.

Groundwater has the advantage that the temperature of the groundwater reservoirs is approximately constant throughout the year. Near the surface the reservoir temperature is equal to the average air temperature at the surface.

The aquifer may be included in the energy system as a storage unit [1] or as the primary energy source/sink [2] or as a combination of both.

When the aquifer is used as a storage unit for warm or cold water, the warm or cold water is injected into the aquifer during the storage period, where it will warm up or cool down the porous structure. When water is then again withdrawn from the aquifer, warm or cold water is regenerated as groundwater passes through the porous matrix and flows to the well.

When the aquifer is used as a direct source in the energy system, native groundwater is withdrawn from the aquifer and used in combination with heat-pumps, where heat exchange takes place in the heat-pump evaporator. The cooled groundwater is then returned to the aquifer after having passed the evaporator.

The reinjected cooled groundwater will be reheated in the aquifer zone by heat influx primarily from the surface. Hence the aquifer acts as a kind of solar-heat collector.

When the aquifer is used as a storage unit the flow must be controlled in such a way that the heat exchange with the surroundings is minimized in order to maintain a high storage efficiency and minimize the environmental impact. In most cases this will imply a design that will give a minimum surface of the aquifer storage zone relative to the volume.

With the use of the aquifer as direct energy source in connection with heat-pumps or for process cooling, it is important to control the groundwater flow so that the reinjected water will be reheated before reaching the pumping well in order to avoid thermal short circuiting of the wells. This will, on the other hand, require that the surface to volume ratio of the effective aquifer zone is large.

With the operational conditions existing in Denmark the use of electrically driven groundwater heat-pumps for room heating can give a reduction in primary energy use of approximately 25% in comparison to heating by individual gasoline furnaces.

Use of groundwater for cooling, replacing conventional CFC-plants, means a reduction in primary energy consumption of 40-85%. In many ways such cooling systems appears to be very promising both from an economical and environmental point of view.

## SYSTEM CONFIGURATIONS

The design of an integrated energy system includes two subsystems: the energy exchange system in the form of heat exchangers etc. at the users end and the aquifer with pumping and injection wells at the producers end.

The energy exchange units may be organized in a number of different ways. The goal is to introduce units that give an optimal integration with the users own cooling or heating systems.

The present section will give an overview of some of the different system configurations that can be used to couple the well units and the user's cooling or heating system.

In principle, two different well configurations can be used: The double-well system where pumping and injection takes place in two different wells and the single-well system where a single well is operated as both pumping and injection well.

The natural heat stored in groundwater aquifers is most commonly utilized for heating single-family houses by the help of electrically driven heat-pumps. Groundwater is circulated from a pumping well through the evaporator of the heat-pump to an injection well as illustrated in figure 1. In the evaporator the groundwater is cooled 2-6 °C depending on the flow rate of the groundwater.

In climates with moderate and low groundwater temperatures, the groundwater can be utilized directly as a source of process cooling or air conditioning as illustrated on figure 2 and 3. In such systems, the groundwater is led to a heat exchanger where it acts as a heat sink and the temperature is raised a few deg. C and then injected through the injection well.

Figures 1-3 all illustrate through-flow systems where the groundwater is pumped only in one direction. However, in climates where the natural groundwater temperature is too high to be utilized directly for cooling, it will be necessary to artificially lower the temperature of the water from the aquifer.

This can be done by using cold outdoor air in the winter time or during night hours to precool the groundwater and then store the cooled groundwater for e.g. use in the summer time by air conditioning systems. The principle for cooling groundwater by outdoor air is shown in figure 4.

A combination of the systems in figure 3 and 4 normally demands groundwater flow in one direction under air conditioning mode and reversed flow direction under cold store mode.

## THE DOUBLE-WELL CONCEPT

### Models for predicting operational conditions.

In the double-well concept, pumping and injection take place through two separate wells. Whether the groundwater is used for heating or for cooling the design of the plant must safeguard against a short circuit by the injected water, that will prevent the plant from reaching an acceptable thermal equilibrium state. When short-circuiting occurs the groundwater injected through the injection well will reach the pumping well before it has reached the original groundwater temperature and the temperature of the pumped groundwater will decrease in a groundwater heat-pump mode and increase in cooling mode unless the natural groundwater flow is sufficient to prevent overflow.

Normally, a certain overflow from the injection well to the pumping well can not be avoided completely but must be controlled.

The parameters that affect overflow are: 1) Position of the wells relative to the natural flow direction of the groundwater. 2) The distance between the wells. 3) Pumping and recharge rates. 4) Reservoir thickness.

In areas with sufficiently strong natural groundwater flow, it may be possible to completely avoid overflow between a pair of wells and thus avoid a thermal coupling between the wells. The overflow is prevented if the injection well is positioned downstream of the pumping well and the distance between the wells or the pumping rate is adjusted properly in according with the natural flow gradient.

Dacosta and Bennett [3] have analyzed the flow fields associated with overflow phenomena using potential flow theory for different regional flow fields, pumping rates and geometries. Figure 5 illustrates a situation of partial overflow between a pumping well and an injection well. In the figure the direction of the areal flow is perpendicular to the connecting line between the two wells. The figure illustrates that only part of the injected water will reach the pumping well. Dacosta and Bennett developed a general procedure to predict the overflow where the overflow is defined as the relative amount of recharged water that will reach the pumping well.

The overflow in the dipole configuration can be expressed as a percentage of the total amount of reinjected water and can be presented as a function of the angle $\beta$ between the direction of the regional flow and the line connecting the two wells for different values of a dimensionless pumping rate that is defined by:

$$\tilde{V}=\frac{2}{\pi}\frac{\dot{V}}{H_a D v_o} \qquad (1)$$

The direction of the regional groundwater flow is defined relative to the line between the pumping and the injection well as illustrated in figure 6.

The results from Dacosta and Bennett [3] is presented in figure 7. Zero or negative overflow indicates that overflow will not occur. Negative overflow is a non-physical result.

If the well pair is placed in an area without a considerable groundwater flow, overflow from the injection well to the pumping well can not be avoided. In order to analyze this situation a mathematical model [4] was developed by which the temperature of water produced could be predicted.

The model developed is an extension of the model by Gringarten and Sauty [5] that was intended for geothermal reservoirs. In their model, energy transport in the geothermal reservoir was described by a simplified model where energy transport horizontally in the reservoir was assumed to be due to advection only (carried with the flowing fluid). Energy inflow from upper and lower confining layers was included by introducing analytical expressions for a one-dimensional vertical flow of heat in these layers. Their model used confining layers of infinite extension.

The extension of this model to groundwater aquifers was based on the following assumptions:

The groundwater aquifer was assumed horizontal with constant height $H_a$ identical to the perforation length. The upper and lower confining layers were assumed impermeable.

The flow in the groundwater zone was assumed to be steady, since transient flow periods were short relative to the lifetime of the system. The pumping/injection rate $\dot{V}$ was assumed constant.

The initial temperature was assumed constant and equal to $T_o$ (the average surface temperature). The thermal equilibrium between the water and the porous structure was assumed to be instantaneous. This corresponds to assuming a heat transfer coefficient of infinite magnitude between the fluid and the porous structure.

Heat conductivity in the aquifer in the horizontal direction was neglected. Hence, horizontal energy transport in the reservoir was assumed to be due to advection only. The temperature was assumed constant in vertical cross sections of the aquifer.

Furthermore, horizontal heat flow in the confining layer was neglected, i.e. only vertical heat flow was considered. The upper confining layer was assumed to be of finite thickness $H_c$, whereas the lower confining layer was assumed to extend to infinity. The magnitude of energy inflow due to a geothermal gradient was estimated at less than 10% of the energy inflow from the surface. Heat flow due to the geothermal gradient was thus disregarded.

The volumetric heat capacity and the heat conductivity were assumed constant and identical for the aquifer and the confining layers.

The decrease of the temperature of the water flowing through the evaporator of the heat-pump was assumed constant and equal to the measured value. The net energy inflow was thus given by:

$$\dot{Q}=\dot{V}(\rho C)\,\Delta T_w \qquad (2)$$

When $\Delta T_w$ was the groundwater temperature change in the heat-pump evaporator.

The main difference between this model and the model developed by Gringarten and Sauty was that the upper confining layer in the aquifer model was of finite extension, whereas an infinitely extending layer was assumed for the geothermal reservoir model.

Gringarten and Sauty solved the problem analytically. In the present case a semi-analytical approach was used. The advective transport in the aquifer was modelled by a finite difference approach, whereas the vertical heat conduction in the upper and lower confining layers was modelled by analytical solutions to the one dimensional heat conduction problems. The temperature of the water leaving the pumping well was calculated by numerical integrating along the stream lines of the groundwater flow field. The streamlines describing the two-dimensional flow were obtained by a solution of the flow equations.

A detailed description of the model was given in [4].

A comparison between the approximate solution and the analytical solution for the geothermal reservoir problem described by [5] is shown in figure 8. In this comparison a large thickness of the upper confining layer was assumed for the aquifer model to conform with the assumptions of the geothermal reservoir model. Break-through was simulated using one, two and tree time steps respectively.

The numerical solution approaches the solution obtained by the analytical model as the number of time steps is increased.

The resulting dimensionless temperature of produced groundwater, which expresses the change in temperature of the produced groundwater relative to the change in temperature over the heat exchanger unit, has been plotted as a function of time. The initial value of the dimensionless recovery temperature will be zero and after the breakthrough from the injection well the dimensionless temperature of the produced groundwater will increase (the absolute value will decrease for a heat-pump plant and increase for cooling plant).

### Design principles for double-well systems.

In the design of systems based on the double-well configuration the design criteria will first of all depend on whether or not a sufficient regional groundwater flow is present. The main concern in both cases is, as mentioned previously, to ensure that the system will not short circuit thermally. If a sufficiently strong regional flow exists and the injection well of the double-well configuration is positioned down stream, the system may be designed in such a way that the injected water will never be able to reach the pumping well and there will be no overflow. If the wells, on the other hand, are placed in an area with little or no regional flow, overflow from the injection well to the pumping well can not be avoided. I this latter case, the effect of overflow must be estimated.

Systems with regional groundwater flow. The dimensioning of systems in areas with regional groundwater flow is based on the following main design parameters: 1) The required groundwater flow and temperature change by cooling or heating. 2) The hydraulic parameters of the aquifer (gradient, permeability, transmissivity, flow direction). 3) Relative position of wells.

Based on these key parameters the overflow from the injection to the production well can be estimated.

1) The required flow and temperature change of groundwater can be calculated based on the desired heating or cooling load from the groundwater system by the use of the energy equation:

$$\dot{Q}=\dot{V}(\rho C)_w \Delta T_w \qquad (3)$$

In this equation $\dot{Q}$ is the required heat flow, $\dot{V}$ the required flow of groundwater and $\Delta T_w$ the change in temperature in the system. If coupled directly to a heat-pump systems the flow and temperature change can be calculated by use of the heat-pump $COP_{HP}$ (coefficient of performance) and the heat production of the heat-pump as shown in figure 4.

$$\dot{V}=3600\cdot\frac{COP_{HP}-1}{COP_{HP}}\cdot\frac{\dot{Q}_{HP}}{\Delta T_w(\rho C)_w} \qquad (4)$$

2) The hydraulic parameters are given by the natural conditions. The average gradient and direction of the groundwater flow can, in principle, be estimated by measuring the water table in 3 wells surrounding the selected area. The overall transmissivity can be estimated from the results of well pumping tests. The in situ horizontal permeability can be evaluated from laboratory tests on borehole samples.

3) To completely avoid overflow the injection well must be situated downstream of the pumping well.

With these specifications the overflow can be estimated using the relationships developed dy Dacosta and Bennett [3]. The wells must be placed in a way that ensures $\beta < 90$ degrees as shown in figure 6. Simple performance considerations will normally ensure that this will be the case. The natural velocity of the groundwater $v_0$ is calculated by:

$$v_0=\frac{T_r}{H_a}\frac{dh}{dr} \qquad (5)$$

Using this relationship in the equation for the dimensionless flow rate gives:

$$\tilde{V}=\frac{2}{\pi}\frac{\dot{V}}{DT_r(\frac{dh}{dr})} \qquad (6)$$

The transmissivity $T_r$ can be determined by a pumping test. The natural flow gradient dh/dr can be calculated from water table measurements.
With a known value of $\beta$ and the dimensionless flow $\tilde{V}$ ,the overflow expressed in percentage can be estimated from figure 7.

If $\tilde{V} \leq 1.0$ the overflow is negative or zero for $\beta <$ 90 deg. and no further calculations are necessary. Negative overflow has a mathematical, but no physical meaning in this context. Conversely with $\tilde{V} <$ 1.0 and $\beta < 90$ deg the minimum distance between the wells to avoid overflow can be determined from (6).

$$D_{min}\geq\frac{2}{\pi}\frac{\dot{V}}{H_a v_0}=\frac{2}{\pi}\frac{\dot{V}}{T_r\frac{dh}{dr}} \qquad (7)$$

Systems without regional groundwater flow.
In the case of no or very week regional flow the thermal lifetime of the energy system must be calculated because in this case overflow will always occur. The thermal lifetime is defined as the time until the temperature level of the pumped groundwater falls below, in the case of heating, or rises above, in the case of cooling, a certain limit set by the heat-pump manufacturer, by the energy system or by environmental considerations.

The dimensionless temperature of groundwater produced, is defined as follows:

$$\tilde{T}=\frac{T-T_0}{\Delta T_w} \qquad (8)$$

In (8) T represents the temperature of produced groundwater, $\Delta T_w$ the temperature increase across the heat exchanger. This temperature difference is assumed constant. $T_0$ is the initial groundwater temperature. The temperature of produced water, T, will always be lower than the initial groundwater temperature in heat-pump mode and higher in cooling mode.

A dimensionless time corresponding to the dimensionless temperature was defined as follows:

$$\tilde{t}=t\frac{\alpha}{H_C^2} \tag{9}$$

A characteristic time for a given double-well configuration is the breakthrough time defined as the time for the thermal front to break through along the direct connecting line between the two wells. This breakthrough time can be related to the distance between the wells, the aquifer height and the pumping rate as follows [4],[5]:
Using the model for the double-well configuration

$$\tilde{t}_{bt}=\frac{\pi}{3}\frac{(\rho C)_a}{(\rho C)_w}\cdot\frac{H_a\alpha}{\dot{V}H_C^2}D^2 \tag{10}$$

described above, the relationship between the dimensionless production temperature and dimensionless time was calculated for different values of the dimensionless break-through time. This relationship is shown graphically in figure 9 for a fixed ratio between the aquifer height and the thickness of the upper confining layer of $H_a/H_c$= 0.7. The graph can be used directly in the design phase to calculate an expected variation of production temperature with time.

A criterion often used in the dimensioning of the double-well groundwater heat-pump configurations is a minimum allowable temperature, $T_{i,min}$, of the reinjected groundwater. Such a minimum value is often prescribed by the heat-pump manufacturers.

Given the value of $T_{i,min}$, the corresponding minimum the production temperature may be expressed as follows:

$$T_{\min}=T_{i,\min}-\Delta T_w \tag{11}$$

and the corresponding dimensionless minimum production temperature as:

$$\tilde{T}_{\min}=\frac{T_{i,\min}-\Delta T_w-T_0}{\Delta T_w}=\tilde{T}_{i,\min}-1 \tag{12}$$

With the known values of $\tilde{t}_{bt}$ and $\Delta T_w$ the dimensionless lifetime of the system can be obtained from figure 9.

Absolute values of the lifetime can be calculated from the definition of the dimensionless time as follows:

$$t_l=\tilde{t}_l\frac{H_C^2}{\alpha} \tag{13}$$

If the calculated lifetime is too short the distance between the wells must be increased or the wells must be relocated in a way that avoids overflow.

**THE SINGLE-WELL CONCEPT**

An alternative design to the double well design is to use a single well for both pumping and reinjection.

The principle of a single-well groundwater heat-pump plant is illustrated in figure 10.

This single-well configuration has many advantages over the double-well solution; primarily the potential for a lower cost of implementation and, in addition, that the thermal disturbance will be limited to a smaller area. However, the single-well concept requires a much more careful design and construction in order not to risk operational problems such as short-circuiting between the pumping and injection zones.

A limitation of the potential for implementing the single-well concept is the reservoir height. A minimum vertical separation distance between the pumping and injection sectors of the well is required.

If the heat source is insufficient, supplemental heating may be established for thermal recharge of the aquifer during off-season periods.

An example of a single-well plant with heat recharge is shown in figure 11. Here, the groundwater heat-pump supply system is extended with a low temperature solar collector, thus allowing operational conditions up to or above the natural groundwater temperature.

Recharge can be required at locations close to drinking water supply systems, where the groundwater supply system may be affected. Both by heat recharge and by heat storage the aim is to maintain the reservoir close to thermal balance with the surroundings.

If the recharge is used to raise the temperature above the natural groundwater temperature, the COP (Coefficient of Performance) of the heat-pump is improved, thus giving the possibility for an economic gain relative to the system without heat storage.

**The single-well aquifer model.**

The conceptual model of the aquifer shown in figure 12 is used as a basis for the derivation of a mathematical model, in the following sections. In the model, it is assumed that the aquifer is confined and consists of an upper and lower confining layer and that the permeable layers are separated by a third layer. The height of the two permeable layers is $H_a$.

The upper confining layer has a thickness of $H_{c1}$, and the height of the separation layer is $H_{c2}$. Water is pumped from the lower layer to the heat exchanger of a heat-pump, cooled down a few degrees and then returned to the upper layer. Heat inflow to the upper aquifer is assumed to be by heat conduction only, and to the lower layer by both heat conduction and advection. Energy inflow from geothermal sources is disregarded and thus the model will give a conservative estimate of the groundwater injection temperature. The flow in both the upper and lower aquifer is assumed to be horizontal without a vertical velocity component. The mass exchange between the two aquifers is handled as a leakage term in the flow equation for the upper aquifer, and as a source term in the lower aquifer. This flow direction will give the most favourable conditions for the reheating of the water that is returned from the heat-pump evaporator, since the heat influx to the upper layer will normally be greater than the geothermal heat influx from below by a factor of 10.

Mathematical model. A mathematical model was developed for the aquifer shown in figure 12. The continuity equations for the radial flow in the upper and lower aquifer were expressed analytically, whereas the energy equations describing the temperature distribution in the upper and lower aquifer were solved numerically using a finite element technique.

By expressing the governing equations for the fluid and energy flow in the aquifer in dimensionless form the following dimensionless groups could be identified:

$$N_V=\frac{\dot{V}}{2\pi r_w H_a K_a}; \quad N_{Pe}=\frac{(\rho C)_w H_a K_a}{\lambda_a} \tag{14}$$

$$N_L=\sqrt{2\frac{K_{c2}}{K_a}\frac{H_a}{H_{C2}}}$$

$$N_{u1}=\frac{\lambda_{c1}}{\lambda_a}\frac{H_a}{H_{c1}}; \quad N_{u2}=\frac{\lambda_{c2}H_a}{\lambda_a H_{c2}}$$

$N_V$ represents a dimensionless production/injection rate, $N_{Pe}$ is a modified Peclet number describing the advective heat transport in the aquifer. $N_L$ is a leakage number describing the leakage between the upper and lower aquifer. $N_{u1}$ and $N_{u2}$ are modified Nusselt numbers for the confining layers and the separating layer between the two perforations.

The analytical solution of the flow equation describing the flow in the upper and lower aquifer can be expressed as:

$$h(r)=\frac{N_V}{N_L}\frac{K_0(N_L r)}{K_1(N_L r_w)} \tag{15}$$

$K_0$ is the modified Bessel function of the 2. sort, zero order and $K_1$ is the modified Bessel function of the 1. sort 1. order. In this equation, $N_V$ denotes a dimensionless injection number defined by equation (14). Differentiation of equation (15) gives the following expression for the dimensionless Darcy velocity:

$$u_D(r)=N_V\frac{K_1(N_L r)}{K_1(N_L r_w)} \tag{16}$$

The $N_P$ and $N_v$ dimensionless numbers may be combined to give a characteristic Peclet number for the energy transfer in the aquifer. This Peclet number $P_e$ is defined as follows:

$$P_e=N_V N_P=\frac{(\rho C)_w \dot{V}}{2\pi\lambda_a r_w} \tag{17}$$

The energy equations for the upper and lower aquifers were solved by using the finite element method with quadratic interpolation and weighting functions. The upper and lower aquifers were discretized separately and the two coupled energy equations describing flow of heat in the aquifers were solved simultaneously. The coupling terms in the two equations describe the energy and mass flow from the upper to the lower aquifer. Hence, this essentially two-dimensional problem was reduced to two one-dimensional problems, by the introduction of the coupling term as a source-sink term in the two equations.

The model was developed to compute the asymptotic steady-state temperature of produced groundwater, i.e. the long-term operational temperature and not, as in the double well case, the transient development in the production temperature. The transient period in the single well case is relatively short. Hence, a steady state solution is more relevant as a design tool than the development of temperature with time. A detailed description of the mathematical model and the solution procedure was given in [6].

Hydraulic parameters A single-well heat-pump plant should be designed for optimal operational conditions for the heat-pump and minimum environmental affect. Both aims are met by ensuring that the temperatures in the aquifers reach a steady-state level that will allow an economic operation of the heat-pump without having a negative effect on the environment.

The design parameter, that to a large extent controls the steady-state operational conditions, is the hydraulic interaction between the upper and lower aquifers.

The hydraulic conductivity between the two aquifers may be estimated by using the aquifer flow model discussed above. From equation (17), the pressure required to inject water at a given injection rate may be calculated by substituting $r = r_w$. Rearranging then gives the following expression for a dimensionless pressure coefficient $N_p$ is obtained:

$$N_P=\frac{\Delta h}{N_V\, r_w}=\frac{1}{N_A}\frac{K_o(N_A)}{K_1(N_A)} \tag{18}$$

where $N_A$ is defined by: $N_A = N_L r_w$ is called the anisotropy number of the formation.

From equation (18), it can be seen that this pressure coefficient is a function of the anisotropy number $N_A$. However, it is the inverse function $N_A(N_P)$ that is used in practical applications, and this function is shown in figure 13.

The model may therefore be used to calculate the vertical to horizontal permeability in an aquifer based on a measured pressure difference in a pumping test from a well with two separate perforation intervals. The pressure coefficient is calculated on the basis of the data from the pressure test. The anisotropy number $N_A$ can then be read from the graph. From a known value of $N_A$ the ratio between the permeability in the aquifer, and the vertical permeability in the aquitard can be calculated.

The absolute value of the aquifer hydraulic conductivity must be estimated by traditional well-testing methods.

### Design of single-well plants

Operational conditions for the single-well plant. Using the model described in the previous section the relationship between the dimensionless steady-state production temperature and the dimensionless groups listed in equation (14) was calculated. Some of the results of this type of parameter study are shown in figure 14.

The data represented in the figure is the dimensionless *injection temperature* $\tilde{T}$ , as a function of the dimensionless injection number $P_e$, for two different values of the dimensionless parameters $N_{u1}$ and $N_{u2}$. The variable $N_L$ is the dimensionless leakage factor and is a measure of the hydraulic conductivity between the aquifers. From the figure it can be seen that the aquifer parameter $N_L$ is extremely important for the operation of the plant.

The influence of the two parameters $N_{u1}$ and $N_{u2}$ is of less importance.

The data represented in figure 14 can thus be used directly in the design of single-well plants. For a given aquifer configuration the dimensionless groups can be evaluated and the steady-state operational temperature determined.

## EXPERIMENTAL TEST RESULTS

### Experimental test results from field experiments at the Technical University of Denmark.

Double-well test facilities. A full-scale test facility was established at the University campus in 1984. The test stand consisted of five wells: two pumping/injection wells and three instrumentation wells for measurements of temperature and hydraulic head in the reservoir. In order to allow thermal break-through phenomena to be studied, the distance between the production and injection wells were only 8 meters. The groundwater system was connected to a commercial single-family house heat-pump with a constant heat load of 10 kJ/s. The groundwater flow could be fixed between 0 and 4 $m^3/h$. Depending on the groundwater flow the temperature of the groundwater was lowered 2 to 3.5 deg °C before reinjection into the reservoir. All temperature measurements and energy flows were recorded by the help of data loggers. The relative temperature changes in the reservoir were sampled with a sensitivity accuracy of 1/100 deg C.

Since the regional flow was very moderate on the campus (only a few meters per year), it was possible to test the thermal double well model without major errors.

The instrumentation wells IW1, IW2 and IW3 were situated around the two groundwater wells as shown in figure 15.

Double-well test results. Three experimental cycles were carried out during the period November 8. 1984 to December 5. 1985. The experimental cycles consisted of six single experiments. These were three cooling experiments and three reheating experiments. The calculated ratio between the heat capacity of the reservoir and that of the ground water i.e. $(\rho C)_a/(\rho C)_w$ based on borehole samples was between 0.524 and 0.601. The average flow rate $\dot{V}$ in the three cooling experiments was 3.03 $m^3/h$, 3.02 $m^3/h$ and 1.56 $m^3/h$ respectively.

The measured temperature of pumped water as a function of time was compared with model predictions for the three cooling experiments. This comparison is illustrated in figure 16 for one of the cooling experiments. As can be seen from the figure, a good agreement between model and experimental data is demonstrated.

The data used in this experiment can be summarized as follows: Perforation length 5 m. Effective aquifer height $H_a$ = 15 m and heat capacity ratio $(\rho C)_a/(\rho C)_w$ = 0.600.

In the three instrumentation wells IW1, IW2 and IW3 the temperatures were measured at different levels during the experiments.

The thermal disturbance in the instrumentation well IW2 that is situated only a few meters from the injection well showed a vertical extension of more than three times the perforation height.

The measurements of thermal propagation was primarily carried out in well IW2 that was located at the connecting line between the two pump wells PB1 and PB2.

An example of the passage of the thermal front in IW2 is shown in figure 17.

Single-Well test facilities. In 1986 a single well with two vertical screens (4 meters apart) was drilled and connected to the heat-pump installation at the University. One important objective was to study thermal break-through between the two well screens.

The siting of the well is shown in figure 18.

The design of the well is illustrated in figure 19. Groundwater was produced from the aquifer through a screen at a depth of 38-43 meters below surface and injected through a screen at a depth of 29-34 meters below surface. The two screens were separated by a packer.

The well was drilled with a diameter of approximately 0.40 m to a depth of 45 meters. The technique was flush-drilling with reversed drilling-water circulation.

Groundwater was produced and circulated with the help of a submerged pump placed 2 meters above the well-screens. The flow rate could be fixed between 1.5 and 3.0 $m^3$/hour.

In the heat-pump installation, the groundwater was cooled 2 to 3 °C before reinjection into the reservoir depending on the groundwater flow. The constant heat capacity of the heat-pump was 10 kJ/s. After each test run, the flow direction was reversed and the groundwater was reheated to its natural temperature by the use of a 24 kW electrical heater.

Data for the single-well installation can be summarized as follows:

| | |
|---|---|
| Perforation length $H_a$ | 5 m |
| Distance between well screens $H_{C2}$ | 4 m |
| Aquifer horizontal permeability $K_a$ | $10^{-4}$ m/s |
| Heat conductivity | 3 W/mK |
| Initial groundwater temperature | 8.8 °C |
| Effective well radius $r_w$ | 0.25 m |
| Tolerance for well radius | 0.05 m |

Results from the single-well plant. The measured temperature of produced groundwater as a function of time is shown in figure 20 The upper and lower estimates of the calculated steady-state temperature level are also shown. As can be seen from the figure, the measured temperature lies within these limits of the steady-state operational temperature.

For the single-well plant it was found that the model developed for the calculation of steady-state temperature of the pumped groundwater could be used to predict the pumping temperature with good precision. The use of the drilling hole dimension as a measure of the well radius in the model combined with the use of the perforation length as a characteristic reservoir height will give a conservative estimate of the temperature decrease to be used in the design phase.

**User experience with groundwater heat-pumps.**

Compilation of operational data for more than 200 Danish installations has shown, that only a minor number of plants have experienced operational difficulties with groundwater recirculation. The experience shows that it is very important to take special care during the drilling of the wells. This is because, in some cases, recharge of groundwater has been less effective because of clogging caused by micro particles or fine sands that has been loosened during drilling or during the completion of pumping wells. Fine sand particles in the pumped groundwater must be avoided by careful dimensioning of the gravel and filter screens, selection of proper sand filters on the ground and by high quality workmanship.

In order to prevent clogging the groundwater plants must be made air tight, and they should not be established in areas with high iron and manganese contents in the groundwater. Partial vacuum in the recharge pipe should be avoided in order to protect the evaporator and in order to avoid dissolution of limestone in the well screen of the recharge well. In order to avoid corrosion, the selection of materials for pipes and heat exchangers must be based on a chemical analysis of the groundwater.

**GROUNDWATER PROCESS COOLING OF A DANISH PLASTIC FACTORY.**

Today process cooling in Danish plastic factories is normally maintained by an open water circulation system designed for a forward/return temperature of of typically 10/15°C.

In this example, the surplus heat is removed by a conventional CFC-compressor installation with a total cooling load of 176 kJ/s. The electricity consumption for cooling including compressors and auxiliary equipment is 295000 kWh/year at 5000 operation hours per year.

Figure 21 shows a groundwater cooling system that is integrated with the existing process cooling water system. A heat exchanger for the groundwater system is installed in the return pipe. The groundwater can then be kept in a closed system and the existing cooling plant can serve as a 100% back-up for the groundwater cooling plant. By heat exchange, the temperature of the groundwater is raised from 9 to 14°C.

The amount of groundwater is approximately 30 $m^3$/h corresponding to 151000 $m^3$/year.

The electricity consumption for groundwater cooling is limited to the pumping work delivered by the groundwater pump which is calculated to be 34300 kWh/year at a back-pressure of 5 bar and an efficiency of the pump of 60%.

The electricity savings for cooling are under these assumptions 260800 kWh/year or 88%.

Money savings are approximately 20000 US $/year which give a pay-back time of 4 years. In Denmark the price of electricity for industrial consumers is about 7 US cent/kWh.

The hydrogeological conditions are suitable for the establishment of the groundwater cooling plant and the local authorities have recently granted a permit to use an aquifer situated 100 m below surface at the factory.

## CONCLUSIONS

Simplified models for the prediction of the operational conditions of groundwater heat-pump heating and cooling were developed and used to analyze single- and double-well configurations. The models have given better insight into basic phenomena and a better overview of factors governing the plant performance. It was further demonstrated that the single-well model can be used for determining the vertical to horizontal permeability ratio, a value which is extremely important for the operational condition of this type of plant.

A comparison with experimental field results from experiments with single and double well configurations showed good agreement between model calculated production temperatures and measured values.

Finally, an example study using groundwater as a secondary cooling fluid for process cooling in a plastic factory demonstrated a potential saving on electricity of more that 80% when using groundwater as cooling medium.

## LIST OF REFERENCES


[1] B. Qvale, S. N. Sørensen, L. S. Ibsen, 1989-."Aquifer Thermal Energy Storage. Status and Future Prospects". CLIMA 2000, Sarajevo, Jugoslavia.

[2] B. Qvale, L. S. Ibsen 1988: "The Danish Aquifer Energy Storage Project. Operational Experience". JIGASTOCK 88, Versailles, France, 1988.

[3] J.A. Dacosta and R.R. Bennett 1960: "The Pattern of Flow in The Vicinity of a Recharge and Discharge Pair of Wells in an Aquifer having Areal Parallel Flow", Helsinki, UGGI/AIHS, Publ. No. 52.

[4] A.C. Gringarten and J. P. Sauty, 1975, "A Theoretical Study of Heat Extraction from Aquifer with Uniform Regional Flow", Journal of Geophysical Research, December 10, pp 4956-4962.

[5] H. Carlsen, N.E. Andersen and J. Reffstrup,1980, "Thermal Consequences of Recharging Cooled Water to the Underground". Ministry of Environmental Protection, Report no. 27, October (In Danish).

[6] S.N. Sørensen and J. Reffstrup, 1992, "Prediction of Long Term Operational Conditions for Single-Well Groundwater Heat Pump Plants", Symposium on Underground Thermal Energy (Heat & Chill) Storage (ATES), IECEC, San Diego, CA, U.S.A


## LIST OF SYMBOLS

| | |
|---|---|
| C | Specific heat capacity. |
| D | Distance between wells in the double well configuration. |
| H | Height of geological layers. |
| $H_a$ | Active aquifer thickness/perforation interval. |
| h | Piezometric head. |
| $H_c$ | Height of confining geological layer. |
| $K_a$ | Darcy velocity m/s. |
| $N_A$ | Anisotropy number. |
| $N_L$ | Leakage number. |
| $N_P$ | Pressure coefficient. |
| $N_Q$ | Injection number. |
| Nu | Modified Nusselt numbers. |
| $P_e$ | Peclet number. |
| $\dot{V}$ | Injection-production rate. |
| $\tilde{V}$ | Dimensionless pumping/injection rate. |
| $v_o$ | Velocity of regional groundwater flow. |
| Q | Heat flow |
| $r_w$ | Well radius. |
| r | Radius. |
| $\tilde{t}_{tb}$ | Dimensionless break through time. |
| T | Temperature. |
| $T_i$ | Initial injection temperature |
| $T_o$ | Initial aquifer temperature |
| $T_r$ | Aquifer transmitivity. |
| $\Delta T_{max}$ | Maximum temperature of pumped groundwater. |
| $\Delta T_w$ | Temperature increase across the heat exchanger unit. |
| $u_D$ | Darcy velocity. |
| $u_L$ | Leakage velocity. |
| $\alpha$ | Heat diffusivity. |
| $\lambda$ | Heat conductivity W/m°K |

Subscripts (not included above):

| | |
|---|---|
| a | Aquifer. |
| d | Darcy. |
| C | Confining layer. |
| c1 | Upper confining layer in single-well model. |
| c2 | Layer between upper and lower perforation zone. |
| w | Well, water. |

SI units have been used consistently throughout the paper.

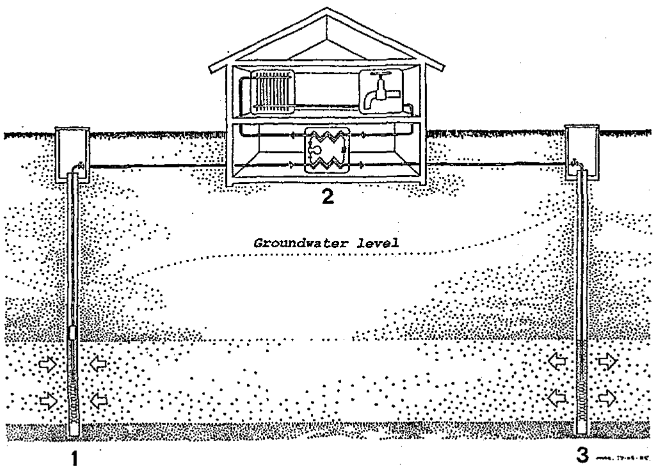



**Figure 1.** Groundwater heat pump with two wells. 1) Pumping well. 2) Heat-pump evaporator. 3) Injection well.

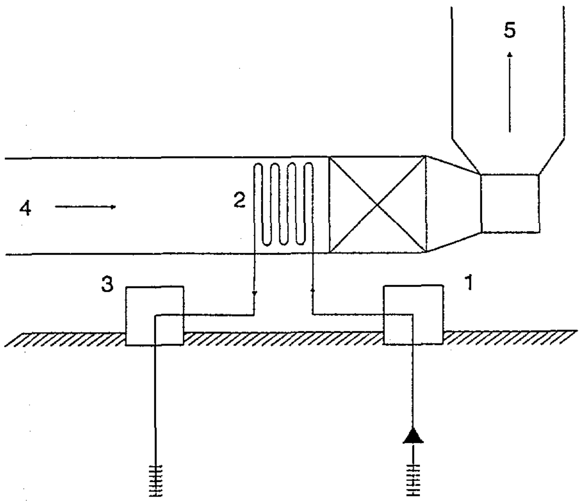



**Figure 3.** Air-conditioning with groundwater. 1) Pumping well. 2) Heat exchanger. 3) Injection well. 4) and 5) Ventilation air.

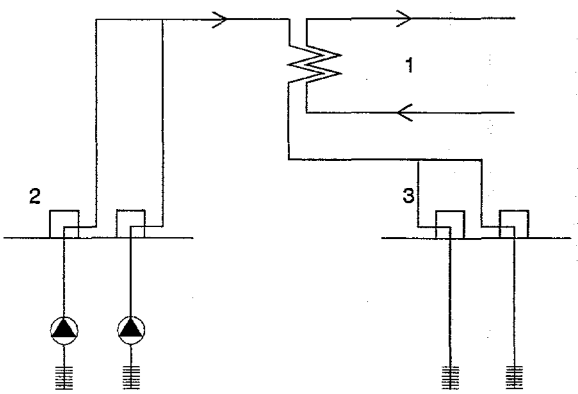



**Figure 2.** Ground-water cooling with a double well configuration. 1) Process cooling water loop. 2) Groundwater pumping wells. 3) Injection wells.

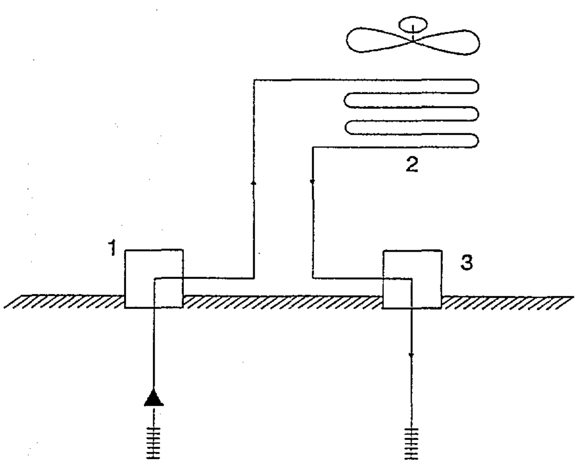



**Figure 4.** Loading the aquifer with groundwater that has been cooled by cold outdoor air. 1) Pumping well. 2) Air to water cooler. 3) Injection well.

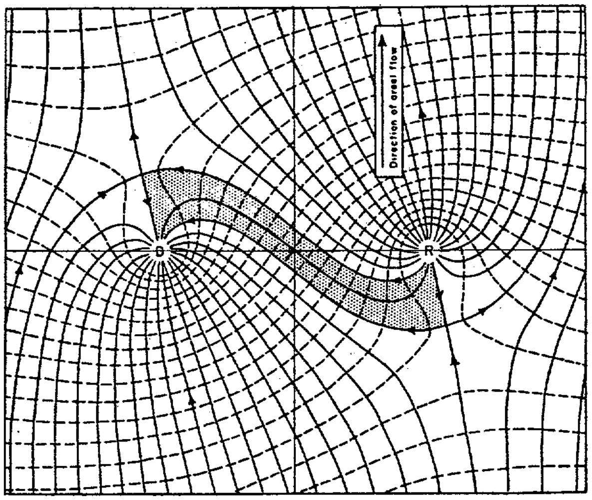


**Figure 5.** Dipole-system with regional gro-undwater flow. Injected water will reach the pumping well only through the stream tube marked by the dotted area in the figure. From Dacosta and Bennett [3].

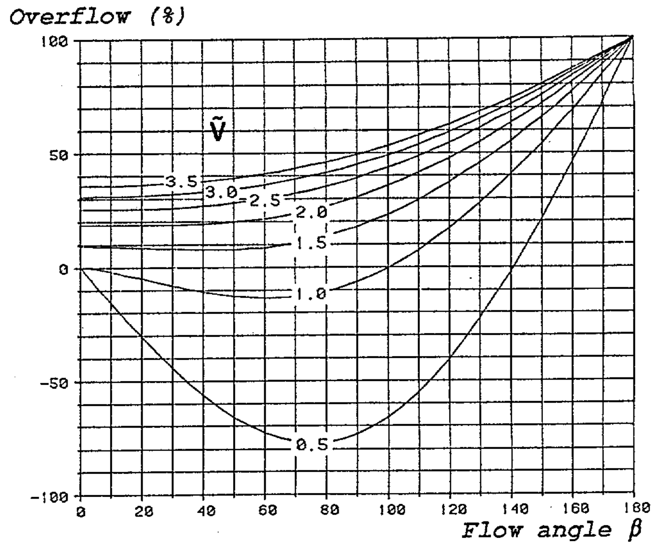



**Figure 7.** The calculated overflow as a function of relative groundwater flow dir-ection and and different fixed values of the dimensionless pumping rates $\tilde{V}$ .

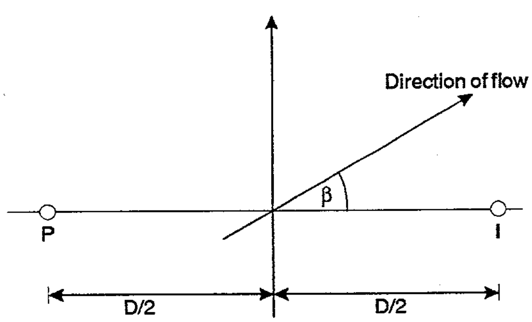



**Figure 6.** Definition of the flow angle $\beta$ to be used in the calculation of the over-flow.

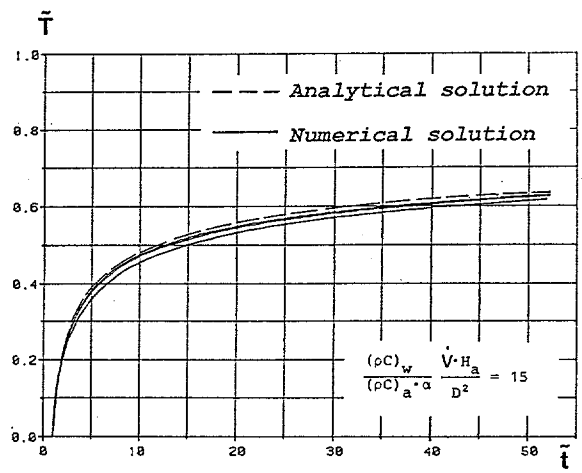



**Figure 8.** A comparison between the numerical model and the analytical model by [5]. The figure shows the temperature in the pumping well as a function of time using descreasing time step length.

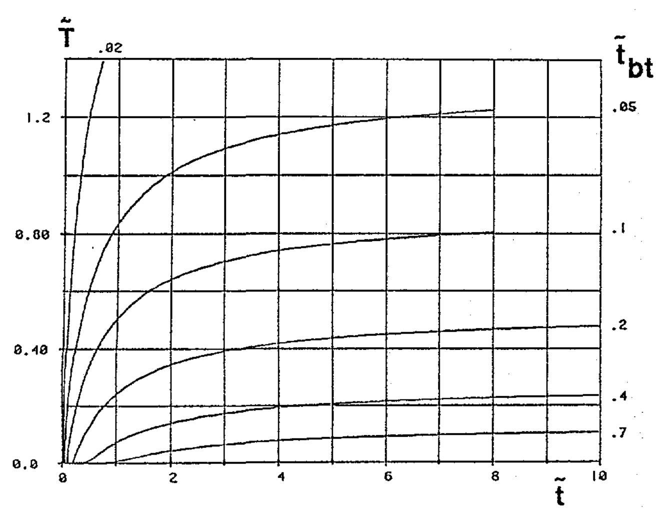



**Figure 9.** Diagram for the life time calculations of double-well groundwater heat pumps. $H_a/H_c$=0.7.

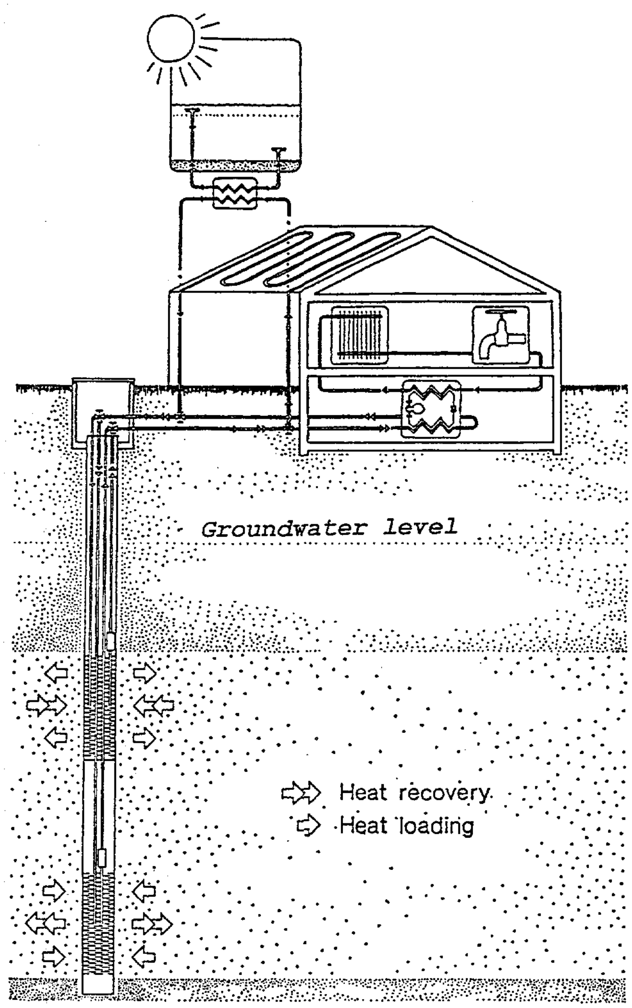



**Figure 11.** Single-well ground water heat-pump plant with a solar heat recharging system.

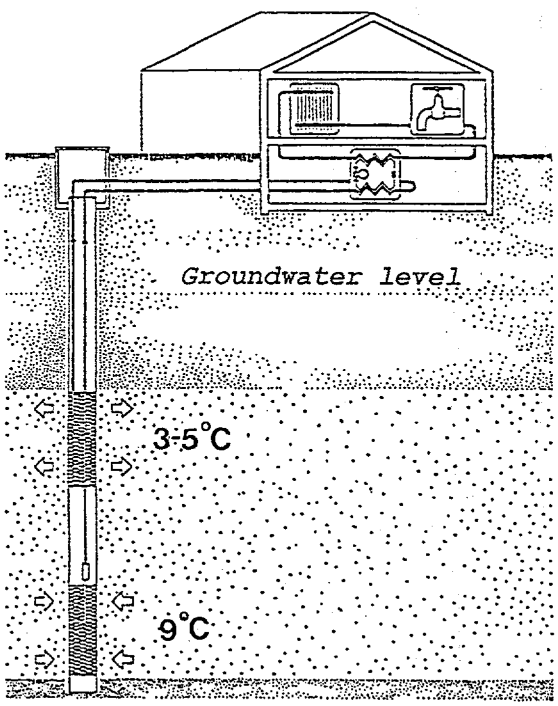



**Figure 10.** Single-well groundwater heat pump plant.

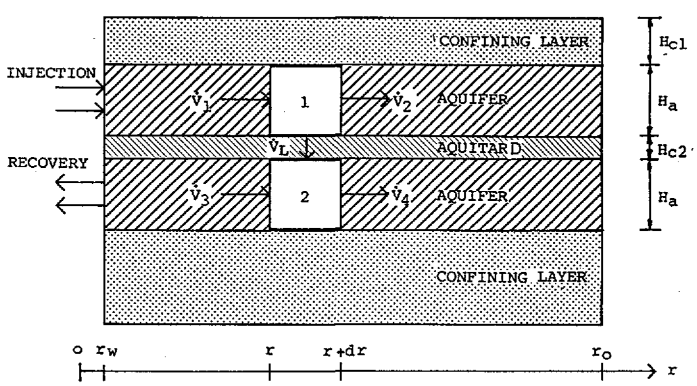



**Figure 12.** Model of Aquifer for a Single Well Heat Pump Plant.

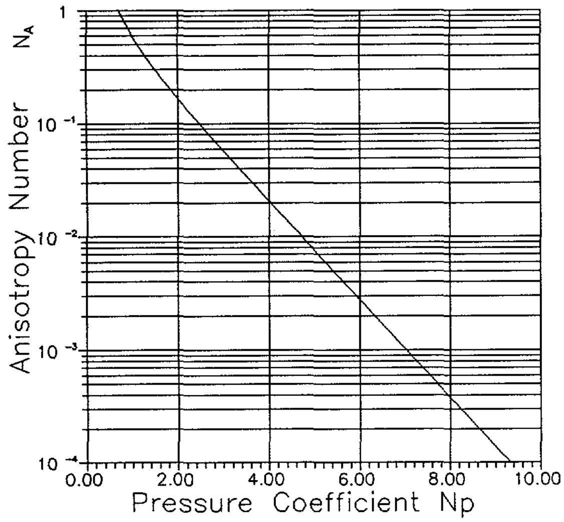



**Figure 13.** Anisotropy number $N_A$ as a function of the pressure coefficient $N_P$.

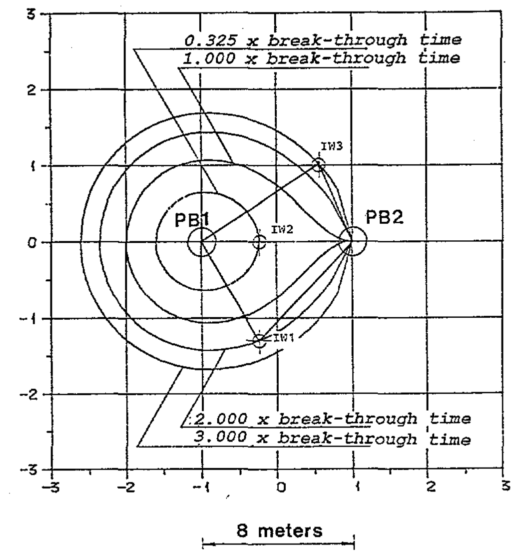



**Figure 15.** Calculation of the arrival time for the thermal front in the different instrumentation wells relative to break-through time for two pumping and injection wells, when cold water is injected in PB1.

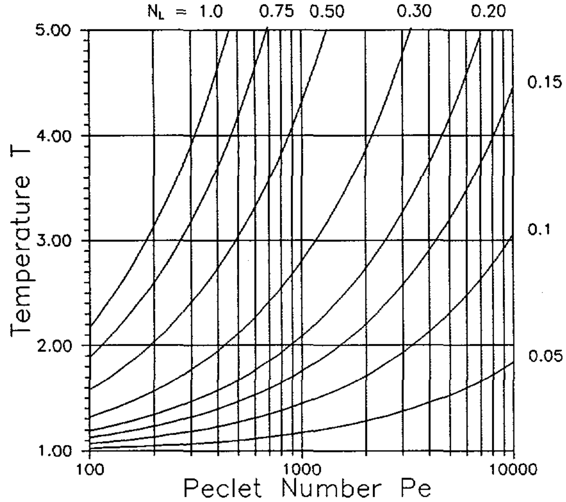



**Figure 14.** Dimensionless injection temperature as a function of $P_e$ and the leakage factor $N_L$ for $N_{u1} = 0.1$ and $N_{u2} = 0.2$

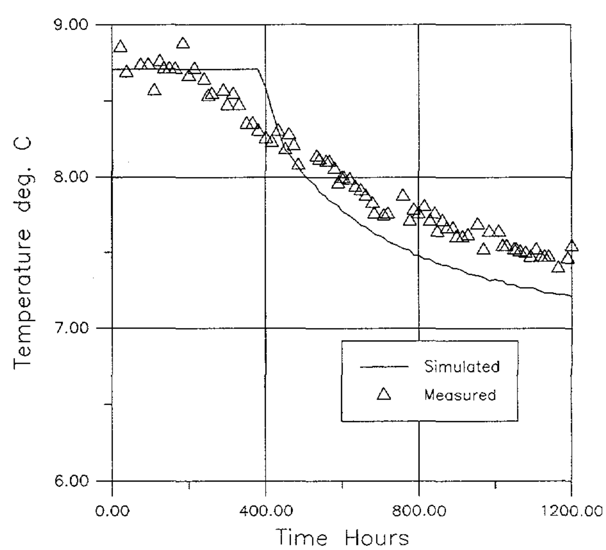



**Figure 16.** Comparison between predicted and measured values for the temperature of groundwater versus time in the pumping well.

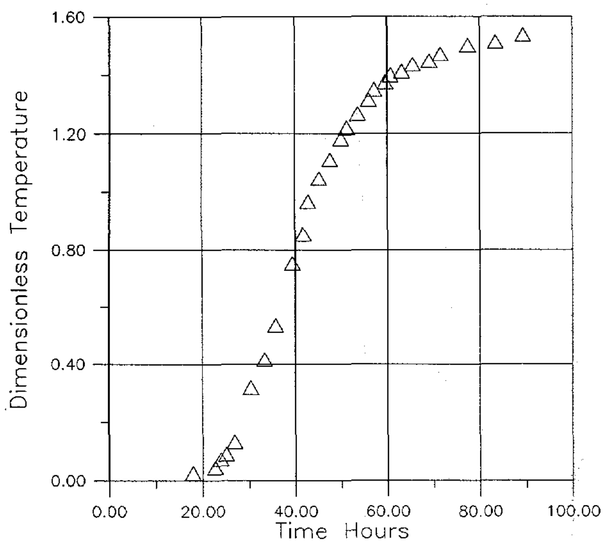



**Figure 17.** Typical thermal front passage in the instrumentation well IW2. Measured data.

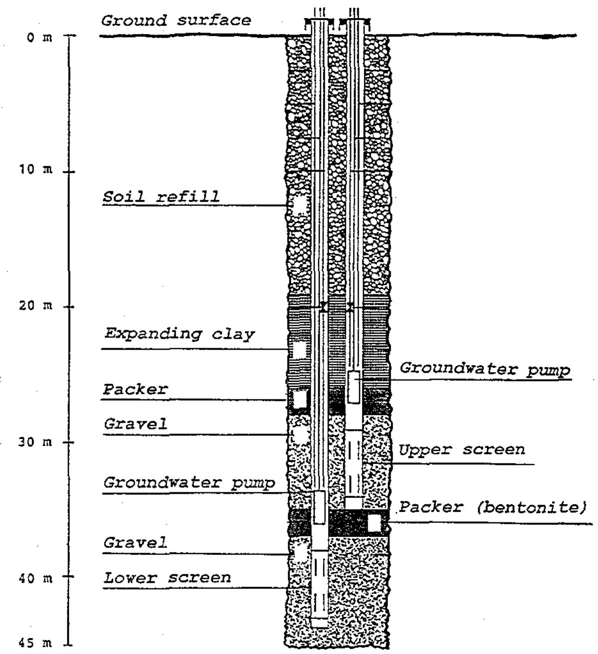



**Figure 19.** The development of the single-well.

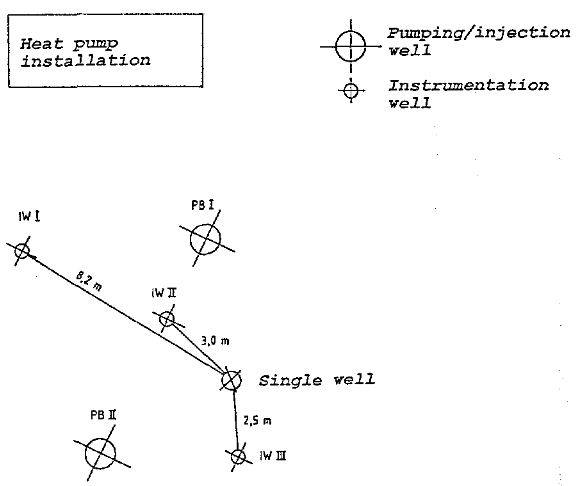



**Figure 18.** Position of wells for single-well groundwater heatpump plant.

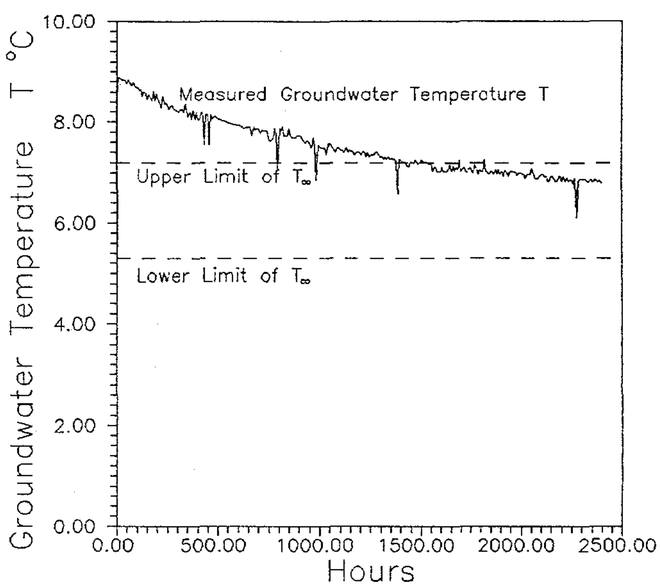



**Figure 20.** The figure shows the measured temperature of produced groundwater as a function of time and the calculated upper and lower limit of the steady-state groundwater temperature $T_{inf}$.

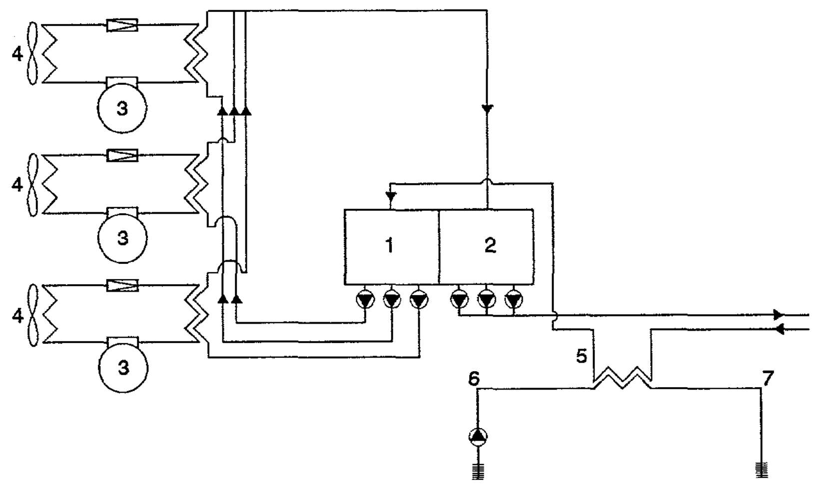



**Figure 21.** Groundwater cooling at a Danish plastic factory. 1) Return water (15 °C). 2) Cooling water(10 °C). 3) Refrigeration compressors. 4) Air-cooled condensers. 5) Water-to water heat exchanger. 6) Groundwater pumping well. 7) Injection well.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# Long-term Experience with an ATES-based Air Conditioning System

• K. Clark Midkiff Jr.
Mechanical Engineering
The University of Alabama
Tuscaloosa, Alabama, USA
• C. Everett Brett
Bureau of Engineering Research
The University of Alabama
Tuscaloosa, Alabama, USA

## ABSTRACT

A 520 kW (peak, thermal) air-conditioning system has operated since 1983 to cool the University of Alabama Student Recreation Center (UASRC) utilizing chilled water stored seasonally in a water table aquifer. Ambient, 18°C ground water is pumped from warm supply wells, chilled during suitable weather by exposure to cold air, reinjected and stored for periods up to several months in cold storage wells. During hot weather, chilled water is pumped from the cold wells and through chilled water coils in the building air handlers. Annual system Coefficients of Performance (COP) have averaged 4.8, about double that for conventional air-conditioning. The energy recovery factor (ERF), which is the fraction of chill energy stored that is actually recovered and used for air conditioning, has ranged from 40 to 85 percent. This paper describes the system development and operation, and presents long-term performance results. Data collected from head and temperature monitoring wells allow seasonal trends of thermal and hydraulic profiles in the aquifer to be determined. Detailed descriptions of some of the obstacles faced in the development of this system and remediative measures taken to overcome these problems are presented. The recent addition of two production wells and a spray pond to increase water chilling capacity and efficiency is described.

## BACKGROUND

The concept of thermal storage in aquifers has existed for several decades. The brief review of the literature presented here is by no means exhaustive but is meant to provide both background for the UASRC system and some sense of similar chill storage research that is underway elsewhere. This study describes the use of aquifer thermal energy storage (ATES) for building air conditioning. In this thermal storage application it is actually "chill" rather than "heat" that is stored. Aquifers are good candidates for large-scale thermal energy storage because they are naturally occurring and all that is needed to utilize the aquifer for energy storage is access gained through the construction of water wells. Aquifers potentially usable for ATES underlie about 75 percent of the population of the United States [1]. Aquifers can be used for diurnal, medium term or seasonal storage of either hot or cold water. This study focuses on the seasonal storage of cold water that has been chilled through exposure to cold winter air. The primary design objective of an ATES system is to reduce building cooling costs by reducing both electric peak demand (kW) and total electric energy use (kWh) charges.

The earliest experimental studies of energy storage in aquifers were performed in the United States and looked at the storage of hot water [2,3]. Although the earliest work was performed in the United States, most research since that time has occurred in northern Europe, Canada, China and Japan. A number of European countries and Canada have made large investments in ATES projects in the past decade or so. Chant and Morofsky [4], e.g., report that the four countries Canada, Germany, the Netherlands and Sweden combined completed an average of 11 aquifer seasonal chill storage projects per year over the four-year period ending in 1990. Most of the projects (83 percent) were developed to cool commercial buildings. In the Netherlands alone, 16 aquifer chill storage projects were in development in 1992 [5]. The driving forces for construction of ATES projects in these countries are fossil energy conservation, environmental benefits and, to a lesser extent, economics. These projects have simple payback periods that range from two to ten years, with about half of the payback periods less than five years [6].

The first chill energy storage studies were conducted at Texas A & M University by Davison et al. [7]. Approximately 7500 $m^3$ of 21°C ground water was pumped from a supply well communicating with one aquifer, chilled to about 10°C in a spray pond, and then injected into a separate aquifer through a storage well. Results of the water recovery tests are not available in the literature. A full-scale air-conditioning system based on chill ATES was first installed in the United States to cool a department store in a mall located in Tuscaloosa, Alabama [8]. The store contained an air-conditioned floor space of 5760 $m^2$ and a peak cooling load estimated to be 700 kW (thermal). A water table aquifer with a 15 m thick saturated zone was utilized for both warm water supply and cold water storage. Water chilling using a cooling tower was initiated whenever outside wet bulb temperature dropped below 10°C. Although air-conditioning costs were reduced by 75 percent compared to conventional air conditioning, several problems arose. Ground water speed and direction fluctuated unpredictably, reducing the efficiency of the storage system. The wells were not well developed initially, consequently, water withdrawn carried fine sediment that had to be filtered, creating a considerable maintenance burden. Because the wells were poorly developed and the aquifer water table was relatively close to the surface, the cold water that was returned from the cooling tower for injection occasionally overflowed the tops of the cold wells, flooding the mall parking lot where the wells were located. Fearing loss of customers and lawsuits from nearby merchants, the department store was forced to discontinue use of the ATES system.

Shortly after the installation of the department store chill ATES system, a second system was designed and constructed to cool the Student Recreation Center (UASRC) that was then under construction on the University of Alabama campus in Tuscaloosa [9]. The chill ATES system at the UASRC, which began operation in 1983, is the subject of this study. Data have been collected on the performance of this system for eight full, annual storage/discharge cycles. This paper reports on the long-term behavior of the system, with a focus on the effectiveness of the aquifer as a storage medium and the performance of the water chilling system. Recent modifications aimed at improving water chilling capacity and efficiency are described. Finally, benefits and disadvantages of ATES based air conditioning revealed through extensive experience are enumerated.

## SYSTEM DEVELOPMENT AND OPERATION

The Student Recreation Center has been constructed in two phases – the original structure, which was built in the early 1980s, and the Addition, which was added about two years ago. The original portion of the UASRC is cooled by the ATES based air-conditioning system and the Addition is heated and cooled by a water-source heat pump using water from one of the ATES system's wells. The original UASRC is the focus of the work presented here, but interaction between the ATES system used to cool the original UASRC building and the heat pump system used to cool and heat the Addition and problems caused by the construction of the Addition are described later.

The original portion of the UASRC is a large, multi-use building having a conditioned floor space of 5760 $m^2$ (62,000 $ft^2$), with 14 handball/racquetball courts, five basketball courts, a running track, dressing/locker rooms and extensive storage and office space. The estimated peak load of the original UASRC structure is 520 kW (148 tons) [10]. Initial plans called only for fan ventilation of the main Recreation Center gymnasium that contains the running track and the five basketball courts. A 20-yr life-cycle-cost analysis identified the ATES system as the most cost effective way to air condition the entire space; using the ATES-based system made air conditioning the gymnasium economically feasible. The original UASRC building was completed in November 1982, at which time water chilling began. Essentially 100 percent of the building air conditioning has been provided by the ATES system since 1983.

The heating, ventilation and air-conditioning system used in the original UASRC building is a four-pipe system employing a total of 30 air-handling units with hot water and chilled water coils. Hot water is for heating is provided by a conventional natural gas fired hot water boiler. In addition to the ATES system there is a 350 kW (100-ton) conventional, air-cooled back-up chiller that was required by the university administration. An economizer cycle provides air conditioning during cooler weather conditions.

The original ATES-based air-conditioning system, which is the primary focus of this study, is shown schematically in Figure 2. The three principal components of the system are: (1) water chilling, provided by a conventional, mechanical-draft cooling tower; (2) seasonal chill storage, provided by the aquifer and a set of six water wells; and (3) building cooling, provided by conventional chilled water coils within the building air handlers. The original aquifer system used six production wells, a row of three "warm" supply wells, numbered 1-3 in Figure 3, and a row of three "cold" storage wells, numbered 4-6 in Figure 3. The production wells are drilled through the aquifer and slightly into the Pottsville formation. The wells are a total of 27 to 30 m deep, use 25 cm (10 in) diameter PVC sand screen, are packed with gravel in the saturated zone, cased with solid PVC pipe above the saturated zone, and grouted with concrete to the surface. Each well contains a three-stage 7.5 kW (10 hp) submersible pump and return riser. Warm well pump design capacity is 34 $m^3$/hr (150 gpm) at 43 m (140 ft) head and cold well pump capacity is 27 $m^3$/hr (120 gpm) at 61 m (200 ft) head.

Certain features of Figure 3, including the spray pond and production wells 7 and 8 were not part of the original ATES system, but have been added recently in a modification of the configuration, as discussed later. The outline of the current UASRC structure is shown in Figure 3, and the large, essentially rectangular portion of the building at its eastern end constitutes the original Recreation Center that the ATES system was built to cool. The designed thermal storage capacity of the original ATES system was 1760 GJ (139,000 ton-hours). The original system, including wells, well pumps, cooling tower, sand filter, piping to the chilled water coils, and valves and fittings cost $190,000. This figure does not include the air handlers, coils, boiler, ductwork, blowers and other indoor HVAC equipment.

Water chilling in the original system was accomplished with a conventional cooling tower having a nominal capacity of 102 $m^3$/hr (450 gpm). The operation of the original system is described here. The tower operates automatically whenever the ambient dry bulb temperature drops below about 9°C. Control of tower operation based on wet bulb temperature is preferable because the rate of heat transfer during the evaporative water chilling process is proportional to the difference between the water temperature and the wet bulb temperature. However, at the time the system was constructed, reliable wet bulb, humidity or moist air enthalpy sensors required frequent maintenance, so a dry bulb thermostat was used instead. During water chilling, ambient (about 18°C or 65°F) aquifer water is pumped from the warm wells to the cooling tower, chilled to below 7°C, and reinjected into the cold wells. In relatively warm weather, water chilling to below 7°C is accomplished by recirculation within the tower. The tower design water cooling range is 11°C, from 18°C entering to 7°C leaving, at 4°C ambient wet bulb temperature. For the Tuscaloosa area there are typically 1200 to 1500 hours below 6°C wet bulb temperature in a year. Chilled water exiting the tower is passed through a sand filter to prevent aquifer contamination and then injected into the cold storage wells. Cooling tower operation is related only to winter weather conditions and is sized, but not linked in time, to the building cooling load.

Chilled water is stored in the aquifer until required for air conditioning. In Tuscaloosa, where some air conditioning may be required during any of the 12 months of the year, the storage period might be a few hours (a cool night followed by a warm day) to several months. During hot weather, the cold well pumps provide cold water upon demand from the building's air-conditioning control system. Typically only one cold well pump is operated at a time, but two pumps are required when outside temperatures exceed 35°C (95°F). The inlet water to the building air handlers varies upward from a minimum temperature of 7°C depending upon the volume of water chilled the previous winter and upon how much water has already been recovered for air conditioning in the current warm season. Ideally, warm water exiting the building would be returned to the warm wells, thus insuring a very small net removal of water from the aquifer. In practice, it has been necessary to divert the warm water leaving the building to the storm sewer. Furthermore, additional water has been pumped from the warm wells that are up gradient from the cold storage zone of the aquifer (referred to as "back pumping") in order to reduce the loss of chilled water in the aquifer due to adverse regional flow within the aquifer. Back pumping is described later.

The chill energy storage medium is a water table aquifer that underlies many square miles in the vicinity of the UASRC site. Figure 1 is a schematic of a cross-sectional cut through the UASRC aquifer constructed from compositional data based on sedimentary analysis of drillings collected during construction of wells at the site [11]. The unconfined aquifer at the UASRC site lies in a geologically young unconsolidated sedimentary layer consisting of terraced alluvial deposits from the nearby Black Warrior River. The aquifer's saturated zone rests above the indurated Pottsville Formation, which acts as an aquiclude, preventing the downward migration of aquifer water. The lower part of the layer is marked with sand and clay, and it becomes more gravelly and less sandy toward the surface, which is mostly red clay. At the UASRC site, approximately 30 m of alluvial material overlies the Pottsville Formation, and the lower 10-12 m of this bed is typically saturated with ground water. Although variations in water table elevation occur as a result of seasonal variations in rainfall, long term monitoring of aquifer water levels have shown these level changes to be minor. Sedimentary analysis and other hydrological measurements [12] indicate that hydraulic conductivity is greatest in the middle and upper portions of the saturated zone, and that water flow is increasingly impeded as the Pottsville formation is approached moving downward in the saturated zone.

## SYSTEM MONITORING

In order to evaluate the performance of the chill ATES air-condition-ing system, data are collected on the performance of its three principal components: water chilling (cooling tower), storage (aquifer) and heat absorption (building cooling coils). The data acquired to evaluate the original UASRC water chilling system include water temperatures into and out of the cooling tower, water flow rates and total volumes through the cooling tower, and power input to the cooling tower, including pumping power for water reinjection. The data acquired to physically define the aquifer performance consist of drilling samples from the monitoring wells, aquifer water head data to determine the natural water level and gradient, water temperature at numerous locations within the aquifer, water injection and withdrawal flow rates and temperatures, and pump electrical energy input. The data collected to evaluate the building cooling system include building inlet and outlet water temperatures, water flow rate through the building, and power input for pumping water. Information on power usage by air blower motors in building air handlers and fuel usage by the heating system has not been collected.

Cooling tower and building cooling performance monitoring consists of measuring water flows, water temperatures, and electricity consumption of the pumps and fans. The system is equipped with integrating water flow meters to record the total volume of water pumped from each row of wells. Hour meters are installed to indicate the accumulated operation time for each pump in the production wells and for the return pump in the cooling tower. Inlet and outlet temperatures for the cooling tower and the building have been measured frequently (several times per week) using insertion thermometers. Electric energy consumption for cooling tower fans and return pump are measured by watt-hour meters. Well pump electricity consumption has been estimated from measurements of hours of usage (from hour meters) coupled with pump motor performance data.

In order to measure aquifer temperatures and water levels, 21 monitoring wells have been drilled, as shown in Figure 3. Water level measurements from three background head monitoring wells (H4W, H4S and H6E), which are far removed from the influence of the aquifer chill storage activity, are used to estimate the undisturbed aquifer flow gradient (slope magnitude and direction). The remaining wells can be used to measure water level and temperatures ("H" wells) or temperatures alone ("T" wells) in or near the active thermal storage zone. Wells used for temperature have copper-constantan (Type T) thermocouples mounted at the Pottsville formation (bottom of the well) and in 3 m vertical intervals upward. The "H" wells use 5 cm (2 in) PVC casing screened through the saturated zone. The "T" wells use 5 cm blind PVC casing. The monitoring wells are not ground packed.

## RESULTS AND DISCUSSION

The chill ATES system has provided virtually all of the building air conditioning at the UASRC since 1983. The performance of the system has been monitored for the past eight annual cycles [11, 13-15]. An "annual cycle" is defined as the 12-month period from October 1 to September 30 of the following calendar year. In Tuscaloosa, some air conditioning usually takes place every month of the year. The earliest fall weather suitable for water chilling typically occurs in October. Water that has been chilled most recently lies physically nearest the well, so air conditioning that occurs after water chilling begins utilizes water chilled in the new chilling season. Thus, the period October 1 to September 30 of the following year approximately corresponds to an annual charge/discharge cycle for the aquifer storage system.

### Water Chilling Performance

Figure 4 reports the monthly volumes of water chilled in the cooling tower during the eight-year period October 1, 1985 through September 30, 1993 as volume "injected." This figure shows the relatively short cold season available at the site, with the bulk of the chilling occurring during December through February. January is usually the peak chilling month, but December 1989, which was a record cold month for the Tuscaloosa area, was the peak water chilling month over the eight-year period.

Table 1 presents annual average cooling tower water inlet and outlet temperatures, reported as $T_{in}$ and $T_{out}$, respectively, in the "INJ" (injected) column, as well as annual volume of tower water throughput, reported as "1000 $m^3$" in the "INJ" column. With the exception of the 1992-93 period, the average annual chilled water injection temperatures vary only slightly from a mean of 5.9°C. The 1992-93 season was quite abnormal because modifications to both the ATES system and the Recreation Center Addition were under construction. Consequently, the water lines from the cooling tower to the wells were frequently disconnected and system management was not ideal. In an effort to chill a greater volume of water in those periods when the chilling system was operable, the cooling tower thermostat was set so that the tower operated in warmer weather during the 1992-93 water chilling season. This resulted in an abnormally high injection temperature of 7.7°C for this annual period.

Annual injected volumes vary considerably, reflecting large variations in weather conditions. The small volume of water chilling reported for 1992-93 reflects not unusually warm weather but the construction interruptions described above. The variation in chilled water injection temperatures (cooling tower outlet temperature) over the winter season is illustrated in Figure 4. The cold water injection temperature is lowest during the coldest months (usually January and February), at the same time the rate of chilled water injection is largest. The abnormal conditions of the 1992-93 period are also evident in Figure 4.

Annual heat rejection data, which are equivalent to annual chill storage, are reported in Table 1 as "Heat Rej" in the "INJ" column for the cooling tower. The annual chill storage closely parallels the volume of chilled water injected. Not counting the unusual 10/92-9/93 period, the average annual chill energy storage is 2580 GJ (203,000 ton-hours). The measured chill energy storage exceeds the "design" thermal storage capacity of 1760 GJ every annual period except for the anomalous 10/92-10/93 period in which frequent construction interruptions occurred. Chill energy storage averaged 47 percent greater than the design capacity. The annual electrical energy consumption for water chilling, which consists of the electricity used to operate the cooling tower blower and the hot well pumps in cold weather, is shown in Table 2. The water chilling energy usage averages 62 MWh and ranges from a low of 54 MWh for the 10/90-9/91 period to a high of more than 72 MWh for the 10/86-9/87 period.

One traditional measure of a chilling system's performance is the COP, defined here as the dimensionless ratio of useful heat transfer to the work input required to produce the heat transfer. Comparing the heat rejected from the cooling tower to the electrical energy required to operate the tower and the hot well pumps, the cooling tower COP on a seasonal average basis ranges from 9 to 13, with an average of 11.5 for the first 7 years of the project (not reported in tables or figures). Cooling tower COP is weather dependent. It is higher in years where the average wet bulb temperature is lower because the tower throughput is greater (less recirculation within the tower) while the tower electrical power consumption is approximately constant (the fan runs continuously during tower operation). Cooling tower COP is also higher if the set temperature at which the tower begins to operate is lower. The set temperature has been adjusted at times by the system operator, plus the set point can in effect be moved if the thermostat sensor gets out of calibration.

### Building Cooling Performance

Figure 4 shows monthly volumes of cold water recovered for building air conditioning. Water is recovered for building cooling virtually year round, although very little air conditioning occurs in December through February. The ratio of volume recovered to volume injected ranges from 1.6 to 2.6, reflecting annual weather variation. This ratio is greater than unity because the dispersion of chill energy into both the solid media and the non-processed water of the aquifer formation necessitates that more water be withdrawn than was stored in order to recover more stored chill energy. This chill dispersion process is accompanied by a degradation in the storage temperature. An additional factor that exacerbates the dispersion of chill at the UASRC is a relatively large regional flow velocity in the aquifer. The natural flow of the aquifer acts to produce additional mixing of chilled and ambient wate. Further, the bulk fluid movement sweeps the chilled water zone away from the cold wells, resulting in increased pumping requirements for recovering chilled water from the cold wells. Adverse regional flow and steps taken to mitigate its effects are discussed later.

When colder stored water supplies are exhausted during the air conditioning season, larger volumes of water only slightly cooler than the aquifer ambient must be recovered to compensate for the small ΔT (or small heat absorption per unit volume) the water experiences in passing through the building cooling coils. Thus, the fact that the recovered-to-injected volume ratio is substantially greater than unity over some annual periods points to sub-optimal cooling performance by the original ATES system. The need to recover substantially greater volumes of water than stored indicates that air conditioning is accomplished with relatively warm water, which leads to poor dehumidification. This problem can be attributed to a combination of insufficient water chilling capacity and excessive chill dispersion in the aquifer.

Further evidence of less than desirable air-conditioning performance is provided by the fact that the average annual cold water recovery temperatures, reported in Table 1 as $T_{in}$ in the "REC" (recovered) column, are so high. Mean cold water recovery temperatures range from 13 to 14°C. These relatively warm water recovery temperatures result in inadequate dehumidification. The cold water inlet temperatures are a very adequate 7°C in the winter months but gradually climb to as high as 16°C, as shown in Figure 5. The deep, narrow trough that appears in about June in the plot of building inlet temperature results when the system operator switches from well 5 to well as the primary cold recovery well. The water in well 4 is significantly cooler when the switch occurs, so the building inlet temperature declines sharply and then increases as the colder water around well 4 is exhausted. The gaps in the building inlet water temperature plot displayed in Figure 5 correspond to periods where no ATES air conditioning was used. The two major gaps in late 1992 and late 1993 are periods where construction of the UASRC addition and modifications to the ATES system interrupted the availability of the ATES system.

Table 1 displays annual air conditioning provided (heat removed from the building in the "Heat Rej" row and "REC" column. "Air conditioning" is defined here as proportional to the temperature difference between the building inlet and outlet water temperatures. Chill storage in the aquifer is accomplished by cooling ground water to a temperature below its ambient state. "Chill recovery" is maximized if water withdrawn from the cold wells for air conditioning is warmed back up to the ambient aquifer temperature as it passes through the cooling coils. At those times when the building inlet water temperature is higher than desirable, the water temperature leaving the building air handlers, reported as $T_{out}$ in the "REC" column of Table 1, exceeds the 18°C ambient aquifer temperature. When this occurs, building cooling is being accomplished not only by chill recovery in warming the water up to the ambient aquifer temperature, but also by "free cooling" as the water is warmed further. Thus, "air conditioning" or "total heat rejection" is the sum of the "chill recovery" and the "free cooling." For the first seven years of data listed in Table 1 (not counting the final, anomalous annual period), the annual air conditioning provided averaged 1920 GJ (151,000 ton-hours), which exceeds the design storage capacity of 1760 GJ by 9 percent.

Chill recovery, defined as explained above, is reported in Table 1. The chill recovery is calculated as proportional either to the difference between the building inlet and outlet temperatures or to the difference between the building inlet temperature and the ambient aquifer temperature, whichever is smaller. Annual chill recovery averages 1600 GJ (126,000 ton-hours) for the first 7 years reported in Table 1. The total annual building heat rejection always exceeds the chill recovery, so "free cooling" occurs every year. Free cooling averages about 16.5 percent of the total air conditioning, and in those years where the winter chill storage is small compared to the summer cooling load, free cooling provides up to 20 percent of the total air conditioning.

The annual electrical energy consumption for building cooling, shown in Table 2, is the sum of the cold well pump and back pumping power consumption. Water has been back pumped from the warm wells during hot weather in an effort to reduce chill loss resulting from adverse regional aquifer flow. The power used for back pumping has increased in recent years as longer periods of back pumping have been employed. Over the past 4 years, back pumping has been used for about five months per year and has accounted for an average of 28 percent, or an average of 35 MWh per year, of the total system electricity usage. Electricity usage for building cooling has averaged 37 MWh over the 8 year period reported, which represents 31 percent of the total power consumption.

## Aquifer Storage Performance

Water levels around the UASRC have been measured at six head monitoring wells (H4W, H1W, H2E, H4E, H6E, and H4S). The water levels at the three head monitoring wells remote from the ATES system activity, wells H4W, H4S and H6E, have also been measured and are used to calculate the undisturbed aquifer hydraulic gradient at the site. The aquifer flow gradient is calculated by linear interpolation on the triangle whose vertices are the location of the top of the aquifer water in the three remote head monitoring wells. The hydraulic gradient, which is proportional to the flow velocity, is typically about 3-4 × $10^{-3}$ (3-4 m per 1000 m) in magnitude. The magnitude of the hydraulic gradient roughly parallels the aquifer water level, with dips in the water level accompanied by lowering of the gradient. The average direction of the aquifer flow is about 62° to the west of north at the UASRC site, with typical variations of ±12° and an extreme variation of 20°. A more detailed review of the aquifer flow and gradient data is presented in Song et al. [16].

Arrows in Figure 3 indicate the average natural aquifer flow direction. For the well field layout employed at the UASRC site, the rows of warm and cold production wells ideally should be located perpendicular to the direction of the aquifer flow. This would allow water removal from the warm wells to counteract the aquifer regional flow during water chilling. The extent and direction of the regional flow at the UASRC site was not known at the time the system was designed, and the well rows are located about 30° off the optimal orientation. Because of the 30° misalignment between the well rows and the natural aquifer flow direction, only wells 2 and 3 are effective at pulling back cold water injected into cold wells 4 and 5. Consequently, wells 1 and 6 were set as the lowest priority in the well utilization sequence.

The natural aquifer flow velocity is proportional to the hydraulic conductivity of the aquifer bearing strata and to the hydraulic gradient, as:

$$\mathbf{V} = K \cdot \nabla \mathbf{h} / \phi \qquad (1)$$

where **V** is the actual regional flow velocity, K is the average hydraulic conductivity, $\phi$ is the effective porosity, and $\nabla$**h** is the hydraulic gradient. From results of the analysis of well drilling samples and pumping tests, the hydraulic conductivity has been estimated as K = 37 m/day and the effective porosity has been estimated as $\phi \cong 20$ percent at the UASRC site [11]. Using a typical aquifer gradient magnitude of 3.5 × $10^{-3}$ in Equation 1, a regional flow speed of $V \cong 0.64$ m/day is obtained for the site.

The thermal front velocity, which is of primary interest for determining the energy storage potential of the aquifer, differs from the water velocity. When chilled aquifer water is injected into the aquifer, "chill" energy is stored in both water and the solid aquifer media. As chilled water moves through the aquifer strata, it is warmed both by mixing with other water and by conductive gains from solid media. The magnitude of the thermal front velocity, $V_{th}$, can be estimated by [1]:

$$V_{th} \cong \frac{V \cdot \phi \rho_w c_w}{\phi \rho_w c_w + (1-\phi)\rho_r c_r} \qquad (2)$$

where $\rho$ is density, c is specific heat, and subscripts "w" and "r" refer to water and aquifer solids, respectively. As Equation 2 shows, it is always true that $V_{th} \leq V$. Using $\phi$ = 20 percent, $\rho_r$ = 1770 kg/m$^3$, and $c_r$ = 0.84 kJ/kg°C, the thermal front velocity is about 0.26 m/day at the UASRC site.

Only limited site geological information was available prior to the drilling of the original six UASRC production wells. The existence of a large regional flow was not discovered until after project completion. Excessive regional flow causes stored chill energy to be convected beyond the potential recovery region surrounding the cold wells. The first measure taken to control the natural flow was to divert the warm water exiting the building cooling coils to the storm sewer rather than to reinject it into the warm wells. Reinjection into the warm wells is preferred from a water conservation standpoint but it exacerbates the problems arising from the natural aquifer flow by increasing the magnitude of the adverse gradient. Active back pumping was performed from mid-July to the end of September in 1988 and from May through September thereafter in an effort to further reduce the loss of chilled water. Wells 2 or 3 have been used for back pumping because they are located directly up gradient from the primary cold storage/recovery wells 4 and 5. A total of 76,000 m$^3$ of water was back pumped in summer 1988, and about 120,000 m$^3$ has been back pumped in each of the summers since.

Aquifer temperatures have been measured in numerous locations during the past eight years. The temperature data grid is sufficiently fine to compute isotherm contours at various elevations in the aquifer. Two such isotherm contours are presented in Figures 6 and 7 for an approximately horizontal plane 6 m above the bottom of the aquifer [14]. Wells 1 - 6, the footprint of the original UASRC structure, and the natural aquifer flow direction are also indicated on these figures. Figure 6 shows the aquifer storage zone in the fully discharged state in early November. At this condition, only a relatively small (30 m diameter) region of cold water at 3 to 4°C below the aquifer ambient temperature remains to the west of well 4. Figure 7 shows the aquifer in the fully charged state in early March. Temperatures as low as 9°C appear on the contour plot. Actual temperature measurements yield some measurements as low as 7°C, but the local extremes tend to be lost in the contouring routine. The effect of the natural aquifer flow on the temperature contours is clearly evident in Figure 7. The coldest water is centered not on well 4, which receives the greatest volume of chilled water from the cooling tower, but to the west/northwest and down gradient of well 4. The objective of back pumping has been to keep the chilled water "bubble" from moving even further down gradient. This objective has been met to a considerable degree as is evident from the position of the cold water zone in Figure 6. A more comprehensive analysis of the effectiveness of back pumping is presented in Song et al. [17].

## Overall System Performance

Choosing parameters for quantifying the performance of a chill based ATES system is not an easy task. An often used figure of merit for the gross thermal storage efficiency of an aquifer system is the Energy Recovery Factor (ERF), proposed by Molz et al. [3]. The ERF is defined as the fraction of the chill energy stored during cooling tower operation that is recovered during building air conditioning over an annual period. Energy rejection from the building accomplished by heating the building air handler water flow to temperatures exceeding the ambient aquifer water temperature is not counted here as recovered chill energy. Table 1 reports measurements of ERF ranging from 41 to 87 percent.

The ERF is a good indicator of the potential to recover chill energy stored in the aquifer, but is not an ideal measure of system effectiveness for two reasons. First, the ERF is strongly dependent upon annual weather conditions. More specifically, for any particular year, the extent of the availability of cold winter weather for water chilling is unrelated to the extent to which hot weather produces a demand for summer air conditioning. The second weakness of ERF as a measure of system performance is that it is only loosely related to building comfort. To illustrate these problems, consider the example of a long, cold winter followed by a mild summer. More cold water is stored than necessary, so the ERF is low. Nevertheless, the building air conditioning will be of high quality, with good dehumidification. The opposite situation, a brief, warm winter followed by a long, hot summer, results in insufficient chilled water storage. The ratio of recovery-to-injected cold water volume is large, which results a high ERF. In this situation the building dehumidification is poor, more of the air conditioning is accomplished by "free cooling", and the quality of the building air conditioning is low even though a large fraction of the stored chill energy is recovered,.

For purposes of comparing the ATES based air-conditioning system to other air-conditioning systems, the overall system COP, defined here as the ratio of air conditioning provided to the electrical energy input required to produce the air conditioning, is the conventional figure of merit. Excluding from consideration the final two annual periods, which saw frequent interruptions caused by construction activity, and taking the dimensionless ratio of the total annual air conditioning (Table 1) to the total annual electricity consumption (Table 2), overall measured system COP has averaged close to 5, as reported in Table 1. This is approximately double the annual measured COP that is obtained from conventional mechanical air-conditioning equipment of this size range. Consequently, the UASRC has been cooled for about one-half the electrical energy consumption of a conventionally air-conditioned building.

The COP and ERF have similar problems as measures of system performance. For a cold winter followed by a mild summer, considerable energy is expended in water chilling, but much of the cold water is not recovered. The ratio of air conditioning provided to electrical energy input (COP) is low even though building comfort is much higher than for the case of mild winter followed by hot summer, which would result in a higher COP. Back pumping also diminishes COP. For recent years in which back pumping has been extensive, annual COP would have been increased by nearly 40 percent if electricity usage included for back pumping had been omitted, although building dehumidification would suffer without back pumping.

As discussed above, both COP and ERF fail to account for building comfort. An alternative parameter for the evaluation of seasonal thermal storage system is the Aquifer Performance Factor (APF), which is defined as [17]:

$$\text{APF} = \frac{T_{t,i} - T_{b,i}}{T_{t,i} - T_{t,e}} \qquad (3)$$

where $T_{t,i}$ is the cooling tower inlet temperature, $T_{t,e}$ is the tower exit temperature (cold water injection temperature), and $T_{b,i}$ is the building inlet temperature (cold water recovery temperature). As defined by Equation 3, the difference between unity and the APF is related to the loss of thermodynamic availability in the stored chill energy. The measured values of APF for the past eight annual periods are presented in Table 1. In terms of APF, the 10/87 - 9/88 annual period was best, but APF values for all years after the implementation of back pumping exceed values of APF for the first two annual periods reported in which no back pumping occurred. A more detailed discussion of quantitative measures of ATES system performance can be found in Midkiff et al. [15].

Except for the last two years, in which construction activities have interrupted system operation, the original ATES system has provided 100 percent of the building cooling at the UASRC. In terms of the conventional figures of merit discussed above, ERF and COP, the UASRC system performance has been quite good. Chill energy storage in excess of the design storage capacity has been experienced each winter, and even the average annual chill energy recovery is greater than design storage capacity. Nevertheless, the potential is large for significant improvement to the system, in terms of both improved building dehumidification and higher operating efficiency.

Poor dehumidification results when chill recovery (building inlet) temperatures are too high. High recovery temperatures stem from excessive chill dispersion caused by adverse regional flow in the aquifer and, perhaps, from storing insufficient chilled water. Regional flow can be partially controlled by back pumping, but the extra pumping energy exacts a substantial penalty on system COP. Based on extensive operating experience, it would appear that the "design" thermal storage capacity of the system is too small to meet the actual annual cooling load. It is possible that the operating hours of the building as well as its usage and occupancy have changed since the building and ATES system were designed.

System efficiency, measured by COP, can be improved by reducing electricity consumption. At present, the cooling tower blower and back pumping are the two largest electricity users. Back pumping could be eliminated by the realignment of the well field, which would involve the construction of several expensive new wells. An alternative is to utilize the pumped well water for some other useful purpose, so that the ATES system benefits from the well being pumped but is not charged for the energy. Immediately adjacent to the UASRC is a large, approximately 10 ha (25 acre), irrigated recreational field. When the University was initially considering irrigation of this field, a proposal was made to utilize water from ATES system warm wells. The water requirement was about equal to, though slightly less than, the production of one warm well. The economic payback on the piping and pressure booster pump required to connect the well to the irrigation system was less than one year. Nevertheless, the administrator making the decision elected to use city water instead, citing the potential unreliability of the wells to supply water! At present, the heat pump that heats and cools the UASRC Addition uses water from one of the ATES wells, so the energy charge for back pumping will be reduced in the future.

## BENEFITS OF CHILL ATES

The benefits of building air conditioning using aquifer chill energy storage are numerous. From the viewpoint of energy savings, ATES systems typically yield both demand charge savings and lowered energy charges. In all but the coolest U. S. climates, most large buildings experience their peak electric demand on hot summer afternoons when the air conditioning is operating at full load. Cooling a building with an ATES system during hot weather requires only that some of the cold well pumps be operated. This uses much less energy than is required to power a conventional vapor-compression chiller and cooling tower combination. As a result, ATES summertime demand charges are greatly reduced. The ATES system reaches its peak electric demand on cold winter nights when maximum water chilling rates are achievable. For many applications, including the UASRC, the building is unoccupied and non-ATES electricity use is minimal. In addition to the demand avoidance savings, the higher COP of the ATES system yields significant electric energy savings to the customer. Utilities also benefits from the peak demand reductions that ATES systems provide. Southern U.S. utilities (and increasingly those in milder climates) experience their peak demands in the hot summer months. These utilities gain lowered capacity requirements as load is shifted from summer to winter.

At present there is strong interest in diurnal thermal storage systems. These systems utilize off-peak power rates to produce large stores of ice or chilled water at night with conventional equipment. Stored ice or chilled water is used to meet air-conditioning needs during the day, thus avoiding operating compressors during times of peak power rates. As is the case for the ATES systems, large demand charge savings result from these diurnal storage methods. However, due to the inherent storage and discharge losses, more total electric energy is required to operate a conventional equipment based diurnal storage system than a similar capacity conventional system with no storage capability. Consequently, the diurnal systems typically have higher energy charges and do not conserve electricity. The system discussed here, which utilizes thermal storage in an aquifer, is more efficient than a conventional system with or without storage because the ATES system does not use a compressor.

In addition to the reduced energy and demand costs, chill ATES-based air conditioning offers several other benefits in comparison to conventional mechanical air conditioning. The reliability of an ATES system during the air-conditioning season exceeds that of a conventional system. The only component required to deliver cold water is a well pump, and several cold storage wells are normally available (supply redundancy). A conventional system depends on a chiller, several pumps, and a cooling tower with fan motors. The failure of a single one of these components disables the system. Several major environmental benefits are associated with the use of an ATES system. The possibility of chlorinated fluorocarbon (CFC) release is eliminated, because no CFC-containing refrigerants are used. CFC's are both greenhouse gases and have been implicated in the chemical destruction of the stratospheric ozone layer. Reduced fossil fuel combustion resulting from ATES electricity savings reduces the associated air pollution problems and the release of greenhouse gases ($CO_2$). A potential health benefit of ATES is a reduction in the possibility of biological infestation of the water chilling system. Continuous treatment with biocides of many cooling towers is required to prevent the growth of microbes, such as the *Legionella* bacteria responsible for Legionnaire's Disease, during warm weather water cooling. Because water cooling occurs only during cold weather in an ATES system, microbial growth in the water cooling system is strongly inhibited. An additional potential benefit of ATES is that the resulting low cost of air conditioning allows new applications, e.g., industrial building cooling.

The primary impediment to commercialization of ATES is its high first costs. Depending upon the site and weather conditions, physical costs of construction and equipment are typically higher than for a conventional system of similar capacity, but they may be lower [4]. Although considerable progress is being made in the development of simplified field testing methods (e.g., Ref. 18) and in software to simplify ATES well field layout [19], the engineering effort required to design an ATES system will likely remain sizable. In order to improve ATES economics, COP must be further improved so that lowered operating costs will yield attractive, short payback times. In order to examine a potentially more energy efficient water chilling method, a major modification to the UASRC ATES system has been implemented in the last two years.

## REVISED ATES SYSTEM

The original UASRC chill-ATES-based air-conditioning system operated successfully for about nine years. It has provided 100 percent of the building cooling in all but a few months of the most recent two years when it was unavailable due to construction activity. Nevertheless, this system was a first-generation, prototypical design with some shortcomings. Excessive temperature degradation of the stored chill energy, coupled with insufficient total stored chilled water volumes often resulted in poor dehumidification in the late summer and early fall. The locations of the production wells with respect to the natural aquifer flow direction compromised the usefulness of wells 1 and 6. In an effort to address these two problems of the initial system design and to explore alternative, possibly more efficient, water chilling methods, the UASRC ATES system has been revised.

Water chilling in the original system was accomplished using a mechanical draft cooling tower. The spray pond may be an economically attractive alternative to the cooling tower for water chilling. The cooling tower has the advantages of requiring less space and generally has a lower first cost. The advantage of the spray pond is that operating costs, i.e., electric power input requirements, should be reduced significantly in comparison to the cooling tower. Power consumption for water pumping is somewhat higher for a spray pond, but a cooling tower requires a substantial input of power for fans to move air while a spray pond achieves air movement through natural convection and wind-aided forced convection. The original UASRC system used 30 to 45 percent of its total annual electricity consumption to operate the tower fan motors (Table 2). In addition to improved energy efficiency, the spray pond may prove more durable and reliable than the cooling tower because it is mechanically simpler.

Figure 10 shows a conceptual schematic of the revised UASRC system, which includes two new production wells (7 and 8) and a spray pond. The approximate locations of these added features are shown in Figure 3. The two new production wells have been sited to compensate for losses due to adverse regional aquifer flow cited previously. Well 8, a warm supply well, is located so that withdrawing water from it provides gradient control for well 6. Chilled water stored in well 6 in the original system was difficult to recover; the addition of well 8 renders well 6 useful for storage. Well 7, a new cold storage well, is located down gradient of cold storage wells 4 and 5. As regional flow gradually shifts the chilled water "bubble" down gradient, well 7 can be used later in the summer to recover chilled water that would have been lost in the original setup.

The spray pond system consists of a pond, spray heads, piping and valving, a spray pump, an injection pump and controls. The pond is a 25 m by 18 m earthen oval with a depth of about 2 m covered by a heavy plastic liner and typically filled with water to a depth of somewhat less than 1 m. There are 11 sets of four spray heads mounted on vertical pipe uprights that provide a spray fall height of 4 to 5 m. A flow of 510 $m^3$/hr of water is circulated from the pond sump to the spray heads by a 56 kW debris-tolerant spray pump. A flow in excess of 100 $m^3$/hr can be diverted to the cold storage wells by a 15 kW injection pump. The pond is equipped with a microprocessor-based control system and is actuated by a moist air enthalpy sensor.

Pond construction took a much longer time than anticipated and only preliminary operating data have been collected in marginal water chilling weather in spring 1994. A design goal for the pond is the storage of $95 \times 10^3$ $m^3$ of water annually (compared to an average of about $50 \times 10^3$ $m^3$/yr for the original system). Only limited data are available at present [20], but it appears that achieving this goal is probable. Future research will provide the data needed to compare the water chilling performance of spray ponds to cooling towers.

## CONCLUSIONS

A cooling system based on seasonal chill energy storage in a water table aquifer has been installed and successfully operated on a long-term basis to provide virtually 100 percent of the air conditioning at the Student Recreation Center on the University of Alabama campus. Performance monitoring indicates that it is possible to recover more than 80 percent of the stored energy, but that high energy recovery fractions have generally been associated with poor building dehumidification (recovery temperatures too warm), at least for the original system. An undesirable degree of chill dispersion in the aquifer has been caused by adverse regional flow conditions. Annual average system Coefficients of Performance have averaged 4.8, about double that achievable by a conventional system. The ATES system has been modified recently to compensate for regional flow problems, to increase water chilling capacity, and to study the potential of spray ponds to reduce water chilling electrical energy usage, thus further increasing system COP.

## ACKNOWLEDGMENT

*Support for this project by the U. S. Department of Energy through Pacific Northwest Laboratory is gratefully acknowledged.*

## REFERENCES

1. W. J. Schaetzle, C. E. Brett, D. M. Grubbs and M. S. Seppanen, 1980, Thermal Energy Storage in Aquifers, Pergamon Press, New York, N.Y.

2. H. R. Henry, J. R. McDonald and R. M. Alverson, 1971, Aquifer Performance Tests Under Two-Phase Flow Conditions, OWRR Project No. B-020-ALA, The Univ. of Ala. and Geol. Survey of Ala., Tuscaloosa, Ala.

3. F. J. Molz, J. C. Warman and T. E. Jones, 1978, "Aquifer Storage of Heated Water 1: A Field Experiment," Ground Water, Vol. 16, pp. 234-241.

4. V. Chant and E. Morofsky, 1992, "Overview of Projects with Seasonal Storage for Cooling from Four Countries," SAE paper no. 929021, IECEC 1992: Proceedings of the 27th Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 3-7, 1992, Society of Automotive Engineers, Warrendale, PA, pp. 4.9-4.13.

5. G. J. van Mourik, 1992, "Aquifer Cold Storage in the Netherlands: State-of-the-Art, Market Potential, and Future Development," in Aquifer Thermal Energy (Heat and Chill) Storage, publ. no. PNL-8381, Pacific Northwest Laboratory, Richland, WA, pp. 9-15.

6. O. Andersson and B. Sellberg, 1992, "Swedish ATES Applications: Ten Years of Development Experience," SAE paper no. 929019, IECEC 1992: Proceedings of the 27th Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 3-7, 1992, Society of Automotive Engineers, Warrendale, PA, pp. 4.1-4.7.

7. R. R. Davison, W. B. Harris and D. L. Reddell, 1979, "Texas A&M Cold Water Storage Project," NTIS, CONF-790328-P1.

8. W. J. Schaetzle, C. E. Brett and D. M. Grubbs, 1980, "Direct Cooling Utilizing Aquifer Thermal Energy Storage," ASHRAE Trans., Vol. 86, Part 2, pp. 609-622.

9. C. E. Brett and W. J. Schaetzle, 1984, "Experiences with Unconfined Aquifer Chilled Water Storage," ASHRAE Trans., Vol. 2B, pp. 169-181.

10. W. J. Schaetzle, C. E. Brett and L. H. Richey, 1983, "Experience with Two Free Cooling Systems Using Aquifer Thermal Energy Storage," Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice, Stockholm, Sweden, June 6-8, 1983, Swedish Council for Building Research, Stockholm, Sweden, pp. 823-828.

11. W. J. Schaetzle and C. E. Brett, 1989, The Aquifer Chill Storage Project at the University of Alabama, Tuscaloosa: Progress Report for 1985 and 1986, publ. no. PNL-6797, Pacific Northwest Laboratory, Richland, Wash.

12. S. H. Hall and D. R. Newcomer, 1992, Hydrologic Characterization of the Unconfined Aquifer at the University of Alabama Student Recreation Center, Tuscaloosa, Alabama, publ. no. PNL-8004, Pacific Northwest Laboratory, Richland, Wash.

13. Y. K. Song, 1990, "Air-Conditioning Systems Based on Seasonal Aquifer Chill Energy Storage," Ph.D Dissertation, The University of Alabama, Tuscaloosa, Ala.

14. K. C. Midkiff, Y. K. Song and C. E. Brett, 1991, "Thermal Performance and Challenges for a Seasonal Chill Energy Storage Based Air-Conditioning System," ASME paper no. 91-HT-29, presented at the National Heat Transfer Conference, Minneapolis, MN.

15. K. C. Midkiff, Y. K. Song and C. E. Brett, 1992, "Long-Term Performance of an Air-Conditioning System Based on Seasonal Aquifer Chill Energy Storage," SAE paper no. 929049, IECEC 1992: Proceedings of the 27th Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 3-7, 1992, Society of Automotive Engineers, Warrendale, PA, pp. 4.49-4.54.

16. Y. K. Song, K. C. Midkiff, W. J. Schaetzle and C. E. Brett, 1989, "Operational Experience with a 150 Ton Air-Conditioning System Based on Aquifer Chill Energy Storage," 9th Miami International Congress on Energy and Environment, Miami Beach, Fla.

17. Y. K. Song, K. C. Midkiff, W. J. Schaetzle and C. E. Brett, 1989, "Control of Aquifer Flow for Improved Aquifer Thermal Energy Storage System Performance," IECEC-89: Proceedings of the Intersociety Energy Conversion Engineering Conference in Washington D. C., August 6-11, 1989, Institute of Electrical and Electronics Engineers, Washington D. C., pp. 1833-1838.

18. S. H. Hall and J. R. Raymond, 1992, "Geohydrologic Characterization for Aquifer Thermal Energy Storage," SAE paper no. 929156, IECEC 1992: Proceedings of the 27th Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 3-7, 1992, Society of Automotive Engineers, Warrendale, PA, pp. 4.101-4.107.

19. L. W. Vail, L. D. Kannberg and C. T. Kincaid, 1988, "Aquifer Thermal Energy Storage System Simulator (ATESSS): User's Manual and Report, publ. no. DOC/DE-AC06-76RL0 1830, Pacific Northwest Laboratory, Richland, WA.

20. K. R. Gelinas, 1994, "The Applicability of Spray Ponds to Chill Water for Aquifer Thermal Energy Storage Systems," M. S. Thesis, The University of Alabama, Tuscaloosa, Ala.

Table 1
Overall ATES System Performance Data

| | 10/85-9/86 | | 10/86-9/87 | | 10/87-9/88 | | 10/88-9/89 | |
|---|---|---|---|---|---|---|---|---|
| | Inj | Rec | Inj | Rec | Inj | Rec | Inj | Rec |
| 1000 m^3 | 56.2 | 92.4 | 44.5 | 111.8 | 54.4 | 97.0 | 39.8 | 102.6 |
| Tin (degC) | 18.1 | 14.5 | 18.3 | 14.3 | 16.9 | 12.8 | 17.4 | 13.9 |
| Tout (degC) | 5.7 | 18.1 | 6.1 | 18.9 | 5.7 | 17.9 | 6.1 | 18.6 |
| Heat Rej (GJ) | 2897 | 1359 | 2288 | 2150 | 2567 | 2078 | 1890 | 2031 |
| Chill Rec (GJ) | | 1176 | | 1741 | | 1803 | | 1642 |
| COP | 4.1 | | 5.4 | | 4.6 | | 4.9 | |
| ERF (%) | 40.6 | | 76.1 | | 70.2 | | 86.9 | |
| APF (%) | 30.4 | | 32.6 | | 43.9 | | 36.2 | |
| | 10/89-9/90 | | 10/90-9/91 | | 10/91-9/92 | | 10/92-9/93 | |
| | Inj | Rec | Inj | Rec | Inj | Rec | Inj | Rec |
| 1000 m^3 | 59.2 | 108.6 | 50.4 | 121.6 | 57.3 | 108.9 | 34.7 | 62.5 |
| Tin (degC) | 18.3 | 13.5 | 18.3 | 14.3 | 17.9 | 14.2 | 16.9 | 14.4 |
| Tout (degC) | 6.0 | 18.2 | 6.3 | 18.3 | 6.1 | 17.8 | 7.7 | 18.2 |
| Heat Rej (GJ) | 3048 | 2148 | 2521 | 2071 | 2823 | 1601 | 1344 | 978 |
| Chill Rec (GJ) | | 1812 | | 1606 | | 1391 | | 893 |
| COP | 4.6 | | 4.6 | | 3.4 | | 2.5 | |
| ERF (%) | 64.0 | | 63.7 | | 49.3 | | 66.4 | |
| APF (%) | 39.2 | | 33.8 | | 33.5 | | 36.5 | |

Table 2
ATES System Electricity Usage

| | 10/85-9/86 | 10/86-9/87 | 10/87-9/88 | 10/88-9/89 |
|---|---|---|---|---|
| Total Power (MWh) | 92 | 111 | 125 | 116 |
| | Percentage Breakdown Of Power Usage | | | |
| Cold Well Pumps | 31 | 32 | 27 | 26 |
| Hot Well Pumps | 11 | 12 | 12 | 9 |
| Back Pumping | 0 | 5 | 15 | 23 |
| Tower Blower | 58 | 51 | 46 | 42 |
| | 100% | 100% | 100% | 100% |
| | 10/89-9/90 | 10/90-9/91 | 10/91-9/92 | 10/92-9/93 |
| Total Power (MWh) | 129 | 126 | 131 | 111 |
| | Percentage Breakdown Of Power Usage | | | |
| Cold Well Pumps | 26 | 30 | 27 | 21 |
| Hot Well Pumps | 12 | 10 | 10 | 12 |
| Back Pumping | 30 | 27 | 29 | 26 |
| Tower Blower | 32 | 33 | 34 | 41 |
| | 100% | 100% | 100% | 100% |

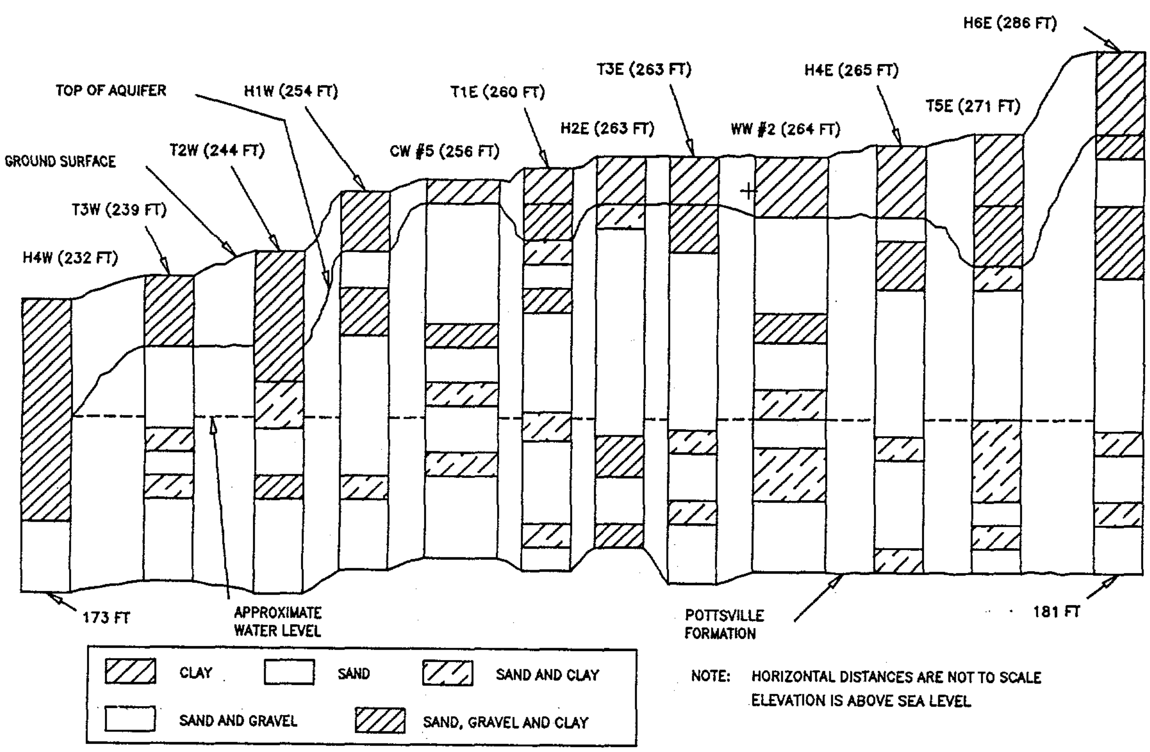



Figure 1. Aquifer cross section, south-to-north, at UASRC site.

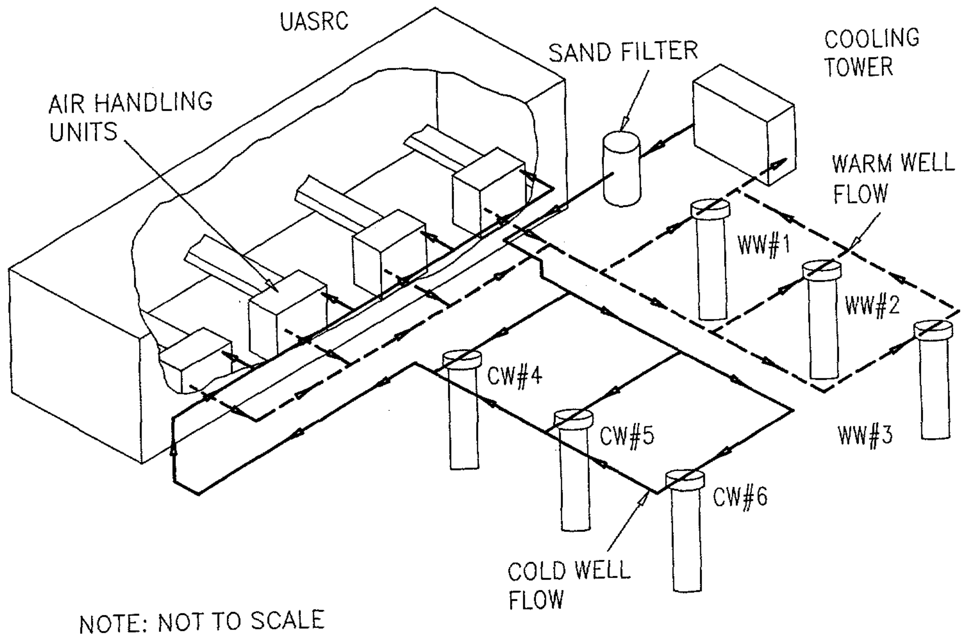



Figure 2. Conceptual schematic of original ATES system.

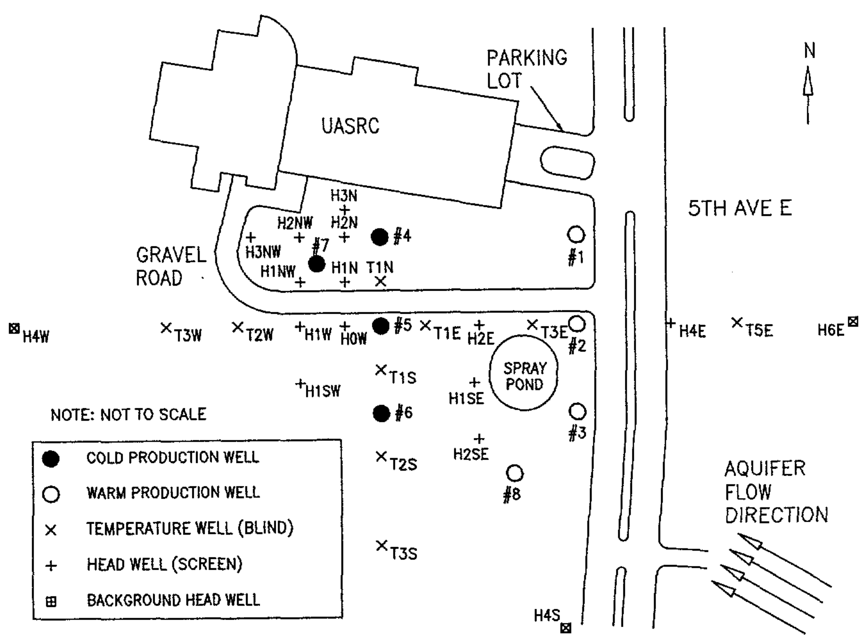



Figure 3. ATES well field layout at UASRC site.

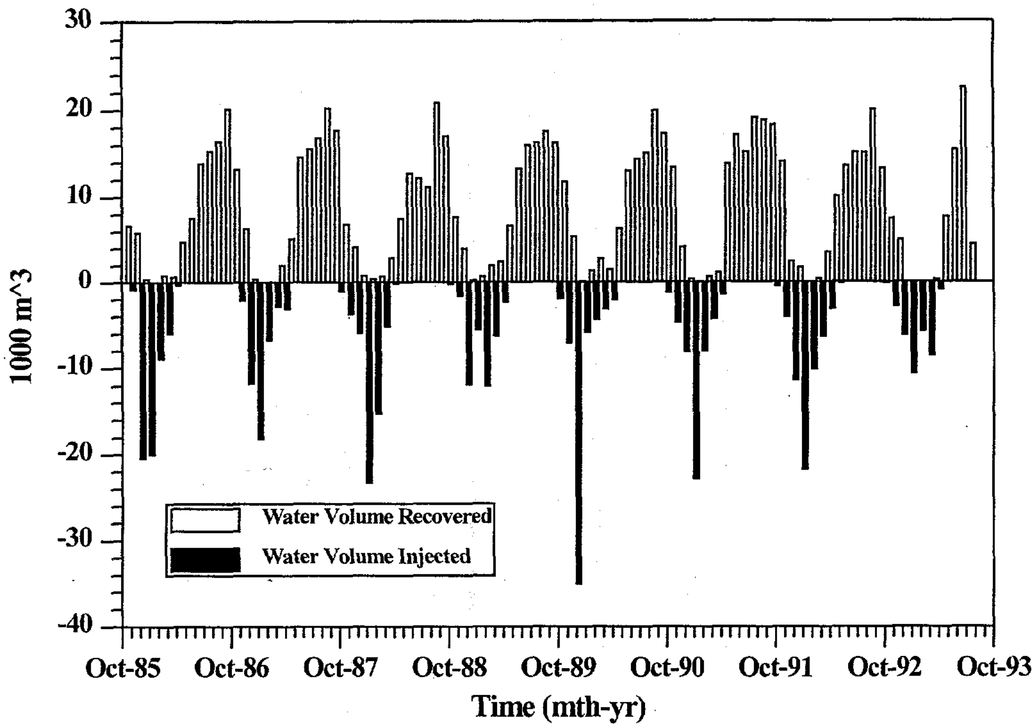



Figure 4. Monthly injected and recovered water volumes.

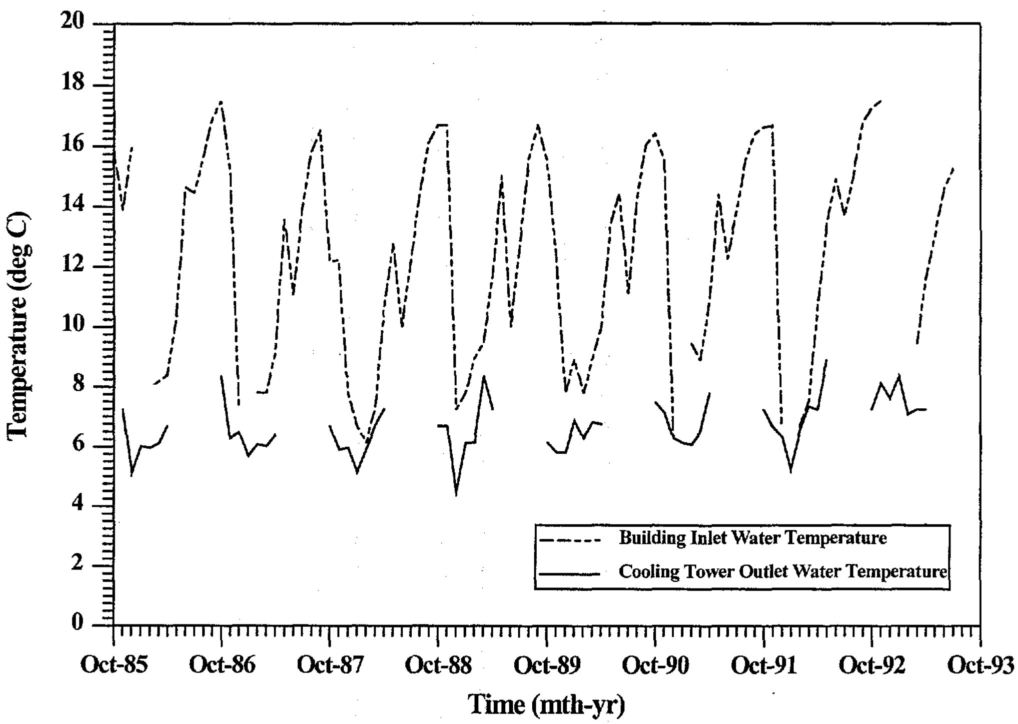



Figure 5. Cooling tower outlet and building inlet water temperatures.

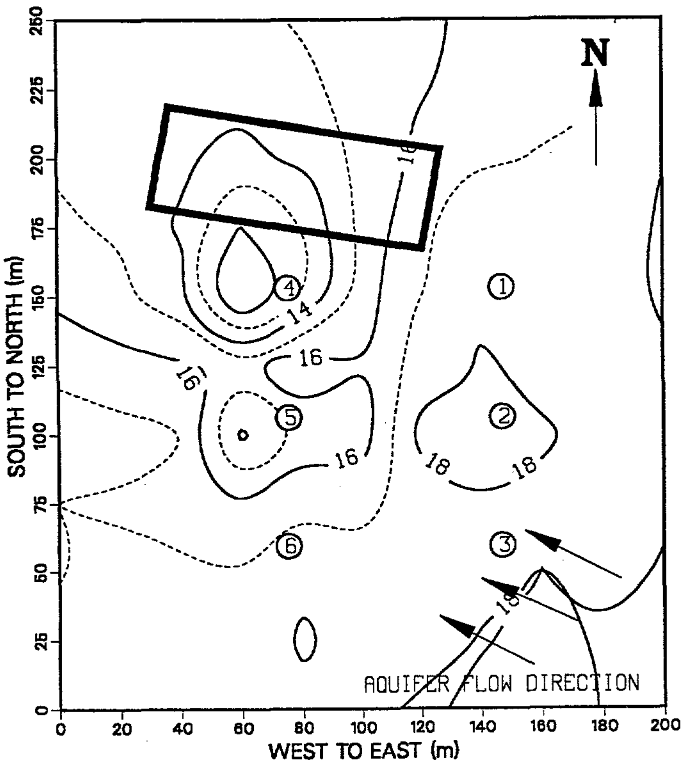



Figure 6. Isotherm contour plot for December 30, 1990.

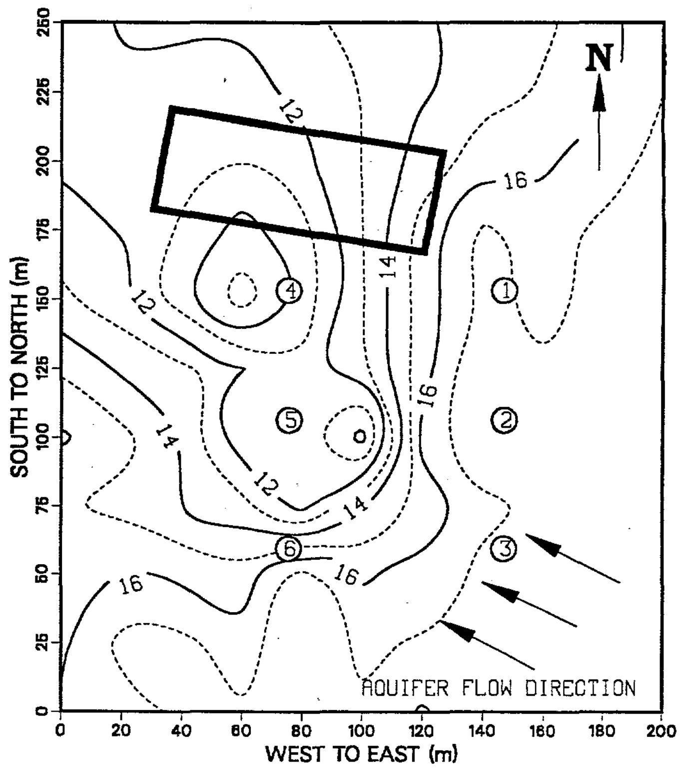



Figure 7. Isotherm contour plot for March 14, 1991.

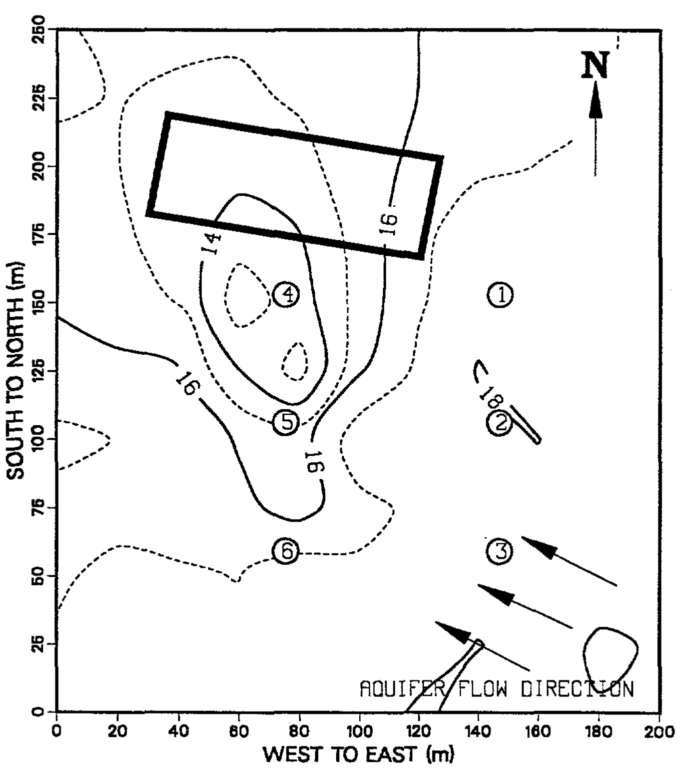



Figure 8. Isotherm contour plot for July 12, 1991.

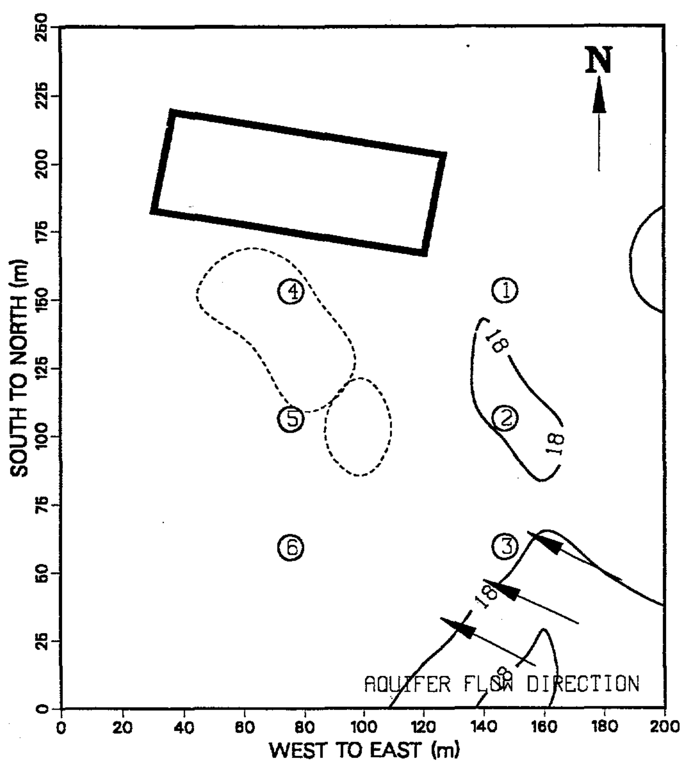



Figure 9. Isotherm contour plot for September 27, 1991.

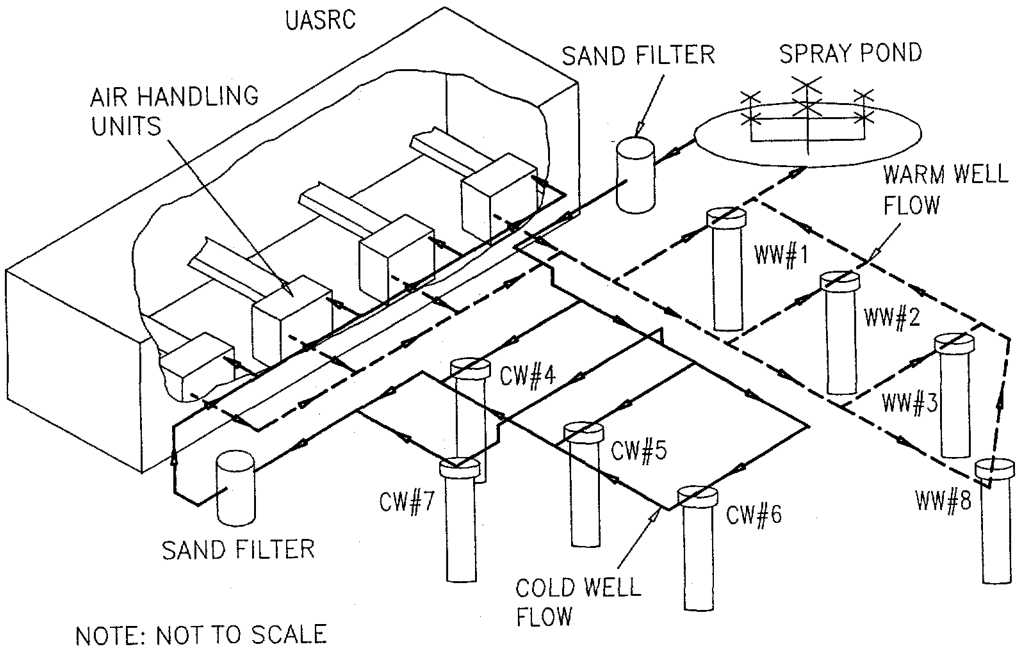



Figure 10. Conceptual schematic of modified ATES system.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Status of Cold Storage in Aquifers in the Netherlands in 1994

• A. (Guus) Willemsen
• G. Bakema
• A.L. Snijders
IF Technology bv
Arnhem, The Netherlands

## ABSTRACT

The number of projects realized with cooling based on aquifer cold storage in the Netherlands has been increasing in the last few years (from three in 1992 to six in 1993 and nine projects realized in the year 1994). Of five projects, brief descriptions are given. The number of projects has risen, mainly because groundwater cold storage compared with cooling with conventional chillers is attractive from the economic point of view. The last few years the cost-effectiveness has even further increased due to the higher costs of chillers caused by the ban on the use of the CFCs R11 and R12. Another matter not to be considered insignificant, are the experiences gained meanwhile, on the basis of which the designs of cold storage systems and of cooling/heating systems for commercial buildings can be considerably better tuned to each other now (system integration). The Dutch Government has to a large extent contributed to the success of cold storage by granting special subsidies for realized projects and by financing supporting studies. A market study for cold storage reveals that the number of projects is likely to increase in the future.

At the time, this development is still unique for the Netherlands, but it is very well possible that the situation will change. In principle, all areas which have climates with both cold winters and warm summers and which rest on a proper aquifer, are suitable for this type of cold storage.

## INTRODUCTION

The principle of cold storage in aquifers is very simple. If there is much natural cold in the winter, this can be stored in the subsoil. In summer the stored cold can be used for cooling purposes. The great advantage of this technique is that no chillers are necessary to generate cold in summer when the outside temperatures are high. Chillers use large quantities of electric energy so that aquifer cold storage can render a major saving on electricity. Furthermore, chillers contain CFCs, whereas a cold storage system does not contain any such CFCs. Aquifer cold storage can also be an alternative to the use of through-flow cooling with groundwater. With through-flow cooling the groundwater is extracted, heated and discharged into the sewer or to surface water. As good-quality groundwater in the Netherlands is scarce, and because groundwater extraction may induce a fall in hydraulic head, more and more attempts are being made to reduce the consumption of groundwater.

Aquifers are present almost everywhere in the Netherlands. This means that aquifer cold storage is difficult to realize only in a few areas of the country. The composition of the water as such does not influence the possibilities from the technical point of view.

The next paragraphs will deal with the main components of a cold storage system, the objects with potential cold demand and the way in which cold can be caught in winter (availability of cold), the effects of the Dutch climate, the effects of the desired cooling water temperature, the possible storage systems, realized storage systems and market prospects.

## THE BUILDING BLOCKS OF A COLD STORAGE SYSTEM

Figure 1 shows schematically how an aquifer cold storage system can look like. The main elements are the wells, the connecting piping, the heat exchanger, the cold supplier (here, a cooling tower) and the cold demander (here an office building). The components will be briefly described below.

### Wells

The number of wells on each side depends on the maximum output required and on the aquifer available (thickness and permeability). The aquifer, which is present on location by nature, is the storage reservoir for the cold. Consequently, this storage capacity need not be built, just the wells to provide access to it. In winter, water is pumped from a well and allowed to cool down by outside air. This cold water is then injected into the "cold" (injection) wells. This water will spread from the wells according to a radial pattern, with the water giving off its cold to the sand grains. The wells have diameters varying between 300 mm and 1,000 mm and are provided with a PVC screen at aquifer height and with a PVC riser. The well is provided with an envelope of screen gravel, clay and supplementary gravel. The well contains a submersible pump to extract the water from the aquifer. Frequently, wells for cold storage also contain injection lines so that the water can be injected into the well. With cold storage no groundwater is extracted in the end. All the water extracted is re-injected on the other side. Consequently, groundwater is indeed replaced from one well to the other.

### Field piping

The wells are connected by piping, part of which will be installed underground in the field and part in buildings. This piping will in most cases be made of plastics (e.g. PVC). The distance between the wells is related to the amount of cold to be stored and the aquifer thickness available. Short-circuiting between warm and cold wells should be prevented.

### Heat exchanger

An aquifer cold storage system will in most cases be equipped with a heat exchanger which provides a hydraulic separation between groundwater circuit and building or process circuit (the cooled water circuit). Where no heat exchanger is installed, the groundwater is directly guided along the objects to be cooled. Where a heat exchanger is available, the cold is passed on from the groundwater circuit to the cooled water circuit in summer, and vice versa in winter.

The presence of a heat exchanger has several advantages and disadvantages, which are briefly given in Table 1. It appears from this table that the advantages of a heat exchanger will often counterbalance the disadvantages, especially if the cooled water has to be lifted higher (with a higher head to be delivered by well pumps) or if the groundwater is corrosive or contains much gas.

### Cold supplier

In winter the groundwater has to be chilled. One of the most obvious methods is the use of dry or wet cooling towers. In a wet cooling tower the water is distributed over a bed, with air being drawn in over the same bed. Part of the water evaporates, causing a cooling effect to a few degree Celsius above the wet-bulb temperature. The water is passed along a heat exchanger where the groundwater or building water can cool down. Other possible cold suppliers will be discussed later below.

### Cold demand

The cold demand may arise from an office building with ventilation air cooling, from process cooling, from cooling of computers, from a concert hall, from farming activities etc. Some of these applications will be dealt with below.

## COLD SUPPLY AND DEMAND

The function of a cold storage system is to buffer the cold supply of the winter so that it can be supplied to an object with cold demand in summer. Finally, the aim is to catch so much cold in winter that the demand in summer can be met. How much cold can be caught, partly depends on the technique applied and on the climate. Table 2 gives a summary of potential cold demanders and cold suppliers.

The supply of cold is always related to the season of the year. The cold demand may be related to the season, or be continuous. For instance, the cooling demand of processes in chemical industries are often continuous, whereas the cold demand from offices is to a large extent strongly related to the season. A continuous cold demand implies a double function for the cold supplier: storage loading in winter, and process cooling. This pattern can also be found in some office buildings where the internal heat load is large due to the presence of (many) computers. An example is given in Figure 1 where, during office hours, part of the cold from the cooling towers is sent to the office building and only part of it to the heat exchanger towards the wells. As a matter of fact this does have consequences for the dimensioning of these components.

If the location of the cold demander is close to surface water, surface water cooling will often be profitable, especially because natural effects have already chilled the water and because it will only have to be pumped along a heat exchanger between groundwater and surface water. If stagnant surface water is used it will, as a matter of fact, have to be considered whether short-circuiting may be significant and to what extent the surface water actually cools down in the mean time.

Where air-handling units (AHUs) are used to load aquifers with cold, only few additional investments are needed to do this. For, the air-handling units are used to cool down the ventilation air in summer, but they can also fairly easily be used to chill the water in winter. At the same time, the ventilation air is pre-heated, which is another contribution to more economy in energy consumption.

## CLIMATE EFFECTS

As a matter of fact, the climate is to a large extent determinative as regards the success of cold energy storage. If the winters are not cold enough, it is not possible to generate enough cold water. For De Bilt, in the centre of the Netherlands (headquarters of the Royal Dutch Meteorological Institute), the average number of hours in a year below a certain temperature during the day and at night has been established. For that location a wet-bulb temperature below 0°C is measured for an average of less than 1,000 hours a year. But a wet-bulb temperature below 10°C is measured for more than 5,500 hours. This indicates that it is much more difficult in winter to chill water to 2°C than to 10°C. Furthermore, at lower temperatures the uncertainty will be greater that not enough cold will be loaded in a given winter because, with decreasing temperatures, the variation (distribution) in the number of hours below a set temperature significantly increases. For that reason storage temperatures are often between 5 and 10°C. The natural temperature of shallow groundwater in the Netherlands amounts to approx. 11 or 12°C. This is slightly higher than the average temperature of outside air in the Netherlands (approx. 9°C). The groundwater temperature increases downwards by about 3°C per 100 m, due to heat conduction from the interior of the earth.

### Temperature level and cooling system

Some processes need (very) low temperatures for cooling. Freezing plants, for instance, demand temperatures below 0°C (as the name already suggests). It will be clear that aquifer cold storage facilities are unable to supply such temperatures. In that case, chillers are indispensable. Table 3 shows a number of cooling techniques with the corresponding cooling water temperature. Which cooling system can be applied for a certain process, depends on the maximum temperature which the cooling water is allowed to achieve.

Through-flow cooling with groundwater and surface water comprises the extraction of these types of water, the cooling of the process using this water, and finally the discharge of the water into the sewer or to the surface water. Where surface water availability and temperature level are such that it can be used for through-flow cooling in summer, it does not make sense to apply aquifer cold storage.

As can be seen from Table 3, aquifer cold storage can be an alternative to the cooling with chillers (mechanical chilling) or to through-flow cooling with groundwater. The investment costs of cold storage and of mechanical chilling are at the same level, but the running costs of cold storage (energy consumption) are considerably lower. If temperatures under 5°C are required, a chiller must be provided. With a large temperature range (e.g. from 15 to 5°C), part of the demand may be met from cold storage.

Cold storage in aquifers is more expensive than through-flow cooling with groundwater, both as regards investment costs and running costs. This may be changed in the near future because of Government plans to impose levies on groundwater extraction. A main advantage of cold storage is that the net groundwater extraction is zero, as extraction and re-injection are performed simultaneously. This advantage also applies when compared with top cooling. Top cooling implies that groundwater is extracted in summer (which is the most critical period for farming and nature). Where higher cooling water temperatures are admissible, more cooling techniques are possible. At higher allowed cooling water temperatures, aquifer cold storage tends to be less attractive from the financial point of view because it will be more economical to dispose of excess heat immediately in summer than to store this heat and be obliged to dispose of it after all in winter.

In short, it may be stated that cold storage in aquifers is an interesting option from both the economy and the energy points of view if:

- no chiller is needed and the cooling water temperature is not less than approx. 5°C;
- through-flow cooling with groundwater is no longer allowed to be used (Government policy) and/or levies are imposed on this technique and the maximum cooling water temperature shall be below approx. 25°C.

## STORAGE SYSTEM

Two different storage systems can be distinguished for the groundwater circuit, namely cold storage/pre-cooling and cold storage/recirculation.

### Cold storage/pre-cooling

Cold storage/pre-cooling implies that the water is pumped from "warm" wells to cold wells in winter, and from cold wells to warm wells in summer. Consequently, there is a seasonal change in flow direction of the water. Wells are mostly both injection and extraction wells (see Figure 1).

### Cold storage/recirculation

With cold storage/recirculation the water is pumped in one direction all the time. The water is pumped from extraction wells and used for cooling, during which the water temperature is raised. In summer this warmed water is injected into the injection wells. In winter, by means of a cold supplier, the water temperature is lowered such that, averaged for the year, no heat is discharged into the subsoil (see Figure 4 and 5). The advantage of this technique is that the wells have a single function, either injection or extraction, which makes them less expensive. Furthermore, this is a very useful system for applications with a constant cold demand, as is often the case with industrial applications. A third advantage is that the system is very suitable for industrial extraction where groundwater is already being used for cooling purposes. In case the Government intends to restrict extraction, e.g. within its policy to curb the adverse effects of a fall in hydraulic head, the existing system can fairly easily be changed into a recirculation storage system, which in many cases allows the use of extraction wells to be continued. A major disadvantage of recirculation storage is that the extraction temperature is always the same as the natural temperature. So, no lower temperatures can be realized, which indeed is possible with seasonal storage. Consequently, the choice between the two systems partly depends on the temperatures to be applied.

## PROJECTS REALIZED AND IN PREPARATION

Tables 4 and 5 contain a list of aquifer thermal energy storage (cold and heat) projects realized or being prepared in the Netherlands (as per September 1994).

The following conclusions can be drawn from the data of these tables:

- There is an increase in the number of projects realized each year.
- The size of realized storage facilities varies from 20 to 480 $m^3/h$ in output and from 10,000 to 200,000 $m^3$ in storage capacity, whereas there is one with a peak performance up to 3,000,000 $m^3$
- Only two heat storage projects in aquifers have been realized in the Netherlands, namely with Utrecht

University (RUU) and with Heuvelgalerie (Eindhoven). In the past, the storage facilities of the BAM office building at Bunnik also provided heat storage. But the solar collectors and the heat pump, which were to adopt the heat to be used for the central heating system, failed to function properly.

- Apart from the aquifer heat storage projects referred to, the storage temperatures on the hot end are all below 20°C, and on the cold end above 4°C.
- The loading of the storage facilities mostly occurs with air-handling units, followed by dry and wet cooling towers.
- The cold and/or heat demand mostly originates from space cooling and/or heating. The demand is often created by a combination of sunlight, warm outside air, people, lighting and electrical equipment (several offices, a hospital, a shopping centre and a multi-functional hall) and any machinery present (e.g. printing presses). In two cases the cooling is to optimize the growth of flowers and plants in greenhouses (subsoil cooling).

Below, three examples will be given of realized projects; furthermore, two interesting projects in preparation will be dealt with in brief.

## THREE REALIZED PROJECTS

### IBM Office, Zoetermeer

The IBM office building at Zoetermeer dates from the early seventies. The building is equipped with an installation to cool offices and computer locations. In 1991 the chillers which provided the necessary cold had to be replaced urgently. As a matter of fact, the chillers could have been replaced by new ones, but another option was to replace them by a cooling system based on cold storage. IBM decided in favour of cooling with cold storage. The system is shown schematically in Figure 1.

The annual cold demand averages 1,200 $MWh_{th}$. In a hot summer the cold demand can be larger whereas in a cold summer it will be less. For a system to supply 1,200 $MWh_{th}$ in summer, it is of course required that a larger amount has to be stored in winter. Starting from an efficiency of 80% and a spare capacity of 15% for climatological fluctuations, an amount of 1,700 $MWh_{th}$ has to be stored in winter. This implies that in an average winter approx. 140,000 $m^3$ water of 5°C has to be injected into the cold wells.

In cold winters the amount injected will be larger. It is estimated that this can be as high as 200,000 $m^3$. In an average summer about 115,000 $m^3$ water will be extracted from the cold wells and re-injected at 15.5°C in the warm wells. For a hot summer with a greater demand for cold this quantity can increase to an estimated amount of 200,000 $m^3$. The main characteristic values for the groundwater system are summerized in Table 6.

The groundwater in the aquifer used in Zoetermeer is brackish and contains much methane. The high methane content makes it necessary to maintain a high pressure (1.5 bar) on the groundwater system. The flow control on the groundwater system is in steps: 17, 30, 50, 63, 87, 100 $m^3/h$. The flow control on the building side is continuous. A thermally layered vessel balances the difference between the two flows. This is shown schematically in Figure 2.

<u>Economic aspects</u> The total cold storage system, including cooling towers, wells, etc., costed 1,500,000 guilders. The feasibility study and engineering plus environmental impact assessment studies costed approx. 200,000 guilders. The conventional cooling system would have costed approx. 900,000 guilders (including engineering etc.). The cold storage system saves about 440,000 kWh electricity a year, which amounts to 120,000 guilders, also because the peak load in electricity demand decreases. The Dutch Government has granted a subsidy on this project of 300,000 guilders. So the simple payout time is 4 years. Without the subsidy the payout time would have been 6 years.

<u>Present status</u> In the winter of 1993/1994 the first cold was stored and in the summer of 1994 the stored cold was used. Apart from some minor start-up problems, the energy store functions properly.

### Royal Netherlands Industries Fair, Utrecht

In October 1993, the Royal Netherlands Industries Fair in Utrecht opened the new multi-functional hall "De Prins van Oranje". This building, measuring 85 m wide, 185 m long and 10 m high, has room for a maximum of 25,000 people and as such is the largest multi-functional hall in the Benelux countries.

In the final design (Figure 3) loading is done by means of fans in each of the air-handling units. Hereby, cold outside air is sucked in by the air cooler and subsequently discharged again. The cooling water is thus chilled in the air cooler and the cold is transferred to the groundwater circuit via the heat exchanger. Loading the cold is done at outdoor temperatures of +3 to -4°C, and takes place at times when the building is not in use. At lower outside temperatures loading is stopped with a view to possible freezing. If the air-handling unit is operating to air-condition the hall when outdoor temperatures are low (< -4°C) freezing is prevented by heating the coolers. The air coolers then function as pre-heaters in the air-handling units.

For hydraulic considerations the groundwater system is separated from the cooling water system by means of a heat exchanger. The flow direction in the groundwater circuit changes per season. To adjust the cooling water system flow to this, a four-valve control has been included. To prevent air entering the groundwater system, it has been so designed that there is overpressure during both standstill and operation. The main characteristic values for the groundwater system are summarized in Table 6.

Economic aspects A cost comparison between mechanical chilling and aquifer cold storage indicates that cold storage is cheaper by about 150,000 guilders. The costs of the complete cooling system, excepting the air supply system, are 3,000,000 guilders. These costs excluded the additional costs of the engineering of the groundwater system and of the license application in view of the Groundwater Act.

The main positive environmental impact would be the saving on electric power. Compared with mechanical chilling, 60% electricity is saved. The savings on electricity costs are even higher (81%, 30,000 guilders) because of a lower capacity rate.

Project status In the winter of 1993/1994 a considerable amount of cold (162 MWh) was loaded without any disturbances worth mentioning.

Given the fact that summer injection into the warm wells took place at an average temperature of 14°C, an amount of about 200 MWh is available for cooling in summer. This means that despite the very short loading period (the system was ready by February 1994) and the relatively mild winter, 50% of the required cold was loaded. Although the summer of 1994 was very hot, the installation was used only twice. This was due to the fact that the hall was not rented for large indoor events.

### Hedera nursery, Luttelgeest

Some pot plant species, e.g. hedera (ivy), can suffer substantial growth damage if the root zone temperature becomes too high. That was the reason why Messrs J.J. van der Berg & Zn. installed a cooling system in the greenhouses of their hedera nursery at Luttelgeest in 1993. The required cold is supplied by groundwater according to the cold storage/recirculation principle.

In summer the water circulating in the greenhouse circuit is cooled by the low-temperature groundwater by means of a heat exchanger. This water in turn cools down the aluminium pyramids on which the hedera pots are placed. The diagram with the working principle of the cooling system with cold storage/recirculation is shown in Figure 4. The cooling of the pot plants is realized as the aluminium gutters in which all pot plants are placed, are cooled. The cooled water is carried through a piping already present at the bottom of the gutters. In winter this duct is used for low-temperature heating.

In winter no groundwater is demanded for greenhouse cooling. To prevent an ongoing heating up of subsoil and groundwater due to the infiltration of heated groundwater in summer, groundwater is re-injected in winter at a temperature *below* the natural groundwater temperature. To chill the groundwater the present rain water pond is used. If the water temperature of the pond is low enough, water is pumped from the pond to chill the groundwater by means of the heat exchanger (see Figure 4).

Economic aspects The cooling system at Van der Berg's required an investment of 190,000 guilders. This includes an amount of 20,000 guilders for measurements which the Province of Flevoland required in the license. The actual project costs amounted to 170,000 guilders. Included are components such as wells, adaptations in the greenhouse, heat exchanger, piping in the greenhouse and PLC (programmable logical control). For this project the Luttelgeest hedera growers were eligible for a 50,000-guilder subsidy from the Dutch Agency for Energy and the Environment (NOVEM). Furthermore, the Province of Flevoland granted a subsidy of 65,000 guilders from an innovation fund. Van der Berg had not been informed previously that they would be eligible for these grants, which consequently came by surprise.

If Van der Berg had invested in the alternative of mechanical chilling, the required 325-kV installation and additional aspects would have required an investment of approx. 150,000 guilders. The annual electricity bill of mechanical chilling would have been 9,000 guilders, whereas the annual amount for the finally installed method is about 1,500 guilders.

## TWO PROJECTS IN PREPARATION

### Plastics factory WAVIN, Hardenberg

WAVIN in Hardenberg produces a wide variety of synthetic products (pipes, crates, foils, etc.). Machinery and product require cooling during the production process. To supply this cooling, the company relies on indirect cooling with the use of groundwater. Cooling compressors are only used to supply after-cooling on a limited scale.

On a yearly basis about 3,000,000 $m^3$ groundwater is extracted to provide the cooling. After use approx. 800,000 $m^3$ of the groundwater is re-injected, with the other 2,200,000 $m^3$ being discharged to the surface water.

In 1992, as part of the Government policy to restrict the use of groundwater for low-quality purposes (such as cooling), a study was carried out to investigate alternative cooling methods. The study compared the use of chillers, cold storage and cold storage/recirculation. This later version proved to be both technically and economically the most suited option for WAVIN.

With cold storage/recirculation (see Figure 5) the groundwater is re-injected after use. If the temperature of outside air is low enough, the groundwater is cooled before it is injected. If the air temperature is higher, the warm groundwater is injected without being cooled first. The underlying idea is that over a longer period of time, the temperature of groundwater after injection will return to its natural level. In summer the injected water temperature will be higher by a few degrees than the natural groundwater temperature, while in winter the injected water temperature is slightly lower than the natural groundwater temperature. With the correct positioning of the injection wells in relation to the extraction wells, there will be no temperature fluctuations in the extracted groundwater. The extraction temperature is therefore virtually constant.

The capacity of the cold storage/recirculation system should be at least 3,600 $kW_{th}$ plus a spare capacity of 15%. A maximum of 480 $m^3$ groundwater per hour needs to be extracted and re-injected after use. In summer, the average injected water temperature is approx. 17,5°C.

To chill the groundwater in winter, WAVIN can make use of the surface water and/or cooling towers.

Compared with the application of chillers, a cold storage/ recirculation system saves 2,000 MWh of electricity on a yearly basis, which works out as approx. 70% of the total electricity consumption required for cooling through chillers.

Economic aspects The capital necessary to replace the present cooling system with a cold storage/recirculation system (using surface water to chill the groundwater before injection in winter) is approx. 2,200,000 guilders (price level 1992). This investment is considerably lower than the capital outlay necessary for chillers. Thus, introducing cold storage/ recirculation constitutes a capital saving as well as a reduction in running costs in comparison with the use of chillers.

Compared with the present cooling methods, there is an increase in annual running costs by approx. 325,000 guilders. This is mainly due to the depreciation of the investment which is included in the annual running costs. This situation will change drastically when a special levy is imposed on the use of groundwater as part of the Environmental Tax Act. For example, a levy of 0.17 guilder per $m^3$ groundwater increases the running costs of the present cooling method by 460,000 guilders a year.

### Schiphol Airport head office, Amsterdam

The cooling system for the new head office of Schiphol Airport is due to be delivered in 1995. In summer, this new office building has a maximum cooling demand of 2,260 $kW_{th}$ for ventilation air. In addition, there is a continuous cooling demand of 165 $kW_{th}$ from the computer locations in the building. Consequently, the maximum cooling demand totals 2,425 $kW_{th}$. In an average year the total cold demand amounts to approx. 2,200 $MWh_{th}$, of which approx. 820 $MWh_{th}$ can be met by free cooling (direct cooling of computer rooms by outside air). The remaining demand of about 1,380 $MWh_{th}$ will be met from aquifer cold storage. In the summer the cold storage will completely supply the demanded cooling capacity.

The storage system has two cold and two warm wells to be used for groundwater extraction from and re-injection into a sandy aquifer. In winter, water is extracted from the warm wells, cooled down to approx. 7,5°C and then injected into the cold wells. Loading is performed with air-water heat exchangers in the air-handling units, which also helps save on heating energy. In summer, the groundwater from the cold wells can chill the cooled water circuit of the building by means of a plate heat exchanger. At a $\Delta T$ of 10 K the required output amounts to a maximum of 215 $m^3/h$.

The overall process diagram of the complete storage and cooling plant (including the building installation) is represented in Figures 6.a (winter) and 6.b (summer).

In the summer season, (Figure 6.b) water is pumped from the cold wells. In the heat exchanger the cold is given off to the building, after which the groundwater is injected into the warm wells. The groundwater circuit is fully hydraulically separated from the building circuit. The building circuit in which the water circulates, is entirely hydraulically closed. After the water has been chilled in the heat exchanger it is sent to a distributor where it is distributed over the air-handling units and the computairs. Here, the water gives off its cold content to the air, achieves a higher temperature and is returned to the heat exchanger.

In the winter season (Figure 6.a) the flow is the other way around. Also now the circuits are fully separated. The building circuit absorbs heat in the heat exchanger. From here the water is either led to the air-handling units (during the day in winter) or to the heat exchanger near the dry cooler (at night in winter). During the day in winter the ventilation air is heated and the building circuit cooled. At night in winter the fans of the air-handling unit are switched off and the water is chilled by means of the dry cooler.

The main design data can be taken from Table 5. The main characteristic values for the groundwater system are summerized in Table 6.

Economic aspects The total investments for the entire cooling system by means of cold storage are approx. 500,000 guilders *lower* than for the equivalent conventional system. The calculations for the conventional system are based on low-energy twin coil cooling batteries. Twin coils reclaim the heat which would otherwise have been discharged into the atmosphere. The economy which twin coils achieve, is especially on energy for heating. With cold storage, no use is made of the twin coil principle in the winter because the heat stored in summer is already added to the supply air. This implies that, in this configuration, the cold storage system considerably saves on investments, whereas the energy to be used for heating does not increase. On the other hand, cold storage is responsible for an economy of approx. 330,000 $kWh_e$ per annum. This is a saving of about 63% compared with the consumption of electric power by a conventional system. In money this boils down to a saving of 44,000 guilders per year. Furthermore, an estimated annual amount of 28,000 is saved on maintenance.

## MARKET PROSPECTS

In Figure 7 the number of realized projects and the number of energy storage feasibility studies have been plotted against time. It can be noticed that there is a clear increase in the number of projects, with the number of feasibility studies being 3 or 4 years ahead of the number realized. The exponential increase visible in the number of projects justifies the expectation that the number will further increase in the next few years. An enquiry among provincial administrations, who are in charge of the licensing, has revealed that the provinces share this expectation.

By far not all projects submitted to feasibility studies are actually being realized. The foundering of a project can have many reasons. A common cause in the past was unfamiliarity with the technology. Nowadays, this cause no or hardly any longer occurs. Other causes of foundering can be:

- The absence of a suitable aquifer.
- Difficulty in integrating cold storage in existing or planned cooling systems.
- Too long a payout period. This may especially apply to small systems and/or to existing systems which have not yet reached the stage where they need complete overhaul.
- The required license based on the Groundwater Act is not granted. This occurred several times in the past. The enquiry among provincial administrations has shown that five applications were refused, three of which because of drinking water interests, one because of nature effects and one because of contaminated subsoil which had not been cleaned up.

### Offices and services buildings

Previous surveys (Public works Canada, 1992) have shown that cooling by means of aquifer cold storage tends to have a payout period of 5 years or less compared with conventional compression chilling. With a maximum cold demand of less than about 300 $kW_{th}$, cold storage is less cost-effective for offices and services buildings. When the period of full-load operation is long, also smaller units can be cost-effective. Currently, only a small part of the new and renovation projects in the offices and services building industry is cooled by means of cold storage. This percentage is expected to increase. The expectation is especially based on the current cost-effectiveness of cold storage.

### Industry

Through-flow cooling with groundwater is especially made frequent use of in the industry. CBS (Dutch Bureau for Statistics) data for 1986 (published 1988) demonstrate that the industry extracted about 250,000,000 $m^3$ fresh groundwater. This is about one-third of the total fresh groundwater consumption in the Netherlands. Of this amount, some 127,000,000 $m^3$ was used for cooling purposes. In 1986 also about 69,000,000 $m^3$ salt groundwater was extracted for cooling purposes. Recent figures for 1990 indicate that the fresh groundwater consumption for through-flow cooling was reduced to approx. 107,000,000 $m^3$, which to a certain extent is due to the Government policy to control the adverse effects of a fall in hydraulic head.

For several years one of the aims of the national government policy is to curb the consequences of a decrease in hydraulic head in the subsoil as it occurs in the Netherlands. One of the means to achieve this, is reducing the extraction of groundwater for low-quality uses, of which through-flow cooling is to be mentioned specifically.

Many provincial administrations have adopted this point of view in their water management plans and have meanwhile started to contact businesses which use groundwater for cooling purposes. Recirculation storage is one of the options to reduce the net groundwater consumption to zero without forcing the businesses to purchase expensive, electricity-demanding and CFC-containing chillers. For that reason several administrations even encourage aquifer cold storage as an alternative to through-flow cooling with groundwater.

The fact that levies to be imposed on the consumption of groundwater are being prepared, is also an important aspect. The relevant bill is now (September, 1994) being read by the First Chamber of Parliament. Drinking-water works are going to pay 0.34 guilder/$m^3$ and industrial consumers 0.17 guilder/$m^3$. For each $m^3$ injected an amount of 0.285 guilder/$m^3$ and 0.115 guilder/$m^3$, respectively, is being reduced from the levies. Energy storage in aquifers is fully exempted from paying levies.

### Agriculture

Several farming sectors apply cooling techniques now. In addition, several other sectors of farming may be expected to start using them in the future. An example may be pig farming, where cooling is not or only hardly practised. The emission of $NH_3$ from piggeries is a substantial contribution to acidification in the Netherlands. It is possible to lower the emission by reducing ventilation by cooling.

Sectors of agriculture and horticulture which have, or will experience in the future, the need for cooling, are the following:

- Greenhouses, especially growing freesia, amaryllis and alstroemeria
- Mushroom farms
- Chicory forcing plants
- Flower bulb processing plants
- Storage facilities (potatoes, fruit, flower bulbs, vegetables or flowers)
- Pig farms
- Poultry farms.

For two farming sectors an estimate has been made of the total present cooling demand:

| Sector | Number of farms | Cooled area p. farm ($m^2$) | Average load (kW) | Total area (ha) |
|---|---|---|---|---|
| Freesia | 350 | 6,000 | 175 | 308 |
| Mushrooms | 1,000 | 1,200 | 150 | 110 |

These figures show that the joint cold demand from these two farming sectors totals approx. 210 $MW_{th}$. With an overall COP (coefficient of performance) of 3, this corresponds with 70 $MW_e$ when use is made of conventional chillers.

## PROVINCIAL POLICIES

In 1994 there was an enquiry among provincial administrations. These are the authorities which decide on the granting of licenses for aquifer cold storage. The administrations were asked to divulge their policies with regard to aquifer cold storage in a number of catchwords. Practically all administrations have a positive attitude towards the principle, though they apply limiting conditions. Major limiting conditions stated include the security of the drinking water supply (not in subsoil protection areas or in certain aquifers), and more generally the involvement of other interests engaged in groundwater management (in conformity with the Groundwater Act). Another limiting condition which was stated various times, was a maximum temperature of 25°C of the re-injected water. Many administrations still have doubts as regards the exact quality effects of the technology. This has caused explicitly one provincial administration to make further applications dependent on the results of trial projects.

To the question, what part provincial administrations see for themselves to play in the development of cold storage, most of them reply to be ready to play an encouraging or active role. No province is inclined to resist the development.

A remark has to be made here that many provinces show some reluctance due to unfamiliarity with several cold storage aspects. These are partly quality aspects in the widest sense (how big are quality risks, if any, what are the exact thermal effects and their further consequences), and also questions about the quantitative options (how many prospective users are there, to what extent might a system draw on the groundwater system etc.).

The following conclusions are drawn from the enquiry:

1. The provincial administrations take a positive attitude as regards aquifer cold storage, and they consider it a good alternative to e.g. through-flow cooling and chillers. They also want to stimulate this application, but clear-cut policy plans are still rare.
2. Next to this positive attitude also some reluctance is shown, especially where potential effects on subsoil quality are involved. This is to some extent caused by the limited experience in the application of cold storage in aquifers, as a result of which the administrations are not familiar with possible risks for subsoil quality.
3. Generally, it is required that cold storage in aquifers shall not adversely affect the supply of drinking water. This requirement is worked out in different ways.

## DISCUSSION AND CONCLUSIONS

In the Netherlands there has been a strong increase in the number of cooling projects based on aquifer cold storage in the last few years. There are several factors to which this increase may be attributed:

- From the economy point of view, cold storage is often more cost-effective than conventional cooling. The payout period is often less than 5 years. In some cases the investment is even lower.
- It occurs more and more that existing chillers containing CFC coolants R11 or R12, have to be replaced. The most current coolant now is R134[a]. Chillers containing this coolant, however, are considerably more expensive than the old machines with R11 or R12. This raises the cost-effectiveness of cold storage.
- The integration of energy storage in the cooling and heating systems of offices and services buildings has considerably improved over time. This has resulted in the creation of a system which is highly competitive from both the economy and the energy points of view.
- Various pilot projects have demonstrated that cold storage is technically feasible and can function without substantial problems. In fact, cold storage systems are even more reliable than chillers. Of course the cold storage design has to consider the hydrological and hydrochemical limiting conditions which are given by the local groundwater situation (Jenne et.al., 1992).
- The Dutch Government plays an important role in three different ways:

a The development of cold storage has been furthered by ad-hoc incentives wherever necessary. If supported projects were confronted with problems or teething troubles, the Government stepped in to solve these problems. As a result, the technology could be fairly smoothly introduced to the market. Many studies on technical bottlenecks have been fully financed by the Government. To give an example, several computer models could be developed and were paid by the Government.

b The licensing authorities are prepared to grant licenses for cold storage projects. A few provincial administrations are still reluctant but most are enthousiastic about this new technology and encourage its further development.

c The Government is pushing back the use of through-flow cooling with groundwater. On the one hand this is achieved by the licensing policy, and on the other hand with (future) levies. With no levies at all being imposed on aquifer cold storage, many businesses will change over from through-flow cooling with groundwater to aquifer cold storage.

As far as known, the rapid increase in the number of aquifer cold storage projects of the last few years only occurs in the Netherlands. But the prospects for aquifer cold storage in other countries seem to be at least as good. The main limiting conditions for the application of cold storage in aquifers are:

- A suitable aquifer at a suitable depth (< 300 m deep).
- A suitable climate: preferably cold winters and hot summers.
- The presence of a cooling demand with adequate purchasing power. This is especially found in countries with highly developed economies. Furthermore, high electricity charges have a positive effect on cooling by means of aquifer cold storage. In the European context, the Netherlands charge relatively low electricity rates of approx. 0.14 guilders (US$ 0.08) per $kWh_e$ for bulk users.

Considering the above limiting conditions, large areas of the USA and Europe are eligible for a successful application of aquifer cold storage. For the USA the first candidate areas might be heavily industrialized zones with relatively high electricity rates such as New York and its surroundings.

## REFERENCES

Jenne, E.A., O. Andersson and A. Willemsen (1992). - Well, hydrology, and geochemistry problems encountered in ATES systems and their solutions. Proceedings 27$^{th}$ IECEC Conference. Volume 4, page 4.77-4.88. Society of Automotive Engineers, Warrendale, PA, USA.

Public Works Canada (1992). - IEA Energy Conservation through energy storage. Innovative and cost-effective seasonal cold storage applications. Summary of national state of the art reviews. Public Works Canada, Ottawa.

## TABLES

Table 1 *Advantages and disadvantages of the integration of a heat exchanger in an aquifer cold storage system*

| Heat exchanger advantages | Heat exchanger disadvantages |
|---|---|
| Reduction of working head of well pumps<br>Reduction of air infiltration, de-aeration and corrosion risks in cooled water circuit<br>Reduction of groundwater pollution risk<br>Possibility of separated control of building water/groundwater | Heat exchanger costs<br>Temperature loss |

Table 2 *Cold supply and demand*

| Supply | Demand |
|---|---|
| Air<br>- cooling tower<br>- dry cooler<br>- air-handling units (AHUs)<br><br>Water<br>- river/brook<br>- basin/canal/lake | Ventilation air<br>- warm and moist outside air<br>- solar heat<br>- internal heat load (people and equipment)<br><br>People<br>- concert building<br>- multi-functional hall<br>- airport<br>- office building<br><br>Equipment<br>- computers<br>- lighting<br><br>Processes<br>- chemistry<br>- plastics<br>- foods and drinks<br><br>Agriculture<br>- greenhouses<br>- mushroom farms<br>- pig farms |

Table 3 *Cooling techniques with relevant maximum usable cooling water temperature*

| Cooling technique | Maximum cooling water temperature (°C) | | | | |
|---|---|---|---|---|---|
| | < 5 | 5-12 | 12-25 | 25-40 | >40 |
| Dry cooling tower (water in closed circuit) | - | - | - | - | X |
| Wet cooling tower (water in open circuit) | - | - | - | X | X |
| Through-flow cooling with surface water | - | - | - | X | X |
| Through-flow cooling with groundwater | - | - | X | X | X |
| Top cooling with groundwater* | - | - | X | X/- | X/- |
| Cold storage in aquifers | - | X | X | X/- | X/- |
| Chiller | X | X | X | X/- | X/- |

X : possible
\- : not possible
X/- : possible, though often not cost-effective
* : with top cooling with groundwater, outside the summer period use is made of through-flow cooling with surface water or of cooling towers.

Table 4 *Aquifer cold/heat storage projects realized in the Netherlands (September 1994)*

| Project | Place | Year | Max. $m^3$/h | Tw °C | Tk °C | Size of storage $m^3$/ season |
|---|---|---|---|---|---|---|
| Perscombinatie | Amsterdam | 1992[a)] | 120 | 14 | 9 | 220.000 |
| BAM office building | Bunnik | 1993[b)] | 28 | 16 | 6 | 15.000 |
| Utrecht University | Utrecht | 1989 | 100 | 90 | 40 | 100.000 |
| Provincial govt. bldg. | Zwolle | 1985 | 60 | 20 | 9 | 70.000 |
| Office building[c)] | Schiedam | 1992 | 125 | 15 | 6 | 20.000 |
| Hospital | Gouda | 1992 | 60 | 15 | 8 | 40.000 |
| Heuvelgalerie | Eindhoven | 1992 | 100 | 32 | 18 | 200.000 |
| IBM office building | Zoetermeer | 1993 | 100 | 15 | 5 | 150.000 |
| Hedera nursery | Luttelgeest | 1993 | 50 | 17 | 5[d)] | 40.000 |
| Freesia nursery | Gameren | 1993 | 50 | 14 | 8[d)] | 80.000 |
| Jaarbeurs | Utrecht | 1993 | 400 | 14 | 7 | 70.000 |
| Museonder | Hoge Veluwe | 1993 | 5 | 16 | 4[d)] | 5.000 |
| Mushroom farm | Gastel | 1994 | 23 | 16 | 6[d)] | 20.000 |
| Pig farm | Raalte | 1994 | 15 | 13 | 9[d)] | 10.000 |

a) In 1992, the temperature levels were changed.
Before 1992: $T_w = 10$, $T_k = 5$
After 1992: $T_w = 14$, $T_k = 9$

b) In 1993, changes from heat storage to cold storage. License granted with trial period for heat storage.
Before 1993: $T_w = 25$, $T_k = 8°C$
After 1993: $T_w = 16$, $T_k = 6$

c) Without heat exchanger between groundwater circuit and air-handling units

d) Supply temperature cooling = 11 to 12°C; injection temperature in winter on average: $T_k$; injection temperature in summer on average: $T_w$

| Project | Place | Storage loading | User | Storage type |
|---|---|---|---|---|
| Perscombinatie | Amsterdam | Dry cooling tower | printing shop space cooling (AHU) | cold storage |
| BAM office b. | Bunnik | AHUs | office space cooling (AHU) | cold storage |
| University | Utrecht | Waste heat total energy | office space heating (central heating) | heat storage |
| Prov. govt. bldg. | Zwolle | AHUs and collectors | office space cooling (AHU) | cold storage |
| Office building[c] | Schiedam | AHUs | office space cooling (AHU) | cold storage |
| Hospital | Gouda | AHUs | hospital space cooling (AHU) | cold storage |
| Heuvelgalerie | Eindhoven | condensor cooling heat pumps | shopping centre space cooling (AHU) | heat storage |
| IBM office bldg. | Zoetermeer | wet cooling tower | office and computer rooms cooling (AHUs, fancoils and inductairs) | cold storage |
| Hedera nursery | Luttelgeest | rain water pond | subsoil cooling | cold storage/recircul. |
| Freesia nursery | Gameren | dry cooling tower | subsoil cooling | cold storage/recircul. |
| Jaarbeurs | Utrecht | AHUs | multi-functional hall space cooling (AHUs) | cold storage |
| Museonder | Hoge Veluwe | heat pump | museum space cooling (heat pump) | cold storage/recircul. |
| Mushroom farm | Gastel | AHU | growing room space cooling | cold storage/recircul. |
| Pig farm | Raalte | AHU | piggery space cooling | cold storage/recircul. |

Table 5 *Aquifer cold storage projects in the Netherlands in preparation (September 1994)*

| Project | Place | Year | Max. $m^3/h$ | Tw °C | Tk °C | Size of storage $m^3$/ season |
|---|---|---|---|---|---|---|
| Head office Schiphol | Amsterdam | 1995 | 215 | 17.5 | 9 | 145,000 |
| Zuider Hospital | Rotterdam | 1994 | 60 | 17.5 | 7.5 | 50,000 |
| Maria Hospital | Tilburg | 1995 | 90 | 16.5 | 7.5 | 100,000 |
| Head office utility | Groningen | 1994 | 70 | 18 | 8 | 50,000 |
| Town Hall | The Hague | 1994 | 360 | 16.5 | 6 | 150,000 |
| Prov. govt. bldg. | Utrecht | 1994 | 60 | 16 | 8 | 35,000 |
| Prov. govt. bldg. | Den Bosch | 1994 | 22 | 19.5 | 8 | 35,000 |
| Prov. govt. bldg. | Groningen | 1995 | 70 | 18 | 8 | 20,000 |
| Plastics factory | Hardenberg | 1994-1995 | 480 | 17.5 | 5 | 3,000,000 |
| State Museum | Amsterdam | 1994 | 70 | 13.5 | 5.5 | 100,000 |
| Head off. travel org. | Hoofddorp | 1994 | 20 | 17 | 8 | 20,000 |

| Project | Place | Storage loading | User | Storage type |
|---|---|---|---|---|
| Head office Schiphol | Amsterdam | AHU | AHU, climate ceilings | cold storage |
| Zuiden Hospital | Rotterdam | AHU | AHU | cold storage |
| Maria Hospital | Tilburg | AHU | AHU | cold storage |
| Head office utility | Groningen | AHU | AHU | cold storage |
| Town Hall | The Hague | AHU | AHU | cold storage |
| Prov. govt. bldg. | Utrecht | AHU | AHU | cold storage |
| Prov. govt. bldg. | Den Bosch | AHU | AHU | cold storage |
| Prov. govt. bldg. | Groningen | AHU | AHU | cold storage |
| Plastics factory | Hardenberg | River | Process heat | cold storage/recirculation |
| State Museum | Amsterdam | Dry cooler | AHU, condensor cooling | cold storage |
| Head off. travel org. | Hoofddorp | AHU | AHU | cold storage |

Table 6 *Characteristic values of groundwater system*

| | | PROJECT | | | | |
|---|---|---|---|---|---|---|
| | | Jaarbeurs | IBM | Hedera | Wavin | Schiphol |
| Number of cold wells | | 2 | 2 | 1 | 6 | 2 |
| Number of warm wells | | 2 | 2 | 1 | 6 | 2 |
| Diameter of wells | (mm) | 800 | 600 | 400 | 800 | 600 |
| Screen setting of wells | (m -bs) | 15-45 | 40-70 | 25-65 | 25-55 | 90-150 |
| Distance cold and warm wells | (m) | 200 | 200 | 70 | 400 | 135 |
| Storage cooling load | ($kW_{th}$) | 2,640 | 950 | 300 | 3600 | 2425 |
| Cooling demand on storage | ($MWh_{th}$) | 400 | 1200 | 230 | 12.000 | 1380 |

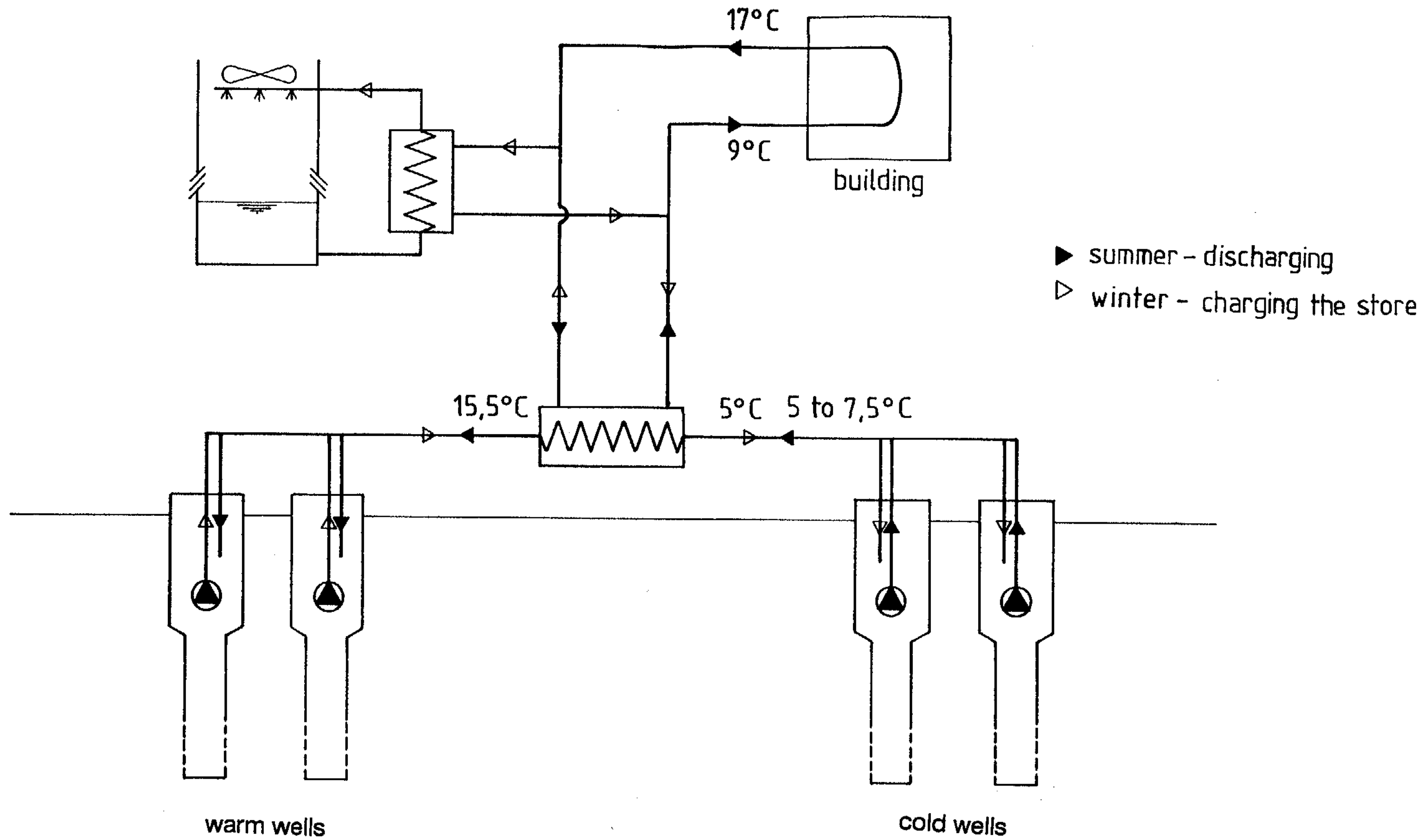



**Figure 1.** ***Schematic diagram of the cold storage system for the IBM office at Zoetermeer***

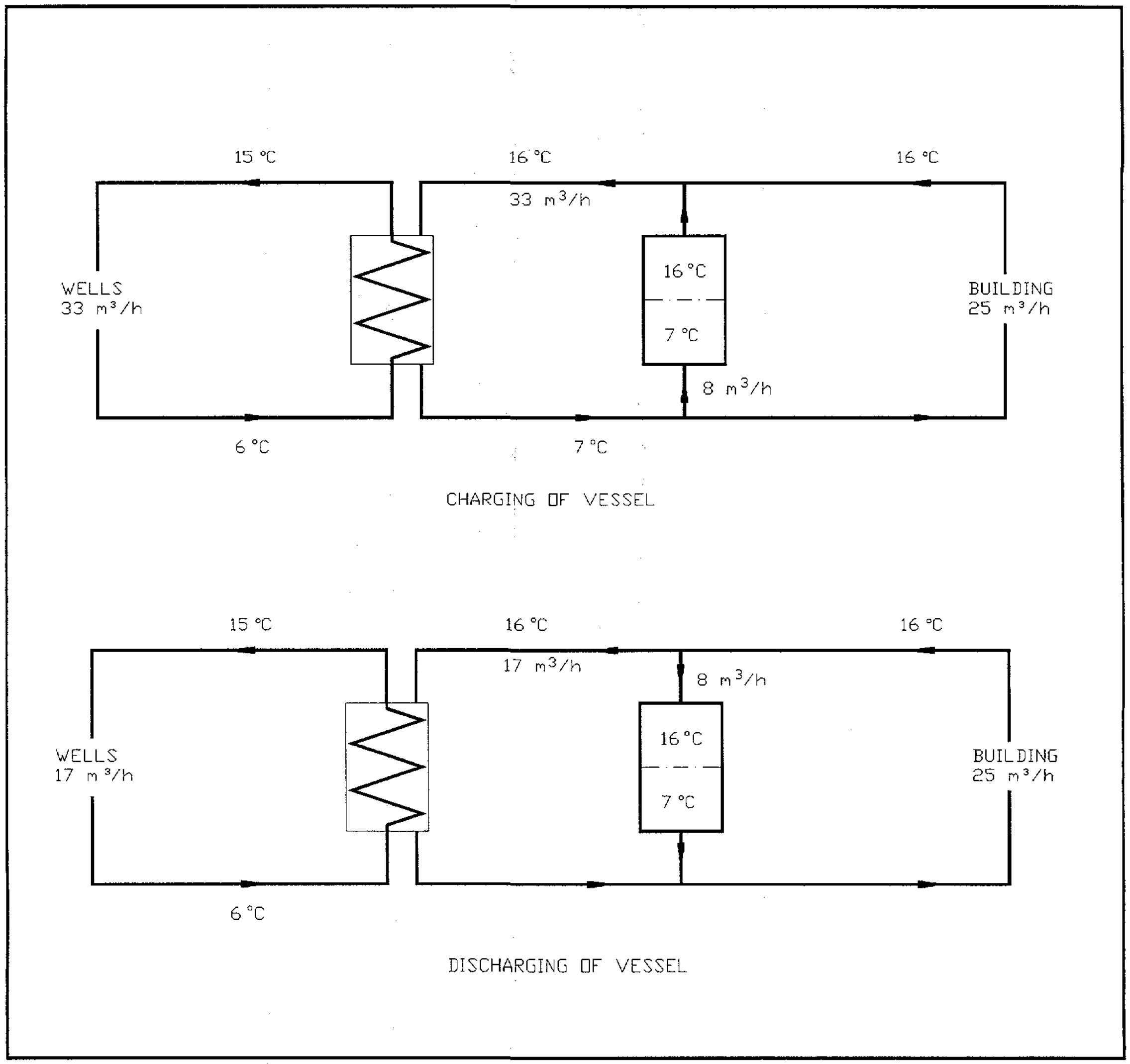



**Figure 2.** ***Schematic diagram of the functioning of the thermally layered buffer vessel for the cold storage at the IBM office at Zoetermeer***

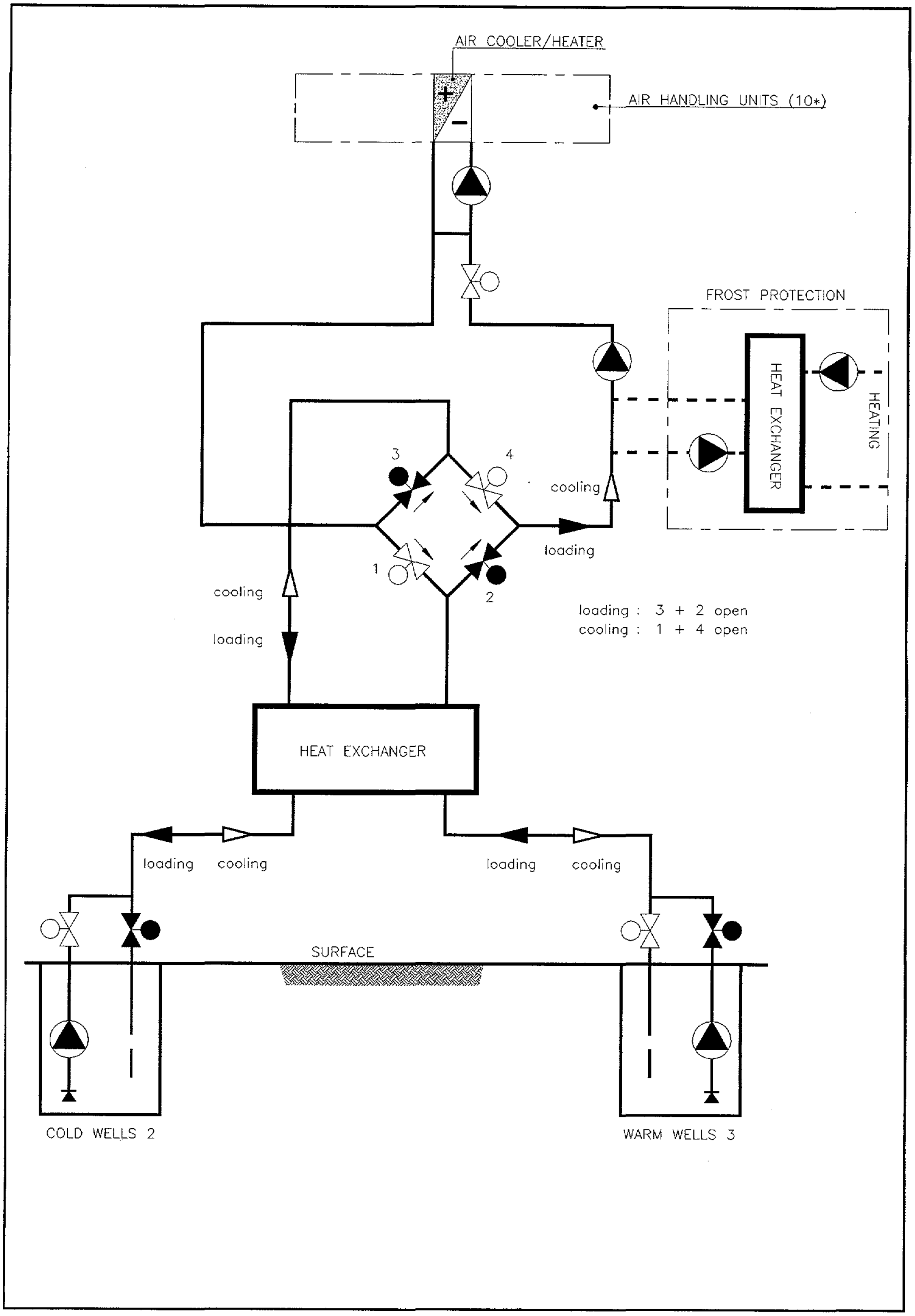



**Figure 3.** ***Schematic diagram of the cold storage system for the Jaarbeurs multi-functional hall, Utrecht***

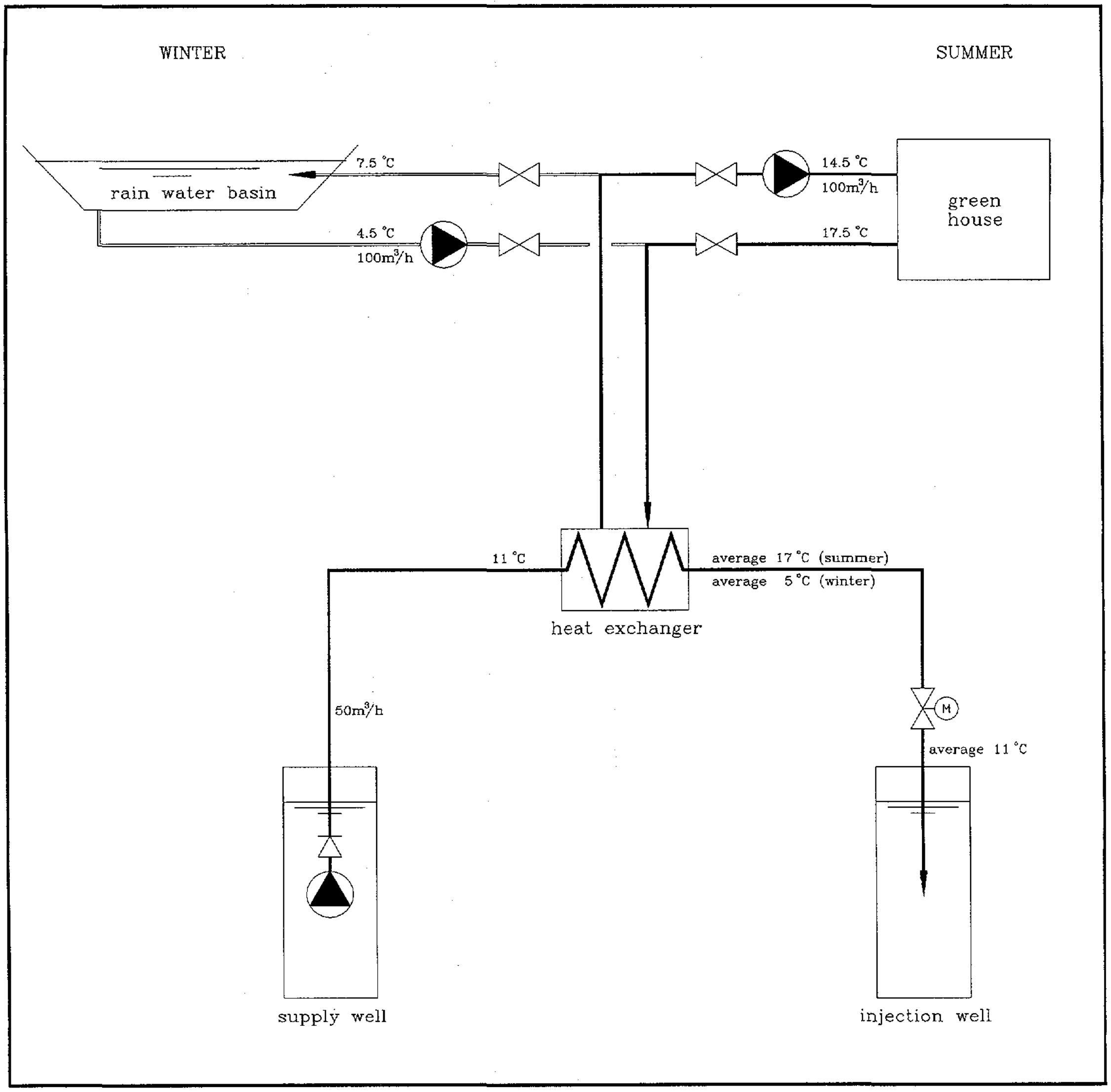



**Figure 4.** ***Schematic diagram of the cold storage system for the Hedera nursery at Luttelgeest***

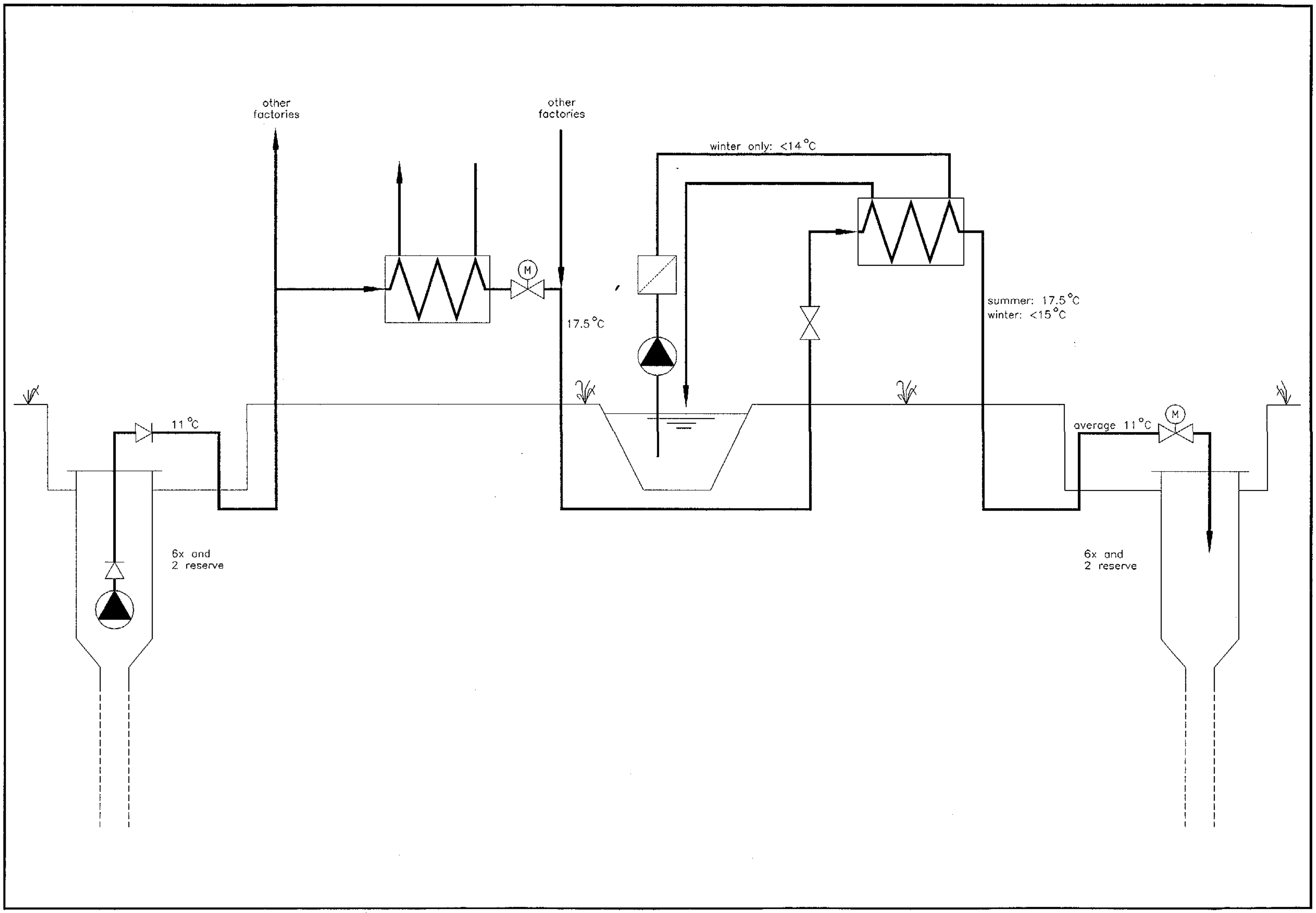



**Figure 5.** ***Schematic diagram of the cold storage system for the WAVIN Plastics factory at Hardenberg***

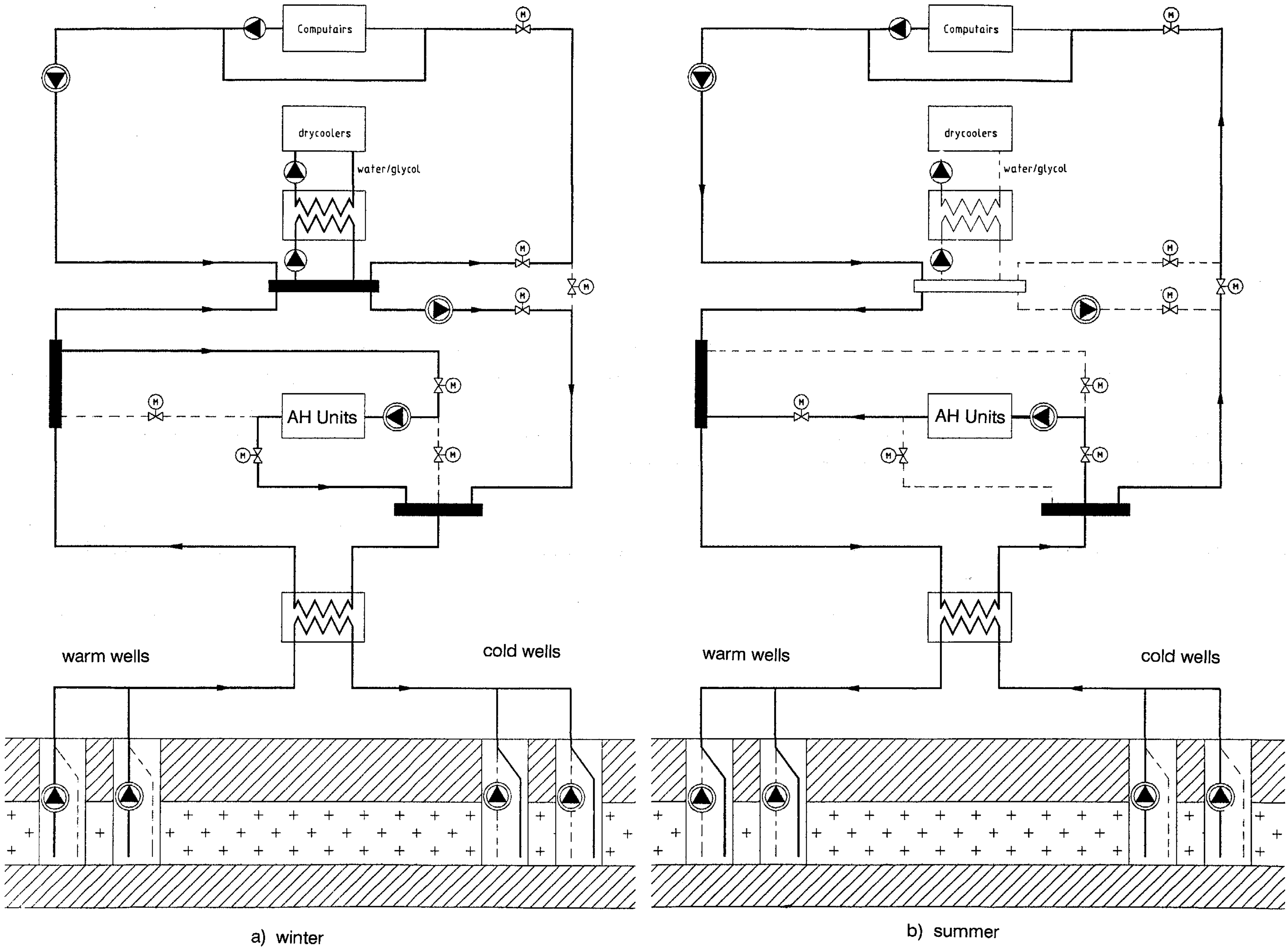



Figure 6. ***Schematic diagram of the cold storage system for the new head office of Schiphol Airport Amsterdam***

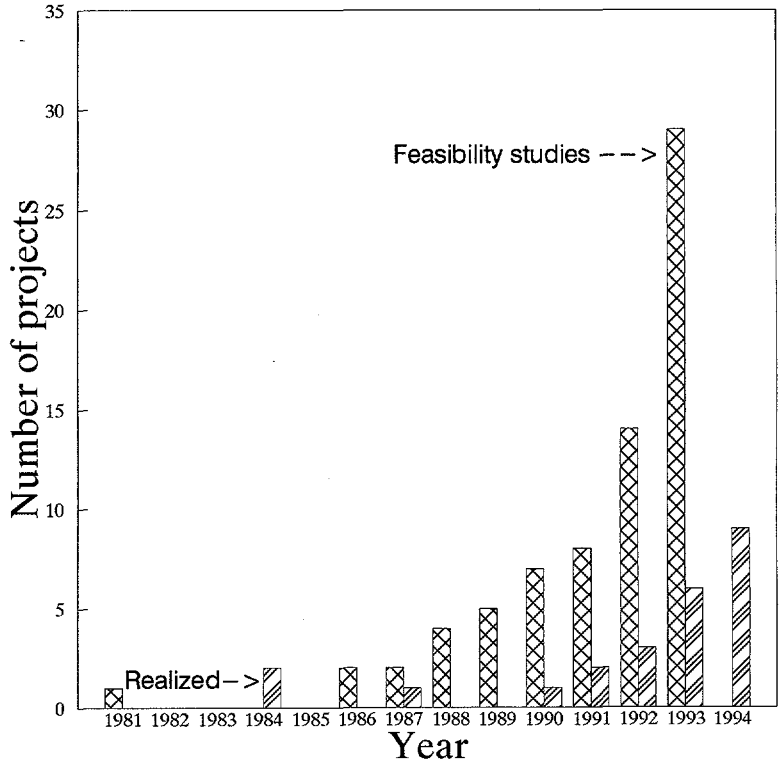



**Figure 7.** ***Number of realized energy storage projects and number of feasibililt studies per year***

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# Single Well Tracer Methods for Hydrogeologic Evaluation of Target Aquifers

• Stephen H. Hall
Earth and Environmental Sciences Center
Pacific Northwest Laboratory
Richland, Washington, USA

## ABSTRACT

Designing an efficient well field for an aquifer thermal energy storage (ATES) project requires measuring local ground-water flow parameters as well as estimating horizontal and vertical inhomogeneity. Effective porosity determines the volume of aquifer needed to store a given volume of heated or chilled water. Ground-water flow velocity governs the migration of the thermal plume, and dispersion and heat exchange along the flow path reduces the thermal intensity of the recovered plume. Stratigraphic variations in the aquifer will affect plume dispersion, may bias the apparent rate of migration of the plume, and can prevent efficient hydraulic communication between wells. Single-well tracer methods using a conservative flow tracer such as bromide, along with pumping tests and water-level measurements, provide a rapid and cost-effective means for estimating flow parameters. A drift-and-pumpback tracer test yields effective porosity and flow velocity. Point-dilution tracer testing, using new instrumentation for downhole tracer measurement and a new method for calibrating the point-dilution test itself, yields depth-discrete hydraulic conductivity as it is affected by stratigraphy, and can be used to estimate well transmissivity. Case study data from a Tuscaloosa, Alabama, ATES project site show that tracer methods can be used to detect vertical flow in well bores caused by hydraulic interaquifer communication. Finally, current research shows that single-well tracer methods may be useful in estimating longitudinal dispersivity as well as both thermal and solute-retardation coefficients.

## INTRODUCTION

Hydrogeologic aquifer characterization is the estimation of ground-water flow patterns in three dimensions and time. Characterization requirements often include estimating aqueous mass transport parameters that govern movement of ground-water solutes, suspended matter, or thermal plumes. Such characterization is legally mandated for environmental monitoring and cleanup of waste disposal sites, is beneficial for water resources investigations, and is critical for engineering aquifer thermal energy storage (ATES) projects. Despite need or mandate, adequate characterization is seldom achieved, because conventional field methods for hydrologic investigation of flow parameters other than transmissivity and hydraulic gradient tend to be prohibitively expensive. For example, dual- or multiwell geochemical tracer tests are useful for direct measurement of ground-water flow rate. However, this method requires extensive sampling and analysis of ground water (often for weeks or months), and may require drilling observation wells otherwise unneeded. Further, the effects of dispersion, dilution, and sometimes adsorption or chemical reaction on the tracer itself can render the tracer tests very difficult to interpret.

Because of the expense of field methods, laboratory examination of rock or sediment samples collected during well drilling often is performed to estimate flow parameters such as effective porosity and solute retardation. Unfortunately, the laboratory data are often inaccurate because collecting geologic samples from the subsurface, especially poorly consolidated sediment samples, can irrevocably alter both physical and chemical characteristics of the material.

Single-well tracer methods and related instrumentation developed in recent years offer economic means for field-estimating ground-water velocity, effective porosity, and the vertical distribution of hydraulic conductivity. Hall et al. [1] showed that by combining the drift-and-pumpback, single-well tracer test presented by Leap and Kaplan [2] with conventional pumping tests and hydraulic gradient measurement, both effective porosity and ground-water flow velocity can be estimated. Hall and Raymond [3] described a new method for performing and interpreting point-dilution tests. This test yields an estimate of hydraulic conductivity as a function of depth, and has been useful in detecting and quantifying vertical currents in wells.

These single-well methods were developed as part of Pacific Northwest Laboratory's* Seasonal Energy Storage program, and were originally tested and demonstrated at three ATES project sites in Tuscaloosa, Alabama. The methods have been useful for providing field data for the design or modification of ATES well fields, and for predicting well field performance using computer modeling. Recent experience, new information, and improved instrument design have increased the efficacy of these tests.

---

*Pacific Northwest Laboratory is a multiprogram national laboratory operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

In this paper, both the power and limitations of the drift-and-pumpback and point-dilution tests are re-examined with respect to recent experience, and within the context of field studies. The case study data are taken from two Tuscaloosa ATES project sites and from an experimental *in situ* bioremediation area at the Hanford Site in Washington State. A discussion of the improved equipment and instrumentation used in conducting the tests is included.

Even within the limited acreage represented by an ATES well field, the transmissivity of wells can vary significantly. The principal means for measuring transmissivity is the constant-discharge pumping test, but it is not necessarily economic or efficient to conduct such tests while each well is completed, developed, and proved. More often than not, economics dictate that formal pumping tests are conducted at only a fraction of the wells in a network. Thus, a method for rapidly estimating the transmissivity of completed wells that does not require a workover rig to set a pump could be useful. Such a method, based on point-dilution testing, is proposed and described here.

Ground-water velocity, effective porosity, and the vertical distribution of hydraulic conductivity do not completely define the movement of a thermal plume. Knowledge of two other flow parameters, dispersivity and thermal retardation, need to be quantified to predict the rate of plume movement and the loss of thermal intensity that is a necessary result of dispersion during movement. Evidence suggests that single-well, injection-withdrawal tracer methods can be used to estimate these parameters as well as the retardation of nonconservative chemical species in ground water. (This latter application may be important to ATES systems that require require water treatment.) This evidence is presented with respect to its potential for characterizing target aquifers.

## IMPROVED APPARATUS

The program of tracer testing introduced by Hall and Raymond [3] includes both a drift-and-pumpback test and a point-dilution test. In that program, a single placement of a tracer into a well bore serves as the start of both tests. Both tests depend on quickly and evenly introducing a flow tracer into the screened interval of the test well; the point-dilution test further depends on downhole instrumentation suitable for monitoring tracer concentration as a function of both depth and time. In this section, recent improvements in equipment used for tracer introduction and measurement are described.

Most target aquifers for ATES projects will be dominated by horizontal advective flow, and the need for evenly distributing a ground-water flow tracer in the water column of a test well is intuitively self-evident. For example, most of the ground-water flow at one of the Tuscaloosa ATES project sites occurs in the approximate lower half of the target aquifer [3]. At that site, if a disproportionately large amount of the tracer were initially confined to the upper half of the aquifer, the results of a drift-and-pumpback test (designed to yield an estimate of net flow within the saturated interval) would be biased toward flow velocity of the upper half.

The original injection apparatus described by Hall and Raymond [3] was a weighted and sealed plastic jug suspended from a flexible 1.6-cm inner-diameter (ID) flexible rubber hose with both ends open. To introduce tracer to the water column, the contained volume of the hose from the lower open end, as it would be situated at the bottom of the well, to the top of the water column was first calculated. The tracer salt (lithium bromide) was then dissolved in that volume of distilled water. The hose was lowered to the bottom of the well, and the tracer poured into the upper end of the hose. The tracer solution displaced the ground water from the hose. When the hose was retrieved from the well, the tracer drained from the hose and was left in place. The weighted jug mixed the tracer in the well bore.

Three problems with this apparatus were identified. First, stretching of the rubber hose, caused by the combined weight of the jug and hose, progressively reduced the inner diameter from the lower end to the surface. Thus, the hose contained somewhat more tracer near the bottom than near the top of the water column, and the volume of tracer solution represented by the difference between the calculated hose volume and the volume of the stretched hose was deposited in the well bore near the lower open hose end. This problem has since been eliminated by using nylon flexible pipe, which does not stretch significantly.

Second, field data indicated poor lateral mixing by the weighted jug within the well bore using this method. In recent field experiments, the jug has been replaced by a cylindrical, two-stage, in-line mixer having an outer diameter slightly less than the inner diameter of the well. The mixer is suspended from the nylon hose by a yoke. When the hose and mixer assembly is retrieved from the well, tracer solution flows from the lower end of the hose directly to the center of the upper opening of the mixer. The internal paddles of the mixer split and recombine the tracer and the well water, leaving the tracer sufficiently distributed laterally and vertically within the well bore.

Mixers of this type, having no moving parts, are commonly used in chemical processing and similar industries for mixing flowstreams, and are commercially available. Generally termed "static in-line mixers," they are installed and used directly in process piping, and usually have more than the two mixing stages employed in the previously described circumstance.

The third problem related to the difference in density between ground water and the tracer solution. The tracer introduced into the test well at one of the Tuscaloosa ATES sites [3] was 125 g lithium bromide mixed into 2.2 L of distilled water; the resulting 0.65 M solution had a density of approximately 1.04 g/mL as compared to the nominal 1.00 g/mL density of ground water. Because of the density difference, the top of the column of tracer solution within the injection hose settled somehat below the top of the ground-water column in the well bore–in this case by 4%. Thus, only the lower 96% of the well-water column received tracer. Excess tracer (like that resulting from hose stretch) was immediately expelled from the lower end of the injection hose.

The problem of density has been overcome since primarily by using a larger hose diameter; the nylon hose used in more recent experiments has an inner diameter of 2.5 cm. With the larger diameter, the volume of water intercepted by the hose for a given well depth is more than 2.5 times that intercepted by the 1.6-cm ID hose. With the larger diameter hose, the concentration of the aforementioned tracer charge would have been 0.26 M, with a density of approximately 1.01 g/mL, and a correspondingly smaller portion of the well water-column that cannot receive tracer.

Despite these better means for introducing tracer to the well, further improvement is warranted. The current method requires that, for reasonable convenience in the field, the tracer injection hose be cut to no more than a few feet longer than the total depth of the well. This stipulation is inconvenient when wells of different depths must be tested. Further, the author's experience in using such equipment in 90-m-deep test wells has yielded convincing evidence that the method is best suited to young and robust investigators. A prototype for a reel-deployed tracer injector that does not require cut-to-length hose, and that avoids problems caused by density differential, has been designed. Construction and testing of this apparatus is anticipated soon.

Bromide solutions often have been used as ground-water tracers because the bromide ion behaves conservatively and is foreign to freshwater aquifers and surface water. Multiple, simultaneous point-dilution tests in a single well have been made possible by the development of submersible ion-selective electrodes (ISEs) suitable for *in situ* measurement of bromide ion as a function of both depth and time [3, 4]. In this analytical method, a reference electrode and a bromide-sensing electrode are immersed in a bromide solution of unknown concentration. The voltage potential developed between the electrodes is a function of bromide concentration, and may be measured with a high-input impedance potentiometer (e.g., $10^{12}\ \Omega$).

However, prototype electrodes first used at one of the Tuscaloosa ATES sites were inconvenient to use, and because of difficulty in measuring the high-impedance signal along more than approximately 30 m of cable, collection of bromide data from deeper wells was difficult. Also, these first electrodes were of crude and cumbersome construction, and attempts to use them in 10-cm ID monitoring wells at the Hanford Site showed that moving the electrodes up and down the well bore induced vertical mixing [5] of the bromide tracer, thus invalidating point-dilution testing. (This was not a problem in the 25-cm ID wells at the Tuscaloosa ATES sites.)

The bromide-sensing apparatus has been improved in three ways. Both the reference and sensing electrodes have been combined into a single streamlined probe body 1.6 cm in diameter and 20 cm long. Recent field experiments have shown that this probe configuration does not induce significant vertical mixing in a 10 cm ID well bore [5]. Also, the probe body now includes an onboard unity gain signal amplifier to reduce signal impedance, thus eliminating depth limitations. Finally, the tendency for the capillary tube of the original electrode design to lose fluid and develop an open circuit has been eliminated.

## FIELD EXPERIMENTS

Experience in conducting both drift-and-pumpback and point-dilution tests at three different test sites has yielded important information that highlights both the power and the limitations of the single-well tracer methods. These sites are the University of Alabama Student Recreation Center (UASRC) ATES well field and the VA Medical Center (VA) ATES well field, both located in Tuscaloosa, Alabama, and the Hanford bioremediation test site north of Richland, Washington.

Test results for these sites show distinctly different patterns. The UASRC test results are most satisfactory; the results have been previously reported [3] and are included here as a basis against which to compare results from the other test sites. The VA site illustrates anomalous and misleading results caused by the unanticipated presence of a perched aquifer immediately overlying the target aquifer. The Hanford test site illustrates the effects of local inhomogeneity on point-dilution test results, and of extremely low natural ground-water flow velocity on a drift-and-pumpback test. The target aquifer at each of these sites is unconfined (except for local confinement by the perched zone at the VA site), and consists of essentially similar, poorly sorted, unconsolidated sediments.

Of most importance here are the data patterns that emerged from the test programs, some of which can be considered diagnostic of the problems encountered at the VA and Hanford test sites. However, before describing the test results, it is appropriate to briefly review the test methods and interpretation.

### Test Methods

In an aquifer dominated by horizontal advective ground-water flow, a drift-and-pumpback test can be combined with conventional hydrologic field methods to yield estimates of ground-water flow velocity and effective porosity [1]. The hydrologic methods usually include a pumping test to determine the transmissivity of a test well, and water-level measurements to determine local hydraulic gradient. A flow tracer (e.g., bromide) is introduced into the test well and allowed to drift for a period of time, often a few days. The well is then pumped to recover the tracer. Ground-water flow velocity, V, is determined as

$$V = Qt/\pi bT^2KI \qquad (1)$$

where
- $Q$ = pumping discharge rate
- $t$ = pumping time to recover center of mass of tracer
- $b$ = aquifer thickness
- $T$ = drift time *plus* t
- $K$ = hydraulic conductivity
- $I$ = hydraulic gradient

After flow velocity has been determined, the effective porosity, n, can be calculated from Darcy's law as

$$n = KI/V \qquad (2)$$

The tracer introduction for the drift-and-pumpback test also can be used to conduct the point-dilution test by using the ISEs to measure tracer concentration as a function of both depth and time. For a given depth, the slope of a plot of the electrode response in millivolts *versus* time is directly proportional to the mean rate of ground-water flow through, and normal to, the axis of the well bore [3, 4]. In a valid point-dilution test, the plot slope must be a straight line, although there is often some curvature, caused by initial inefficient mixing, in the early stage of testing.

Recent work has shown that in a minimally developed well, the flux through the well bore should be nearly proportional to hydraulic conductivity at each test depth [6]. It must be emphasized that "minimal development" should not be interpreted as "poor development." Development must be sufficient to ensure that the hydraulic conductivity of the well screen and artificial filter packing material is much greater than that of the surrounding aquifer, and that any skin effect caused during the drilling of the well (e.g., by mud cake) is negated. A minimally developed well is one that has not been pumped enough to remove a significant amount of fines from the surrounding aquifer; that is, the hydraulic conductivity of the aquifer immediately adjacent to the well bore has not been altered.

If conditions are met for a minimally developed well, the slopes of the plots of electrode response *versus* time for the test depths in a well will be proportional to hydraulic conductivities at those depths. Because the net hydraulic conductivity of the screened interval of the well is known from pumping tests, relative hydraulic conductivities (slopes) can be converted to absolute values by back-calculating using weighted averages.

It is important to note that the mean flow velocity through the well bore, $V^*$, at any given depth only indirectly reflects the rate of ground-water flow through the aquifer at that depth. This velocity is influenced by effective porosity and a flow distortion factor [7] according to

$$V^* = Vna \qquad (3)$$

where $V$ = flow velocity within the aquifer
$n$ = effective porosity
$a$ = flow distortion factor

The flow distortion factor arises because the hydraulic conductivity of the well installation is much greater than that of the aquifer, therefore causing the flow net in the horizontal plane to converge towards the well on approach, and to again diverge downgradient from the well. It is generally accepted that the flow distortion factor is determined by well construction [6, 7]; wells having identical construction should have the same flow distortion factor.

### University of Alabama Student Recreation Center

The UASRC ATES project has operated since 1985 [3], so it is unlikely that point-dilution results accurately reflect the vertical distribution of hydraulic conductivity, because the wells are past being "minimally developed." With that single caveat, however, field data from the tracer testing program illustrate near-ideal test results.

The saturated aquifer thickness at the site was 11.3 m. Hydraulic gradient was 0.0045, and the hydraulic conductivity of the test well was 25 to 28 m/d based on constant-discharge pumping tests. A tracer consisting of 125 g lithium bromide was introduced to the test well, allowed to drift for slightly more than 2 d, and recovered by pumping at 227 L/min. The center of mass of the tracer was recovered after 51 min; the tracer plume was virtually completely recovered after 4 h. Net ground-water flow velocity was calculated to be 0.6 to 0.7 m/d, and effective porosity was 16 to 21%. Figure 1 shows the results of recovery pumping.

Tracer introduction for the drift-and-pumpback test also was used as the beginning of a point-dilution test. The total test duration was 6 h. Figure 2 includes plots of electrode response *versus* time at all test depths; note that each plot tends toward a straight line.

After normalizing the plot slopes to that of the 6.9-m depth, which had the steepest slope observed, the relative rates of ground-water flow through the well bore were plotted as a function of depth. The resulting plot is compared in Figure 3 to sediment stratigraphy derived from samples collected during well drilling. This comparison shows that most ground-water flow occurs in a 4.6-m-thick sand layer approximately representing the lower half of the aquifer.

### VA Medical Center

In February 1993, Pacific Northwest Laboratory staff conducted hydrologic testing at the VA site to provide design data for an ATES well field. At the principal test well, H3, static water-level measurements indicated that 24 m of saturated sediment overlay the Pottsville Formation, which consists of well-indurated shales and limestones and is the regional lower boundary of the unconfined aquifer. Total depth to the Pottsville Formation was 65 m. The 25-cm ID well fully penetrated the saturated interval, which was presumed at the time to represent the regional unconfined aquifer.

A constant-discharge pumping test indicated a transmissivity of 619 $m^2$/d for the entire saturated interval. Static water-level measurements at H3, one other 25-cm ID well, and two 5-cm ID observation wells were used to prepare a water-table map. The map showed that the hydraulic gradient in the vicinity of H3 was 0.0035. The measured well transmissivity and gradient are consistent with hydraulic properties found at other Tuscaloosa test sites [1, 3]. However, repeated measurements at three other observation wells, at distances from H3 of 46, 131, and 183 m, displayed anomalously high static-water levels. Compared to the prepared water-table map, the anomalies were 11.9, 4.9, and 13.4 m, respectively. Water levels from two remaining observation wells, 23 and 38 m distant from H3, were unstable, but consistent with the water-table map.

The 5-cm ID wells were constructed to fully penetrate the saturated sediments, but were developed only by brief air-lifting. It was assumed that poor development had caused insufficient hydraulic communication between the well bores and the sediments, and that the anomalous water levels may have been caused by inadvertent infiltration of surface water into the wells. (In other words, for lack of a better explanation, the anomalies were ignored.)

A drift-and-pumpback test was initiated in H3 by introducing 250 g of lithium bromide into the well using a rubber hose and weighted jug as described previously. The tracer was allowed to drift for 4.05 d, and recovery pumping was started at the rate of 303 L/min. A conventional bromide ISE was used for monitoring the bromide concentration of the effluent stream. The initial bromide concentration was 0.4 mg/L, and after 1 h of pumping the concentration decreased to 0.3 mg/L. The pumping rate was increased to 420 L/min, the maximum discharge of the pump. Recovery of the main tracer plume did not begin for another 90 min. The center of mass of the tracer plume was recovered after 358 min of pumping, and the pump was stopped 45 min later.

The tracer recovery curve is shown in Figure 4. Application of equations (1) and (2) yielded a ground-water movement rate equal to 1.2 m/d, and an effective porosity of 7.8%. These values are comparable to those found at another Tuscaloosa test site [1], where the estimated flow velocity was confirmed with a dual-well tracer test conducted under natural gradient. Nevertheless, the delayed tracer recovery from H3 was unique among results from Tuscaloosa-area test sites (e.g., compare Figure 4 to Figure 1).

A point-dilution test was conducted at H3 using 100 g of lithium bromide to prepare the tracer solution (it had not been convenient to do the point-dilution test coincident with the start of the drift-and-pumpback test). The tracer concentration was monitored over time at 16 depths from 42.7 to 64.6 m. Figure 5 includes plots of the electrode response *versus* time for four representative depths.

In Figure 5, the plots for the 45.7- and 63.4-m depths appear consistent with the requirement that suchs plots for a valid point-dilution experiment be a straight line. The former displays a steep positive slope, which is consistent with rapid flushing of the tracer from the well bore. The latter plot shows fluctuations of approximately 10 mV about the mean, but has a net slope of nearly zero, which indicates a depth interval with little or no ground-water flow.

The plot for the 45.7-m depth shows the greatest slope, +4.3 mV/min, for any of the depths monitored in well H3. However, the greatest slope shown in Figure 2 for the UASRC site is +0.12 mV/min. These slopes differ by a factor of 36, which from equation (3) would indicate that at the 45.7-m depth, well H3 had either a flow rate or a flow distortion factor that was unrealistically high.

Further, plots in Figure 5 from the 53.3- and 57.9-m depths show negative slopes for the first 23 and 42 min of the test, respectively, followed by positive slopes nearly as great as that for the 45.7-m depth. In other words, the negative slopes from the first part of the test at these depths show that tracer concentration at these depths clearly increased.

The cause of these perplexing test results was eventually deduced by plotting depth profiles of actual tracer concentration in the well bore at various times during the test. Representative plots are shown in Figure 6. Inspection of the plots shows that initial tracer distribution was uneven, and at 5 min into the test there was a concentration peak clearly visible at the 45.7-m depth. The peak descends through the well bore over time, with virtually no dilution, at the rate of 0.24 m/min, and disappears near the bottom of the well. That is, the tracer moved vertically through the well bore in virtual plug flow, and the rate of flow was sufficient to overwhelm any significant tracer dilution by horizontal advective ground-water flow.

Vertical movement in the well bores at the VA site was confirmed by placing a tracer slug at the top of the water column and monitoring its position over time. Well drillers have noted that a highly transmissive stratum, in which drilling circulation is easily lost, lies just above the Pottsville Formation. It is reasonable to conclude that virtually all of the tracer injected into these wells was lost to that stratum, and that the results of the earlier drift-and-pumpback test reflected recovery of tracer from that stratum and do not reflect properties of the whole saturated interval.

The hydraulic head driving downward flow in the wells is best explained by postulating existence of a perched aquifer immediately overlying the regional sedimentary aquifer. A perched aquifer, and probable poor development of the 5-cm ID monitoring wells at this site, is consistent with observed water-level anomalies. A clay layer approximately 18 m above the Pottsville Formation was subsequently identified as the likely boundary between the regional aquifer and the perched aquifer.

## Hanford Bioremediation Site

Tracer test data from the Hanford bioremediation test site [5] are included here for two reasons. First, the results from the drift-and-pumpback test at this site illustrate the effect of insufficient tracer drift on the tracer recovery curve. Second, the results of point-dilution tests conducted at two wells 7.9 m apart highlight the power of this test to elucidate local aquifer inhomogeneity.

The program of tracer testing began at the bioremediation test site in June 1992. At that time, a drift-and-pumpback test using a lithium bromide tracer was attempted at well 299-W11-30. For the tracer solution, a volume of 4.6 L of water was used to dissolve 80 g of lithium bromide. The tracer was allowed to drift 10 d, because the best estimate of ground-water flow velocity available before tracer testing was 0.3 m/d or slightly less; in the author's experience, a net drift of 2 to 3 m seems to be generally optimal.

The well was pumped at a discharge rate of approximately 40 L/min to recover the tracer, and the bromide concentration of the discharge stream was monitored in the field using ISEs. The tracer recovery curve for this test is shown in Figure 7. Inspection of the figure shows that peak tracer concentration during recovery occurred as soon as pumping began, that is, the tracer had virtually not moved away from the well bore.

Insufficient drift can bias the results of a drift-and-pumpback test [1, 2]. Analysis of test data using equation (1) yielded an apparent flow rate of 0.03 m/d, but because of the experimental uncertainty, this value was taken as an upper bounding limit only. Confirmation of the actual flow velocity was done using a two-well tracer test conducted under natural gradient, where a second tracer slug was introduced into 299-W11-29, and well 299-W11-30, which is 7.9 m downgradient from 299-W11-29, was monitored for bromide. This test required several months of sampling and analysis of ground water from the downgradient well, and yielded a net flow velocity of approximately 0.027 m/d.

In January 1994, point-dilution tests were conducted at wells 299-W11-29 and 299-W11-30. Before the test, the standing water column of each well was found to be approximately 9.4 m. Both wells had a 10-cm ID, and the volume of water in each borehole was 74 L. A tracer charge of 25 g of potassium bromide per well was used, yielding an initial mean concentration of 230 mg/L as bromide in each well.

The results of the point-dilution tests are shown in Figure 8. Neither of the test wells has been extensively pumped; it is assumed that development has been adequate. Thus, the wells are considered to meet the criteria for a "minimally developed well." Data from both wells were normalized to the highest V* obtained during the tests, which was at the 76.5-m depth in well 299-W11-29. Therefore, assuming identical well construction specifications, the figure may be presented as a representation of the relative hydraulic conductivities of the two wells.

These tests show that the mean hydraulic conductivity of well 299-W11-30 is approximately 37% that of well 299-W11-29. Test data [5] obtained by monitoring well 299-W11-30 while conducting development pumping and a step-drawdown test at well 299-W11-29 yielded a transmissivity, and therefore mean conductivity, nearly equal to the transmissivity obtained from a constant-discharge pumping test at well 299-W11-30 where well 299-W11-29 was used for observation. This result occurred because the use of an observation well yields a transmissivity that reflects the mean characteristics of the sediments lying between the two wells. In both instances, the same body of sediments was interrogated. The point-dilution test, on the other hand, reflects characteristics of the sediments only in the immediate vicinity of a well.

## DISCUSSION

Widespread acceptance of single-well tracer methods will depend in the future on the availability of practical equipment for performing the tests, and on the distribution of information suitable to aid in designing tests and interpreting results. The intent of this paper has been to move toward fulfillment of these two requirements by describing and comparing test experiences at three distinctly different sites, and by briefly presenting advances in the design of test apparatus. Equipment is not yet generally available, although servicable apparatus can be constructed from information in this and other published work [3, 4].

To date, the single-well methods discussed here have proved useful for estimating flow velocity, effective porosity, and the vertical distribution of flow at several field sites. Other single-well tracer methods have been conceived, but not yet practiced at field sites. Two such methods, briefly presented below, will serve to illustrate the direction of future research for field tracer methods.

Well transmissivity is best determined using conventional hydrologic field methods such as a constant-discharge pumping test. However, such testing is equipment- and time-intensive, so the number of tests performed at a field site–regardless of the number of available wells–is often limited. A simple and less expensive method for estimating well transmissivity is needed to determine which wells should be chosen for more extensive testing (e.g., in an ATES well field or in a network of monitoring wells at a waste disposal site). Under certain circumstances, point-dilution testing as described here can serve this purpose. First, all wells must be constructed to the same specifications (e.g., size of open hole, packing material, screen type, and slot size) so the flow distortion factor from equation (3) is the same for each well. Second, the transmissivity of at least one of the wells must be known (e.g., from a constant-discharge test). Third, each well must meet the criteria for a minimally developed well. Fourth, the local hydraulic gradient in the vicinity of each well must be known.

Equations (2) and (3) can be combined and rearranged as

$$V^* = KI/a \quad (4)$$

Equation (4) relates the V* and K for each tested depth. However, the equation also relates the mean V* for the well to the mean hydraulic conductivity. Further, the factor V* is proportional to the slope of a plot of millivolts *versus* time, derived from point-dilution tests. Like the flow distortion factor, a, the proportionality constant, p, that relates V* to plot slope, m, depends on well construction specifications and will be the same for all wells. Substituting the product of plot slope and the proportionality constant for V* yields

$$pm = KI/a \quad (5)$$

Two wells may then be compared using equation (5) as

$$(pm_1/pm_2) = (K_1I_1/a)/(K_2I_2/a)$$

and

$$K_2 = K_1I_1m_2/m_1I_2 \quad (6)$$

Thus, if the hydraulic conductivity of one well is known, the hydraulic conductivity of another may be calculated from the respective local hydraulic gradients and point-dilution data, where the factors m are the mean slopes of the plots of electrode response in millivolts *versus* time for the two wells. The transmissivity of the second well is then calculated by multiplying $K_2$ by the aquifer thickness.

Figure 8 suggests a second application of this type of analysis. Transmissivities (and mean hydraulic conductivities) assigned to the wells represented in Figure 8, based on pumping tests at each well, were nearly the same because each pumping test interrogated nearly the same body of sediments. That is, the design of the pumping tests masked small-scale, local inhomogeneities that may be important in the analysis of bioremediation experiments planned for this test site. Point-dilution data showed that the mean hydraulic conductivity of well 299-W11-30 is 37% of that of well 299-W11-29. Pumping tests yielded a mean conductivity of approximately 7.6 m/d for the body of sediments between the wells. For modeling and analyzing the results of the bioremediation demonstration, a somewhat better representation of local hydraulic conditions might be obtained by assigning hydraulic conductivities of 4.3 and 11.0 m/d to these wells, respectively (yielding a mean of 7.6 m/d).

Finally, a body of evidence shows that single-well, multiple tracer, injection-withdrawal experiments may be useful for estimating flow parameters such as dispersivity and solute retardation. Consider, for example, a series of tracer experiments conducted in 1986 in deep basalt aquifers at the Hanford Site [8]. (Many of the confined aquifers within the regional basalt flows are highly transmissive and are sources of irrigation water, although natural ground-water flow velocities are negligibly low.) In one of the experiments, 38,000 L of water labeled with a lithium bromide tracer was injected into the Sentinel Gap flow top aquifer at borehole DC-18. The injection was followed immediately by a chaser of 30,000 L of fresh water. One week later, pumping was begun to recover the tracer and continued for 6 d. Figure 9 shows the results of tracer recovery, where bromide and lithium concentrations are plotted against pumped volume normalized to the total injected volume (68,000 L).

Three facets of this figure are striking. First, the recovery plots of both lithium and bromide tend toward a straight line. Second, the slopes of the individual plots are distinctly different. Third, the recovery plots are unaffected by the rate of pumping. Analysis of these results suggests that the slope of the plot of the conservative bromide ion depends on aquifer dispersivity. The difference in slope between the lithium and bromide plots must reflect the tendency for lithium to reversibly adsorb to mineral phases in the aquifer. Such adsorption is responsible for retardation of certain solutes (e.g., lithium) in ground-water plumes, and is in many ways analogous to the heat exchange between ground water and mineral phases that causes retardation of thermal plumes.

Tracer behavior similar to that shown in Figure 9 has been observed in other aquifers (e.g., sedimentary aquifers), and for other tracers [8]. However, there is currently no method for quantitatively translating the shape of recovery plots from single-well, injection-withdrawal tests into numerical factors for modeling dispersion or retardation. Development of such a method is a main goal of continuing research.

## ACKNOWLEDGMENTS

The author is grateful to Mr. Darrell R. Newcomer and Mr. Vince R. Vermeul of Pacific Northwest Laboratory for supplying hydrologic analysis and assistance in conducting field experiments, and to Prof. C. Everett Brett, Prof. K. Clark Midkiff, and Mr. Ken R. Gelinas of the University of Alabama for aid in organizing and conducting tests at the Tuscaloosa sites.

## REFERENCES

1. S. H. Hall, S. P. Luttrell, and W. E. Cronin, 1991, "A Method for Estimating Effective Porosity and Ground-Water Velocity," Ground Water, Vol. 29, no. 2, p. 171-174.

2. D. I. Leap, and P. G. Kaplan, 1988, "A Single-Well Tracing Method for Estimating Regional Advective Velocity in a Confined Aquifer: Theory and Preliminary Laboratory Verification," Water Resources Research, Vol. 23, no. 7, p. 993-998.

3. S. H. Hall, and J. R. Raymond, 1992, "Geohydrologic Characterization for Aquifer Thermal Energy Storage," in Proceedings, 27th Intersociety Energy Conversion Engineering Conference, August 1992, San Diego, California, Vol. 4, p. 101-107, Society of Automotive Engineers, Warrendale, Pennsylvania.

4. S. H. Hall, 1993, "Single-Well Tracer Tests in Aquifer Characterization," Ground Water Monitoring and Remediation, Vol. 13, no. 2, p. 118-124.

5. D. R. Newcomer, L. A. Doremus, S. H. Hall, M. J. Truex, V. R. Vermeul, and R.E. Engleman, 1994, Geology, Hydrology, Chemistry, and Microbiology of the In Situ Bioremediation Test Site, Pacific Northwest Laboratory, Richland, Washington (in press).

6. C. D. Palmer, 1993, "Borehole Dilution Tests in the Vicinity of an Extraction Well," Journal of Hydrology, Vol. 146, p. 245-266.

7. P. M. Kearl, J. J. Dexter, and J. E. Price, 1988, Procedures, Analysis, and Comparison of Groundwater Velocity Measurement Methods for Unconfined Aquifers, UNC/GJ-TMC-3, UNC Geotech, Grand Junction, Colorado.

8. S. H. Hall, 1986, "Evaluation of Groundwater Tracers for Columbia Plateau Basalt Aquifers at the Hanford Site, Washington," Geological Society of America Abstracts with Program, Vol. 18, no. 6, p. 625.

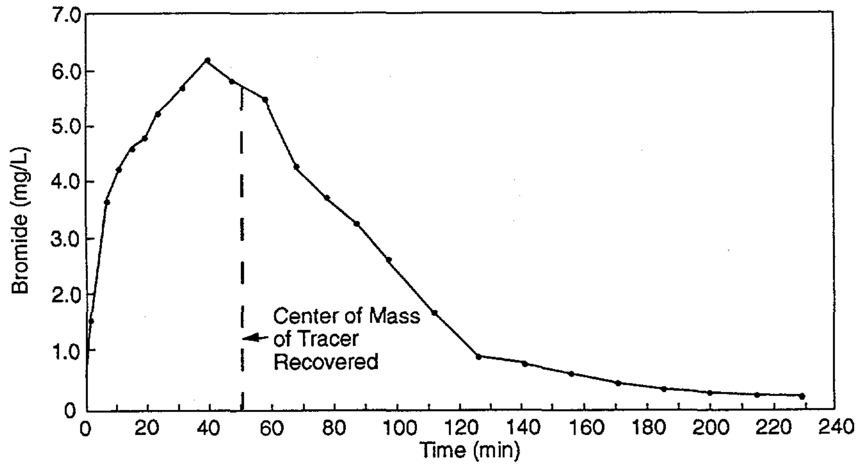



Figure 1. Bromide concentration *versus* time during the tracer recovery stage of the drift-and-pumpback test at the University of Alabama Student Recreation Center.

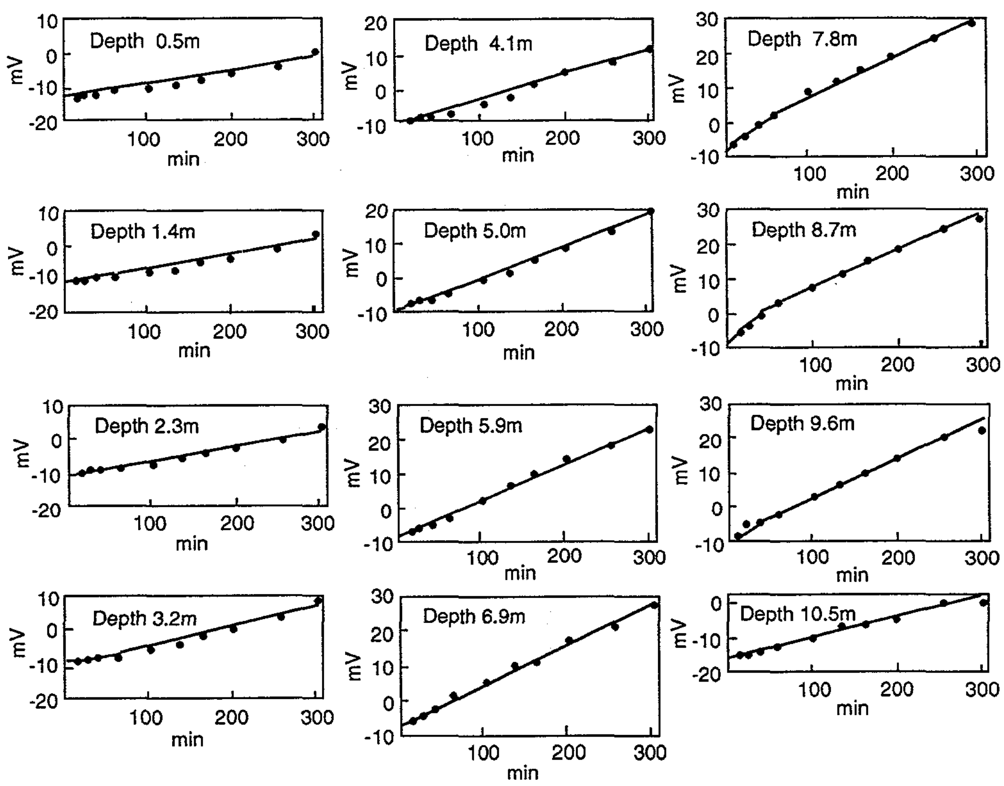



Figure 2. Bromide ion-selective electrode response *versus* time at 12 depth intervals during the point-dilution test at the University of Alabama Student Recreation Center.

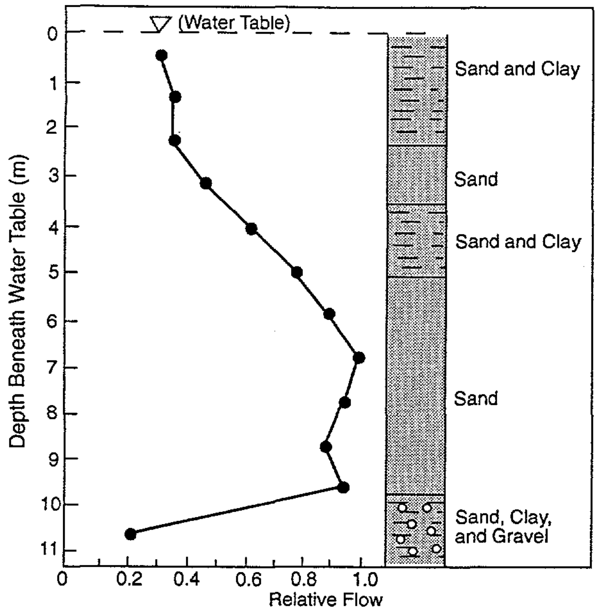



Figure 3. Relative horizontal ground-water flow *versus* depth within the bore of the test well at the University of Alabama Student Recreation Center. The flow profile is compared to stratigraphy based on the examination of drill cuttings.

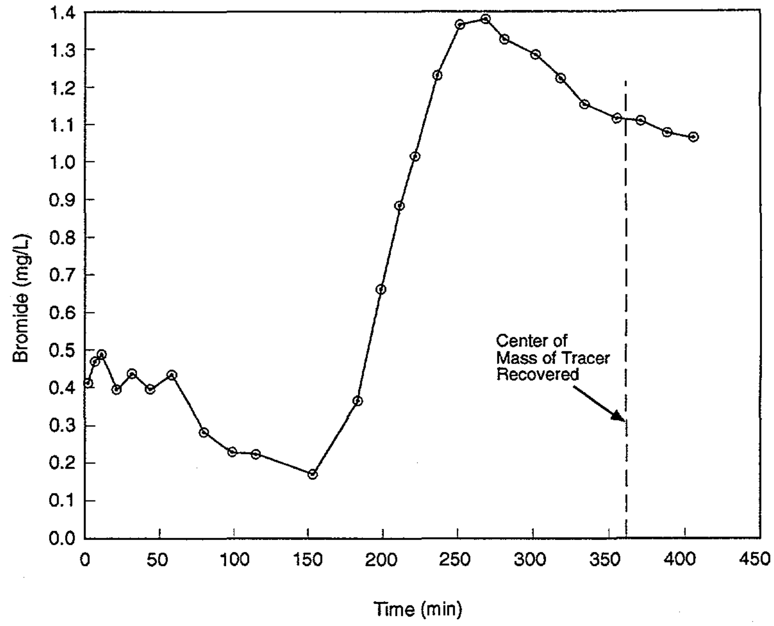



Figure 4. Bromide concentration *versus* time during the tracer recovery stage of the drift-and-pumpback test at the VA Medical Center.

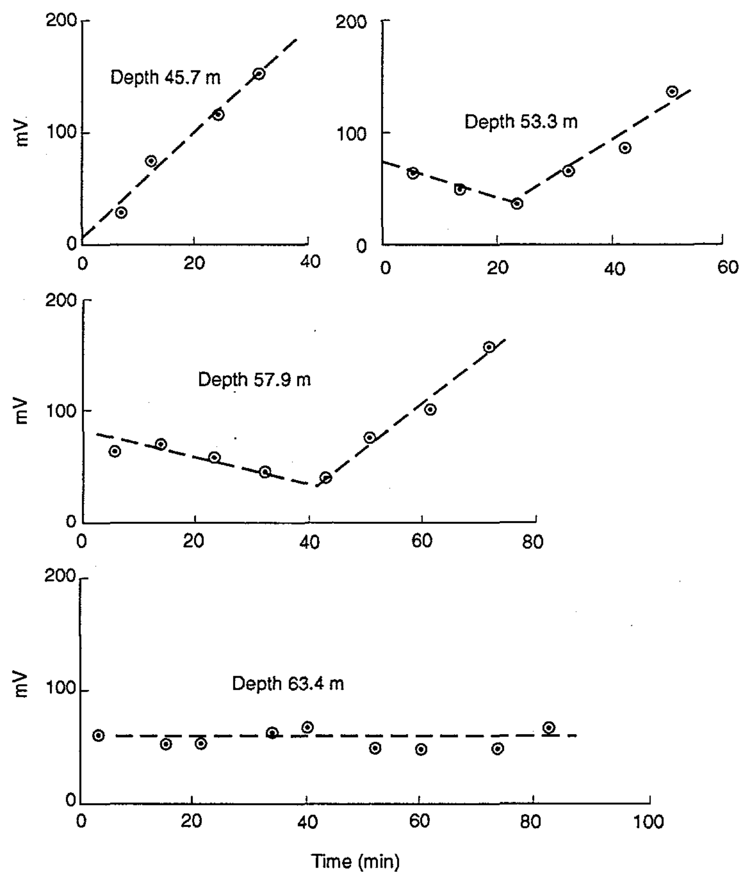



Figure 5. Bromide ion-selective electrode response *versus* time at four selected depth intervals during the point-dilution test at the VA Medical Center.

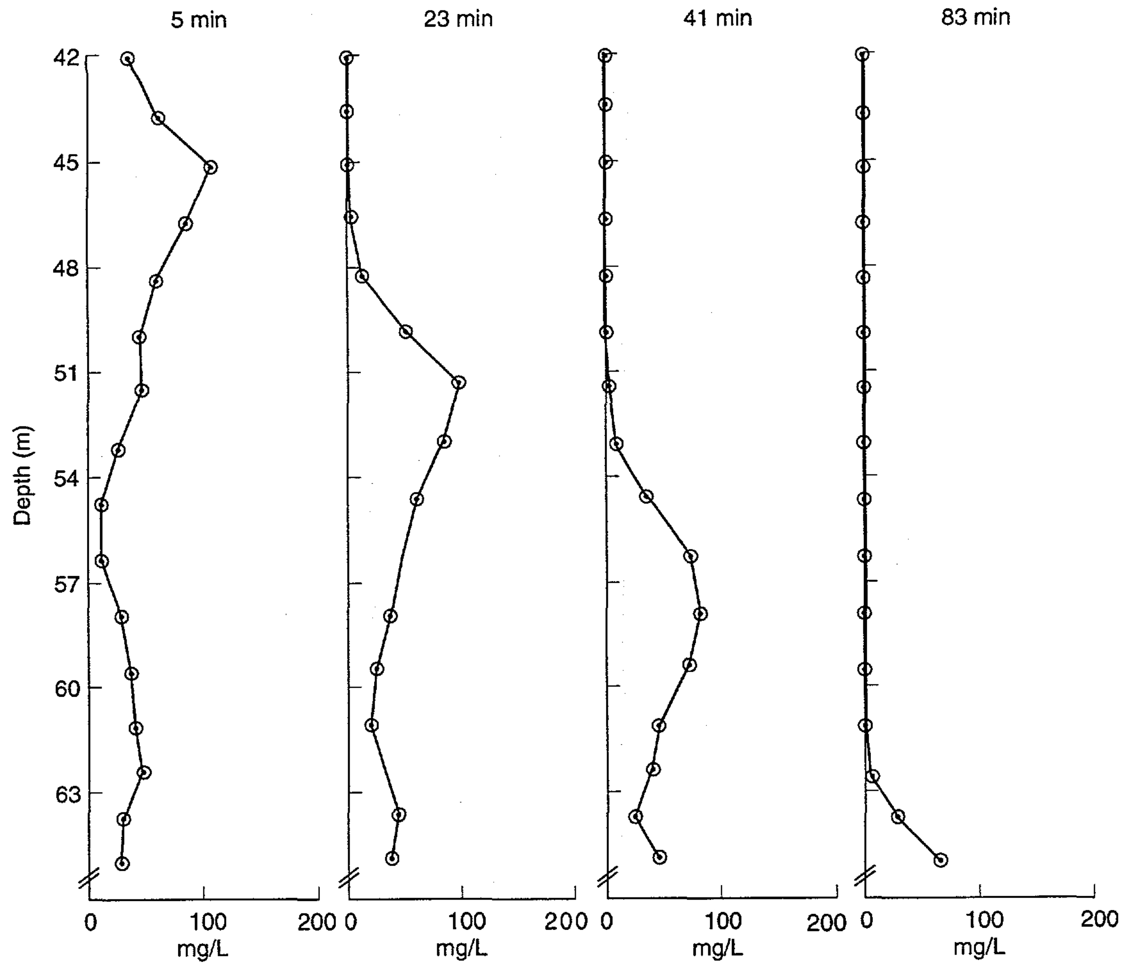



Figure 6. Bromide concentration *versus* depth at various times during the point-dilution test at the VA Medical Center.

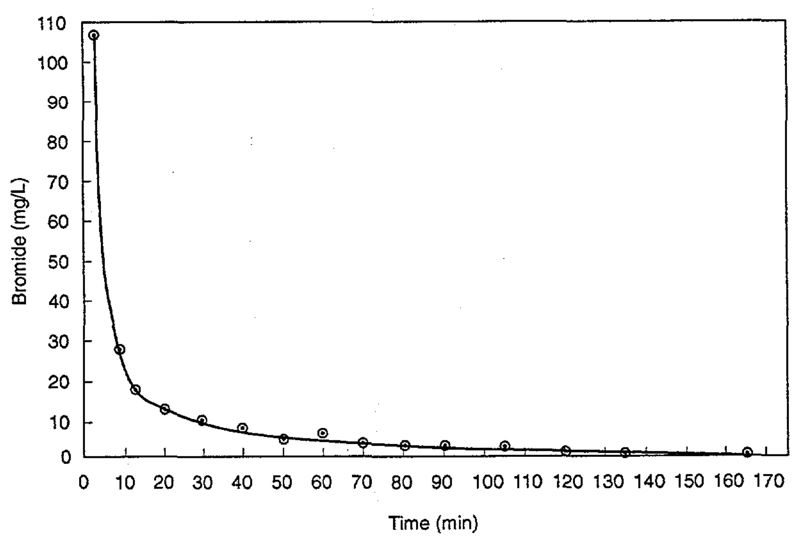



Figure 7. Bromide concentration *versus* time during the tracer recovery stage of the drift-and-pumpback test in well 299-W11-30 at the Hanford bioremediation test site.

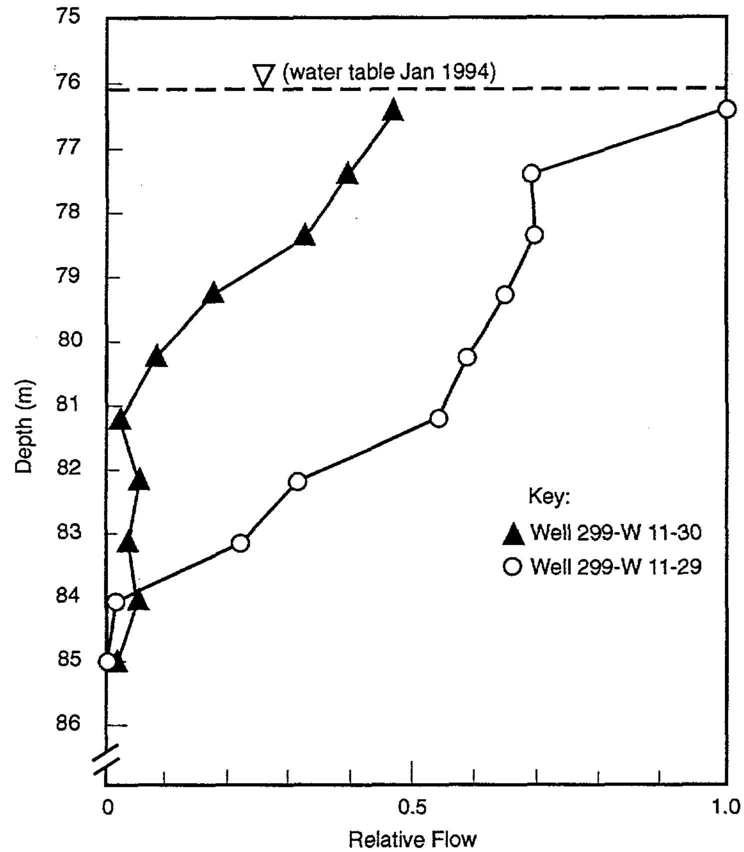



Figure 8. Relative horizontal ground-water flow *versus* depth within the bores of two test wells at the Hanford bioremediation test site.

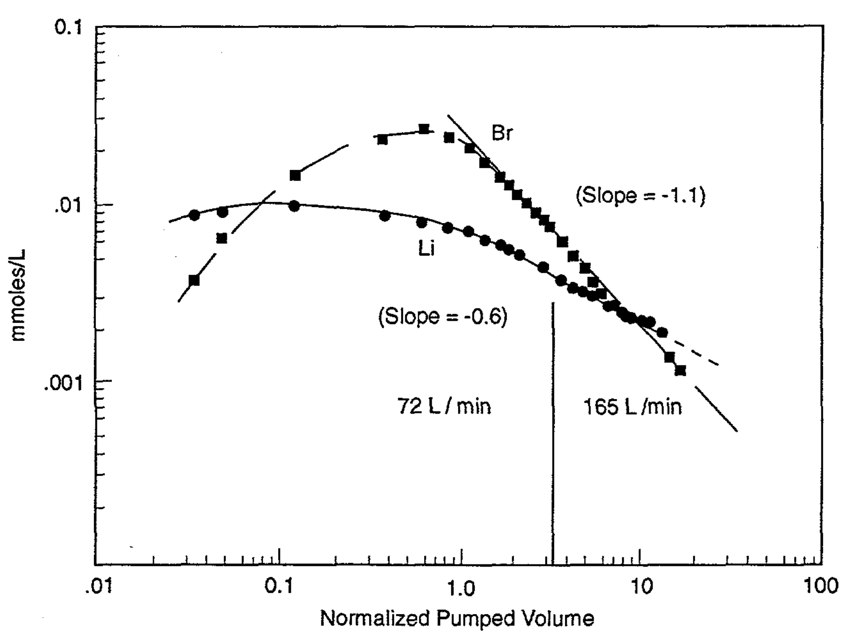



Figure 9. Concentrations of lithium and bromide tracers *versus* pumped volume during the tracer recovery stage of an injection-withdrawal test in a confined basalt flow top aquifer at the Hanford Site. Pumped volume is normalized to the 68,000 L tracer volume injected for the test.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# Thermohydraulic Evaluation of Two ATES Projects in Southern Sweden

• Thomas Probert
Dept. of Mathematical Physics
Lund University
Lund, Sweden
• Göran Hellström
Dept. of Mathematical Physics
Lund University
Lund, Sweden
• Johan Claesson
Dept. of Building Physics
Lund University
Lund, Sweden

ABSTRACT

This paper presents the thermohydraulic evaluations of two ATES projects in Southern Sweden. In Malmö, a fissured limestone aquifer at a depth of 6 to 75 metres is used as a source for heating and cooling office buildings and a shopping mall. There are six wells on the warm side and eight wells on the cold side. The average volume of groundwater that is pumped back and forth in the wells is 70,000 m$^3$ and 50,000 m$^3$ in the heating and cooling mode, respectively. Injection temperatures are roughly 10 °C on the warm side, and 3 °C on the cold side. The recovery temperatures are roughly 12 °C on the warm side, and between 7 and 12 °C on the cold side. The ambient groundwater temperature is about 12 °C. Due to a malfunctioning of the control system in the cooling mode, the heat budget of the aquifer is unbalanced, so that there is a gradual cooling of the aquifer. The energy extracted from the aquifer in the heating mode is 800 MWh per year. The energy stored in the aquifer in the cooling mode is 150 MWh per year. Estimates of the thermal extent show that the wells interact strongly but despite this fact the wells can be simulated quite satisfactorily using a single well model.

Another ATES system with similar operating conditions has been used by the local power company in Lomma (a few kilometres north of Malmö) for district heating. The aquifer is thermally recharged in the summer using warm surface water from a nearby river as a heat source. The homogeneous aquifer is located at a depth of 40 to 65 metres. There are five wells on both the warm side and the cold side. The average amount of water pumped, back and forth, in the aquifer is 650,000 m$^3$ in the heating mode and 350,000 m$^3$ in the recharge mode. The average injection temperature is about 14 °C on the warm side, and about 4 °C on the cold side. Average recovery temperatures are 12 °C on the warm side, and 5 °C on the cold side. The ambient groundwater temperature is about 9.5 °C. There have been problems with clogging during reinjection in the warm wells, which has led to an unbalanced energy budget in this case. The energy extracted from the aquifer is 8000 MWh per year. The energy stored in the aquifer during recharging is 5000 MWh per year. Numerical simulations show that, except for a partial thermal breakthrough, the ten wells do not interact thermally. There is a good match between calculated and measured extraction temperatures.

The aim of the evaluations is first to confirm that our models can be applied to the ATES system in question. Secondly, when confident that our models give sufficiently accurate results, we want to be able to make reliable predictions about future recovery temperatures and temperature distributions in the aquifer given the planned injection temperatures and pumping rates. A prediction might show that a planned pumping strategy will lead to a thermal breakthrough. Predictions can also be used to decide the optimal pumping strategies in given situations. In Lomma we believe that our models can be used to make reliable predictions. In Malmö, on the other hand, it is harder to assess the reliability of our models because of the uncertainties in the aquifer.

## INTRODUCTION

An ATES system (Aquifer Thermal Energy Storage) consists of a number of wells that penetrate an aquifer. The wells form two groups: The 'warm' and the 'cold' wells. The two types of well penetrate different parts of the aquifer. Heat (warm groundwater) is stored around the warm wells and chill (cold groundwater) is stored around the cold wells. When heat is needed, for instance for space-heating, groundwater is pumped from the warm wells and heat is extracted. After the heat extraction process, where the groundwater is cooled, the groundwater is returned to the aquifer via the cold wells. When the store is utilized for cooling purposes, groundwater is extracted from the cold wells and used as a coolant. Thus, the groundwater is heated and returned to the warm side of the aquifer via the warm wells.

The hydraulic and thermal activity in the aquifer result in a thermohydraulic process where heat is conveyed via convection and conduction.

Inhomogeneities in the aquifer cause a certain amount of mixing of the groundwater (dispersion) which leads to more heat losses or gains. The presence of convective movements, such as regional groundwater flow and buoyancy flow, can also lead to heat losses or gains.

The complex thermohydraulic problem can be solved numerically given physical data of the aquifer and its surroundings, the complicated groundwater flow pattern, pumping rates and injection temperatures. This is practically an impossible task without actually having the exact physical data of the ground. The parameters needed to describe the hydrothermal properties of the aquifer come from measurements in the boreholes or from different types of tests performed in the boreholes or on the ground surface. Trying to describe a large 3-dimensional region 50-60 metres under the ground surface with a few 1-dimensional peep-holes (boreholes) makes much of the modelling pure guess-work when it comes to local inhomogeneities in the aquifer.

A great deal can be learnt about the well system by simply mapping the movement of the groundwater in the aquifer caused by pumping in the wells. This method assumes that the groundwater flow pattern is given by an analytical expression. Even more can be learnt by taking into account the thermal effects in the aquifer, but still assuming that the groundwater flow is given by an analytical expression.

An understanding of the thermohydraulic processes in the aquifer is necessary for a proper design of an ATES system under given thermohydraulic conditions. The main design considerations concern the location of the wells, the loading conditions (injection temperatures and pumping rates), heat losses, temperature quality losses, thermal breakthrough time etc. It is also important to assess the consequences of the uncertainties associated with storage in an underground region beyond detailed investigation.

The main aim of the thermalhydraulic analysis is to predict the recovery temperatures from the aquifer given the groundwater injection temperatures and flow rates.

## THERMOHYDRAULIC MODELS

The thermohydraulic analysis requires a calculation, or at least a reasonable knowledge, of the groundwater flow and the temperatures in the aquifer and the surrounding ground. The groundwater flow is often quite complex. In general, it must be computed numerically for an aquifer with its more or less complicated inhomogeneities. There are, however, many important applications that can be analysed assuming that the groundwater flow pattern is given by an analytical solution or a so-called conformal transformation (Claesson and Bennet [1]). A more thorough discussion of the thermohydraulic models is given in [2].

### Conformal Flow

The basic assumptions are that the groundwater flow is two-dimensional without a vertical component and that the hydraulic properties of the aquifer are homogeneous in the horizontal plane of the flow. The groundwater flow is also presumed to follow Darcy's Law, and compressibility effects and the effect of density and viscosity variations are neglected. The most general case that can be treated with use of this conformal technique is an aquifer with an arbitrary number of parallel, horizontally homogeneous aquifer strata.

### Thermal Front Tracking Model

The first model concerns the groundwater flow and the motion of thermal fronts for any set of wells and any regional flow. The flow field, with streamlines and stagnation points, is presented graphically on the screen. The motion of the thermal fronts is determined by particle tracking. The thermal fronts are considered to be sharp interfaces that are not influenced by heat diffusion, thermal dispersion or tilting (a buoyancy flow effect). This interactive model has proven to be a very convenient and useful design tool.

### Detailed Thermal Models

The second set of models concerns the heat balance of the store. These two models also calculate the temperature of the extracted groundwater as well as the temperature distribution in the aquifer. The groundwater flow is in each case generated by a conformal transformation. The three-dimensional thermal process with combined groundwater and heat flow in the aquifer and heat conduction in surrounding impermeable layers is solved numerically with use of the explicit finite difference method (FDM). The numerical mesh is generated based on the streamlines and equipotentials of the conformal groundwater flow. The calculation is performed in the transformed orthogonal coordinate system, so that the convective transport only takes place along one coordinate axis — the streamlines (Hellstöm and Bennet [3]). This approach, combined with the entropy conservation technique that eliminates numerical dispersion (described and discussed in Lantz [4], Claesson [5] and Hellström *et al* [6]), makes the iterative calculation very fast and accurate. A large number of cells can be used in the numerical mesh without excessive execution times. Both types of models (thermal front tracking models and detailed thermal models) are described in greater detail in [2].

### List of Computer Programmes

The PC programme CONFLOW, graphically presents the groundwater flow, the pressure field, and the motion of thermal fronts on the screen interactively.

The other two PC models used in this paper have been developed for simulation of the heat balance in aquifers. The first model AST is a single well model and the second TWOW is a doublet well model. The two models calculate the temperature of the extracted groundwater, the temperature distribution in the aquifer, and the heat balance.

CONFLOW: Basically any number of wells in an aquifer with infinite horizontal extent or with a single, straight hydraulic boundary (closed or open). The stagnation points, stagnation lines, stream lines, pressure field and thermal fronts are displayed on the screen.
AST: Heat storage around a single well in an aquifer stratum with infinite lateral extent. The groundwater flow is assumed to be in the radial direction from the well. Calculates the temperature of the extracted groundwater, the temperature distribution in the aquifer, and the heat balance.

TWOW: Heat storage model of a doublet system. Calculates the temperature of the extracted groundwater, the temperature distribution in the aquifer, and the heat balance.

All three models are carefully documented and are available on PC (Hellström *et al* [6]; Hellström and Bennet [3]). The models have been validated against a few field experiments and they are used extensively for design studies and parameter sensitivity studies. (Doughty *et al* [7]).

## THE LOMMA PLANT: A GROUNDWATER SYSTEM

### Description of the Aquifer and Well System

The aquifer in Lomma is 25 metres thick and is situated 40 metres below the ground surface. The aquifer consists mainly of different types of sand from very fine sand in the upper regions to gravel in the lower regions. For practical reasons the aquifer is sub-divided into two layers. The upper layer, which is 13 metres thick, consists of sand and fine sand, and the lower layer, which is 12 metres thick, consists of sand and gravel. Taking into account the different permeabilities of the two layers it can be shown that 75% of the groundwater injected into or extracted from the wells, flows in the lower layer and only 25% flows in the upper layer. The aquifer is confined above by a 40 metre thick layer of clay. Below, the aquifer is confined by low permeable limestone. There is a natural groundwater flow present in the aquifer but it is negligible. The aquifer used in Lomma is part of an aquifer called the Alnarpsström. This aquifer has a large lateral extent and its thickness in the area around Lomma is uniform.

The aquifer is penetrated by ten wells, five for cold water and five for warm water. The well configuration is shown in Figure 1. The shortest distance between the warm and cold wells is 217 metres. The average distance between the wells on the warm side is well over 100 metres. This also applies to the wells on the cold side. A well used solely for monitorial purposes has been bored slightly to the north of the area of influence, which, regretfully, makes it redundant. The observation well is 138 metres from the nearest extraction/injection well.

In the winter, groundwater is pumped from the warm wells, cooled by heat extraction, and returned to the cold wells. In the summer the pumping is reversed and the warm wells are thermally recharged. The heat source for this recharging is surface water from a nearby river.

The plant, in this 10 well configuration, has been in operation since early 1991. There have been a few problems that have disturbed the running of the plant since then. There was a biofouling problem that was remedied, and there was and still is a problem with clogging of injection wells. The well clogging has resulted in groundwater being dumped into the local river.

The plant was used prior to 1991 as a groundwater system without thermal recharging. Only 6 wells were used then, 3 cold wells (401, 402 and 403), and 3 warm wells (411, 412 and 413). After a few winters a severe thermal breakthrough occurred between wells 403 and 412. The remnants of this thermal breakthrough can still be noticed after long extraction periods. In the monitoring well, the cold water from this breakthrough, has a temperature between 7-8 degrees but regions of colder water between 3-6 degrees still exist around some of the older cold wells.

Flow rates and groundwater temperatures for each well have been monitored and recorded by the Monitoring Centre for Energy Research at Chalmers University of Technology (MCTH), for the period between 1st April 1991 and 31st May 1993. The groundwater temperature at different depths is measured in the observation well.

The temperature of the groundwater injected into the cold wells has been between 3 and 5 °C excluding the first winter when it was 7 °C. The temperature of the groundwater stored in the aquifer on the warm side has mainly been between 12 and 15 °C. The recovery temperatures were between 10 and 12 °C. The ambient temperature in the aquifer is approximately 9.5 °C. The total volume of groundwater that is pumped back and forth in the aquifer is roughly 350,000 $m^3$ in the summer and 650,000 $m^3$ in the winter.

The recharging of the aquifer on the warm side in the summer does not compensate for the total amount of energy withdrawn during the previous winter. This is mainly due to clogging of the injection wells resulting in groundwater being dumped into the nearby river. This energy imbalance implies that the aquifer is undergoing a gradual cooling process that could lead to a serious thermal breakthrough in a not too distant future.

The Lomma plant was evaluated by MCTH, Lund Institute of Technology and VIAK AB on behalf of the Swedish Council for Building Research (BFR), and the results are to be published in a BFR report.

### CONFLOW Simulations

This section describes how the actual physical processes in the aquifer were studied and how, by analysing flow rates and temperatures, appropriate and justified mathematical models were chosen. The results from computer simulations based on these simple mathematical models paved the way for more accurate simulations with more detailed and complex mathematical models.

The main focus of our part of the BFR report was on whether or not thermal breakthrough had occurred, and if this had not happened, whether it could occur in the near future. Recovery temperatures were of secondary interest. It turns out that calculating recovery temperatures is easier than we predicted in the beginning of the BFR survey.

A study of the recovery temperatures from the warm wells convinced us that thermal breakthrough had not occurred. Simple calculations of the thermal ranges around each well told us that influence between most wells was probably small. We also discovered that the observation well was outside the area of influence of the wells.

The aquifer used is part of a larger aquifer which has undergone numerous and detailed investigations. Thus, its characteristics in the area around Lomma are very well known. Approximating the aquifer with a model aquifer that is homogeneous, uniform in thickness with an infinite lateral extent is a good approximation. If we presume that the CONFLOW model can be applied to this system we can calculate the groundwater flow pattern. As was stated earlier in this chapter the aquifer consists of two layers with different permeabilities. This is in conflict with the condition of homogeneity but within each layer the condition is fulfilled. All simulations are done in the lower layer where 75% of the groundwater flows, and where the thermal range has its largest extent.

## Results and Conclusions of CONFLOW Simulations

The results after simulating the system, with the CONFLOW model, for the period 1st April 1991 to 11th October 1992 are shown in Figure 2. The simulation was continued until 9th May 1993 and those results are shown in Figure 3.

In both Figures 2 and 3, the cold wells, numbered 401–405, are to the left, and the warm wells, numbered 411–415, are to the right. The solid lines are streamlines and they start at a warm well and end at a cold well in Figure 2, and *vice versa* in Figure 3. The dashed lines are stagnation lines. The point where two stagnation lines intersect is a stagnation point. The groundwater flow is zero at a stagnation point. Stagnation lines are streamlines that connect stagnation points to wells.

The shaded areas to the left in Figure 2 are the cold volumes that are confined by the thermal fronts. There are two different shades of grey; the lightest shade represents cold groundwater that was injected between 1st April and 2nd July 1991 (Around wells 401, 404 and 405); the darkest shade is for cold groundwater injected during the period from 26th September 1991 to 22nd May 1992 (Around every cold well). The shaded areas around the warm wells were created by injecting warm groundwater into the warm wells during the summer of 1992 (23rd May to 11th October), when the aquifer was being thermally recharged. The circular shape of the thermal fronts around some of the wells implies that these wells are not disturbed by the other wells.

A CONFLOW simulation for the next winter period from 12th October 1992 to 9th May 1993 is shown in Figure 3. The heat stores on the warm side have gradually decreased in size until all but one have vanished. The small shaded area near well 415 is the last remains of the warm groundwater that was stored during the last summer. This is because of warm groundwater being extracted from the warm wells for heating purposes. At the same time a new set of cold regions has been created around the cold wells because of injected cold groundwater.

In the middle of March 1993 cold water, injected into the cold well 403 during the winter of 1991/1992, infiltrates the warm well 412; a partial thermal breakthrough occurs (See Figure 3). The temperature in well 412 was dropping slowly before this occurrence and the infiltrating thermal front has been in thermal contact with warmer groundwater for over a year's time. The simulation shows that the *thermal breakthrough* is partial. Only about 40% of the groundwater extracted from the warm well is cold. The rest of the extracted groundwater has a temperature equal to the ambient temperature 9.5 °C. We must also remember that are simulations are done in the lower layer of the aquifer. In the upper layer, where only 25 % of the groundwater flows, a thermal break through has not occurred. This means that it is only 30% of the extracted groundwater that is actually from the cold well. This makes it very hard to detect the thermal breakthrough in the temperature data for well 412.

The simulations confirmed our beliefs that most of the wells are uninfluenced by each other, and that thermal breakthrough had not occurred in any well. The fact that most of the wells function as autonomous units makes it possible to use a single well simulation model, like for instance the programme AST, which is a radial model, that calculates recovery temperatures. The thermal ranges that were calculated earlier underline this fact since the criterion stated by Hellström and Bennet in [3] is fulfilled. The warm well 412 and the cold well 403 influence each other. Recovery temperatures for these two wells can be calculated using the TWOW model which is a heat storage model of a doublet well system.

A CONFLOW simulation of an ATES plant is a fast way to see what happens to the groundwater that is injected into the aquifer. By following the motion of the sharp thermal fronts we can roughly see how the thermal energy is stored in the aquifer. The programme CONFLOW is a useful tool for visualizing and assessing the extent of the thermal and hydraulic processes in the aquifer.

## AST Simulations

As was stated earlier, the regional flow in the aquifer is negligible and the influence of viscosity differences between different flow paths is small. According to the results of CONFLOW simulations most wells are undisturbed by the other wells. However, wells 403 and 412 interact more than the other wells because of the short distance between them.

The AST model needs injection temperatures and pumping rates as well as physical data about the aquifer in order to calculate extraction temperatures. Velocity-dependent dispersion is accounted for in the simulations. The parameter that largely effects the results (in low-temperature applications) is the temperature in the aquifer in the beginning of the simulation. By varying the temperature distribution in the aquifer different results can be obtained. This distribution should be chosen wisely, and should be based on measurements or other similar information.

All the wells were simulated using the AST model. The initial temperature in the aquifer was set to a constant equal to the extracted temperature according to measurements after a long period of extraction for each well. This constant initial temperature varied between 5-10 degrees for the cold wells and between 8-10 degrees for the warm wells.

The results corresponded remarkably well to the measured recovery temperatures. The results for two of the warm wells (412 and 415) and one of the cold wells (405) are presented here. The results are shown in Figures 4, 5 and 6. The two wells 405 and 415 are least disturbed by the other wells, whereas the well 412 is disturbed the most (According to estimations of the thermal extent and CONFLOW simulations). This well and the cold well 403 can be simulated by the TWOW model, which is a doublet well model. The thermal breakthrough that occurred in the CONFLOW simulation was between these two wells (See Figure 3).

The AST simulations underlined the importance of knowing the initial temperature distribution in the aquifer especially in the case of low-temperature heat stores. The wrong initial temperature data led to incorrect extraction temperatures.

## THE TRIANGELN PROJECT IN MALMÖ

### Description of the Plant

The seasonal ATES system in Malmö is similar to the system in Lomma. The main difference is that the heat stored in the aquifer in Malmö is surplus heat from the office buildings and shopping mall, instead of from the warm surface water of a river, like in Lomma. The aquifer is used for both heating and cooling purposes. In the winter heat is extracted from the groundwater and in the process the groundwater is chilled. This groundwater is then stored until it is needed in the summer for cooling. When the groundwater is used for cooling, heat is absorbed and the groundwater becomes warm. This groundwater is, in turn, stored until it is needed for heating in the winter.

The aquifer is confined above by a 4-6 metre thick layer of boulder-clay and below by bedrock which in this case is chalk. The aquifer, which actually is the upper part of the bedrock, is about 70 metres thick and consists of limestone with horizontal flint layers. The flint layers are associated with horizontal fissures (fissure planes). The hydraulic conductivity in a horizontal fissure plane is extremely good. In contrast, the hydraulic conductivity between different fissure planes is quite poor. This means that wells situated in the same fissure plane influence each other more than wells situated in different fissure planes. This could be an advantage or disadvantage depending on the function of the wells in question.

A preliminary heat injection response test showed that the groundwater flow in the aquifer takes place in a few crack planes in the upper regions of the aquifer interspersed with more impermeable layers.

The aquifer is penetrated by 6 warm wells and 8 cold wells. There are also 3 monitor wells between the warm and cold wells. The well configuration is shown in Figure 7. The average distance between the wells in the warm field is roughly 10 metres. This is also the average distance between the wells in the cold field. This makes the well configuration in Malmö more compact than that of Lomma. The shortest distance between the warm and the cold wells is 95 metres.

Temperatures and flow rates were measured by MCTH. The total flow between the warm and cold wells, as well as the average temperature on both sides was measured. The monitor wells are 75 metres deep. The temperature is measured in each monitor well at about 15 different depths between 0 and 75 metres.

The temperature profiles (temperatures versus depth) in the monitor wells told us two things. First, there was a difference of as much as 1 °C between the initial temperature profiles, even at depths of over 40 metres. Secondly, during the three years of operation, almost all the thermal activity occurred in the upper 30 metres of the ground.

The ambient temperature of the groundwater is 12 °C. The average temperature of the groundwater, when it was stored and when it was recovered is shown in Table 1 for both stores. The arrows indicate the direction of the groundwater, whether it is injected (↓) or extracted (↑). Somehow, the recovery temperatures in the warm wells are roughly equal to 12 °C, although the stored temperatures were 1.5 to 2 degrees below this temperature. This could mean that the cold groundwater was warmed in the fissures by the warmer surroundings, or, that the cold groundwater is channeled away from the well and is replaced by warmer ambient groundwater.

**Table 1.** Stored (↓) and recovered (↑) temperatures. The stored temperatures in the warm wells are below 12 °C, and the recovery temperatures are roughly equal to 12 °C. The extracted groundwater from both warm and cold wells is gradually becoming colder.

| Period | 'warm' wells | | 'cold' wells | |
|---|---|---|---|---|
| | Stored | Recovered | Stored | Recovered |
| Summer '90 | ↓ 12.4 | – | – | ↑ 12.1 |
| Winter '90–'91 | – | ↑ 12.6 | ↓ 6.9 | – |
| Summer '91 | ↓ 10.9 | – | – | ↑ 10.5 |
| Winter '91–'92 | – | ↑ 12.2 | ↓ 3.3 | – |
| Summer '92 | ↓ 10.4 | – | – | ↑ 8.4 |
| Winter '92–'93 | – | ↑ 12.2 | ↓ 3.2 | – |
| Summer '93 | ↓ 10.1 | – | – | ↑ 7.6 |
| Winter '93 | – | ↑ 12.0 | ↓ 3.7 | – |

The somewhat erratic behaviour of the groundwater in the aquifer in Malmö makes modelling very tricky indeed. Extracted groundwater from a cold well could come from a fissure plane closer to the ground surface where the groundwater is much warmer. Warm groundwater injected into a warm well could be led, by a fissure, directly to a cold well. Two wells, side by side, could penetrate different fissure planes, and by doing so they can by hydraulically insulated from each other. Not knowing how the different fissure planes are interconnected, and not knowing which wells penetrate which fissure planes, makes modelling pure guess-work. We have still tried to model the system in Malmö.

Simulations and Conclusions

Simulations were performed using the CONFLOW model. These simulations told us one thing. The warm wells influenced each other to a large extent as did the cold wells.

The CONFLOW simulations indicate that the wells in Malmö disturb each other and do not function as single wells (See Figure 8). Despite this fact we have simulated each well using the AST model and the match between calculated and measured extraction temperatures is fairly good. The main assumption in these calculations is that the main flow occurs in a thin layer in the upper regions of the aquifer.

The distances between the warm wells and the cold wells respectively are shorter and in some cases much shorter than the distances between the warm wells and the cold wells (See Figure 8). This implies that the warm wells and the cold wells can be approximated by a single warm well and a single cold well respectively. After these approximations the TWOW model, which simulates a doublet well system, can be used to obtain extraction temperatures.

The main problem with the Malmö system is that we do not know the complex structure of the aquifer. No matter how advanced the numerical model is one still needs specific information about the aquifer. The more advanced the model is the more detailed the information about the aquifer has to be. It makes no sense to use a complex model if you do not have a detailed description of the aquifer.

REFERENCES

1. J. Claesson and J. Bennet 1987, "Thermohydraulics of Conformal Groundwater Flow", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.

2. J. Claesson, G. Hellström and T. Probert, 1994, "Simulation Models for ATES", in proceedings of the International Symposium on Aquifer Thermal Energy Storage, University of Alabama, Tuscaloosa, Alabama USA.

3. G. Hellström and J. Bennet 1989, "Model of Aquifer Storage System: Doublet Well. Manual for Computer Code", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.

4. R.B. Lantz 1971, "Quantitative Evaluations of Numerical Diffusion", Soc. of Petroleum Eng. J., p. 315, Sept. 1971.

5. J. Claesson 1978, "Entropy Analysis of Numerical Diffusion", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.

6. G. Hellström, J. Bennet and J. Claesson 1986, "Model of Aquifer Storage System: Radial Ground Water Flow. Manual for Computer Code", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.

7. C. Doughty, G. Hellström, C.F. Tsang and J. Claesson 1982, "A Dimensionless Parameter Approach to the Thermal Behaviour of an Aquifer Thermal Energy Storage System", Water Resources Research, Vol. 18, No. 3, pp.571-587.

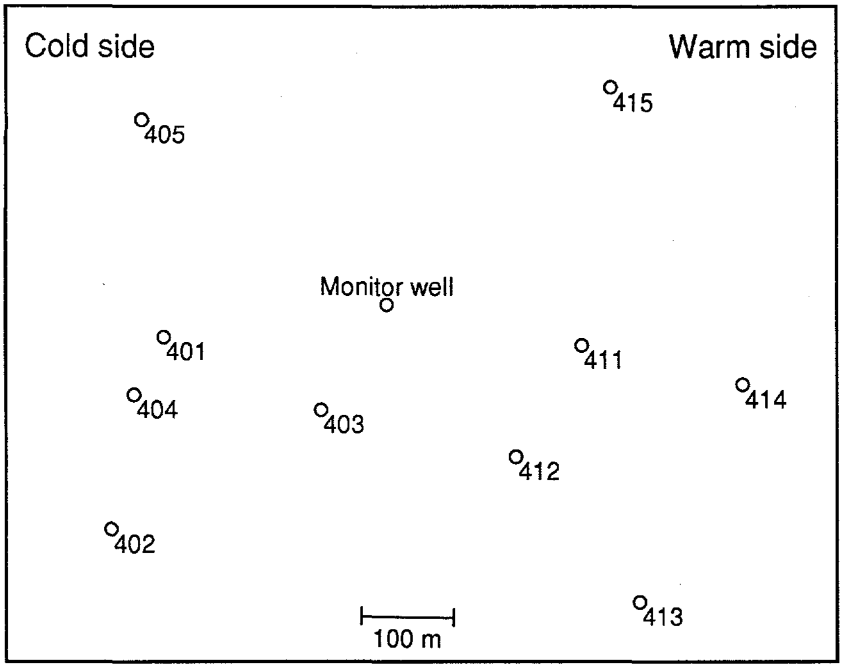
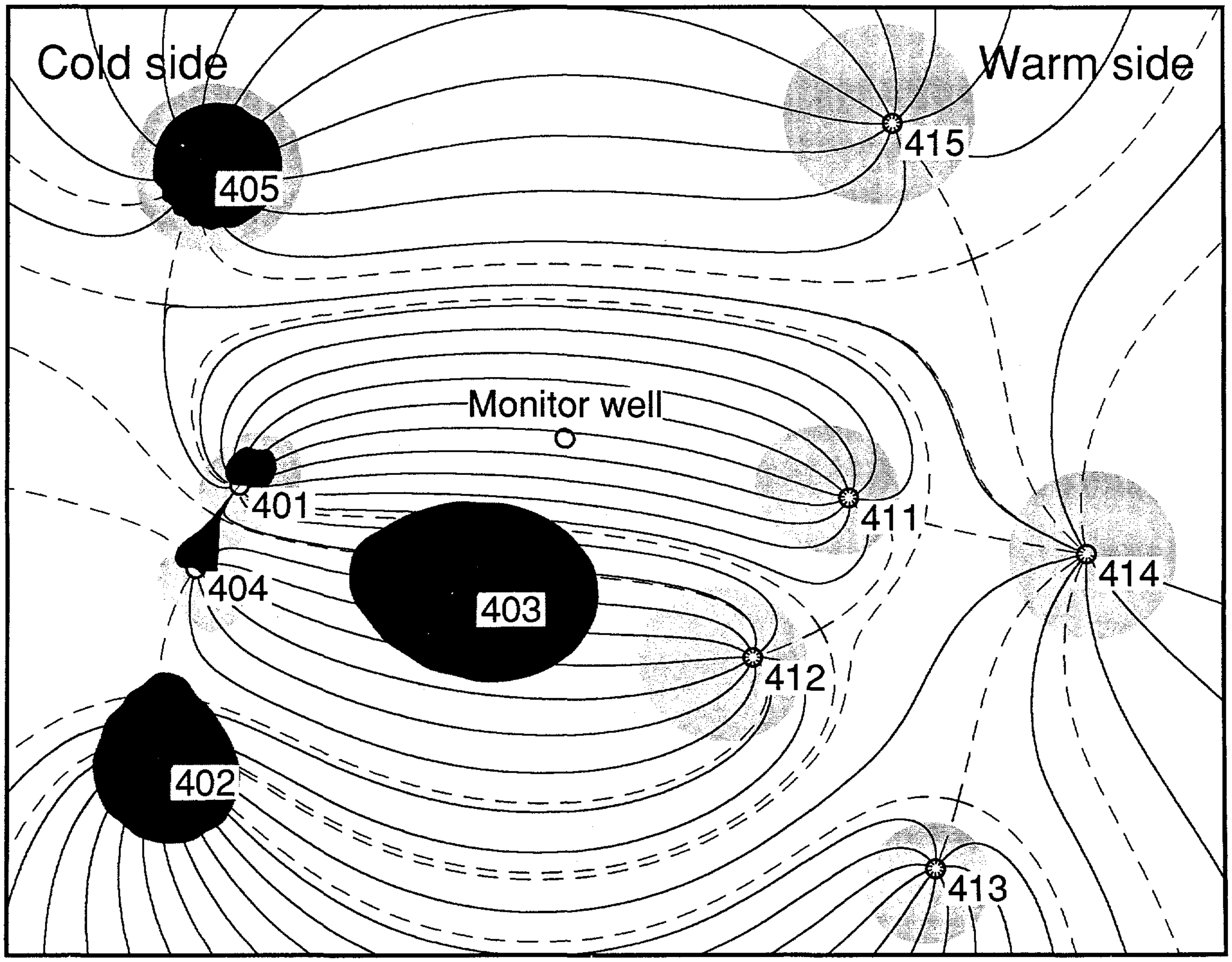
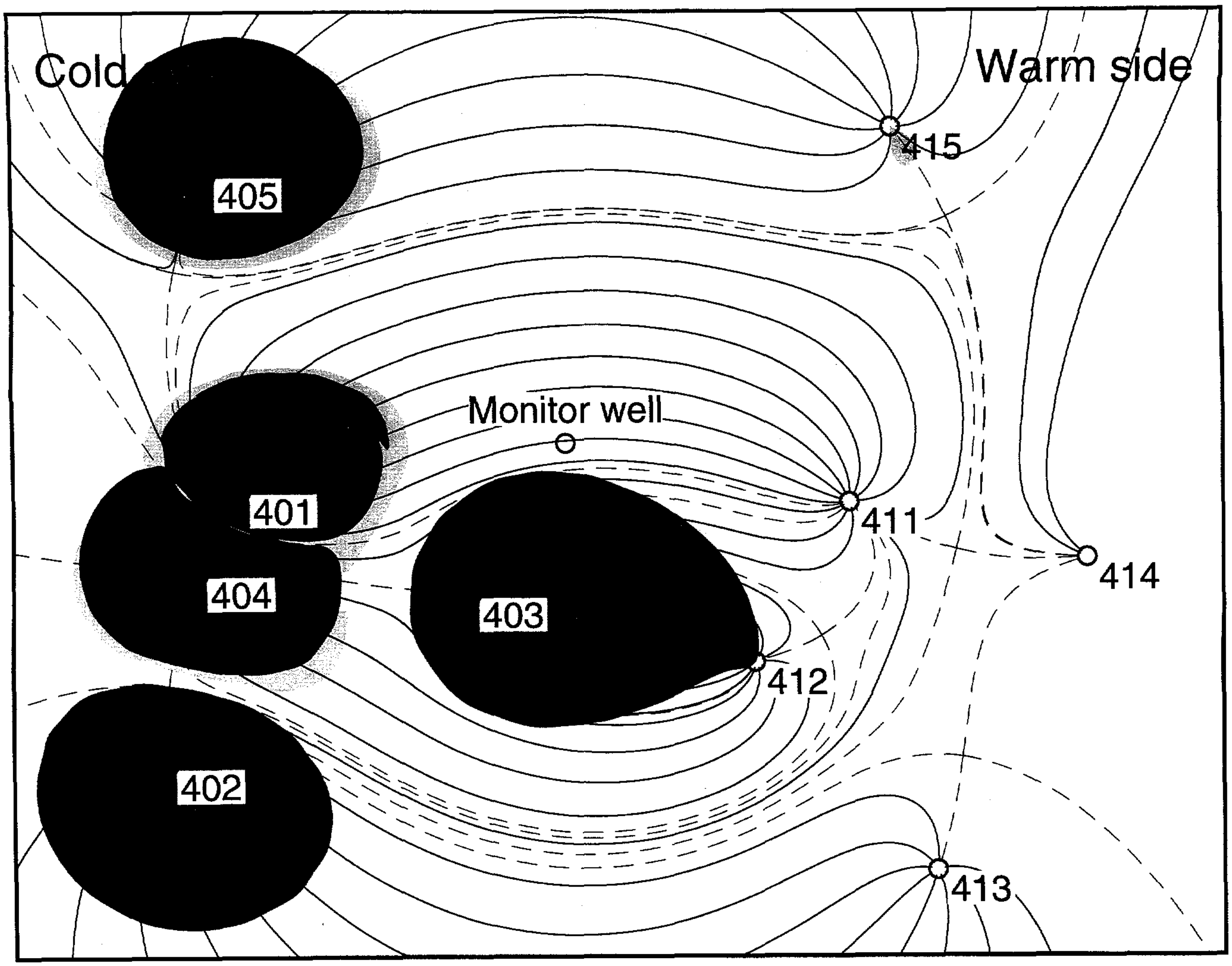



**Figure 1.** (Left) The well configuration in Lomma. The 'cold' wells 401-405 are to the left and the 'warm' wells 411-415 are to the right. The distances between the wells is well over 100 metres. The distance between well 403 and well 412 is 217 metres.

**Figure 2.** (Below) A CONFLOW simulation of the Lomma system. The horizontal cross-section of the aquifer shows the thermal fronts (shaded areas) after nearly two years of simulation (two winters and two summers). The fronts on the warm side were created during the summer of 1992. The dark fronts on the cold side are form the winter of 1992 and the lighter fronts are from the winter of 1991. The nearly circular shape of some of the thermal fronts means that the wells do not interact that much. Notice also that water injected into well 404 has been drawn into well 401. The solid lines are streamlines and the dashed lines are stagnation lines.





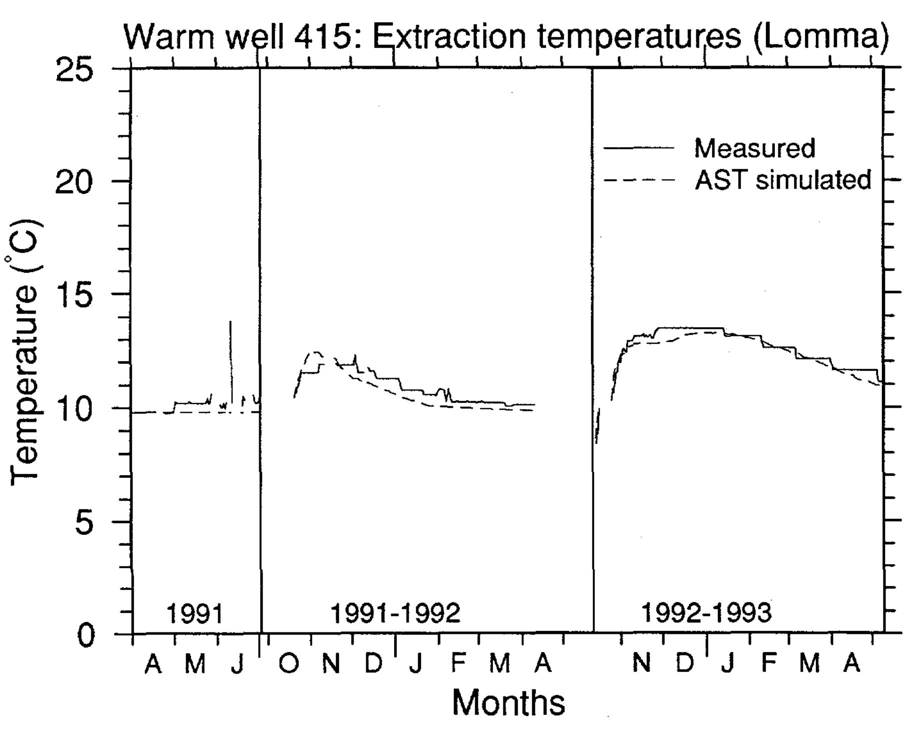




**Figure 3.** (Above) The thermal extent in the aquifer after over two years of CONFLOW simulation (three winters and two summers). Three sets of cold fronts, formed during the last three winters (1991-93), can be seen. There is a trace of a warm front near well 415. This CONFLOW simulation is a continuation of the simulation shown in Figure 2. During the winter of 1993, warm water was extracted from the warm wells, decreasing the size of the thermal fronts on the warm side, and cold water was injected into the cold wells increasing the size of thermal fronts there. Notice the partial thermal breakthrough in well 412. The solid lines are streamlines and the dashed lines are stagnation lines.

**Figure 4.** (Left) A comparison between measured and AST calculated extraction temperatures for the warm well 415. The fit is quite good during all three extraction periods (Winters of 1991 to 1993). This well is undisturbed by the other wells according to CONFLOW simulations.

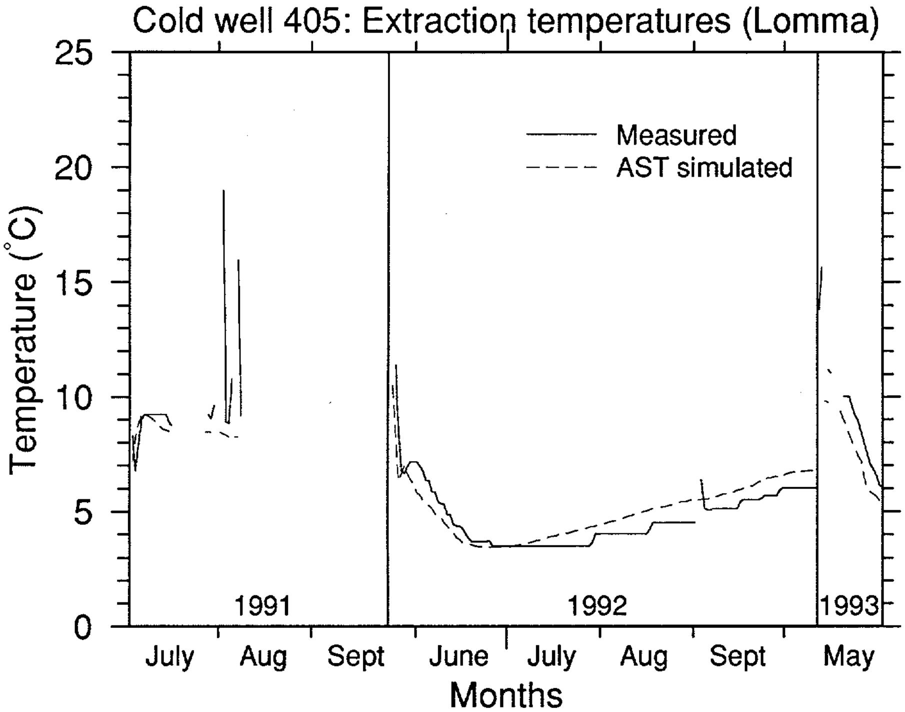



**Figure 5.** (Left) A comparison between measured and AST calculated extraction temperatures for the cold well 405. The fit is quite good during all three extraction periods (Summers of 1991 to 1993). This well is undisturbed by the other wells according to CONFLOW simulations.

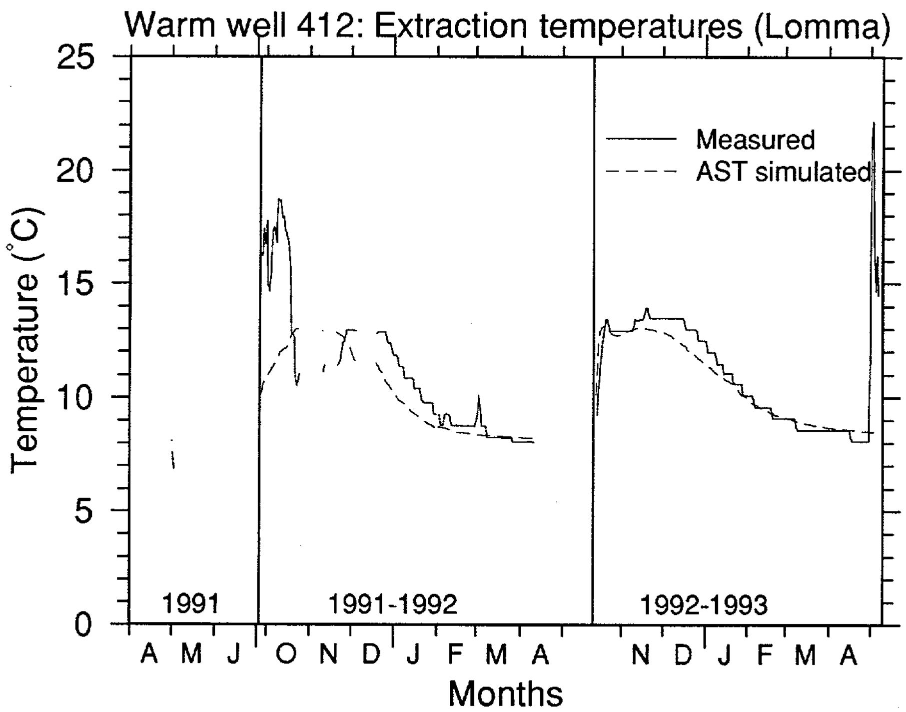



**Figure 6.** (Left) A comparison between measured and AST calculated extraction temperatures for the warm well 412. The fit is not bad but it is not as good as that of the two previous figures. This well is mainly disturbed by the cold well 403, according to CONFLOW simulations.

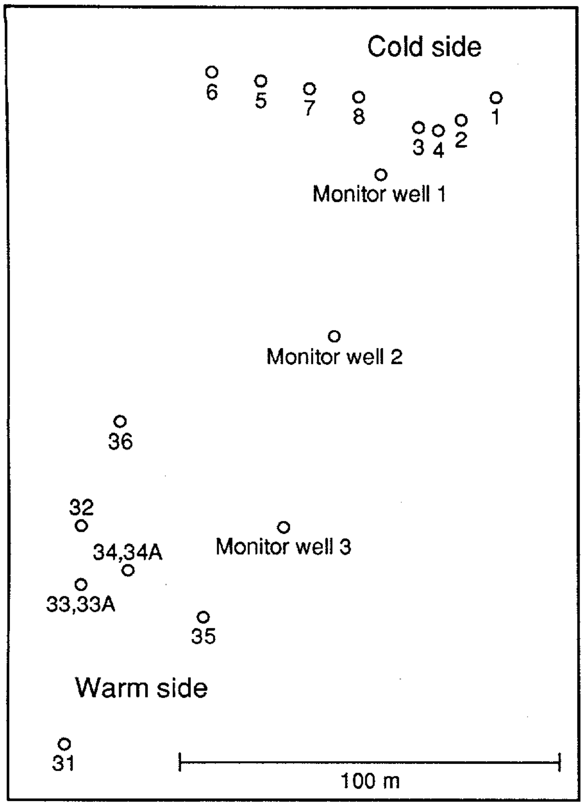
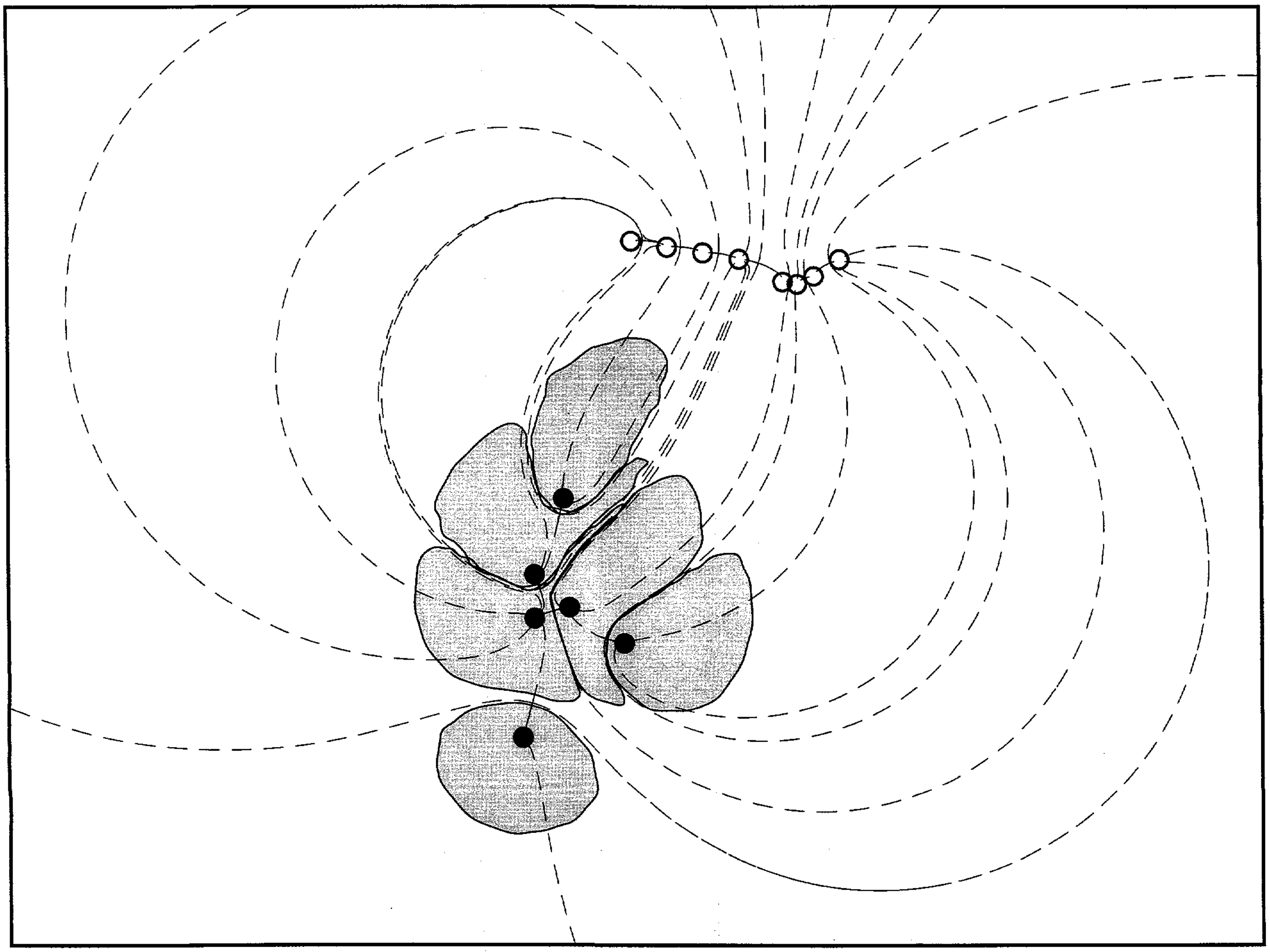



**Figure 7.** (Left) The well configuration in Malmö. The 'warm' wells are numbered 31-36 and the 'cold' wells 1-8. The distances between some of the wells is less than 10 metres. The distance between well 36 and well 6 is 95 metres.

**Figure 8.** (Below) A CONFLOW simulation of the Malmö system. The figure shows a horizontal cross-section of the aquifer. The shaded regions are the thermal fronts created by injecting warm groundwater into the aquifer during the summer. The irregular (non-circular) shape of the thermal fronts implies that the wells interact with each other. The dashed lines are stagnation lines. The intersection of two stagnation lines is a stagnation point. The groundwater flow in a stagnation point is zero. Notice that the groundwater flow pattern, indicated by stagnation lines, resembles the flow pattern of a doublet well system.



INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Aquifer Thermal Energy Storage In Atlantic Canada

• Frank Cruickshanks
Groundwater Hydrogeologist
Environmental Conservation Strategies Division (ECSD)
Environment Canada
Dartmouth, Nova Scotia, Canada

**ABSTRACT**

Since the late 1970's, a technology for conserving significant amounts energy using aquifers for storage, on a seasonal basis, has been developed in Canada, the USA, and several countries in Europe. In *Aquifer Thermal Energy Storage (ATES)* applications, waste *heat* and *chill* from commercial buildings or from power plants is *stored* in underground water bearing rock formations known as aquifers. The stored energy is used by withdrawing groundwater at the stored temperature, less normal losses or gains, for heating or cooling purposes.

The Environmental Conservation Strategies Division (ECSD) has taken the lead role for Environment Canada in developing national and international partnerships in order to research and develop Environment-Energy-Economy linkages; Environmental Assessment Procedures and an ATES Technological base.

This paper describes the nature of ATES and overviews ATES initiatives at several locations in Atlantic Canada.

## INTRODUCTION

An economically viable technology for conserving waste energy using natural aquifers for storage on a seasonal basis, has been developed in Canada, the USA, and several countries in Europe. In Aquifer Thermal Energy Storage, heat or cold is stored in relatively shallow water bearing geologic formations known as aquifers. Depending on aquifer characteristics, the addition of waste building heat or the supplemental cooling of aquifer water (groundwater) by exposure to ambient air in winter can be a practical seasonal storage.

The early application of aquifer-based energy applications in Canada involved groundwaters' direct use for space and process cooling. The gradual warming of some local aquifers gave rise to interest in the use of aquifer based heating *and* cooling to attempt to preserve thermal equilibrium and increase energy efficiency. The stored energy is recovered by withdrawing groundwater at the stored temperatures, which can range between 90° C and 4° C, depending on the heating and/or cooling application. In industrial applications, a 25 MW power plant can yield 50 MW of waste heat for thermal storage in aquifers. Recovering only half of the stored energy equals the original energy output of the power plant.

In commercial buildings groundwater can be used for space heating, ventilation air preheating, space cooling and process cooling (Figure 1). Augmenting ATES with such applications typically reduces energy costs by 50%.

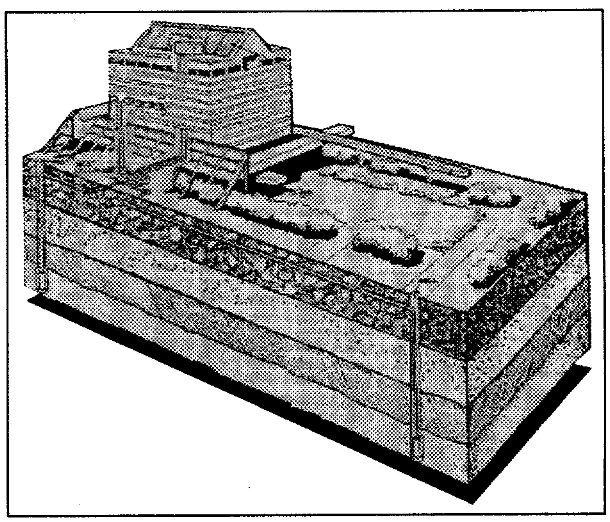


Figure 1: Scarborough Government of Canada Building.

Studies sponsored by Environment Canada and their partners, concluded that off-setting electrical energy usage with ATES can reduce atmospheric emissions from power plants by 70 % [1].

## BACKGROUND

### General

The use of energy storage in North America is being accelerated by time of use rates and peak shaving incentives. Electrical utilities are beginning to look at energy storage as one of the main elements of their peak load management programs. The growth of storage has been principally for cooling in commercial buildings and ground and groundwater source heat pumps for combined heating and cooling in residential buildings, presently there are approximately 35,000 such applications in Canada. However, it appears that even greater economic and environmental benefits can be derived from combined heat and chill storage in Aquifer Thermal Energy Storage systems.

The most promising application for ATES is in heating and cooling of commercial and industrial buildings. In Canada, the average daily temperature ranges from 30°C in summer to below -20°C in winter. Therefore, all commercial buildings require heating in winter and cooling in summer. Storage of excess heat for use in winter, and storage of cold for cooling in summer allows for large reductions in purchased energy demand, and more importantly, in peak power demand.

The application of ATES can be very cost-effective, depending on site-specific parameters and load characteristics. A review of 55 commercial projects in four countries showed that there is growing interest in this type of application [2]. Since buildings which use ATES systems decrease the need for conventional energy, the goal of demand side managementespoused by Canadian utilities can be met. Waste heat from industry, incinerators, and thermal power plants can also be stored (Figure 2). A power plant yielding 25 MW per hour of electricity and operating at 30% efficiency, would yield 50 MW per hour of waste heat to ATES; and incinerators, that are not in combination with electricity production, would offer significant advantages for thermal energy storage from pure heat production. Moreover, when properly, conceived and designed, ATES is environmentally beneficial.

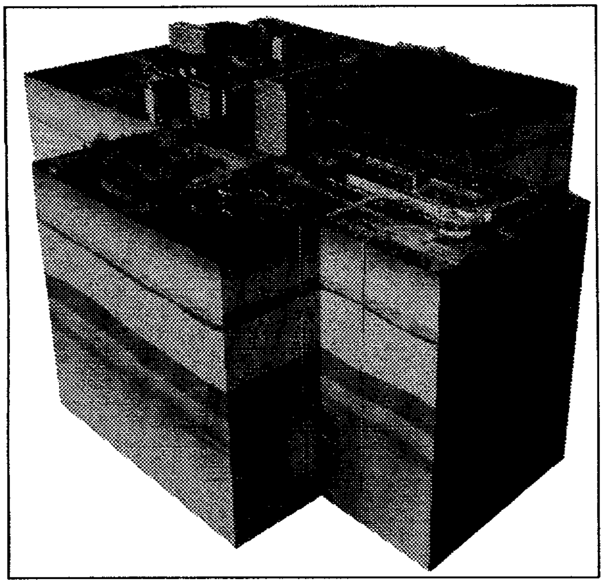


Figure 2: Schematic of University of Utrecht High Temperature ATES Plant - 90°C Heat Storage

The aquifer's groundwater is not exposed to contamination in the closed ATES system, and there is no net addition or removal of groundwater from the aquifer. However, *the* most important factor in ATES is the subsurface environment, which must be properly assessed and taken into account in the systems design. Therefore, to mitigate against undesirable environmental impacts, ATES systems require an extensive analyses of geology, hydrogeology, water chemistry and microbial activity. The benefits to be derived from *Energy Conservation through Energy Storage (ECES)* include:

* greater energy and water conservation compared to conventional earth energy systems;
* demand side management for utilities;
* reduced emissions of greenhouse gases from the combustion of fuels;
* direct cooling of commercial buildings with groundwater in a post-CFC world;
* more economical district heating from seasonally stored thermal energy in aquifers;
* increase competitive advantages for industry and consumers energy savings;
* and increased global opportunities for environmental industries in ATES niche markets.

The main barriers to ATES use are its potential for higher initial capital cost, lack of ATES awareness by the professions and the public at large, and the general suspicion of that which is not already common.

## Rationale for Organizational Involvement in ATES

Aquifer Thermal Energy Storage is of interest to federal government departments such as Environment Canada (EC), Public Works and Government Services Canada (PW&GSC) and Energy, Mines and Resources (EM&R) Canada. Cooperation among between these three federal departments is carried out through Memorandums of Understanding (MOU's) concerning activities in groundwater, energy and the environment. There is also increasing interest in ATES from provincial government departments, institutions and from non-government agencies. As well, the reasons for supporting ATES and the form that support takes varies considerably among the supporters.

Using the Sussex Hospital ATES pilot plant as an example, it is evident that project funding is based upon different perspectives of the various contributors. The Sussex Hospital and Health Centre, from an institutional point of view, wishes to become as energy efficient as possible for obvious financial reasons. The hospital would also like to replace their large, expensive, CFC-dependent cooling systems with groundwater. This in turn will allow the hospital to comply with new federal laws to ban the use of CFC refrigerants such as R11, by the end of 1995.

Federal and provincial environment departments wish to promote optimum sustainable use and stewardship of natural resources, such as groundwater and air, while simultaneously promoting energy conservation and stimulating economic activity. The Panel on Energy Research and Development (PERD), a federal funding agency, is interested in environmentally sustainable energy efficiency for reasons of energy security, thus they wish to develop several hydrogeologically diverse ATES sites in order to investigate experimental ATES water treatment technologies.

The electrical utilities, which are a mix of crown and private corporations, need to reduce $CO_2$ emissions for regulatory reasons. However, they also need to keep their operating costs and utility rates as low as possible in order maintain a reasonable return on investments and a healthy domestic economy. The electrical utilities in Canada agree that underground thermal energy storage (UTES) technologies such as ATES are "cleaner", relying on renewable energy sources, and have Demand Side Management (DSM) potential to displace significant amounts of energy that would normally be produced by "dirtier" technologies, such as burning fossil fuels. ATES also presents a significant business opportunity that is consistent with the principles of sustainable development [3]. Expanding on this theme of "ATES rationale" from Environment Canada's perspective only, it is evident that the department is interested in ATES in terms of both the potential environmental benefits from proper application of the technology and the possible detrimental effects from improper applications.

From a non-regulatory sustainable development perspective, less expensive energy supports development. ATES utilization, done properly, is sustainable. Acceptance of ATES technology will therefore, enhance the fledgling earthenergy industry, including heat pump manufacturers, the well drilling industry, and hydrogeological and mechanical engineering consultants for site and building assessments, as well as environmental planners and other specialists involved in community-based ATES applications. Financial benefits are already beginning to accrue to this region through the export of earth energy systems to the United States, and Environment Canada's small role in this has been acknowledged [4].

From a Federal Water Policy perspective, reference is made to several areas germane to ATES activity including:

- Groundwater Contamination (possible with poor ATES practices)
- Water Use Conflicts (water management)
- International Water Relations (Canada is a participant in International Energy Agency (IEA) activities, which include the Implementing Agreement (IA) on Energy Conservation through Energy Storage).
- Research Leadership (Environment Canada's activities include applied research in demonstrating the usefulness of ATES.)
- Technological Needs (further research, which is being carried out by ECSD, into water treatment technologies and computerized screening and decision tools for environmentally beneficial implementation of ATES is necessary for the sustainable application of the technology).

ATES utilization will also be scrutinized under the new Canadian Environmental Protection Act (CEPA), and under Canada's *Green Plan*, the Federal Government has promised to "... publish a series of guidelines and codes of practice to help local authorities deal with groundwater problems". Therefore, with impetus from both the Green Plan and the CEAA, and support from PW&GSC, EM&R, the IEA, the Canadian Electrical Association (CSA), the Canadian Standards Association (CSA) and others, ATES Environmental Assessment Procedures (ATES-EAP) are being developed. The ATES-EAP will, over time, be expanded to include other kinds of Underground Thermal Energy Storage (UTES) technologies.

### Overview of ECSD Activities in ATES

The Environmental Conservation Strategies Division (ECSD) in Dartmouth, Nova Scotia, has taken the lead role in ATES for Environment Canada (EC). The division has been continuously promoting sustainable development concepts prior to its involvement with ATES and is motivating others towards reaching common environmental goals. ECSD has moved beyond the traditional relationships of government control to true partnerships with other parts of government, the institutional and private sectors. For example, ECSD has provided "seed" money for ATES partnership development, with funds from the Canada Water Act (CWA).

The CWA, allows the Federal Government to pursue research and other studies in waters of significant national interest. The leveraging of CWA funds has in turn allowed ECSD to develop numerous integrated partnerships which support ATES activities in Atlantic Canada and elsewhere.

Cash and in-kind contributions have been forthcoming from Environment Canada's Green Plan; the Panel on Energy Research and Development (PERD); the Federal/Provincial Water & Economy Agreements; the Province of New Brunswick through the Departments of the Environment, Supply and Services, and Natural Resources, and the New Brunswick Environmental Trust Fund (ETF); the New Brunswick electrical utility, NB Power and the Canadian Electrical Association (CEA) have also contributed financial and in-kind resources; other federal government departments are involved, such as Public Works and Government Services Canada (PW&GSC) and Energy Mines & Resources (EM&R); vital technology transfer has occurred through international accords and subsequent cooperation agreements with other nations under Annex 6, 7 and 8 of the International Energy Agency (IEA) Implementing Agreement on Energy Conservation through Energy Storage (IA-ECES); Memorandums of Agreement (MOAs) have also been signed between Environment Canada and the Nova Scotia Agricultural College (NSAC) and the Sussex Hospital in New Brunswick; support has also been forthcoming through cooperation with the Sussex Town Council, Strata Engineering Corporation, Adsett & Associates Limited and the Canadian Standards Association (CSA).

To this end, ECSD has sponsored studies to develop a framework for ATES guidelines development and to assess the economic and environmental feasibility of ATES in Canada. ECSD has also participated in Annex 6 research, on the chemical and environmental aspects of ATES, under the aegis of the IEA.

Activities in Atlantic Canada include further research and development of new two new and promising water treatment methods that were initially identified under Annex 6 of the IEA Thermal Storage Implementing Agreement. These treatments prevent problems due to the precipitation of carbonates, iron and manganese, without the addition of undesirable chemicals to the groundwater, in hard water and high temperature (>40$^0$C) thermal storage applications. Being further developed is the $CO_2$ treatment system to control pH and prevent calcite scaling, and the reactor fluidized bed heat exchanger (RFBHE) to promote the deposition of calcite on sand grains within the reaction column.

An Earth Energy Suitability Assessment Model was developed using a Geographic Information System (GIS) to determine capabilities for implementation of Earth Energy Systems (EES) employing Groundwater Source Heat Pumps (GWSHP). The assessment model was developed for EES screening on a regional basis and is an adaptation of existing models which include those which have been used to classify and target areas for groundwater source heat pump (GWSHP) use; to determine minimum distances wells should be spaced in twin-well recharge systems; to quantify land use; and to provide methods for hydrogeological mapping.

The concept of ATES integration into planning activities at the community level is also being advanced. The planning and design of community oriented ATES applications will require the development of screening and sensitivity mapping systems. The best tool for such activities are GIS. Environment Canada, which has employed GIS technologies for many years, is presently embarking on the development of a Groundwater Information Desktop Mapping Application (GIDMA) from existing data bases, using inexpensive and user friendly desktop mapping software.

ATES feasibility studies are being conducted for the Agricultural College in Truro, Nova Scotia and the Westviking College, in Cornerbrook, Newfoundland. Energy R&D and technology transfer will be important aspects of the work undertaken at these institutions.

Through the partnerships developed by ECSD, the development of a Community-based ATES project under way in Sussex, N.B. The Regional Hospital Complex is being converted to ATES, energy cost savings will be at least 50 % [5]. Over time, various earth energy projects and technologies will be integrated with the local water supply protection program.

Most recently, ECSD has assissted in developing a five year international work sharing arrangement under the auspices of Annex 8 of the IEA, Energy Conservation through Energy Storage (ECES) Implementing Agreement (IA). Annex 8 aims to speed the introduction of UTES in the building, industrial and agricultural and aquaculture sectors.

These activities are expected to encourage the integration of various earth energy technologies into municipal environmental programs, and will make knowledge of thermal storage technologies more readily available to universities, the utilities, engineering groups, energy experts and environmental managers.

In light of the above, the goals of Environment Canada are to assist potential ATES users and regulatory agencies in the sustainable application of this emerging conserver technology. In promoting sustainable ATES three general conditions must be met, including; *no net consumption of the groundwater supply, maintenance of groundwater quality, and thermal balancing of ATES aquifers.* Long term strategies to meet these criteria, include:

1) The incorporation "ATES Guidelines" into sound environmental planning at the community level;

2) Identification and incorporation of linkages between the economy, environment, and technology into ATES strategic planning;

3) Advancement of ATES as a standard design option through the implementation community oriented research, development and demonstration.

4) Deployment of a Geographic Information System (GIS) for Community-based ATES Environmental Screening and Decision Support.

## ATES INITIATIVES IN ATLANTIC CANADA

### ATES Economic Assessment

Under the terms of a water/economy agreement between the Province of New Brunswick and the Government of Canada, a study was commissioned to develop a framework for the economic and environmental assessment of ATES technology in Canada [11]. The purpose was to relate existing experience with ATES, to the current Canadian situation with respect to the opportunity for utilizing aquifer storage for low-temperature heating and cooling applications.

To assess the cost and performance of ATES applications, the cost and energy performance of ATES systems were compared to conventional reference systems. Detailed analyses were performed using low, high and average costs. Discussed here are the results of the average costs. Cost parameters for ATES configurations depend on location generally due to weather, energy pricing, groundwater depth(s) and well-drilling costs that are site-specific. The costs used in this study reflect the most probable regional conditions in the Prairie, Central and Atlantic regions of Canada.

Both heating and cooling were considered and the most common and economically available fuel for heating was used as the "reference". The lowest cost fuels are oil in New Brunswick and natural gas in Ontario and Manitoba. Energy cost assumptions used in the analyses are given in Table 1.

**Table 1. Energy/Fuel Cost Assumptions For Economic Analyses**

| Province | Energy/Fuel Type | |
|---|---|---|
| New Brunswick | Oil $8.00/GJ | Elec. $16.00/GJ |
| Manitoba | Gas $6.00/GJ | Elec. $13.60/GJ |
| Ontario | Gas $6.00/GJ | Elec. $11.20/GJ* |

**(Canada/New Brunswick Water and Economy Agreement Data, 1992)**

The study found that commercial ATES systems were economically more attractive than were conventional energy systems in the three locations in Canada examined, even for discount rates of 4, 8 and 12% (Table 2). Energy/fuel cost results which were given in terms of delivered energy in cents per kilowatt hour (c/kWh), using conventional heating costs as a base for comparison purposes. Manitoba and New Brunswick show the greatest economic benefit due to the fact that electrical rates in Ontario are much less than in the other two provinces. However, the Ontario situation has changed, with an upward revision of the average electrical energy cost from $11.20/GJ to $20/GJ*. Further electrical rate increases equalling approximately 20% in Ontario and 5% in New Brunswick were announced this year.

**Table 2. Cost of delivered energy (c/kWh) - Commercial Building**

| | Conventional Energy | | | A T E S | | |
|---|---|---|---|---|---|---|
| **Province** | **N.B.** | **Ont.** | **Man.** | **N.B.** | **Ont.** | **Man.** |
| **Discount Rate** | | | | | | |
| 4% | 5.1 | 4.7 | 4.4 | 4.2 | 4.0 | 3.7 |
| 8% | 5.4 | 5.0 | 4.7 | 4.4 | 4.3 | 4.0 |
| 12% | 5.7 | 5.3 | 5.0 | 4.8 | 4.7 | 4.4 |

**(Canada/New Brunswick Water and Economy Agreement Data, 1992)**

## ATES Environmental Assessment

The methodology used to determine the environmental benefits of a reduction in generation of electricity were based on data for amounts of emissions, per kWh, of $CO_2$, $NO_x$, and $SO_2$. Benefits for New Brunswick and Manitoba have been calculated taking into consideration the appropriate energy production mix in these provinces (Table 3). The data used to quantify the impacts of displacing conventional electrical energy was based on " Emission Factors for Greenhouse and Other Gases", EMR (1990) [6].

**Table 3. Comparison of annual emissions for commercial building applications - (tonnes)**

| Province and Heating Mode | $CO_2$ | $NO_x$ | $SO_2$ |
|---|---|---|---|
| **Reference Case** | | | |
| New Brunswick (Oil) | 1204 | 1.2 | 8.0 |
| Ontario (Gas) | 752 | 1.3 | 3.9 |
| Manitoba (Gas) | 449 | 0.43 | 0.07 |
| **ATES** | | | |
| New Brunswick | 731 | 0.9 | 9.1 |
| Ontario | 413 | 1.1 | 4.9 |
| Manitoba | 35 | 0.09 | 0.08 |

**(Canada/New Brunswick Water and Economy Agreement Data, 1992)**

There is a clear environmental benefit in all three provinces resulting from conversion to, or the use of, ATES systems for commercial buildings. Reductions in $CO_2$ emissions range from 39% to 92%; reductions in $NO_x$ range from 10% to 78%, with an insignificant increase in $SO_2$ levels in all three provinces. The replacement of fossil fuels with ATES in commercial buildings in New Brunswick and Ontario would result in slightly higher levels of $SO_2$ emissions (1.0 tonnes each) than in Manitoba (0.01 tonnes). However, reducing the use of electricity in commercial ATES applications always reduces air emissions.

## ATES Developments Using GIS

GIS stands for Geographic Information Systems, computer systems which are designed to organize an analyze statistical information relating to geography. In GIS applications, standard computer processing is taken one step further by processing data and relating the resulting output to real geographic locations. GIS combines database management and statistical analysis with computerized mapping and image processing to create a powerful tool for use in *spatial data analysis*, the analysis of data with a spacial dimension.

A Geographic Information System was used to develop an earth energy suitability assessment model for the Town of Amherst, Nova Scotia [7] (Figure 3).

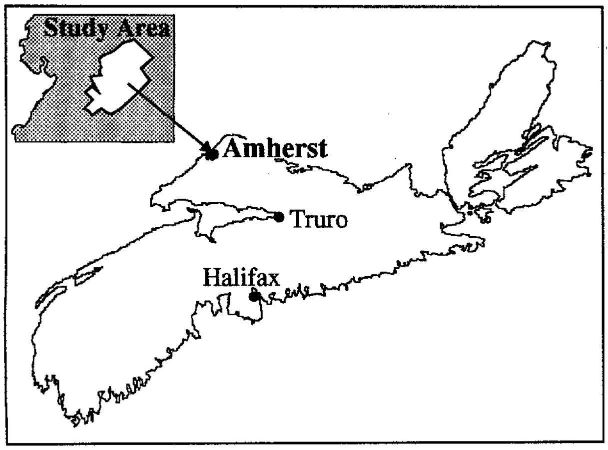



Figure 3: Study Boundary - Amherst Earth Energy GIS.

The model helped determine a planning approach for implementing residential earth energy systems employing groundwater-source heat pumps (Figure 4). The study area was a 10 km² region of northern Nova Scotia with the Town of Amherst located roughly at its centre.

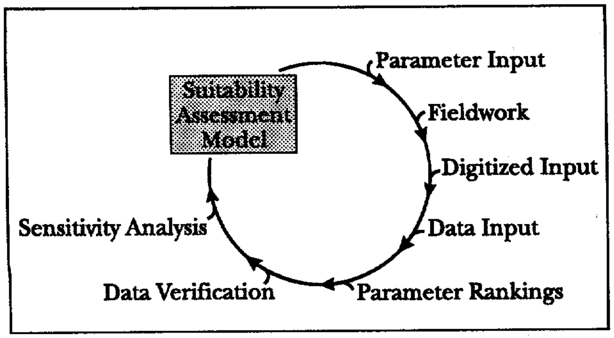



**Figure 4: Depiction of GIS Planning Process.**

Parameter data were compiled, relational and spacial data basis were developed and GIS analysis using Spatial Analysis System (SPANS) was performed to determine suitability and minimum well spacings required for twin-well earth energy systems at the pumping rates of 0.076 and 3.78 litres per second.

The model consists of parameters which were selected in consultation with a Project Advisory Committee. Parameter Importance Values (PIU), or weighting factors, were applied to each of the variables (Table 4), with the value of 20 being the highest. Parameters included groundwater availability, aquifer potential, static water levels, groundwater temperatures, groundwater chemistry relating to its corrosive/encrusting potential, soil drainage and topography.

**Table 4. Parameter Importance Values for Earth Energy Suitability Model (After Aquifers)**

| PARAMETER | PIU |
|---|---|
| GROUNDWATER AVAILABILITY | 20 |
| AQUIFER AVAILABILITY | 20 |
| DEPTH TO WATER LEVEL | 15 |
| GROUNDWATER TEMPERATURE | 5 |
| GROUNDWATER CHEMISTRY | 5 |
| SOIL TYPES | 5 |
| TOPOGRAPHY | 5 |

A cursory review of all parameter themes rolled-up into one map shows that 68% of the study area ranked as ideal or good for implementing earth energy systems (Figure 5). Similar maps were generated for minimum well spacing requirements. The results for twin-well systems pumping at a rate of 0.76 l/s and 3.78 l/s were between 15 to 30 metres and 30 to 60 metres, respectively.

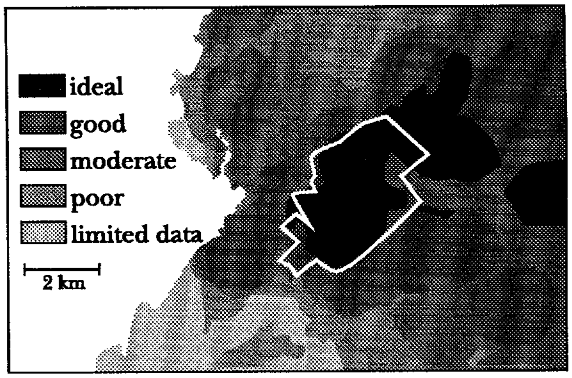



**Figure 5: Earth Energy Suitability Map.**

In 1988 a comprehensive inventory of all 47 municipal groundwater supplies and an analysis of the susceptibility to contamination of each well site was conducted in the province of New Brunswick [8]. The large body of knowledge which was produced is currently only available on hard copy. The utility of this information, in terms of availability, speed of access, ease of maintenance and updating, data manipulation and analysis, and the variety of products available, such as community-based environmental screening, would be greatly enhanced if the information were in a suitable electronic format. Therefore, a GIS Groundwater Information Desktop Mapping Application (GIDMA), based on inexpensive and user friendly desktop mapping software will be developed.

The GIS package will contain regional scale summary data on groundwater supplies for 47 New Brunswick communities and one Indian Reserve, as well as detailed information for each community. The application will include base maps, water quality data, well locations and hydrogeological characteristics, development pressures as well as interpretive products based on the raw data, scanned images and photographs, text files and documents.

A Desktop Mapping User Interface will be developed for the GIDMA application which will provide the user with help menus, data inventories, contact lists and other information that will enhance the utility of the application. The final product, which will take approximately six months to complete, will include all GIS databases, base maps and modelling products produced during project development.

Environmental screening and sensitivity analysis could then be performed using the data files in the GIS, which can be used to set the initial conditions for modelling and model runs. The results generated by the model(s) would be calibrated using the available data sets, and the model results could be critically analyzed by updated data. Since the GIS is capable of generating a digital terrain model (DTM), the effects of the terrain would be directly incorporated into any model, at what ever scale is required.

### The Sussex Hospital Pilot Plant

The Sussex Health Centre, which is located in Sussex, New Brunswick, Canada, is implementing Aquifer Thermal Energy Storage into a Hospital, Medical Centre and Nursing Home complex [9](Figure 6). Much of the required equipment, including the water wells and various interfaces have been installed. Total investment in the project is estimated to be $800,000.00, however, approximately half of this amount is for research and technology transfer.

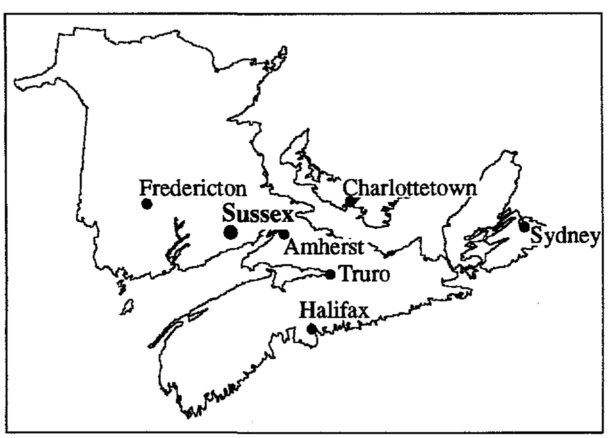



Figure 6: Town of Sussex Location Map.

The Sussex Hospital, which uses electricity as its only energy source, occupies a floor space of 7,500 m$^2$. An addition to the Hospital increased its size by 1,000 m$^2$, the addition is referred to as the Hospital Extension. The Nursing Home, which uses #2 fuel oil for heating, has a floor area of 3,000 m$^2$. Construction of a 1,300 m$^2$ Medical Centre was commissioned in May 1994 (Figure 7).

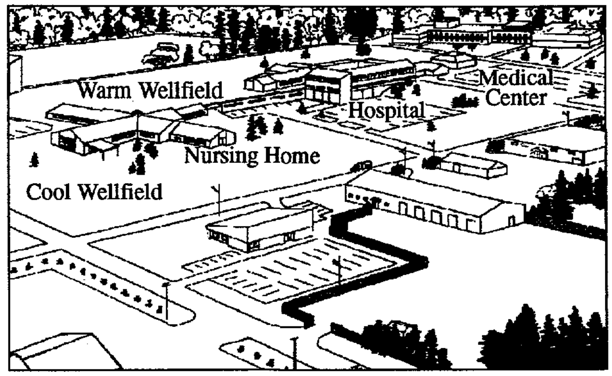



Figure 7: Sussex Hospital ATES Complex and Well Fields.

The Medical Centre, which has zonal air conditioning, uses 21 water source heat pumps to transfer energy to and from the aquifer. Total energy consumption for the Hospital is 3.5 X 10$^6$ kW. Of this amount, approximately 800,000 kW's is used for air preheat. It is this consumption that the ATES system will reduce during the heating season. Annual life cycle cost savings of approximately $86,000 are anticipated due to an energy consumption reduction of 1,100 MWh (Figure 8) and an electrical demand saving of 450 kW.

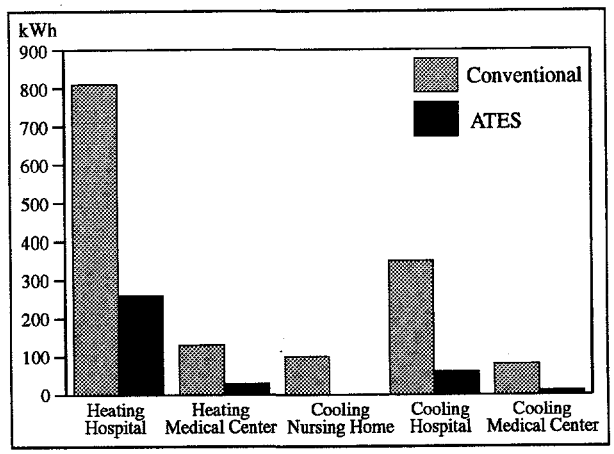



Figure 8: Conventional Versus ATES Energy Use in the Sussex Hospital Complex.

Extensive monitoring will be undertaken to determine energy consumption and demand savings, and subsurface environmental conditions. Automated monitoring will be performed by a data acquisition and control program developed by the project engineer.

There are two well fields, one cool and one warm, located on either side of the complex. In the first year of ATES operations groundwater is being transferred from the cool well field to the warm well field during the cooling season. It is intended to reverse this process during the heating season in November 1994. Final temperatures for the cool and warm well fields are projected to be 6$^0$C and 14$^0$C, respectively.

## ATES Feasibility Studies

It is proposed to first develop a groundwater cooling application, and later, an ATES heating and cooling application utilizing the aquifers underlying the Fisher Institute in Cornerbrook, Newfoundland (Figure 9). Preliminary site investigations indicates that the bedrock underlying the Fisher Institute may be suitable for ATES applications, however, no drilling or testing has taken place as yet.

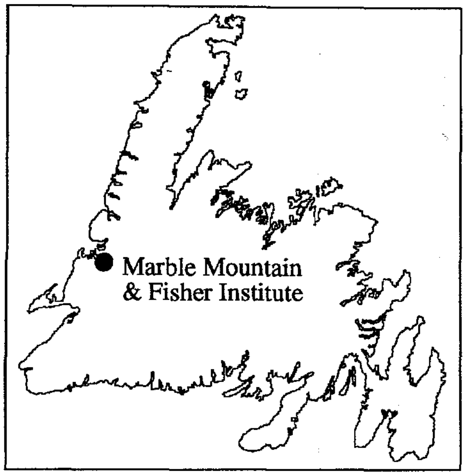



Figure 9: Location Map of Fisher Institute and Marble Mountain, Newfoundland

Discussions with representatives from the Fisher Institute and The Newfoundland department of Works, Services and Transportation indicate that plans are being developed to retrofit their existing energy systems. There may also be also be further building development on the site in the next two or three years. There is an immediate need for cooling in the existing facility, which has a floor space of approximately 10,000 $m^2$. A thermal warm store would be developed for use in the proposed new building.

Preliminary discussions concerning ATES have been held with the operators of the Marble Mountain Ski Resort in Cornerbrook, Newfoundland. Over the next several years the ski resort will be transformed into an all season resort with a new children's centre, base lodge, hotel and approximately 150 town houses and chalets (Figure 10). Early indications are that thick overburden deposits of sand and gravel underlie this site.

In order to transfer technology to Newfoundland, conceptual ATES design work would be performed in agreement and in close cooperation with the local consultants.
As well, detailed design work would be undertaken by local consultants.

An ATES pre-feasibility study has also been undertaken at the Nova Scotia Agricultural College (NSAC), where there are thirty-five buildings located on campus [10](Figure 11). The study centred on an evaluation of the energy efficiency of the heating and cooling systems at the college. The methods of heating, cooling and waste heat management were investigated and evaluated for possible integration with ATES. The study also looked at the best location for installing modified pilot scale versions of the Reactor Fluidized Bed Heat Exchanger and the $CO_2$ water treatment systems.

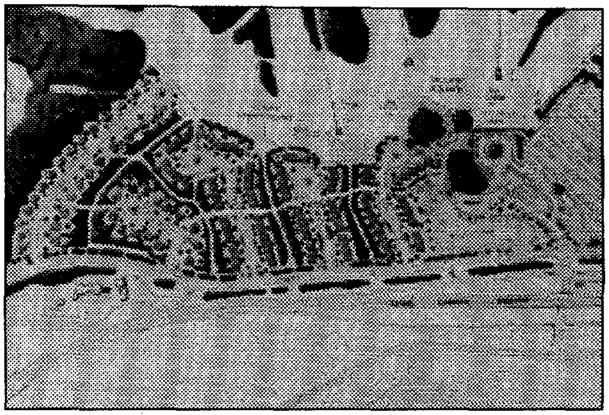


Figure 10: Plan View of Proposed Marble Mountain Development.

A Central Heating Plant (CHP) supplies steam to almost half of the campus buildings, while electricity is utilized in heating a few of the smaller complexes not incorporated into the central heating scheme. Electricity is also used in many of the larger buildings requiring air cooling units. Moreover, there appears to be s significant amount of groundwater used in chilling applications, which is eventually discharged into the store water system as warm water. Among other measures, efforts will be made to alleviate the problems and inefficiencies associated with discharging this groundwater to waste.

## ATES Water Treatment Technologies

Scaling in heat exchangers and piping systems due to the precipitation of carbonate minerals is of concern in high temperature ATES systems [11]. As part of the International Energy Agency Implementing Agreement for a Programme of Research and Development on Energy Conservation Through Energy Storage - Annex VI "Environmental and Chemical Aspects of Thermal Energy Storage in Aquifers and Research and Development of Water Treatment Methods" the Dutch and German working groups developed two new water treatment methods for the prevention of this scaling.

The German team investigated $CO_2$ treatment (CO2 TREATMENT) to control pH and prevent calcite scaling, while the Dutch team developed a reactor fluidized bed heat exchanger (RFBHE) to promote the deposition of calcite on sand grains within the reaction column. However, both systems were tested only on a limited basis and neither system is generally available for use, at least in the North American market place.

It is intended to evaluate, and to modify as required, these two promising ATES water treatment methods for use in high temperature heat storage applications. (Figures 12 and 13). Both systems will be designed, fabricated and pre-tested

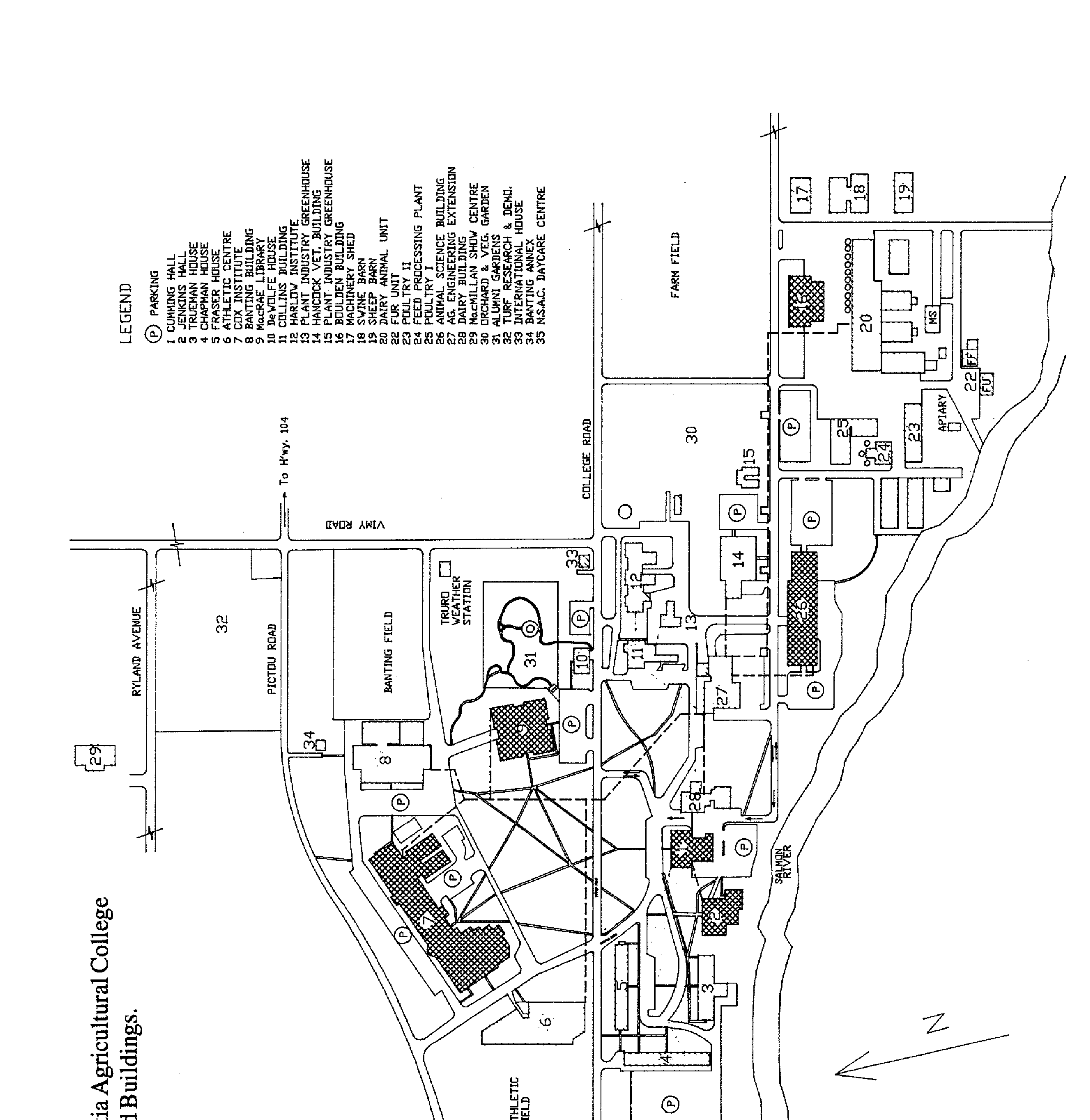



Figure 11: Plan View of NSAC Campus and Buildings.

at the Nova Scotia Agricultural College (NSAC), in Truro. NSAC has the facilities, technicians and researchers available for the purpose.

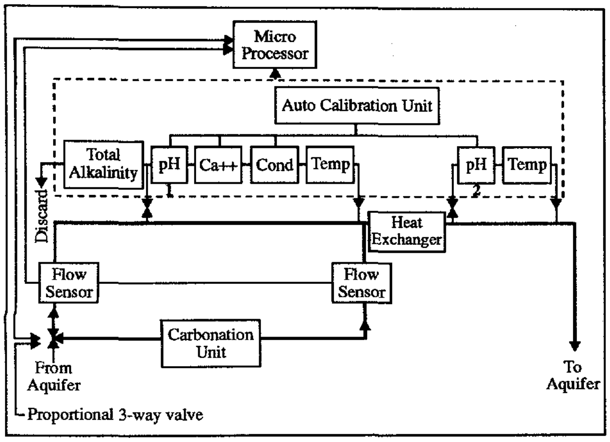



Figure 12: Schematic of Modified $CO_2$ Treatment System

The Banting Building, which houses the NSAC Agricultural Engineering Department and technology support staff, will likely be the site of the ATES water treatment test facilities. This building has several large mechanical and construction shops. In addition, the required steam and water lines are present and would require minimal modification to incorporate into the pilot project. Technology transfer will also be facilitated by placing the ATES water treatment test facility at NSAC, which can use this project as a teaching aid.

Two aquifer types will be selected and hydrogeologically characterized for use in conducting field trials of the RFBHE and the CO2 TREATMENT systems, one aquifer will be located at NSAC and the other at the Sussex Hospital, in New Brunswick (Figure 14).

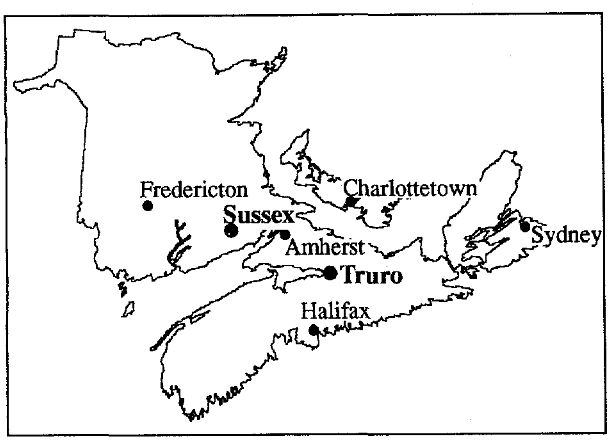



Figure 14: Proposed Test Sites for ATES Water Treatments.

The Weldon Formation, a bedrock aquifer in Sussex, N.B., has been hydrogeologically evaluated, and for one year will be monitored under low-temperature ATES conditions. Field testing of one or more of the anti-scaling water treatment system will be undertaken in 1995/1996, once ambient subsurface chemistry and thermal conditions at the Sussex site are reasonably understood. The other test site at NSAC will under go detailed hydrogeological testing in 1995/1996.

**IEA-Implementing Agreement Activities**

Environment Canada, through ECSD, and PW&GSC have recently negotiated a new IEA collaborative agreement as part of the ECES-IA. Annex 8 "Implementing Underground Thermal Energy Storage Systems (UTESS)" aims to conserve energy and improve the environment by speeding the introduction of UTES into the building, industrial, agricultural and aquaculture sectors. Annex 8 will encourage the adoption of energy storage in standard project designs by developing procedures and tools based upon documented applications in various energy efficient systems. Screening and decision tools will be provided to ensure ecologically sensitive UTES applications.

The following are specific objectives of Annex 8,

a) Document and disseminate in a suitable format the emerging underground thermal energy storage technologies and their applications in various energy efficient system applications;

b) Identify the project characteristics and boundary conditions within which UTES is technically and financially feasible and disseminate these requirements in easily understood formats suitable for specific target audiences;

c) Ensure that UTES is developed in an environmentally sensitive manner by documenting the environmental aspects of UTES on the ground and groundwater and by providing screening and decision tools for environmentally beneficial applications of UTES.

d) Develop procedures for the widespread application of UTES by applying community-based integrated concepts in concert with environment and legal planning agencies.

Canada is primarily responsible for Subtask B, which includes *Techniques for Environmental Screening and Community-based UTES*. Canada will therefore;

a) Develop environmental impact assessment procedures for use on UTES projects and studies.

b) Perform an environmental evaluation.

c) Develop analytical and engineering tools to evaluate and design community-based UTES developments (GIS).

## CONCLUSIONS

Although Canadian buildings of all sizes are potential candidates for energy storage, economically viable applications can usually be focused on all buildings that are cooled and/

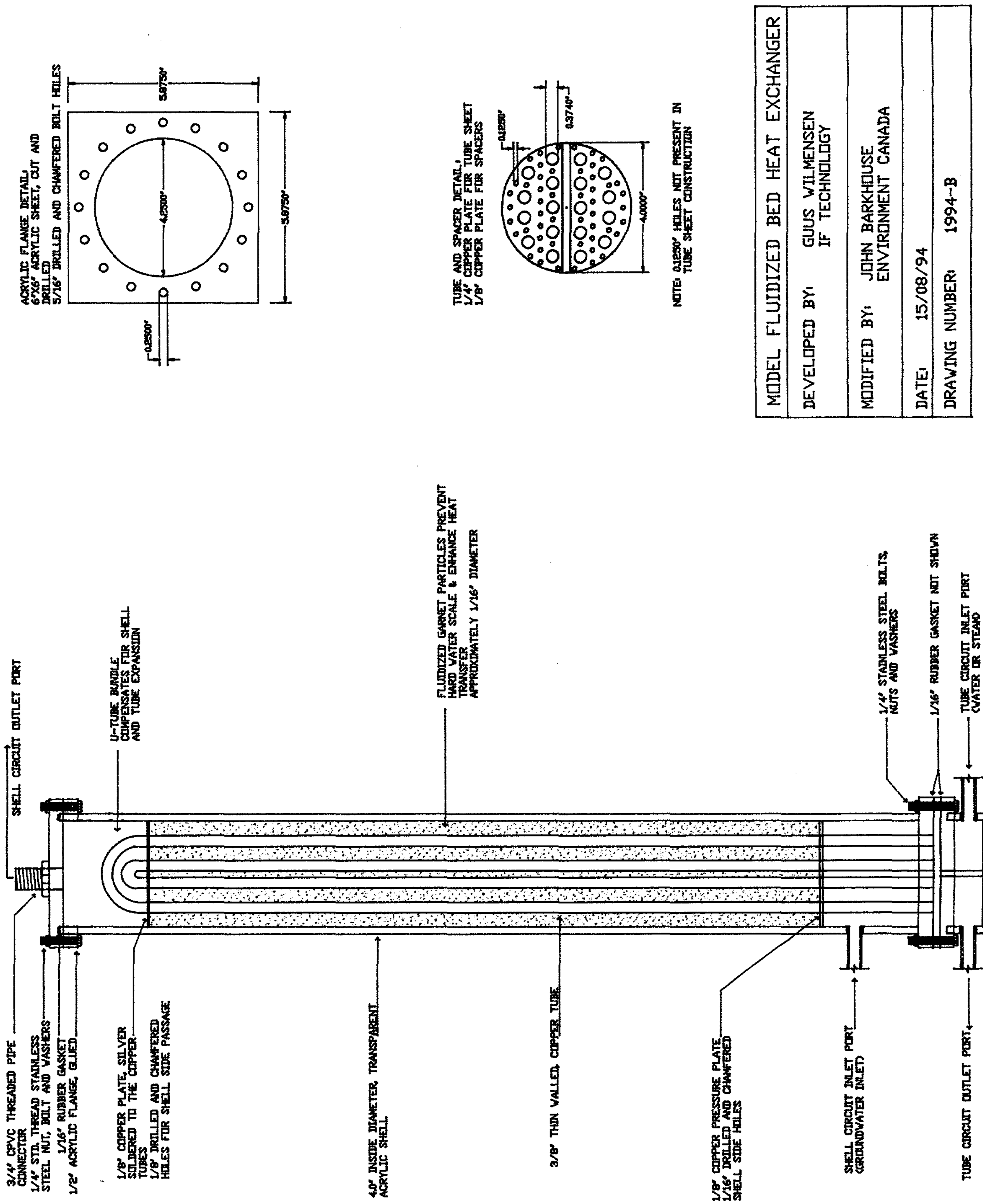



Figure 13: Modified Version of RFBHE.

or heated with electricity, new buildings, building expansions needing new heating and cooling retrofits and retrofits to reduce or eliminate CFC's.

The economic analyses covered capital and operating costs only, without incorporating the externalities of emissions of $CO_2$, $NO_x$ and $SO_2$ which are associated with the use of conventional energy sources. Regardless of externalities, which would otherwise favour the use of ATES, the results showed that ATES is definitely economical in larger commercial buildings in the three locations in Canada which were studied. As well, potentially significant environmental benefits from reduced air emissions were identified, especially in Atlantic Canada, where the major source of electricity is from fossil fuel power plants.

A key characteristic of ATES systems is that they are relatively high in capital costs and low in annual operating costs. Thus the economics of such systems depends on the interest or discount rate. Hence, the results of economic analyses for a range of real discount rates should be were used in economic analysis. Moreover, ATES analysis is sensitive to site-specific conditions. Therefore, an analysis needs to be performed specific to the application before project cost effectiveness can be adequately assessed.

With the implementation of the new Canadian Environmental Protection Act (CEPA), there will be a greater need for Environment Canada to enhance its capacity to fulfil its obligations, as both an initiator of projects and as an expert department. Therefore, practical environmental screening tools will be developed. Much of this work will take place in the context of partnerships, particularly where areas of interest or jurisdiction overlap.

Regarding this, the New Brunswick Department of the Environment is cooperating with Environment Canada in a GIS project that will enhance our capability to readily access environmental information required for sound decision making.

The final GIS product will be a completely documented desktop mapping application which can manipulate and modify information, and run groundwater or relational database programs tied to information contained in each of community-based GIS files. It is expected that the Groundwater GIS application will greatly enhance our ability to conduct ATES sensitivity analysis at the community level.

The planned changes and new developments taking place at the West Viking College and the Marble Mountain sites, may present good opportunities to implement ATES in the Province of Newfoundland. These projects may also present an opportunity to dovetail the federal and provincial governments desire to transfer environmentally sustainable energy technology to the institutional and private sector.

Evaluations and monitoring of the mechanical (above ground) and hydrogeological (below ground) aspects of the Sussex Hospital, and the Nova Scotia Agricultural College sites are ongoing. It is anticipated that at least one of these sites will be used for high temperature ATES field testing purposes, once the building and bench testing of the Reactor Fluidized Bed Heat Exchanger and the $CO_2$ Treatment systems are completed at the Nova Scotia Agricultural College.

In August 1994, CALORSTOCK+94, the 6th International Conference on Thermal Energy Storage was held in Espoo, Finland. The IEA Energy Storage Implementing Agreement organized a morning plenary session on the accomplishments of the Implementing Agreement (IA) including Annexes 5, 6 7 and 8 with an overview by the Chairman. The Solar and District Heating IAs also sponsored sessions on their work related to energy storage. As a result several additional countries expressed an interest in joining the work of the IA including Turkey, Japan, Poland, Hungary, Belgium, the UK and Mexico. Belgium, Finland and probably Turkey will soon join the work of Annex 8 and Japan, Poland and Mexico as well in the future.

There were some conclusions of interest to Canada that came out of the conference. Thermal cool storage can be a reliable, environmentally acceptable and cost-effective building technology. Interest in cold storage is great due to increasing cooling loads and increased electrical costs. This has generated interest in natural gas-fired cooling, microcogeneration and cold storage.

On a national basis the linkage between energy storage and environmental objectives for protection of groundwater, energy efficiency and air emissions is being recognized and collaboration among government agencies is increasing.

This is illustrated in Canada by the collaboration among Environment Canada, PW&GSC and the National Research Council of Canada (NRCan) on groundwater projects and technology transfer. Environment Canada has been actively participating in the IEA Energy Storage Annex 6. A Memorandum of Understanding (MOU) concerning the roles of various government departments, nationally and internationally, with intersest in the area of thermal energy storage is being considered for the new Annex 8 collaboration (Implementing Underground Thermal Energy Storage Systems).

There is a need to continue with thermal storage research on a national basis and to show the significant economic benefits of thermal storage (the Economy - Energy - Environment linkages). The Netherlands has the most successful cold storage program based on aquifers. Their implementation approach includes subsidies for feasibility studies for those who are amongst the first to adapt the technology to their needs. There is also financial support to overcome environmental, mechanical or design issues without delay.

The Netherlands also targets designers and owners for short practical training on the technology and provide expert advice and assistance to designers and contractors who encounter problems. This approach guarantees a number of successful applications and would seem to be adaptable for

ATES and other thermal storage technologies. This is an approach that might well be adapted to Canadian circumstances.

It is expected that the success of ATES endeavours in Atlantic Canada and elsehwere will help make ATES a standard design option in Canada by exposing administrators, government officials, engineers, architects, students and professors to the merits of ATES, and possibly other underground thermal energy storage (UTES) technologies.

**REFERENCES**

[1] Environment Canada-New Brunswick Department of the Environment, 1992. *A Framework for ATES Guidelines Development.* Report prepared for the Canada/ New Brunswick Water and Economy Agreement.

[2] *Innovative and Cost-effective Seasonal Cold Storage Applications,* Summary of National State-of-the-Art Reviews, International Energy Agency (IEA), Energy Conservation Through Energy Storage Implementing Agreement (ECES-IA) (Annex 7), Public Works Canada, PWC/RDD/96E, Ottawa K1A 0M2, June 1992, 41 p.

[3] *Personal Communication,* H. Howes, Senior Environmental Advisor, Environmental Division, Ontario Hydro. September, 1993.

[4] Article *"Heat Pump Appeal",* Saint John Telegraph Journal, December, 21, 1993.

[5] Adsett & Associates Ltd. 1992. *Feasibility Study, Earth Energy Systems Integration - Sussex Health Centre.* Report submitted to Sussex Health Centre, NB, February.

[6] Pace University. 1990. *Environmental Costs of Electricity.* Pace University Centre for Environmental Legal Studies. Report prepared for New York State Energy Research and Development Authority.

[7] Environment Canada- Nova Scotia Department of the Environment, 1993. *Suitability Model for Development of Groundwater Source Heat Pump Technology.* Report prepared for the Canada-Nova Scotia Cooperation Agreement for Sustainable Economic Development (SEDA).

[8] Environment Canada, Conservation and Protection, *Inventory and Review of New Brunswick Municipal Groundwater Supply Areas.* DSS Contract UP-H6-007, 1988, 3 vols.

[9] Cruickshanks, F. 1994. Sussex Hospital Aquifer Thermal Energy Storage. *Proceedings, Calorstock'94, 6th International Conference on Thermal Energy Storage, Espoo, Finland.* pp. 89-95

[10] Environment Canada 1994, Internal Report, *Pre-feasibility Study of Heating and Cooling Systems Integration for use in ATES - Nova Scotia Agricultural College.*

[11] Wagner, R. Koch, M. and Andinolfi, M. (1988). *Chemische und Biologische Prozesse in Aquifer-Warmespeichern.* Stuttg. Ber. Siedlungswasswirtsch. 101.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Developing an Expert System for Aquifer Thermal Energy Storage

• Cameran Mirza
Strata Engineering Corporation
Don Mills Ontario Canada
• Michael W. Goutama
Falcon Transnational Corp.
Toronto, Ontario Canada
• Ka C. Lau
Ontario Hydro Technologies
Toronto, Ontario Canada

## ABSTRACT

Aquifer thermal energy storage (ATES) is a maturing technology. Over the last four decades a number of ATES projects have been implemented in several countries, starting with China, with varying degrees of success. The experience from such projects can now be accumulated and made available to others through expert or knowledge based decision support systems (KBS). Because expert system technology is evolving, limitations include inherent shortcomings such as narrowness of expertise, inability to recognize knowledge boundaries, limited explanation facilities, and difficulty in validation. In ATES applications it is considered unwise to try to keep the expert system from regular use until its knowledge base is complete. Like human specialists, expert systems may make mistakes and may require time to advance from apprentice to expert status, incrementally over a period of time. The best candidates for expert systems are those knowledge domains which are small but important, and in which data, test cases, and the knowledge and experience of human experts can be captured for further development and validation. In this sense, ATES is an ideal candidate for expert system development.

## INTRODUCTION

Aquifer thermal energy storage (ATES) involves storing thermal energy over seasonal periods. The storage medium is an aquifer of suitable properties. Energy transfer between the storage medium and the user facility is accomplished by means of groundwater, pumps and heat exchangers. The degree of efficiency and effectiveness of ATES depends on many inter-disciplinary and inter-dependent factors as well as overall management from inception to delivery. In many instances ATES is also expected to satisfy several missions simultaneously, such as:

- demand side management
- consumer cost reductions
- beneficial environmental enhancement
- security of energy supplies
- conservation of non-renewable fossil fuels.

The seasonal storage of thermal energy in aquifers requires satisfying the following three conditions:

1. Availability of a suitable aquifer with acceptable regional groundwater flow velocities.

2. Little danger of groundwater supply and receptor wells clogging or loosing their efficiency under "in/out" (groundwater flow), "on/off" (seasonal standby) and "high/low" (temperature) operating conditions.

3. Efficient collection, transfer and redistribution of stored energy with minimum loss.

Not all cities or buildings are located above ideal aquifers. But when groundwater is abundantly available ATES should be considered as a viable energy conserving alternative. ATES offers distinct environmental benefits through its capacity to reduce demand for conventional energy derived from non-renewable fossil fuels. In electrical power distribution grids where most of the electricity is generated from coal or oil, the environmental benefits of reducing $CO_2$ and other undesirable gaseous emissions are real and worthy of pursuit.

However, an abundant supply of groundwater is by itself not the sole criterion for ATES deployment. Considerations of economics, depth to the aquifer, ambient temperatures, potential well yields, groundwater chemistry, potential negative environmental impacts and similar factors are all important in decision making and final implementation of an ATES project. An ATES expert system can be very useful in helping with such decisions.

The first international conference on seasonal thermal energy storage was held in Seattle in 1981. The most recent sixth international conference on thermal energy storage was held in Helsinki in August, 1994. These conferences and several national and regional seminars and workshops, as well as intersociety energy conversion engineering conferences have produced a wealth of data on

ATES, ranging from theoretical speculations to case histories of performance. This International Symposium is the first of its kind dedicated solely to ATES. Recent as this flurry of technical exchanges might seem, in actual fact experience with ATES goes back to the late 1960's and early 1970's in North America and Europe, and as far back as the early 1950's in China. Therefore, ATES technology spans a period of four decades.

Early ATES knowledge was neither precise nor complete. Today, the knowledge base is more precise and more complete. It is therefore an excellent time to capture rational and heuristic ATES knowledge, data and experience within an ATES expert system.

## EXPERT SYSTEMS

### Introduction

Expert systems offer a convenient means of transferring both rational knowledge and heuristics about a particular subject domain to a user as a method of supporting the decision-making process or for selecting the most viable option from a number of alternatives.

Expert systems could also be used as "training" programs, by designing the system to elicit specific information from the user, thus forcing the user to research the response needed by the expert system. Expert systems can also be used as "check-lists" of things to do or to be concerned about in designing or implementing ATES.

Expert system development began in earnest in the mid-1960's and is now a common tool used by many firms and in many disciplines such as medicine, mineral exploration, finance and engineering. Expert systems developed for engineering applications are shown in Table 1. The use of fuzzy sets and logic (Zadeh, 1965; Juang, 1988) is also growing, as for example in the development of a program called FLOPS, Fuzzy LOgic Production System (Siler and Tucker, 1986) for the preliminary selection of a pile foundation (Juang and Ulshafer, 1990).

The uncertainty of knowledge is accommodated in knowledge based decision support systems using a certainty factor, CF, which lies between 0 for total ignorance and 1 for absolute knowledge. CF can be supplied either by the domain knowledge expert or be computed from rules established for its determination. In expert system programming, if a CF is not specified, the default value is usually 1.

The growth in expert system applications has led to compilation of expert system data bases for on-line interrogation. One recent example is the data base created for master's theses and doctoral dissertations involving the use of expert systems, knowledge-based systems or artificial intelligence programming techniques for solving civil engineering problems (ASCE, 1993).

In multi-disciplinary fields of engineering (and ATES is a good example of such a field) the development of knowledge-based systems has been relatively slow, because of problems associated with getting all the experts together from their respective fields of expertise to input their knowledge, and lack of programming capability to accommodate the specialized requirements of each discipline.

### Historical Development

Expert systems are an outgrowth of research into artificial intelligence (AI) which began in the mid-1960's. AI is that sub-field of computer science which is concerned with understanding human reasoning and thought processes, and the application of this understanding to the development of intelligent computer technologies. Branches of AI include robotics, vision, speech recognition, and expert systems.

Expert systems are computer programs which perform specialized tasks requiring knowledge, experience or expertise in some field. One of the very first expert systems developed by a group of researchers at Stanford University was DENDRAL, a project started in 1965 and developed through the 1970's. It embodies extensive knowledge of molecular structure analysis, and was selected simply as an illustration of the ability of computer based systems to master an area of scientific knowledge. A follow up project, Meta-DENDRAL (Hopgood, 1993) was capable of automatically devising new rules for DENDRAL; but it had problems dealing with partial or inaccurate data, and intertwining of multiple concepts in the same data set.

Other expert systems followed DENDRAL, such as MACSYMA, an expert system from MIT for performing complex mathematical analyses and HEARSAY, an expert system from Carnegie Mellon University to serve as a natural language interpreter. MYCIN (Shortliffe, 1976; Johnson and Keravnov, 1988) was developed in the mid-1970's as an expert system at Stanford University to diagnose blood disease and was one of the first expert systems to handle uncertainty factors. The MYCIN shell was later used to create E-MYCIN (essential or empty MYCIN), a rule based backward chaining system used for applications in medicine, geology, engineering and agriculture. In mineral exploration, the PROSPECTOR series of expert systems is credited with the discovery of significant ore bodies (Campbell et al., 1982).

### Definitions

Gaschnig et al. (1981) define an expert system as:

> "... interactive computer programs incorporating judgement, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks".

The following terms are commonly used in expert systems:

**Domain Knowledge** - domain refers to a specific area of application (eg. ATES) or knowledge which is specific to the domain (eg. hydrogeology), rather than general knowledge or common knowledge.

**Inference Mechanism** - the software which controls the reasoning operations of the expert system. This is that part of the computer program which deals with making assertions, testing hypotheses, and reaching conclusions based on the logic or reasoning provided by the expert. It is through the inference mechanism that the reasoning strategy or method of solution is controlled.

**Knowledge Based System** (KBS) - is that part of a computer program in which the domain knowledge is stored in the form of facts and heuristics.

**Knowledge Engineer** - a person who works with domain knowledge experts to provide the transition from human knowledge to the appropriate computer representation. Knowledge engineers provide the AI expertise and play a major role in designing the computer system.

**Heuristics** - refers to expert "rules of thumb" which are usually empirical in nature and based on experience, judgement and intuition, and which do not require strict mathematical or scientific proofs.

Adeli (1985) makes distinctions between knowledge based expert systems and traditional programs, as follows:

- Expert systems are knowledge intensive programs.
- In expert systems, expert knowledge is usually divided into many separate rules.
- Rules forming a knowledge base or expert knowledge are separated from the methods for applying the knowledge to the current problem. These methods are referred to as inference machines, reasoning mechanism, or rule interpreter.
- Expert systems are highly interactive
- Expert systems have user-friendly/intelligent user interface.
- Expert systems to some extent mimic the decision making and reasoning process of human experts. They can provide advice, answer questions and justify their conclusions.

Hayes-Roth et al. (1983) contend that expert system development is predicated on the assumption that an expert system is generated through cooperation of two groups - one or more domain experts with experience and knowledge about the application domain, and one or more knowledge engineers.

Knowledge engineers are knowledgeable about several expert system frameworks and help the domain expert in selecting an appropriate representation or inference strategy, and developing the relevant knowledge base. They also implement the domain experts' knowledge base in the selected framework.

Fenves (1986) holds the view that the next generation of expert systems will be written by today's application programmers educated in their respective application domains and capable of incorporating substantial segments of domain knowledge into their expert systems based on their own personal expertise. This view is a departure from the Hayes-Roth et al. (1983) concept of two distinct bodies being required to develop expert systems.

Because ATES is multi-disciplinary, the Hayes-Roth et al. (1983) concept will likely remain for some time to come. Several domain experts will likely interact with a knowledge engineer to ensure that their particular expertise in the various aspects of ATES is properly represented in and deployed by the ATES expert system.

Expert Systems and ATES

Expert systems are necessary and justified for ATES whose management is a particularly challenging task (Mirza et al., 1994). The knowledge fields associated with ATES can be classed into four broad expert domain categories:

1. The subsurface domain, consisting of the geology, hydrogeology and aquifer characteristics of the ATES site.

2. The surface domain consisting of the building or facility to be served by the ATES project.

3. The operating domain which consists of the wells, pumps, pipes, heat exchangers and control systems.

4. The external or global domain which comprises the biosphere and ecosystem lying outside the boundaries of the ATES project.

Expert advice is required from all four expert knowledge domains if an ATES project is to succeed. It is therefore logical that one or more expert systems should be developed for one or more of these knowledge domains, either individually or in some convenient combinations.

There are generally two main approaches to problem solving in expert systems (Maher, 1986):

(1) the derivation approach, which involves deriving a solution most appropriate for the problem from a list of pre-defined solutions stored in the knowledge base of the expert system, and

(2) the formation approach which involves forming a solution from the eligible solution components stored in the knowledge base. Depending on its complexity, an expert system may use one or both approaches.

The derivation approach implementation requires the following strategies - forward chaining, backward chaining and mixed initiative. The goal states represent the potential solutions and the initial states represent the in/out data. The use of these strategies requires the development of an inference network representing the connections between initial states and goal states.

"Forward chaining" (also known as bottom-up, data-driven or antecedent) works from an initial state of known facts towards a desired goal, as illustrated in Figure 1. The value of all facts from a knowledge base are provided as input. The input facts might include overburden thickness, aquifer thickness, permeability and transmissivity, and test well data. These facts are checked to satisfy certain conditions and if those conditions are met a check is made to satisfy one or more subgoals. It is however extremely wasteful to require all data as input for all possible conditions of an ATES system. In many cases, all the facts about an ATES project are not known or relevant at the start.

Forward chaining is useful when there are a number of hypotheses and few input data, since the program has no *a-priori* knowledge of the possible solutions. Acquired information is used to evaluate the tree of possibilities, as it progresses through the solution procedure from an initial state, in which the program has no knowledge of the solution, through intermediate states in which the program's knowledge of the solution improves, to the final goal state.

"Backward chaining" refers to a built-in method to make an initial hypothesis as to what the solution is. The initial hypothesis might be that ATES is feasible. The program assumes one possible solution to be true. The procedure then attempts to prove that the assumption or hypothesis is correct, by asking the user (or using its own inference capabilities) to confirm all of the pre-requisite conditions, such as whether or not an aquifer is present. If the solution is disproved through the non-existence of a prerequisite condition, then the program chooses a different possible solution and proceeds to prove this one in the same manner. The order in which the hypotheses are pursued is predefined, normally by the knowledge expert, but with the guidance of the domain expert.

In both forward and backward chaining strategies, the program acquires information either in the form of a question to the user, or by means of accessing other programs and data bases.

A "mixed initiative" (Maher, 1986) combines both forward and backward chaining strategies. It starts with an initial state of known facts. A probability is assigned to each of the potential goal states. The system then tries to support the goal state with the highest probability by setting up sub-goals and requesting additional information from the user.

In the mixed initiative approach the order in which hypotheses are checked depends on the problem at hand. One advantage of this approach is that the user supplies only the data which is relevant to the problem at hand and not all possible values as in forward chaining.

Expert systems are more likely to be successful if the application area is well bounded and understood and at least one human expert is available to explain the knowledge required for the expert system being developed.

In addition, one or more of the following conditions need to be met for any expert system to be worthy of development: (1) shortage or unavailability of human experts/specialists; (2) need to preserve the expert's expertise; (3) high cost of expert advice or incorrect decisions; (4) critical requirements of expert advice; and (5) routine, detail-dependent decision making.

Expert system technology can be applied for use with ATES in five major ways:

1. As an intelligent "user" - the system acts as a data base for other software packages; interaction with the software package and/or data base is not its primary objective but merely a convenient means of accessing data. This might be the case for example where hydrogeological field data are stored in the expert system and utilized by a commercial groundwater analysis program to calculate aquifer transmissivity.

2. As an intelligent "representative" - the expert system uses mathematical logic to represent general facts about data in the software package and/or data base to increase the usefulness of the package and/or data base in responding to queries. This might be the case with the use of building energy data to compute groundwater flow requirements for a given temperature differential across the heat exchanger.

3. As an intelligent "prober" - the system supports browsing through a data base or program and also supports query modifications either to narrow or to broaden the scope of the request to make it more understandable. This might be the case where the expert system is designed to be used as a training tool.

4. As a natural language interface software package - the system allows the user to search for and process information without having to learn specialized command languages.

5. As a natural language text "analyst" - the system processes a user's natural langauge input text to produce appropriate responses to user posed queries. The capability of the expert system to understand natural langauge text in a given field permits the user to enter data in a relatively flexible form.

## ATES EXPERT SYSTEM

### Introduction

ATES is a multi-disciplinary field. Some disciplines associated with ATES are:

. Geology
. Hydrogeology
. Aquifer Characterization
. Water Well Technology
. Thermodynamics and Heat Transfer
. Geothermal Analysis
. Geochemical Analysis
. Coupled thermo-chemical/biological analyses
. Pathology and Public Health
. Environmental Laws and Regulations

- Economic and Financial Analyses
- Numerical Modelling
- Building Sciences/Envelope Design
- Energy Use Optimization
- Heating, Ventilation and Air-Conditioning
- Geotechnical Engineering
- Mechanical Engineering
- Systems and Controls Engineering

and more.

Therefore, the development of one or more expert systems dedicated to ATES has been slow. Some success has been achieved in developing knowledge-based systems to assist with specific aspects of ATES, such as the program H2O-TREAT (Vail et al, 1992). H2O-TREAT deals with the analysis of groundwater chemistry to prevent clogging and/or corrosion in pipes and mechanical systems and helps select an appropriate preventive water treatment method.

To date, however, no full scale attempt has been made at collecting and collating all of the multi-disciplinary expertise of ATES into a single comprehensive ATES expert system. Since ATES is a diverse multi-disciplinary field it will be extremely difficult to accommodate comprehensive rules and logic for the design and installation of ATES systems at any given site. However, an attempt can be made at developing less comprehensive systems, such as for screening a given site for ATES suitability, or for environmental impact assessment, or for aquifer characterization, or for pumping test data reduction, or to optimize building system energy options, and similar end uses.

The authors have developed a simple ATES expert system using Pascal and C, to assess the feasibility of ATES at a given site (ATES/FE-ES, 1.0). The logic and rules used in ATES/FE-ES 1.0 cover a rather wide range of ATES knowledge domains but in an "overview" type of manner, to keep the system itself simple and easy to use. As an example of simplicity the first question asked is "Is an aquifer present?". This is the starting point of the expert system "interview" or interrogation process. If the user responds "no", the expert system decides that ATES is not feasible (simple logic!) and the program ends. If the user responds "yes", the expert system initiates further enquiries. At any time during the interrogation process a "no" response either ends the expert system dialogue or initiates further enquiries for extra knowledge or data.

In version 1.0 of ATES/FE-ES no attempt is made to couple logic to data bases which are available or which can be programmed into the system. Nor has any attempt been made to make the expert system shell interact with other shells. For example, the user is asked to supply data on groundwater chemistry. Although the expert system programming can be easily expanded to conduct an ion balance check from the user supplied data, this has been deliberately omitted from ATES/FE-ES 1.0, in the interest of "educating" the user.

For example, instead of analyzing the supplied water chemistry data by means of either commercially available programs linked to the expert system or with the use of a simple spread sheet, the user is asked whether or not the cation/anion balance is within 5 per cent. This is a deliberate ploy to force the user to learn about water chemistry or to get external help from experts in water chemistry.

This procedure helps the user to learn about the importance of groundwater sampling, transportation and storage protocols. It teaches the user the need to prevent the loss of dissolved gases from the collected groundwater sample. It teaches the requirement of sample acidification to prevent premature metal ion precipitation, and so on.

ATES/FE-ES 1.0 can be expanded in the future to include certain design standards and considerations, particularly with respect to supply (production) and receptor (injection) groundwater wells. ATES wells are different from routine groundwater supply wells in many respects (Mirza, 1994). Unlike regular water supply wells, an ATES well must supply and receive groundwater. Flow into and out of an ATES well is reversed twice a year, in most common ATES applications. Hence, special considerations are required for their design and efficient operation over a number of years.

ATES/FE-ES 1.0 was designed with the following four major ATES operating domains in mind:

The Subsurface Domain

The subsurface domain consists of the geology and hydrogeology of the ATES site and other key features of the aquifer formation. In many cases, there is insufficient, inadequate, improper or inappropriate data on geology and hydrogeology. Information deficiencies may be the result of any number of factors, such as investigative time and cost constraints, or lack of recognition of the importance of geology and hydrogeology to the ultimate success of the ATES project.

Often, the capacity of the aquifer to sustain groundwater supplies to meet peak load energy demands is overlooked. In some cases, the need to inject large amounts of groundwater back into the aquifer is not sufficiently recognized. These then result in an ATES system which is either inefficient or uneconomical, or one that does not perform its intended function to the standards expected of it.

Lack of recognition of the significance of regional groundwater flow and the heat or cold losses that can occur with the associated advective movement of the thermal storage plume is another problem. Supply and receptor well positions could easily be reversed so that only a fraction of the stored energy is available when needed.

Partial screening of a supply or receptor well can result in apparent loss of stored thermal energy due to buoyancy caused by convection. This can happen if warm water is stored in an aquifer formation in which the receptor wells are screened only in the lower half of the aquifer formation. The warmer water being lighter than cold water rises above the upper level of the well screen. In winter, when the receptor well becomes a supply well, the warm stored groundwater becomes unavailable, since the screen now draws colder water from the lower part of the aquifer formation.

The opposite effect is also possible for cold supply wells if the screens are located only in the upper half of the aquifer formation. In summer, the warmer water reaches the well screen first, the colder heavier water remaining in the unscreened lower portion of the aquifer formation.

Several analytical tools are currently available for the analysis of coupled groundwater-heat flow in porous, fractured and equivalent porous isotropic or anisotropic geological media. Some are closed form solutions, others require numerical techniques.

The computational capacity of PC's has increased to the point where many complex numerical problems can be solved relatively easily, provided the input parameters are correct and correctly input. However, modelling alone is insufficient to ensure peak performance of an ATES system. Adequate funds and time should be set aside to permit validation of modelling results through specifically designed experiments and field tests. An ATES expert system could be designed to steer the user to specific analytical and computational techniques most appropriate for the subsurface domain conditions at the proposed ATES site.

## The Surface Domain

The surface domain consists of buildings and facilities which require seasonal cooling or heating. In summer disposal of waste heat is the prime goal. Even in winter some finite amount of heat is generated from occupants, lights, computers and solar gain. Surplus heat can be rejected by means of cooling towers or passed on for long term storage to an aquifer; or it could be stored temporarily in tanks or in phase change materials (PCM's) for diurnal use.

Efficient use of energy requires that in winter all available heat from the facility should be utilized first, before additional heat is demanded either from short or long term storage or from specifically designated heating units, such as boilers. The optimization of utilization of all available energy sources and resources lies clearly within the surface domain of ATES technology.

In one case it may prove to be more efficient and wiser to use the stored warm energy for pre-heating of winter supply fresh air than for direct space heating, whereas the opposite may be more appropriate in another facility. It may even be very appropriate to run a chiller during winter, using the condenser heat to provide warmth while storing very cold water from the evaporator side of the chiller in an aquifer for relatively low cost air conditioning in summer. An understanding of the linkages between the surface and subsurface domains of an ATES facility is a necessity for overall operational optimization.

An appropriate ATES expert system should be capable of interrogation intended to optimize energy use. Obviously more than one domain expert is required to develop this type of ATES expert system, to ensure that the linkages between the surface and subsurface domains are appreciated and linked in a meaningful way.

## The Operating Domain

The operating domain consists of the physical accessories associated with ATES, such as the supply and receptor wells, pipes, pumps, heat exchangers and any groundwater treatment or processing facilities. Also included within the operating domain are monitoring and control systems which help the building or facility operator select the most efficient mode of operating and managing energy utilization within the building or facility.

In many ATES projects geochemical reactions are caused by loss of dissolved gases during production of groundwater and/or by changes in temperature of the coupled groundwater-aquifer matrix system (Jenne et al., 1991). Such reactions can lead to corrosion and/or scaling of physical components of the operating domain, such as well screens, pipes, pump intakes and heat exchangers. An understanding of the interaction between groundwater chemistry and its equilibrium status at ambient temperature with the aquifer matrix is also extremely important if problems are to be avoided during ATES operation.

Research conducted within Annex 6 of the International Energy Agency (Snijders, 1994) shows that such problems are capable of being identified in advance. Certain chemical and microbiological reactions occur through perturbations caused by temperature and pressure changes within the subsurface domain as a result of ATES implementation. Such reactions ought to be analyzed or tested thoroughly to anticipate potential problems and to design appropriate mitigative measures.

Some ATES projects have not performed because of problems with water wells. Either the water wells have not been properly positioned with respect to the overall thermal field of the ATES system, or the positions of the receptor and supply wells have been reversed in a non-homogeneous or anisotropic aquifer, or the aquifer matrix composition was not properly analyzed or provided for in the selection of a gravel pack and screen. In such cases, an ATES expert system would be extremely beneficial, providing guidance and caution to the designer through appropriate enquiries about aquifer and aquifer matrix properties, followed by rational or heuristics guidance on screen and gravel pack selection, quality control parameters and the like.

Certain linkages between the subsurface and operating domains are often overlooked in ATES design. ATES projects located in bedrock aquifers with shallow overburden may suffer from excessive loss of pumped water due to seepage caused by unbalanced hydrostatic heads.

Inadequate attention to hydrostatic pressures created by injection into receptor wells may cause structural and topographical distress through either hydraulic fracturing or by an unacceptable increase in the pore water pressure of foundation materials and subsequent reductions in effective stresses and load supporting capacities. In such systems, the receptor well casings should be deepened well below the bedrock-overburden contact to accommodate the upward hydraulic forces anticipated from injection pressures.

### The External Domain

The external or global domain consists of all that lies beyond the ATES site but is or can be affected by the ATES subsurface, surface and operating domains. The impacts can be both positive and negative. In developing an expert system to consider the ramifications of an ATES project on the external domain, it is essential to first overcome all possible negative outcomes and impacts. If the negative impacts are such that ATES can not be licensed or proceed, then analysis of the positive outcomes of the ATES project is wasteful. Therefore, a backward chaining procedure is called for, in which queries elicit responses which indicate no negative impacts.

In ATES/FE-ES 1.0, for example, the second question posed is whether interference caused by aquifer use for ATES is acceptable within a 5 km radius of the ATES site. If the answer is yes, the expert system continues with the interrogation process. If the answer is no, the expert system decides that prior water users may be adversely affected and the project should therefore either not be considered feasible or that further hydrogeological tests and evidence should be sought.

Should it be necessary to overcome or resolve potential negative impacts on the external or global domain, an hierarchy of solutions can be developed for use in an ATES expert system. The solutions reached will depend on (1) the proper identification of the problem and (2) the proper assessment or weighting of the intensity or degree of the problem. Here, certainty factors are required if the problems are not distinct. The use of fuzzy logic may also be justified in dealing with the external domain of ATES projects.

## CONCLUSIONS

Because of the multi-disciplinary and multi-missioned nature of ATES, expert systems appear to be justified. Increasing availability of technical data and case histories of ATES projects now presents an opportunity which was not available a decade or so ago. Expert systems have been developed for applications in several engineering fields. However, their extension to ATES is more difficult because of the diversity of expertise and disciplines involved. Nonetheless, a case can be made for the development of targeted expert systems, if only to promote technology transfer and communication between and amongst the various disciplines involved in ATES.

An example output from ATES/FE-ES 1.0 is given in Figure 2. The data set apply to the Canada Centre ATES project in Scarborough, Ontario (Mirza et al., 1985). The printed output serves as a checklist of data provided to the expert system by the system user. If errors are found, a new data set must be entered.

The development of one or more ATES expert systems will help significantly in the reduction of perceived risks of application. Such views are held now by the uninitiated, the professional who operates only in a single domain and has little knowledge of the other domains of ATES, and by owners who tend to be skeptical of all new technologies.

It is imperative that a start be made. Sophistication and expansion can come later. If complications arise, the expert system can be kept simple. Much better to solve a small problem than to solve none at all.


## ACKNOWLEDGEMENT

This paper is presented with the permission of Mr. Robert A. Calinot of the Energy Diversification Research Laboratory (EDRL) of CANMET, Energy, Mines and Resources Canada. The development of ATES/FE-ES 1.0 was made possible by a cost-shared funding program under the auspices of the Panel on Energy Research and Development (PERD) and co-funding from several government and private sector agencies and organizations.

The expert shell used in ATES/FE-ES 1.0 was developed by GCL International. The knowledge engineer for the system was Dr. Michael Goutama. Dr. Adrian M. Crawford of the University of Toronto made several suggestions. His assistance in reviewing the manuscript is greatly appreciated.


## REFERENCES CITED


ADELI, H. 1985. Knowledge-Based expert systems in structural engineering. Proc. Second International Conference on Civil and Structural Engineering Computing, London UK, December.

ASCE. 1993. "Expert systems theses go on line". American Society of Civil Engineers, ACSE News, October, p. 10.

CAMPBELL, A.N., HOLLISTER, V.F., DUDA, R.O. and HART, P.E. 1982. Recognition of a hidden mineral deposit by an artificial intelligence program. Science, vol. 217, No. 3, September.

FAYEGH, D. and RUSSELL, S.O. 1986. An expert system for flood estimation. In C.N. Kostem and M.L. Maher (Eds). Expert Systems in Civil Engineering. American Society of Civil Engineers, New York, NY, pp: 174-181.

FENVES, S.J. 1986. What is an expert system. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 1-6.

FINN, G.A and REINSCHMIDT, K.F. 1986. Expert systems in an engineering-construction firm. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 40-54.

GASCHNIG, J., REBOH, R. and REITER, J. 1981. Development of a knowledge based system for water resources problems. SRI Project 1619, SRI International, August.

GRIVAS, D.A. and REAGAN, J.C. 1988. An expert system for the evaluation and treatment of earth slope instability. Fifth Int. Symposium on Landslides, Lausanne, Switzerland, vol. 1, pp: 649-654. Balkema Publishers.

HANNA, P.B., HANNA, A.S. and PAPAGIANNAKIS, T.A. 1993. Knowledge-based advisory system for flexible pavement routine maintenance. Can J. Civ. Eng., vol. 20, pp: 154-163.

HAYES-ROTH, F., WATERMAN, D.A., and LENAT, D.B. (Eds) 1983. Building Expert Systems. Addison-Wesley Publishing Co., Reading, MA.

HOPGOOD, A.A. 1993. Knowledge Based System for Engineers and Scientists. CRC Press, Inc. Boca Raton, FL.

JENNE, E.A., ANDERSSON, O. and WILLEMSEN, A. 1992. Well, hydrology and biochemistry problems encountered in ATES systems and their solution. Proc. 27th Intersociety Energy Conversion Engineering Conference, San Diego, CA, vol. 4, pp: 77-88.

JOHNSON, L. and KERAVNOV. 1988. Expert System Architectures. Kogn Page Limited, London UK.

JUANG, C.H. 1988. Development of a decision support system using fuzzy sets. Journal of Microcomputers in Civil Engineering, vol. 3, pp: 157-166.

JUANG, C.H. and ULSHAFER, M.L. 1990. Development of an expert system for preliminary selection of pile foundations. Transportation Research Record No. 1277, National Research Council, Washington DC, pp: 153-160.

KOSTEM, C.N. 1986. Design of an expert system for the rating of highway bridges. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 87-95.

LAW, K.H., ZIMMIE, T.F. and CHAPMAN, D.R. 1986. An expert system for inactive hazardous waste site characterization. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 159-173.

LEVITT, R.E. 1986. Howsafe: a microcomputer-based expert system to evaluate the safety of a construction firm. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 55-66.

MAHER, M.L. 1986. Problem solving using expert system techniques. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 7-17.

MIRZA, C., LAU, K.C., MOROFSKY, E.L. and CRAWFORD, A.M. 1985. ATES experience with the Scarborough field trial. Proc. Enerstock '85, Public Works Canada, Toronto, pp: 110-114.

MIRZA, C. 1994. Criteria for ATES wells. Proc. Calorstock '94, Espoo, Finland, vol. 1, pp: 17-24.

MIRZA, C., CRUICKSHANKS, F., and MOROFSKY, E.L. 1994. Managing ATES. Proc. Calorstock '94, Espoo, Finland, vol. 1, pp: 25-32.

O'CONNOR, M.J., DE LA GARZA, J.M., and IBBS, Jr., C.W. 1986. An expert system for construction schedule analysis. In C.N. Kostem and M.L. Maher (Eds): Expert Systems in Civil Engineering, ASCE, New York, NY, pp: 67-77.

SHORTLIFFE, E.H. 1976. Computer Based Medical Consultations. American Elsevier, New York, NY.

SILER, W. and TUCKER, D. 1986. Program and User Manual, version 1.2c. Kemp-Carraway Heart Institute, Birmingham AL.

SNIJDERS, A.L. 1994. ATES: Water treatment and environmental impacts. Proc. Calorstock '94, Espoo, Finland, vol.1, pp: 317-325.

VAIL, L.W., JENNE, E.A. and EARY, L.E. 1992. H20 TREAT: A software aid for evaluating water treatment requirements for aquifer thermal energy storage. Proc. 27th Intersociety Energy Conversion Engineering Conference, San Diego CA, vol. 4, pp: 131-136.

ZADEH, L.A. 1965. Fuzzy sets. Information and Control, vol. 8, pp: 338-353.

**Table 1. Engineering Applications of Expert Systems**

| Application | Reference |
|---|---|
| Construction | Finn & Reinschmidt, 1986 |
| Safety | Levitt, 1986 |
| Scheduling | O'Connor et al., 1986 |
| Structures | Adeli, 1985 |
| Pavements | Hanna et al., 1993 |
| Slope Instability | Grivas and Reagan, 1988 |
| Pile Foundations | Juang and Ulshafer, 1990 |
| Fuzzy Sets | Juang, 1988 |
| Highway Bridges | Kostem, 1986 |
| Hazardous Waste | Law et al., 1986 |
| Flood Estimation | Fayegh and Russel, 1986 |

**GOAL:** A T E S

**SUBGOALS:**

| | | |
|---|---|---|
| Duration: | Short Term | Long Term |
| Seasonal: | Yes No | Yes No |
| Storage: | Yes No | Yes No |
| Temperature: | Cold | Hot |
| | Hot | Cold |

**CONDITION OF THE AQUIFER:**

Confined Yes No
Artesian Subartesian
Leaky Non-leaky
Soil Rock
Porous Fractured
&c. &c. &c.

**FACTS:**

Aquitard 10 m;
Aquifer 20 m;
Aquiclude 30 m;
Well Dia. 200 mm;
Pump Rate 20 L/s;
Duration: 24 Hrs;
Drawdown: 10 m;
Obs. Well 30 m away
Drawdown Obs. Well 2 m;
Transmissivity $m^2$/day
Storage coefficient
Cations/Anions, mg/L;
DOC, TOC, TIC
Gases, Types
&c. &c. &c.

**Figure 1. Information hierarchy of an expert system for ATES.**

```
DATAFILE FOR ATES SYSTEM AS REPORTED BY USER
===========================================================================
Thickness of overburden                              =      80.00  m
Depth to aquifer                                     =      50.00  m
Average aquifer thickness                            =      10.00  m
Ambient temperatue                                   =       9.00  Celcius
Regional flow velocity                               =      24.00  m/year
Aquifer transmissivity                               =     100.00  m2/day
Aquifer Storativity                                  =    0.00030
Maximum pumping rate for test well                   =      30.00  [L/s]
Maximum drawdown for test well                       =      15.00  [m]
Distance between test well and observation well      =      15.00  [m]
Maximum drawdown for nearest observation well        =       3.00  [m]
Depth of cased portion of tested well                =      70.00  [m]
Drawdown for nearest active well                     =      15.00  [m]

Based on the above information, expert decision is as follows:
---> PROCEED FURTHER WITH INPUT


Maximum operating temperature of proposed ATES       =      15.00  Celcius

Based on the above information, expert decision is as follows:
 ---> proceed further with input

Maximum temperature of injected water                =      15.00  Celcius
Maximum sustained injection rate                     =      30.00  L/s
Maximum head increase in injected well               =      20.00  m
Distance between injection and nearest obs'n wells   =      15.00  m
Head build up above static level in nearest obs'n well =     5.00  m
Maximum temperature change in nearest external well  =       3.00  Celcius
Depth of cased portion of tested well                =      70.00  m

Based on the above information, expert decision is as follows:
 ---> Proceed further with input

Aquifer type                                        = Confined

AQUIFER MINERALOGY
Quartz (%)                                          =      55.00
Calcite (%)                                         =      25.00
Feldspars (%)                                       =      25.00
Micas (%)                                           =       0.00
Smectite (%)                                        =       0.00

Organic matter                                      = Not present

PARAMETERS FOR AQUIFER GROUNDWATER

pH                        =      8.00
Eh (mV)                   =    250.00
Conductivity (uS)         =    810.00
TDS (mg/L)                =    450.00
Alkalinity (mg/L)         =    410.00
sulfate (mg/L)            =      0.00
Chloride (mg/L)           =      2.50
Sodium (mg/L)             =      4.00
Potassium (mg/L)          =      1.00
Calcium (mg/L)            =    120.00
Magnesium (mg/L)          =     31.00
Iron (mg/L)               =      0.00
Manganese (mg/L)          =      0.20

Based on the above information, expert decision is as follows:
--->Proceed further with input

The saturation index for calcite is          =     0.10

Ortho phosphates                                  = Not present

Based on the above information, expert decision is as follows:
--->Proceed further with input

Microbiological tests have been conducted
--->Proceed further with input

HUMAN HEALTH OR HYGIENE IS NOT AFFECTED BY BACTERIA/SPORES/FUNGICIDES/VIRUSES
--->Proceed further with input

--->BUILDING ENERGY LOADS HAVE BEEN CALCULATED

--->PEAK DEMAND CAN BE SATISFIED

Based on the above information, expert decision is as follows:
--->PROCEED WITH DETAILED DESIGN


CanCentre
```

**Figure 2. Example data set output from ATES/FE-ES**

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# H20--TREAT: Applications to ATES Sites

• Everett A. Jenne
Pacific Northwest Laboratory
Richland, Washington, USA
• Joseph P. Zipperer
Pacific Northwest Laboratory
Richland, Washington, USA
• Lance W. Vail
Pacific Northwest Laboratory
Richland, Washington, USA

ABSTRACT

This manual addresses the use of a public-domain software package developed to aid engineers in the design of water treatment systems for aquifer thermal energy storage (ATES). The manual has been modified and expanded to maximize its information content. The software, H2OTREAT, was developed by the Pacific Northwest Laboratory for use by engineers with little or no experience in geochemistry. The software provides guidance on treatment system requirements and capacities to prevent problems in ATES systems (i.e., the formation of scale in heat exchangers, clogging of wells, corrosion in piping and heat exchangers, and degradation of aquifer materials causing a reduction in permeability). Preventing such problems frequently requires the use of water treatment systems. Because individual water treatment methods vary in cost, effectiveness, environmental impact, corrosion potential, and acceptability to regulators, treatment options must be fully evaluated to determine the feasibility of ATES systems.

The software is available for DOS- and UNIX-based computers. It uses Version 4.1 of the MINTEQ geochemical model to calculate the saturation indices of selected carbonate, oxide, and hydroxide minerals based on water chemistry and temperature data provided by the user. The saturation index of a mineral defines the point at which that mineral is oversaturated and hence may precipitate at the specified temperature.

Cost calculations are not performed by the software; however, treatment requirements are provided. Treatments include Na and H ion exchange, fluidized-bed heat exchanger and pellet reactors, and $CO_2$ injection. The H2OTREAT software also warns the user of geochemical problems that must be addressed, such as Fe and Mn oxide precipitation, $SiO_2$ precipitation at elevated temperatures, corrosion, and clay swelling and dispersion.

## GEOCHEMICAL PROBLEMS

The most common geochemical problem encountered in ATES systems is the precipitation of calcium carbonate (e.g., scale formation) on heat exchangers. The clogging of injection wells by Fe and Mn oxides and/or carbonates is also a significant problem in some areas, e.g., Scandinavia. Use of Na-exchange water treatment to prevent carbonate precipitation may cause clays within aquifers to swell as the sodium concentrations within the aquifer increase, possibly clogging the aquifer. Degassing of oversaturated gases during reinjection may also clog the aquifer because of the formation of a separate gas phase. The corrosive nature of natural aquifer waters can be exacerbated by heating and by some treatments used to prevent scale formation.

### Carbonate Precipitation

Scale formation on heat exchangers can greatly reduce their thermal transfer efficiency. Precipitation on the well screen, in the gravel pack, or in the aquifer markedly decreases the injection rate at a fixed pressure [1]. Because the solubility of carbonate minerals decreases with increasing temperature, the higher the storage temperature, the more likely carbonate scale will form. Although calcite (a common calcium carbonate mineral) is the predominant carbonate mineral formed, ferrous carbonate (siderite) is suspected as the cause of reduced permeability in some Swedish ATES systems.*

The departure from equilibrium with respect to a specified solid phase can be calculated by determining the aqueous speciation of the dissolved components (e.g., Ca, dissolved carbonate) and calculating the ion activity product (e.g., the activity of $Ca^{2+}$ times the activity of $CO_3^{2-}$), which at equilibrium is equal to the solubility product of the mineral at the temperature of the water. The logarithm of the ratio of the ion activity product to the solubility product is known as the saturation index (SI). At SI values of less than 0.3, carbonate precipitation occurs too slowly to pose a problem anywhere in the ATES system [2,3,4] because such components as dissolved organic carbon (DOC), Mg, and $PO_4$ interfere with the precipitation process [4,5]. Another factor that affects precipitation and SI values is the formation of solid solutions of Mg, Fe, and Mn with $CaCO_3$.

* Olöf Andersson, personal communication.

phase that can block aquifer pores, greatly decreasing permeability and causing a system to fail. If the concentration of $CO_2$ in the ground water is greater than the value in equilibrium with the atmosphere and the system is allowed to degas, the pH will increase with resultant precipitation of Ca, Fe, or Mn carbonates.

### Corrosion

Metal surfaces commonly react with constituents in the medium with which they are in contact, in this case water, to form corrosion products such as oxides or sulfides. This has the undesirable effect of thinning the unoxidized metal, leading to leakage of water. Corrosion is enhanced by strongly reducing conditions. Elevated temperatures also increase the rate of corrosion. Oxygen is significantly more corrosive in the presence of elevated chloride; the corrosion rate produced by $O_2$ alone increases up to about 5.5 mg/L of $O_2$ [10]. Chloride and sulfate each increase the corrosion rate rapidly up to individual concentrations of 10 to 20 mg/L. Carbon dioxide is more corrosive in soft water (i.e., water with low Ca and Mg concentrations); the corrosion rate increases up to about 150 psi of $CO_2$ [10]. The presence of $H_2S$ at concentrations greater than a fraction of a milligram per liter may cause corrosion; corrosion is also more severe in high-salt water [10]. Assuming oxygen is excluded, significant corrosion potential exists if any of the following conditions occur: the pH is below 5.5; $H_2S$ concentrations are greater than 0.1 mg/L; $CO_2$ partial pressure is greater than 150 psi; either Cl or $SO_4$ concentrations exceed 20 mg/L; or microbiological growth occurs on or adjacent to the metal.

## TREATMENT METHODS

Sodium and H exchange, $CO_2$ injection, and fluidized-bed heat exchanger treatment are the methods for preventing carbonate precipitation that are considered by the software. Nitrate injection and cascade treatment to mitigate Fe and Mn oxide precipitation are also briefly discussed in this section.

### Ion Exchange

H2OTREAT estimates the fraction of water that must be treated by either Na or H exchange to prevent formation of carbonate scale in the heat exchanger.* To perform this calculation, H2OTREAT starts at the highest temperature with 100% treatment and successively decreases the fraction of treated water until one of the cations (Ca, Fe, or Mn) in the sample analysis yields a SI

* Treatment levels are computed for a range of temperatures. The high temperature should reflect the highest temperature any water in the heat exchanger will experience, usually at the wall of the heat exchanger. Some heat exchanger designs may involve wall temperatures significantly higher than the design bulk injection temperature.

If the SI estimated at the temperature to which the water is to be heated is at or below the threshold of calcite precipitation, no water treatment is required. For SI $\geq$0.3, water treatment is generally necessary. Because storage at a lower temperature than originally planned might make the water treatment unnecessary, it is important to estimate the temperature at which $SI_{calcite}$ is <0.3. The calculated amount of water that must be treated may be unreliable because of errors in the water chemistry analysis caused by the loss of $CO_2$ during pumping and sampling and while awaiting analysis. The result may be an increased pH and the absence of components, such as Fe and Mn.

### Oxide Precipitation

The oxides and hydroxides of Mn and Fe, respectively, hereafter referred to as oxides, precipitate on reaction with air as the reduced metal oxidizes. In aquifers that are depleted of oxygen, Fe2* and Mn2 are the dominant valence states of dissolved Fe and Mn. The depletion of oxygen is primarily a result of microbial processes that occur as surface water infiltrates. Because every oxygen molecule that comes into contact with reduced ground water can oxidize four Fe2 atoms to Fe3 or two Mn2 to Mn4, the entry of even small amounts of air into an ATES system may cause a considerable amount of oxide precipitation. Therefore ATES systems should preclude air entry if the source water concentration of Fe or Mn is >0.1 mg/L, because $O_2$ entry and the resultant oxide precipitation may cause scaling and clogging and may also increase corrosion rates.

### Sodium Hazard

The dispersion of fine-grained sediment and the swelling of clays may also reduce aquifer permeability. Dispersion may occur as a result of physical disturbance [6], but more generally it occurs with increased sodium saturation of expandable clays, which may be caused by use of Na-exchange water treatment or a significant reduction in ionic strength, as when a water of lower ionic strength is introduced into a saline aquifer [7]. The likelihood of clay dispersion, swelling, and reduced permeability is characterized as the "sodium hazard". Sodium hazard is a function of conductivity and the sodium adsorption ratio, which is the ratio of Na to the square root of one-half the sum of the Mg and Ca concentrations in milliequivalents [8,9].

### Degassing

Gases are often present in ground water in amounts greater than would be in equilibrium with atmospheric pressure. If, during injection, the hydrostatic pressure on the water is reduced as a result of inadequate back pressure, the gases may come out of solution and create a discrete gas

* The number following the chemical symbol specifies the oxidation state.

for calcite, siderite, or rhodochrosite that exceeds 0.3. The last treatment fraction before the fraction resulting in precipitation is taken as the fraction to be treated. If the user elects to evaluate the tradeoff between temperature and treatment requirements (by also selecting a low temperature for treatment), calculations are repeated for the low temperature and for a temperature halfway between the high and low temperatures. The ion-exchange process is assumed to be ideal (i.e., all relevant cations are replaced with an equal-molar amount of either Na or H). To anticipate the extent of treatment required for the heat-extracted water when the water is recovered from storage, the user will need to either sample the stored water before its recovery and reheating or perform laboratory experiments to determine the changes in composition that will occur during storage.

Either NaCl brine or HCl solutions are used to recharge the cation exchanger. Sodium exchange is generally preferred over H exchange, because the H-saturated exchanger lowers the pH and allows additional dissolution of carbonate minerals during storage of the heated water. In addition, the fraction of stored water that must be treated is expected to decrease with each cycle when Na exchange is used, but to increase when H exchange is used.* However, H exchange may be preferred if the aquifer contains a significant amount of expansible clays (Sodium Hazard), particularly if they are poorly cemented, or if only traces of carbonate minerals are present and degassing can be facilitated. Where siderite ($FeCO_3$) clogging may occur, acidification without degassing may decrease the concentration of $CO_3$ enough to bring the $SI_{siderite}$ to $\leq 0.3$ with minimal increases in dissolved Fe concentration at pH values above 5.

## $CO_2$ Injection

H2OTREAT starts with a high partial pressure of $CO_2$ and decreases it to determine the partial pressure of $CO_2$ in equilibrium with the original water sample. Then the partial pressure of $CO_2$ is increased incrementally** until the $SI_{calcite}$ is <0.3. The difference in moles of $CO_2$ between these two points is then converted to the amount of $CO_2$ (in mg/L) that must be dissolved in the water to prevent calcite precipitation. Because the dissolution of $CO_2$ is sensitive to total pressure as well as to the partial pressure of $CO_2$, the total pressure in the heat exchanger must be input, with a default of 1.5 atm (22.05 psi).

* Injection of hydrogen into the aquifer reduces the pH of the water, making carbonate more soluble. Although some calcium ions are replaced by hydrogen ions, the low pH water will have the capacity to dissolve additional carbonate during the storage cycle.

** The default increment is 0.2 of the log K (equilibrium constant) for the reaction. This increment can be changed from the DOS menu system or the control.fil (see Appendix A).

The software CO2* has been specifically developed to calculate the amount of $CO_2$ that must be injected to treat water. CO2 uses a SI threshold of 0.0 (compared to 0.3 for H2OTREAT) so it will estimate a larger treatment. The SI threshold for H2OTREAT can be changed using the control file.

## Fluidized-Bed/Pellet Reactor

Calcite can be removed from the water prior to its injection into the aquifer by a fluidized bed/pellet reactor. In the reactor, where high pumping rates cause fine-grained sand to be fluidized, calcite precipitation is enhanced by the high surface area of the fine sand [11]. If the SI for calcite is excessive, i.e. >2.5, very fine-grained precipitates may form in the aqueous phase and require sand filtration for their removal. If the water is still significantly oversaturated when it is injected, further precipitation may occur and clog the aquifer. The amount of $CaCO_3$ (in mg/L) to be removed is estimated from the initial concentration of Ca (in meq/L) and the fraction of water that must be treated at the particular temperatures by Na-exchange treatment.

## Nitrate Injection

In a low-nitrate environment, the *in situ* oxidation of reduced Fe and Mn can be accomplished by injecting nitrate upgradient from a source well. Microbial growth is stimulated when nitrate is added to low-nitrate environments, resulting in Fe2 and Mn2 oxidation [12]. However, in the absence of detailed data on Fe and Mn precipitation rates under such conditions and given the significant impact of DOC on the oxidation of Fe, it is wise to treat all of the water to be used in an ATES system. If $Fe(OH)_3(a)$** or birnessite ($\delta$-$MnO_2$) is oversaturated (SI $\geq$0.3), H2OTREAT warns the user that these minerals may precipitate unless treated.

## Cascade and VYREDOX Treatments

In the cascade treatment, water is aerated by dropping it on a cement apron partially covered with small rocks that provide oxide-coated surfaces to catalyze the oxidation of Fe2 and Mn2. Suspended precipitates are removed by passing the water through a slow sand filter. The treated water infiltrates the aquifer and creates a local body of treated water that is used as the source water for heating and storage in the aquifer.

* CO2 version 2.0 (1993). M. Koch, H. Nordsieck, H. Waldhauser, and W. Ruck, Institut für Siedlungswasserbau, University of Stuttgart. To obtain contact Michael Koch, Solweg 3, D-73066 Uhingen-Baiereck, Germany.

** $Fe(OH)_3(a)$ is amorphic $Fe(OH)_3$.

In the VYREDOX treatment [13], ground water is extracted, aerated, and reinjected in an outer circle of four to six wells. The water flows toward the source well, and although there is some mixing with local ground water, the water reaching the source well will have a significantly lower concentration of Fe (if the system is properly designed). In the case of eskers-type aquifers, the air-saturated water can be injected upgradient of the source well, as in the nitrate method.

## RUNNING THE CODE

H2OTREAT allows a user to perform the complex geochemical calculations required to design ATES water treatment systems without mastering the input and output data structures of a general purpose geochemical model. The geochemical model used in H2OTREAT is version 4.1 of the MINTEQ code [14]. The MINTEQ code is a thermodynamic model used to calculate solution equilibria for geochemical applications. Version 4.1 contains formulations for correcting equilibrium constants for the effect of temperature (from 0° to 300°C) and pressure. The MINTEQ User's Manual [15] describes the input files, input options, database files, and method for using the MINTEQ code. However, this information is not necessary for the operation of H2OTREAT.

### Data Requirements

Because the quantity of available water chemistry data varies widely, input data have been divided into Required and Optional. Required data are essential for a meaningful analysis and for the code to run correctly. Inclusion of certain optional data may result in a significant improvement in the reliability of the analysis. Both required and optional data are identified in Table 1.

The major cations (Ca, Mg, and Na) and major anions (Cl and $SO_4$) must be specified for the speciation calculations to be meaningful. The pH and sample temperature must always be specified for the aqueous speciation calculations and for the solubility calculations. The high and low temperatures are required to determine treatment requirements over a temperature range. If the sample, high, and low temperatures are all the same, the treatment will be determined for that one temperature only. Conductivity is needed to calculate the sodium hazard for the Na-exchange treatment. Although measured conductivity values are preferred, conductivity can be estimated from the relationship*

$$Conductivity(\mu mho/cm) = 100 * [cations_{Ca+Mg+Na+K+Mn}](meq/L). \quad (1)$$

A comparison of reported and calculated conductivities is given in Table 2. Alkalinity ($CO_3$, $HCO_3$, $H_2CO_3$) must be input because of the importance of the carbonates of Ca, Fe, and Mn and oxides of Fe and Mn as scale-forming agents. The pressure of the heat exchanger is necessary, and the head must be provided, especially if the water comes from depths of 500 ft (150 m) or more. For shallower depths, the head is of little consequence but still should be supplied.

* Derived from Figure 20 of [9].

It is important that the concentration of Si be included if the storage temperature exceeds 100°C, but Si is of little importance at lower temperatures. Iron and Mn may not be important where calcium carbonate scaling is the major problem, and so they are not required for the general case. However, well clogging in Sweden is increasingly being attributed to siderite, an Fe carbonate. In many waters, Fe and Mn oxides are the only important scale-forming agents; it is therefore always desirable to include Fe and Mn, and it is essential that they be included in areas where red or black precipitates are observed in water samples. It is doubtful that air can be totally excluded from an ATES system; hence, it is advisable to rerun H2OTREAT on the data set with an increased redox potential (Eh).

Providing optional data on chemical components is likely to increase the accuracy of the calculations. Potassium, $NH_4$, $PO_4$, and F concentrations are optional, not required, because they are rarely in high enough concentrations in ground water to exert a significant effect on Ca or $CO_3$ speciation. The concentrations of F and K are useful in that their presence increases the accuracy of the speciation calculations because of complex formation with metals and ionic strength effects, respectively. Similarly, although $NH_4$, $NO_3$, and $NO_2$ are not involved in any SI used to trigger the treatment requirement and have minimal effect on speciation calculations, they do provide valuable corroboration of a measured Eh value. The concentrations of Cl, S (i.e., $H_2S$, $HS^-$, $S^{2-}$), and $CO_2$ are important in the evaluation of corrosion potential. The concentrations of $CO_2$ and $CH_4$ are useful in that they may indicate the need for an increased back pressure to avoid degassing during injection.

If a required constituent is not available, a value from other analyses of the same aquifer can be used, with the recognition that the results will be significantly less reliable.

### Input File

The input file can be created manually or with the DOS menu system. The file contains both the aquifer data and the forms of measurement. The structure of this file is illustrated in Table 3.

### Starting H2OTREAT

To start H2OTREAT, type 'treat <*input filename*>' on the command line. *Filename* cannot have an extension in DOS, but can it in UNIX. The batch file *treat* creates the file *treat.out* from the input file, and MINDRIVE uses *treat.out* to run MINTEQ 4.1. In DOS, if the name of an existing file is given, H2OTREAT will allow the user to edit the existing data with the menu system. If the filename is new, H2OTREAT will create the file from data entered with the menu system. Since there is no menu system in UNIX, the user must create the input file manually.

After the user exits the menu system, H2OTREAT will determine the necessary treatments. The current treatment and its magnitude are displayed on screen to inform the user as to the progress of the solution. Each screen update is followed by "MINTEQ4 cycle complete" when the results of the treatment have been determined. When H2OTREAT finds the solution, it displays the output file (Exhibit 1).

## Menu Input

On DOS-based computers, H2OTREAT users have the option of using a menu system to create the input file. In the main menu, the up and down arrow keys are used to highlight a sub-menu. The sub-menu is then accessed by pressing ENTER. To return from a sub-menu to the main menu, the ESCAPE key is pressed. Each sub-menu has toggles and data inputs. Toggles are operated with the right and left arrow keys. Data are entered by highlighting the data input and typing the information. When the component form is changed, the related data values are automatically converted to the new form.

Exhibit 2 shows the layout of screens in the DOS menu system. The first selection on the main menu is used to access the Runtime Parameters screen. The next four selections allow the user to access the sub-menus used for data entry. The sixth selection allows the user to view values calculated by the program. The next option starts the treatment simulation. The last option quits the program without calculating any treatments.

The Runtime Parameters sub-menu allows the user to alter the treatment simulation execution guidelines. In this menu, the user can change the units of concentration between units of mg/L and mmol/L during data entry. The next option allows the user to change the filename used to save the input (for possible later use) and output data. The last item allows the user to change the size of the treatment increments (in percent). A small increment will yield more accurate results, but will take longer. A large increment will take less time, but the results will not be as accurate. The treatment increment range is from 1% (running time about 3 hours on a 386SX-25) to 20% (10 minutes on a 386SX-25), with a default value of 5%.

The Required Components sub-menu contains all of the data that are required for H2OTREAT. The major cations (Ca, Mg, Na), anions ($SO_4$, Cl) and pH are all in fixed forms. The range of pH is from 1 to 10. Conductivity can be input as either mS/m or $\mu$mho/cm (S=mho). Alkalinity can be input as either [$CO_3$] or [$HCO_3$], measured by titration or combustion. Temperature is entered as degrees Celsius or Fahrenheit. The sample temperature is the temperature at which the water quality was determined. The low and high temperatures are the minimum and maximum temperatures for which treatments will be evaluated. The heat exchanger pressure can be entered as psi or mbar, and has a default value of 22.05 psi (1500 mbar or 1.5 atm). Table 4 can be used for manual conversions.

The Optional (Alternative Form) Components sub-menu allows the user to enter optional data that are measured and recorded in many forms. For instance, $NH_4$, $NO_2$, and $NO_3$ can be entered as [$NH_4$], [$NO_2$], and [$NO_3$], respectively, or each can be entered as [N]. Iron can be entered as total iron and a redox potential ([Fe(tot)] & Eh (mV)), or as [Fe2] and [Fe3]. Although the initial SI calculations of Fe carbonates are made at the measured Eh value, if the waters contain elevated levels of Fe, the prime concern is likely to be the possible precipitation of oxides/hydroxides of these metals. Therefore with Fe concentrations of >0.1, sensitivity analyses on oxide precipitation are advisable. These analyses can be performed by increasing the Eh (in 50- or 100-mV increments; Eh has an allowable range of -400 to 800). Sulfur can be entered as [S], [HS], or [$H_2S$]. Silicon can be entered as [Si], [$SiO_2$], or [$H_4SiO_4$].

The Optional (Fixed Form) Components sub-menu allows the input of optional data that are measured only one way. These components include [K], [Mn2], [$PO_4$], [F], $pCO_2$ and $pCH_4$ (in mbar). Manganese is entered as Mn2 because the maximum concentration of Mn3 or Mn4 is very small. As in the case of Fe, if the concentration of Mn is >0.1, sensitivity analyses are advisable. The $pCO_2$ and $pCH_4$ (partial pressures of $CO_2$ and $CH_4$) have allowable ranges of 0.00001 to 1.

The Aquifer and Physical Properties sub-menu allows the user to input data about the physical properties of the aquifer. The carbonate minerals and expansible clays (in percent), dissolved organic carbon, and degassing observed options are not used in the current version of H2OTREAT. Head can be entered as feet or meters. Head has a range of 0.1 to 3500 feet; its default value is 100 feet (since it is still required but not relevant under 500 feet).

The Calculated Values sub-menu shows certain calculated values that may be useful to the user. The Total Sediment Iron is not used by this version of H2OTREAT. The Sum of Base Cations can be used to calculate the conductivity if one is not reported in the water analysis. The Sodium Hazard reported here is calculated without the sodium exchange treatment.

When all components have been entered, select FINISHED ENTERING PARAMETERS from the main menu. If all required components have been entered, this selection will save the data to the named file, exit the menu system, and proceed with the calculation phase of H2OTREAT. If any required components have not been entered, the cursor will move to the first "missing*data" in the Required Components sub-menu and allow the user to enter the missing values of required components. The user may also exit without any calculations or saving data by selecting ABORT from the main menu.

## Output File

Exhibit 1 is an example of the output generated by H2OTREAT. The output file is named *filename.tbl*, as specified by the user. The extent of each treatment required to prevent scaling for each of the design temperatures is provided (for ion exchange treatments, results are given in fraction of water treated; those for other treatments are given in mg/L). The reported treatment requirement has an error of -x%, where x is the treatment increment specified by the user, e.g., 75% treatment actually means 70-75% when estimated using 5% increments.

Under the heading "Hazard", the letters N, H, and C are used to indicate that oxides are calculated to be oversaturated for specific temperatures of Na exchange, H exchange, and $CO_2$ treatment, respectively. The same symbols are used if corrosion is likely for the treatment in question. The degree of sodium hazard for the sodium exchange treatment is also indicated. If no oxides are oversaturated or if corrosion is not likely, a dash is inserted instead of N, H, or C. If no treatment is required for the highest temperature and no oxides will precipitate, the output file contains the words "No treatment is required." If no treatment is required but oxides will precipitate, the output file contains the words "No treatment for carbonates required but treatment for Fe and/or Mn required."

In addition to the treatment summary shown in Exhibit 1, H2OTREAT can create supplementary output for use in debugging. The file *input.h2o* is a listing of all the MINTEQ 4.1 input files. The file *filename.sat* is a listing of all the saturation indices of the minerals of interest. The file *output.h2o* is a listing of all the MINTEQ 4.1 output files (it can reach a size of 20 MB). By default *input.h2o* and *output.h2o* are not created by H2OTREAT. To have H2OTREAT create these files, the batch file *treat* must be edited. In the DOS batch file lines 48 and 49 must be un-remarked. In the UNIX batch file lines 40 and 41 must be un-remarked. By default *filename.sat* is created.

## Sensitivity Analysis

A sensitivity analysis was carried out using values that represent common analytical uncertainties in the input values. As can be seen in Table 5, the resultant changes in percent treatment required all appear reasonable.

The dependence of calcite saturation on temperature is illustrated by calculating the SI at progressively higher temperatures for a water that has a SI of about 0.2 at ambient ground water temperature. As shown in Figure 1, the extent of oversaturation has increased severalfold at 100°C. Pressure has much less effect than temperature, amounting to an increase in calcite SI of about 0.1 as the water head increases from 10 to 3000 feet (Figure 2).

## APPENDIXES

### Appendix A: Mindrive Control File start.ctl

The file *start.ctl* controls certain aspects of the treatment requirement calculations performed by H2OTREAT. In the DOS menu system, the "Treatment increments" value is used to change line 2 in the *start.ctl* file. For UNIX-based users, the only way to change the execution parameters of H2OTREAT is by direct modification of this file. An asterisk indicates lines used during calculations only; modifying them has no effect.

| Value | Description |
|---|---|
| 2 | Number of temperatures |
| 20 | Number of Na and H exchange treatment intervals (a value of 20 implies 5% increments) |
| T | *Do two-temperature run at start |
| F | Start with $CO_2$ injection treatment (calculates CO2 only) |
| F | Start with H-exchange treatment (calculates H and CO2) |
| T | Start with Na-exchange treatment (calculates Na, H, and CO2) |
| 0 | *Current temperature |
| 0 | *Current treatment increment |
| 0.3 | Saturation indices threshold |
| 0 | *Calcite SI |
| 0 | *Rhodochrosite SI |
| 0 | *$Fe(OH)_3(a)$ SI |
| 0 | *Birnessite SI |
| 0 | *Chalcedony SI |
| 0 | *$SiO_2$ SI |
| 0 | *Siderite SI |
| 0 | *Ca in meq |
| 0 | *Mg in meq |
| 0 | *Na in meq |
| 0 | *Fe2 in meq |
| 0 | *Fe3 in meq |
| 0 | *Mn2 in meq |
| 0 | *H in meq |
| 0 | *K in meq |
| 18.4 | Current $CO_2$ log K value |
| 0.2 | Current $CO_2$ log K increments |
| 0.0 | *Moles of $CO_2$ |
| 18.4 | Starting $CO_2$ log K value |
| 0.2 | Starting $CO_2$ log K increments |

### Appendix B: Files Included in H2OTREAT

| MINTEQ 4.1 | H2OTREAT | TEMPORARY |
|---|---|---|
| DOS Version | | |
| MINTEQ4.EXE | MINDRIVE.EXE | CONTROL.FIL |
| ALK.DAT | STRIP.EXE | MINOUT.DAT |
| AQUEOUS.DAT | TABLE.EXE | SAMPLE.DAT |
| COMP.DAT | TREAT.BAT | SUM.H2O |
| GAS_RDX.DAT | START.CTL | TEMP.DAT |
| PRCOEF.DAT | TABLE.BLK | TREAT.OUT |
| SOLIDS.DAT | SCREEN.EXE | OUTPUT.H2O |

| | SAT.BLK | INPUT.H2O |
|---|---|---|
| UNIX Version | | |
| minteq4 | mindrive | control.fil |
| alk.dat | table | minout.dat |
| aqueous.dat | treat | sample.dat |
| comp.dat | start.ctl | sum.h2o |
| gas_rdx.dat | table.blk | temp.dat |
| prcoef.dat | strip | treat.out |
| solids.dat | sat.blk | output.h2o |
| | | input.h2o |

ACKNOWLEDGMENTS

This work, supported by the U.S. Department of Energy, is part of the Thermal Energy Storage Program at the Pacific Northwest Laboratory. The Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

REFERENCES CITED

1. E.A. Jenne, O. Andersson, and A. Willemsen, 1992, "Well, Hydrology, and Geochemistry Problems Encountered in ATES Systems and Their Solutions", Paper no. 929153 in 27th Intersociety Energy Conversion Engineering Conference Proceedings P-259, Vol. 4, pp. 4.77-4.88. American Society of Automotive Engineers, Warrendale, Pennsylvania.

2. A. Willemsen and C.A.J. Appelo, 1985, "Chemical Reactions During Heat Storage in Shallow Aquifers in the Netherlands: Laboratory Experiments and Geochemical Modeling", in Hydrogeology in the Service of Man, Memoirs of the 18th Congress of the International Association of Hydrologists, part 4, pp. 68-78.

3. A. Banck, 1989, Lomma Pilot ATES Plant: Experiences and Results, Report 29-E, Annex VI, International Energy Agency, VBB, Malmö, Sweden.

4. J.C. van Dijk and D. Wilms, 1990, "Water Treatment Without Waste Material: The Dutch Experiences with Pellet Reactors", in Ontharding van drinkwater, Proceedings of a Studieday in Antwerpen, Belgium, December 11, 1990, Technologish Institute KVIV Genootschap Milieutechnologie, Antwerpen, Belgium.

5. J. Griffioen, 1992, Cation-Exchange and Carbonate Chemistry in Aquifers Following Groundwater Flow. Jasper Griffioen, Amsterdam.

6. E.A. Jenne, 1990, "Aquifer Thermal Energy Storage: The Importance of Geochemical Reactions", in J.C. Hooghart and C.W.S. Posthumus (eds), Hydrochemistry and Energy Storage in Aquifers, Proceedings and Information No. 43, p. 19-36, TNO Committee on Hydrologic Research, The Hague, Netherlands.

8. F.O. Jones, 1964, "Influence of Chemical Composition of Water on Clay Blocking of Permeability", Journal of Petroleum Technology, Vol. 16, p. 441-446.

7. F.J. Molz, A.D. Parr, and P.F. Angersen, 1981, "Thermal Energy Storage in Confined Aquifer: Second Cycle", Water Resources Research, Vol. 17, p. 641-645.

9. L.A. Richards, 1954, Diagnosis and Improvement of Saline and Alkali Soils, U.S. Department of Agriculture, Handbook no. 60, U.S. Government Printing Office, Washington, D.C.

10. M.L. Jackson, 1958, Soil Chemical Analysis, Prentice-Hall, Englewood Cliffs, New Jersey.

11. O. Andersson, 1991, Scaling and Corrosion, Final Report on Subtask E, Annex XI, International Energy Agency. VBB VIAK, Malmö, Sweden.

12. V. Vanek, 1990, *In situ* Treatment of Iron-Rich Groundwater by the Addition of Nitrate, ISSN 1100-6366, Department of Ecology, University of Lund, Lund, Sweden.

13. R.O. Hallberg and R. Martinel, 1976, "VYREDOX-*In situ* Purification of Ground Water", Ground Water, Vol. 14, p. 88-93.

14. L.E. Eary and E.A. Jenne, 1992, Version 4.00 of the MINTEQ Geochemical Code, PNL-8190, Pacific Northwest Laboratory, Richland, Washington.

15. S.R. Peterson, C.J. Hostetler, W.J. Deutsch, and C.E. Cowan, 1987, MINTEQ User's Manual, NUREG/CR-4808, PNL-6106, U.S. Nuclear Regulatory Commission, Washington, D.C.

TABLES

Table 1. Required and Optional Data (brackets signify concentrations)

| Required | Optional |
|---|---|
| [Ca] | [K] |
| [Mg] | [$NH_4$] |
| [Na] | [Mn] |
| [$SO_4$] | [Fe2] |
| [Cl] | [Fe3] |
| pH | [F] |
| Conductivity | [$PO_4$] |
| Head | [$NO_2$] |
| Sample Temperature | [$NO_3$] |
| High Temperature | [Si] |
| Low Temperature | [S] |
| Alkalinity | [DOC] |

Table 1. (cont'd)

| | |
|---|---|
| Heat-Exchanger Pressure | Eh |
| | Partial Pressure $CO_2$ |
| | Partial Pressure $CH_4$ |
| | % $CO_3$ Minerals in Aquifer |
| | % Expansible Clays |
| | Degassing Observed? |

Table 2. Comparison of Calculated and Reported Conductivities

| ATES Site | Total Cations (meq/L) | Calc. Cond. ($\mu$S/cm) | Reported Cond. ($\mu$S/cm) |
|---|---|---|---|
| Saskatoon Airport, Canada | 29.6 | 2,960 | 2,640 |
| Toronto, Canada | 2.5 | 250 | 280 |
| Almere, Netherlands | 147.2 | 14,720 | 13,230 |
| Bunnik, Netherlands | 3.5 | 350 | 360 |
| Delft, Netherlands | 39.2 | 3,900 | 4,080 |
| Biblioteket in Malmö, Sweden | 39.9 | 3,990 | 3,700 |
| St. Paul, Minnesota, U.S.A. | 4.7 | 470 | 424 |

Table 3. Structure of Input File. Concentrations [shown in brackets] are in mg/L by default.

| Line | Value | Comments |
|---|---|---|
| 1 | 1 | Units: 1 = mg/L |
| 2 | [Ca] | Calcium |
| 3 | [Mg] | Magnesium |
| 4 | [Na] | Sodium |
| 5 | [SO4] | Sulfate |
| 6 | [Cl] | Chloride |
| 7 | pH | |
| 8 | 'mS/m' | Conductivity as |
| 9 | Conductivity | |
| 10 | 'Combustion' or 'Titration'[a] | Alkalinity by |
| 11 | 'CO3' | Alkalinity as |
| 12 | [Alk] | Alkalinity |
| 13 | 'Celsius' | Temperature as |
| 14 | SampleT | Temperature of aquifer water sample |
| 15 | LowT | Lowest value of temperature range |
| 16 | HighT | Highest value of temperature range |
| 17 | 'feet' | Heat exchanger pressure as |
| 18 | $P_{Hx}$ | Heat exchanger pressure |
| 19 | 'NH4' | Ammonium as |
| 20 | $[NH_4]$ | Ammonium |
| 21 | 'NO2' | Nitrite as |
| 22 | $[NO_2]$ | Nitrite |
| 23 | 'NO3' | Nitrate as |
| 24 | $[NO_3]$ | Nitrate |
| 25 | 'Fe2_&_Fe3' or 'Fe(tot)_&_Eh' | Iron as |
| 26 | [Fe2] or [Fe(tot)] | Fe2 or Total iron |
| 27 | [Fe3] or Eh | Fe3 or Redox potential in millivolts |
| 28 | 'HS' | Sulfur as |

Table 3. (cont'd)

| | | |
|---|---|---|
| 29 | [S] | Sulfur |
| 30 | 'H4SiO4' | Silicon as |
| 31 | [Si] | Silicon |
| 32 | [K] | Potassium |
| 33 | [Mn2] | Manganese |
| 34 | $[PO_4]$ | Phosphate |
| 35 | [F] | Fluoride |
| 36 | $P_{CO_2}$ | Partial pressure $CO_2$ in mbar |
| 37 | $P_{CH_4}$ | Partial pressure $CH_4$ in mbar |
| 38 | %carb | % Carbonate minerals[b] |
| 39 | %expa | % Expansible clays[b] |
| 40 | DOC | Dissolved organic carbon[b] |
| 41 | 'maybe', 'yes', or 'no' | Degassing observed[bc] |
| 42 | 'feet' | Head as |
| 43 | head | Head in aquifer |
| 44 | | Total sediment iron[d] |
| 45 | | Sodium adsorption ratio[d] |
| 46 | | Sum of base cations[d] |
| 47 | | Sodium hazard[d] |

[a] The geochemical model corrects for non-carbonate alkalinity when the alkalinity is determined by acid titration. If the method of determining alkalinity is not known, use acid titration, which is the more common method of alkalinity determination.

[b] These variables are not used in the current H2OTREAT version.

[c] Oversaturation of the aquifer with $CO_2$ may be indicated by an increase in pH immediately after sample collection or by a laboratory pH that is significantly higher than that found in the field. Conversations with drilling personnel or the on-site geologist may indicate that gas bubbles were observed immediately after water samples were retrieved. If there is a significant possibility that the aquifer is over-pressured with $CO_2$, it is advisable to run a sensitivity analysis by incrementally increasing the partial pressure of $CO_2$.

[d] Values calculated by the DOS-menu system. These are left blank when the input file is created manually.

Table 4. Unit Conversions

Pressure

1 psi = 2.30673 feet (of $H_2O$)
1 mbar = 0.03346 feet (of $H_2O$)
1 atm = 33.8995 feet (of $H_2O$)

Length

1 foot = 0.3048 meter

Conductivity

1 mS/m = 10 $\mu$mho/cm

Table 5. Sensitivity Analysis Results

| Treatment | Temp °C | Na % | H % | $CO_2$ mg/L | Fluid Bed mg/L | Hazard Fe | Mn | Si | Corrosive | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| Ca -15% | 120. | 94. | 36. | 310 | 143 | --C | --- | --- | NHC | low |
| | 20. | 74. | 4. | 7 | 113 | N-- | --- | --- | NHC | low |
| Ca +15% | 120. | 96. | 34. | 302 | 194 | -HC | --- | --- | NHC | low |
| | 20. | 82. | 4. | 7 | 165 | NH- | --- | --- | NHC | low |
| Mg -15% | 120. | 96. | 36. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Mg +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Na -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Na +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| $SO_4$ -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| $SO_4$ +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Cl -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Cl +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Mn -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Mn +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| $PO_4$ -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| $PO_4$ +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| F -15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| F +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| temp -2.5 | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 76. | 4. | 7 | 133 | NH- | --- | --- | NHC | low |
| temp +2.5 | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 80. | 4. | 7 | 140 | NH- | --- | --- | NHC | low |
| head -250 ft | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| head +250 ft | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| pH -0.15 | 120. | 94. | 34. | 303 | 165 | -HC | --- | --- | NHC | low |
| | 20. | 62. | 2. | 7 | 109 | NH- | --- | --- | NHC | low |
| pH +0.15 | 120. | 96. | 36. | 303 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 86. | 4. | 12 | 151 | NH- | --- | --- | NHC | low |
| Eh -15 mV | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | N-- | --- | --- | NHC | low |
| Eh +15 mV | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Cond -5 mS | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| Cond +5 mS | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |
| $CO_3$ -15% | 120. | 94. | 30. | 300 | 165 | -HC | --- | --- | NHC | low |
| | 20. | 76. | 2. | 7 | 133 | NH- | --- | --- | NHC | low |
| $CO_3$ +15% | 120. | 96. | 40. | 327 | 168 | --C | --- | --- | NHC | low |
| | 20. | 80. | 4. | 18 | 140 | NH- | --- | --- | NHC | low |
| Fe -15% | 120. | 96. | 34. | 302 | 168 | --C | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | N-- | --- | --- | NHC | low |
| Fe +15% | 120. | 96. | 34. | 302 | 168 | -HC | --- | --- | NHC | low |
| | 20. | 78. | 4. | 7 | 137 | NH- | --- | --- | NHC | low |

EXHIBITS

Exhibit 1. Sample Output

| Temp | Treatment: Exchange | | CO2 | Fluidized Bed | Hazard: Oxides | | | Corrosive | Sodium |
|---|---|---|---|---|---|---|---|---|---|
| | Na | H+ | | | Fe | Mn | Si | | |
| °C | % | % | mg/L | mg/L | | | | | |
| 120. | 85. | 20. | 70.0 | 122. | --- | --- | --- | NHC | high |
| 100. | 75. | 10. | 42.0 | 108. | -HC | --- | --- | NHC | high |
| 80. | 45. | 5. | 26.0 | 65. | NHC | --- | --- | NHC | medium |

Exhibit 2. Menus in the DOS Menu System

**Main Menu**

Runtime Parameters
Required Components
Optional (Alternative Form) Components
Optional (Fixed Form) Components
Aquifer and Physical Properties
View Calculated Values
FINISHED ENTERING PARAMETERS
ABORT

Use arrows or First letter to move to selection
Hit ENTER to make your choice

**Optional (Alternative Form) Components (mg/L or mmol/L)**

```
          Ammonium
   Ammonium as          -  NH4 (or N)
   Ammonium             :  _____
Nitrite
   Nitrite as           -  NO2 (or N)
   Nitrite              :  _____
Nitrate
   Nitrate as           -  N03 (or N)
   Nitrate              :  _____
Iron
   Iron as              -  Fe2_&_Fe3 (or
                           Fe(tot)_&_Eh)
   Ferrous          Fe2:   _____
   (or Total Iron)  Fe(tot)
   Ferric           Fe3:   _____
   (or Redox Potential) mV
Sulfur
   Sulfur as            -  HS (or S or HS)
   Sulfur               :  _____
Silicon
   Silicon as           -  H4SiO4 (or Si or SiO2)
   Silicon              :  _____
```

Use ESCape to leave entry screen

**Aquifer and Physical Properties**

```
Carbonate minerals          %:  _____
Expansible clays            %:  _____
Dissolved organic carbon(mg/L): _____
Degassing observed          -   maybe (or yes or no)

Head
   Head as                  -   feet (or meters)
   Head                     :   100*
```

Use ESCape to leave entry screen

* Default Values.

**Runtime Parameters**

```
Units                    -  mg/L (milligrams/liter)
                            or mmol/L (millimoles/liter)
Output file              :  _____
Treatment increments %:     _____
```

Use ESCape to leave entry screen

**Required Components (mg/L or mmol/L)**

```
Calcium                 Ca:  missing*data
Magnesium               Mg:  missing*data
Sodium                  Na:  missing*data
Sulfate                SO4:  missing*data
Chloride                Cl:  missing*data
pH                        :  missing*data
Conductivity
   Conductivity as        -  mS/m (or µmho/cm)
   Conductivity           :  missing*data
Alkalinity
   Alkalinity by          -  Titration (or Combustion)
   Alkalinity as          -  CO3 (or HCO3)
   Alkalinity             :  missing*data
Temperature
Temperature as            -  Celsius (or Fahrenheit)
   Sample Temperature     :  missing*data
   Low Temperature        :  missing*data
   High Temperature       :  missing*data
Heat Exchanger Pressure
   Pressure as            -  psi (or mbar)
   Pressure               :  22.05*
```

Use ESCape to leave entry screen

**Optional (Fixed Form) Components (mg/L or mmol/L)**

```
Potassium               K:  _____
Manganese              Mn:  _____
Phosphate             PO4:  _____
Fluoride                F:  _____
Partial Pressures (mbar)
   Carbon dioxide     CO2:  _____
   Methane            CH4:  _____
```

Use ESCape to leave entry screen

**Calculated Values**

```
Total Sediment Iron           :  missing*data
Sodium Adsorption Ratio       :  missing*data
Sum of Base cations (meq)     :  missing*data
Sodium Hazard                 :  missing*data
```

Use ESCape to leave entry screen

FIGURES

Figure 1. Variation in Calcite Saturation Index with Temperature

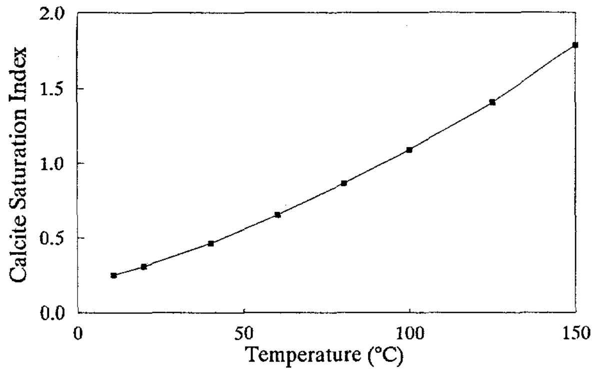
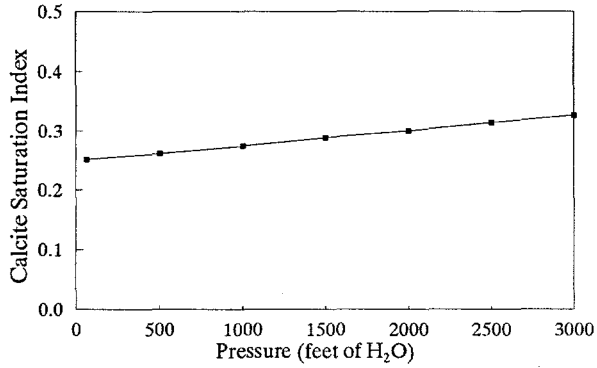



Figure 2. Variation in Calcite Saturation Index with Pressure



INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# MANAGES: A Personal Computer Software for the Management and Evaluation of Groundwater Monitoring Data

•Dan V. Patel
Southern Company Services
Consulting and Testing Service
Birmingham, Alabama, USA

## ABSTRACT

Thermal energy storage in aquifers poses many challenges. One of the most important is timely detection of adverse changes in groundwater chemistry resulting from hot water storage in an aquifer. Such changes can cause a significant increase in the rate of fouling of wells, piping and heat exchange equipment. The fouling in turn reduces the efficiency of the energy storage project. This paper presents the capabilities of an innovative personal computer program called MANAGES™ that simplifies the detection of groundwater chemistry changes using graphical and statistical methods. The methods presented should provide a means for early detection of changes in geochemical conditions that could develop over time in an energy storage aquifer. The author assumes that groundwater monitoring data are being collected from wells or piezometers so that detailed data analyses can be performed.

The MANAGES code provides a means of efficiently managing and interpreting groundwater monitoring data. While originally developed for addressing environmental groundwater monitoring requirements, the MANAGES program is equally suitable for energy storage project applications. The code allows management of data from surface water monitoring points, piezometers, field replicates, and blank quality assurance samples. The usefulness of the code lies in its ability to easily retrieve, view, sort and report data, and in being able to quickly perform a wide range of graphical and statistical data evaluations. Features include easy checking of data quality, detection and assessment of data trends over time, cross-correlations between wells for a single measured parameter, and correlations between multiple parameters at a well. Data entry using MANAGES is fully menu-driven, with field-specific help information. Data import and export through ASCII files are also available.

## INTRODUCTION

Changes in aquifer chemistry can occur slowly over a long period of time. The effect of the changes, however gradual, may be real in terms of increased thermal energy storage equipment fouling and degradation of performance. The purpose of this paper is to describe how a computer program called MANAGES™ can be applied to readily detect chemistry changes for discrete groundwater monitoring points (or wells), and changes in the differences in chemistry between monitored points. Once potentially adverse changes in groundwater composition are identified, action can be taken to protect equipment or step up equipment cleaning schedules before excessive fouling or damage occurs.

MANAGES, Version 1.0, operates on IBM-compatible personal computers (386 or higher) equipped with EGA or VGA video card, and 560K available memory. The code also operates on local area networks, allowing easy sharing of data. MANAGES supports data storage, management, analysis, and reporting, as summarized briefly in the following paragraphs and Figure 1.

### Data Storage and Management

Capabilities are provided for storage and management of data that describe the facility, groundwater wells, analytical parameters, field and laboratory sample analysis results, and regulatory permit limits. Permit limits are generally used for compliance with environmental monitoring applications, and need not be used for energy storage data management. There are no coded limits on the number of wells or parameters that can be managed.

MANAGES contains a database of commonly used groundwater monitoring parameters. Additional parameters may be added as needed.

MANAGES allows addition of new sites, wells, and monitoring results at any time. Data integrity checks prevent inadvertent deletion of information or unwise modification of attributes for existing parameters. MANAGES also allows entry of confidence band information for parameters such as radionuclides. The program accommodates "N/A" entries for parameters that were not entered because data were not available or applicable for that sample, zeros for "non-detects," and "less than" values for parameters that may not have been detected due to limitations of analytical methods.

### Data Analysis and Reporting

Data graphics show variation of parameter concentrations as a function of time or space. For example, up to four parameters may be displayed for a single well to evaluate possible interparameter relationships. Alternatively, plots may be graphed with up to four wells for a single parameter. Both line and bar chart styles are available for most graphs. Graphics also allow viewing of certain statistical measures, including Sen slope line and standard deviation values. When well coordinates are entered in MANAGES, area plots (z-plots) of parameter values and statistical measures can be displayed for up to 15 wells to show spatial relationships. Graphics control features facilitate study of seasonal groundwater quality changes by allowing seasonally averaged data to be plotted. Seasons may be defined as one month, two months, quarter, biannual, or annual.

Statistical analyses (Appendix A) can be used for single well or multi-well tests to detect significant changes in groundwater quality. In addition to standard statistical measures (e.g., mean, standard deviation, maximum/minimum), three tests for data trends over time are available: the Mann-Kendall test; Sen estimate of slope; and linear regression. Other statistical tests include: a calculation of data excursion probability, defined as the percentage of the data values that exceed a specified upper permit limit; a test for data seasonality using the Kruskal-Wallis test; well mean comparison for groups of three or four wells using the Kruskal-Wallis test; a test for data normality using the Shapiro-Wilk W test; and tests for differences in chemical concentrations in well pairs using the Mann-Whitney U test (nonparametric) and the Student-t test (parametric). These data analysis approaches are widely used for evaluation of water quality data. In addition to providing the numerical results of statistical tests, MANAGES provides easily understood bottom-line interpretations of the numbers.

Reports are designed to provide information that is readily usable for data analysis and verification. For example, data overview reports that summarize *all* data stored for each well help verify data entry. Reports listing all exeedances above the data entry limits or permit limits help to quickly identify data entry or water quality problems. MANAGES' statistical analyses and data sorting features produce reports allowing study of trends in water quality over time to identify potential future water quality problems.

### Program Structure

MANAGES stores site data and sample results using eight databases. The Site and Parameters databases are global and are maintained in the MANAGES directory. The Site database stores basic name and address information for each site. The Parameters database contains identification codes, analysis methods, and units of measure for more than 100 parameters.

Six databases used for site-specific data are maintained in a subdirectory for each site.

The Wells database contains physical attributes of and descriptive information about wells, piezometers, and surface water monitoring points.

The Permit Limits database contains concentration limits that may be specified in a site's operating permit, and is used to compare site water quality data to regulatory limits and to prepare limits exception reports.

The Entry Limits database contains upper and lower limits that can be used to identify potential data-outliers. Entry limits can be based on permit limits, historical minima and maxima tabulated by the program, standard deviations tabulated by the program, or user-defined values.

Sample data are stored in two databases. The Sample Description database contains sampling dates, sampling point identification, sample identification, analytical lab names, sampling and well-purging methods, space for reporting field tests such as pH, water level, and temperature, and space for comments. The Sample Parameters database contains analytical results and brief descriptions of methods used for each parameter tested in a given sample.

The Parameter List database contains user-specified lists of parameters, which can be used to simplify entry to the Sample Parameters database.

All databases use the DBase III™ .dbf file format.

## USING MANAGES

Several graphical and statistical tests are available for examining data stored in the Sample Parameters database (sample detail screen). These options are all available under the Interpret menu.

### Data Interpretation

A choice of two graphic presentation styles are available in most cases – line chart or bar chart. In line chart form, lines join data points on the graph, with each well's data series having a different color, or a different texture on black and white laser printer output. For bar chart form, data are presented as vertical bars centered at each time marker on the x-axis. Each data series has a different color or different texture.

Programmed graphics and statistical analysis capabilities use only "active" data values residing in sample detail records under "active" samples. If a sample is inactivated, all of its' parameter values are also inactivated. Note that analytical results stored as "less than" values are treated as one-half the "less than" value in all graphs and statistical calculations. Lists of data used in graphs and statistical calculations do not indicate whether values were derived from a "less than" value.

The following tests are grouped by single-well or multi-well applications. Detailed descriptions and references for statistical tests discussed in these applications are presented in Appendix A.

## SINGLE WELL INTERPRETATION

Single well interpretations are used for analyzing trends of a single parameter over time and correlating fluctuations among parameters over time.

### Graph of Parameter Value vs. Time for One to Four Parameters at a Single Well

Objective: Seasonal and temporal trends; outlier detection. Both line graph and bar chart forms are available for the single parameter graph – only line graph form is available if more than one parameter is selected. The graphs for one well and two wells are shown in Figures 2-4. Figure 2 illustrates how an outlier value does not affect the Sen estimate of slope, correctly indicating zero trend. Figure 4 shows an upward trend for sulfate, as indicated by the Sen estimate of slope. The graphing of more than one parameter for a well helps to detect possible correlations that would otherwise go unnoticed. Figure 3 shows how total dissolved solids are not anomolously high in the sample that is exhibiting high sulfate.

### Data Frequency Distribution Graph for One Parameter at a Single Well

Objective: Data normality assessment. Only bar chart form is available. If a permit value is stored for the relevant groundwater class and parameter, the permit value is shown as a vertical line on the graph.

### Data Frequency Distribution Report for One Parameter at a Single Well

Objective: Data normality assessment; outlier detection. Report listing the number of data values in each of the parameter value ranges.

### Detailed Statistics and Trend Analysis Report for One Parameter at a Single Well

Objective: Detection of temporal and seasonal trends; data normality. Report listing general statistical data, including mean, median, minimum and Sen's estimate of slope for parameter trend in time, and statistical test for seasonality in data; if data averaging is not requested on the Interpret menu, test statistical analyses.

### Statistical Summary Report for One to Four Parameters at a Single Well

Objective: General statistical information; outlier detection. Report listing mean, median, maximum, minimum, standard deviation and relative standard deviation of selected parameters.

### Data Sorting Report by Value or Date for One Parameter at a Single Well

Objective: Data completeness; outlier detection; data verification. Report listing parameter values sorted either in chronological order using sampling date, or by magnitude using parameter values.

### Data Summary of All Parameters at a Single Well

Objective: Database completeness. Report tabulating all parameter values for a well by sampling date.

## MULTI-WELL INTERPRETATION

Multi-well interpretations are used for evaluation of single parameter trends over time, statistical differences in parameter values at two wells, and spatial distributions of parameter values (or means, maxima, etc.).

### Graph of One Parameter at Multiple Wells

Objective: Parameter correlations. Line graph and bar chart are both available. Line graphs show all data points within the selected period. Bar charts show average value for the parameter over the selected period. When statistical tests comparing wells indicate significant differences for a parameter, a graph such as the one shown in Figure 5 helps to visualize the variation over time.

### Area (Z) Plot of Analysis Result or Statistical Value for One Parameter

Objective: Spatial distribution of data or statistical results. Z-plots display the areal distribution of ONE statistical result (e.g., value, mean, median, maximum, minimum, standard deviation, or relative standard deviation) for 1 to 15 wells. Wells are represented by symbols on an x-y plot, with each well identified by its well number. The northing-easting coordinates of each well are used as x-y values. The z value appears immediately beneath the appropriate well number. When looking at analysis results from one sampling event, choose the "value" option and a single sampling date. If a range of sample dates are selected, all values for the selected parameter recorded during that time span are averaged.

### Statistical Comparison of One Parameter at Two Wells

Objective: Difference in means/medians. Report listing general statistics for two wells (means, medians, etc.), a nonparametric comparison of well medians, a parametric comparison of well means (assuming data normality and equal variances in the two data sets), and a list of data used in the statistical analyses. The non-parametric and parametric comparison tests are repeated with data seasonality removed. Data averaging is automatically selected for two well comparisons.

### Statistical Comparison of One Parameter at Three or Four Wells

Objective: Difference in well means in a group of three or four wells. Report that identifies whether one well mean is significantly greater than one or more of the other well means. The test performed is the Kruskal-Wallis test. The test can help ensure, for example, that a group of wells can be treated as background wells.

### Statistical Summary of One Parameter at Multiple Wells

Objective: General statistical information; outlier detection. Report listing mean, median, maximum, minimum, standard deviation and relative standard deviation of a parameter at selected wells.

### Summary of Analysis Results for One Parameter at All Wells

Objective: Data completeness. Report tabulating all well samples for a specified parameter by date. If more than one parameter value is stored for a given well and sampling date, each parameter value is reported regardless of the status of the active/inactive flags of the samples and parameter.

### Limit Exceptions Report Using Permit or Entry Limits

Objective: Detect values outside permit or entry limits. Report listing all parameters with analysis results outside either the limits set for data entry or the limits specified in the permit. Both upper and lower limits are used in report generation. For parameter values stored as "less than" values, only the upper permit limit or the upper entry limit is used.

### Site Data Overview Report for All Parameters at All Wells

Objective: Database completeness. Report tabulating the number of wells defined for the site, the total number of active data values stored, the first and last sampling dates for "active" samples stored, and the number of "active" samples on a well-by-well basis.

## REPORTS

A number of data reports are available under Reports in the main menu. These reports are designed to help verify data entry. They do not include any statistical calculations, and, as such, list all stored parameter data, even if the data are inactive for graphics and statistics.

Analysis Results by Well Report provides a tabulation of all parameter values as a function of sampling date for a specified well.

Analysis Results by Parameter Report provides a listing of all data at all wells for a specified parameter.

Sample Database Report provides a compilation of all field and laboratory analysis data and information stored for each sample, for one well or for all wells.

Well Database Report provides a means of verifying descriptive well information.

Parameter Database (S) Report provides a complete list of all parameter definition information, using short parameter names.

Parameter Database (L) Report provides a complete list of all parameter definition information, using long parameter names.

Parameter List Database Report provides a compilation of parameters in each parameter list used for data entry.

Permit Limits Database Report lists all permit limits stored for all parameters on a groundwater class-specific basis. The type and effective dates of permit limits are also given.

Entry Limits Database Report lists all stored data entry limits for parameters on a groundwater class-specific basis.

## CUSTOMIZING REPORTS

R&R Report Writer™ personal computer software has been used successfully to design and save report formats that access MANAGES database files directly. This and other programs may be used to read MANAGES databases and report results in custom forms which may be required for special applications.

## DIRECT EDITING OF DATABASE FILES

It is possible to directly edit database files used by MANAGES using certain spreadsheets, generic database programs, and word processors that are able to read DBase III™ files. The most common reason for such a need will be for changes in parameter units and codes.

## APPENDIX A. OVERVIEW OF STATISTICAL TESTS IN MANAGES™

### Sen Estimate of Slope

The Sen estimate of slope is the median of all slopes between all possible unique pairs of individual data points in the time period being analyzed [1]. The slopes represent rate of change of the measured parameter, with the y-axis being parameter value and the x-axis being calendar days.

This intensive calculation is performed automatically by MANAGES. Sen's estimate of slope is robust, and insensitive to the presence of a small fraction of outlier data values. In contrast, linear regression is significantly more sensitive, and more likely to give erroneous slope indications, even when only a few outlier values are present.

When data averaging is not activated, the Sen slope is calculated using individual data points and actual sampling dates. When data averaging is active, multiple data points within specified season segments are reduced to one data point by averaging and placing the average value at the day in the middle of that period. The Sen slope calculation is memory intensive to the extent that only up to about 50 data points can be handled for a data analysis period.

The significance of the Sen estimate of slope can also be calculated [1]. It should be noted that a confidence band for the Sen estimate of slope is not necessarily symmetrical about the estimate. The results of the Sen estimate of slope should be compared with that for the Mann-Kendall test for trend. Sen's test is preferable to the Mann-Kendall test when only a few years of data are being analyzed, or when data seasonality is present or suspected. The mathematical formulae used in calculation of the Sen estimate of slope are summarized in Table 1.

### Mann-Kendall Test for Sen Slope Significance

The Mann-Kendall test for trend is insensitive to the presence or absence of seasonality. The test is non-parametric and does not assume any type of data distribution. Nonetheless, two forms of the test are provided in MANAGES—one ignoring data seasonality even if it is present, and one considering data seasonality. In the test, the null hypothesis, $H_o$, is that the Sen trend is zero, and the alternate hypothesis, $H_a$, is that the trend is non-zero.

In general, the Mann-Kendall test considering seasonality indicates a larger range for allowable Sen estimate of trend when seasonality is actually present than the range indicated by the test performed ignoring seasonality. The mathematical equations used in calculation of the Mann-Kendall test for Sen slope significance are summarized in Table 2.

### Linear Regression Estimate of Slope

The linear regression line estimate of slope is sensitive to the presence of seasonality [1], and as such, is likely to give erroneous estimates of true slope for seasonally dependent groundwater data. For this reason, the Sen estimate of slope is recommended as a superior estimator of true slope.

### Detrending Methodology

Data trends must be removed before evaluating whether data are normally distributed. MANAGES accomplishes this task by removing the Sen slope from each data value before performing the Shapiro-Wilk W (normality) test. In a follow-up test, data are adjusted for removal of both trend and seasonal effects prior to application in the W test.

In the Sen trend removal method, a line having a slope equal to the Sen estimate of slope is passed through the mean of the data values placed at the day that falls midway between the starting and ending dates of the data analysis period. The slope is then removed by adding or subtracting the difference between the Sen slope and a horizontal line also passing through the mean of the data values on the day that falls midway between the starting and ending points of the data analysis period. The result is a set of values that have been adjusted to remove the effect of temporal trend.

### Kruskal-Wallis Test for Seasonality

To perform the Kruskal-Wallis test for data seasonality, data points are first segmented according to season [1]. The null hypothesis, $H_o$, is that all seasons have the same mean value. The alternative hypothesis, $H_a$, is that at least one season has a mean larger or smaller than the mean of at least one other season. [2] provides additional information on groundwater data seasonality. The mathematical equations used in calculation of the Kruskall-Wallis test for data seasonality are summarized in Table 3.

### Deseasonalizing Methodology

Data deseasonalization is used to remove effects of seasonal variation, prior to application of the W test for data normality assessment, or before performing well pair mean or median value comparisons. The procedure involves segmenting data into user-defined seasons, calculation of overall data mean and a mean for each annual season. The individual deseasonalized value is calculated by subtracting the appropriate seasonal mean from the data point, and then adding back the overall data mean for the time period being analyzed.

### Shapiro-Wilk W Test for Normality

The Shapiro-Wilk W test effectively tests whether data have been drawn from an underlying normal distribution [1]. The null hypothesis is that the population has a normal distribution. The alternative hypothesis is that the population does not have a normal distribution. As coded in MANAGES, the W test is limited to use for less than 51 points. The mathematical equations used in calculation of the Shapiro-Wilk test for data normality are summarized in Table 4.

### Coefficient of Skewness for Normality

The coefficient of skewness is another measure for data normality [1]. MANAGES provides the value of the coefficient of skewness for further study of data normality. Additional information on data normality is given by [2]. The equation used to calculate the coefficient of skewness is given in Table 5.

### Student t-Test for Mean Comparison

The Student t-test compares means from two data series. If confidence ranges for the means overlap, then the two means are not significantly different. MANAGES provides

Student t-test results for unadjusted data and for deseasonalized data.

The Student t-test makes three key assumptions: (1) that the two well data sets are independent and not serially correlated, (2) that both well data sets have normal distributions, and (3) that both data sets have equal variances [1]. Under most conditions, one or more of these assumptions will not be true for any given well pair. In general, more than 25 data values in each of the two sets are required to satisfy the normality and variance assumptions of the Student t-test [3]. For these reasons, it is suggested that, under most conditions, the Mann-Whitney test should be used for determining whether two well medians are different [4]. The mathematical equations used in calculation of the Student t-test for mean comparison are summarized in Table 6.

### Mann-Whitney Test for Median Comparison

Assumptions in the Mann-Whitney test are generally more reasonable for groundwater data than those in the Student t-test. The Mann-Whitney test assumes that: (1) both data sets contain random values from their respective populations, and (2) in addition to independence within each data set, there is mutual independence between the two sample sets. No assumptions are made about data distribution. The null hypothesis is that the two well medians are equal, and the alternative hypothesis is that the two well medians are different. Additional information concerning the Mann-Whitney test is given by [4] and [5]. Mann-Whitney test theory and tables are given by [6]. In MANAGES, Mann-Whitney test results are provided for unadjusted data and for deseasonalized data. Equations used for calculation of the Mann-Whitney test are given in Table 7.

### Kruskal-Wallis Test for Comparison of Three or Four Well Means

The Kruskal-Wallis test applied to a group of three or four wells tests the hypothesis that all well means are equal against the alternative hypothesis that at least one of the wells has a mean that is greater than the mean of at least one other well ([5], p. 229). The test uses ranking of data and is more rigorous than a straight comparison of well medians. For the case of two wells, the Mann-Whitney test for median comparison should be used.

In practice, results from the multi-well Kruskal-Wallis test can be used to detect similarities or differences within certain well groups, e.g., downgradient wells, or upgradient wells, or a combination of the two.

This test uses the same set of equations as the Kruskal-Wallis test for seasonality.

## PROGRAM AVAILABILITY

The MANAGES program is available free to education and government establishments, tax-exempt organizations and Electric Power Research Institute-member electric utilities. Interested parties should call the Electric Power Software Center, (214) 655-8883.

## ACKNOWLEDGMENTS

I thank Ishwar Murarka, Electric Power Research Institute, for his valuable suggestions and support of the MANAGES software development project. I also thank the software programming team members at Southern Company Services -- Diane McCraw, Dave Moser, Tommy Tye, Dan Walther, Mark Schurmann, Tommy Rusodimos and Linc McIntyre. My thanks also to the following individuals for their helpful suggestions and evaluations of the software: Rachel Allen (Gulf Power Company), Ken Ladwig, Bruce Hensel (Science & Technology Management, Inc.), Tom Johnson, Christine Diebels, Jim Lingle (Wisconsin Electric Power Company), Charles Bohac (Tennessee Valley Authority), Jill Witts and Bill Witts (Illinois Power Company).

## REFERENCES

1. R.O. Gilbert, 1987, Statistical Methods for Environmental Pollution Monitoring, Pacific Northwest Laboratory, Van Nostrand Reinhold, New York, NY.

2. R.H. Montgomery, J.C. Loftis, and J. Harris, 1987, "Statistical Characteristics of Ground-Water Quality Variables," Ground Water, Vol. 25, No. 2, pp. 176-184.

3. J.P. Sgambat and J.R. Stedinger, 1981, "Confidence in Ground Water Monitoring," Ground Water Monitoring Review, Vol. 1, No. 1, pp. 62-69.

4. J.C. Loftis, J. Harris, and R.H. Montgomery, 1987, "Detecting Changes in Ground Water Quality at Regulated Facilities," Ground Water Monitoring Review, Winter 1987, pp. 72-76.

5. W.J. Conover, 1971, Practical Nonparametric Statistics, 2nd ed., Texas Tech. University, John Wiley & Sons, New York, NY.

6. R.H. Myers and R.E. Walpole, 1987, Probability and Statistics for Engineers and Scientists, 2nd ed., MacMillan Publishing Company, New York, NY.

7. W. Mendenhall, D.D. Wackerly, R.L. Scheaffer, 1990, Mathematical Statistics with Applications, PWS-KENT Publishing Company, Boston, MA.

Table 1

| **Sen's Estimate of Slope** calculates the trend of a single data series. | |
|---|---|
| Slope, Q | $= \dfrac{y_i' - y_i}{i' - i}$<br><br>where $y_i'$ and $y_i$ are data values at times $i'$ and $i$, respectively, and where $i' > i$. |
| N' | Number of unique data point pairs that can be made for the observations in the data set, for $i' > i$. |
| Sen's Estimate | Sen's estimator = median slope<br><br>$= Q_{[(N'+1)/2]}$ if N' is odd<br>$= \frac{1}{2}(Q_{[N'/2]} + Q_{[(N'+2)/2]})$ if N' is even |
| $Z_{0.975}$ | Statistic for the cumulative normal distribution (Gilbert, 1987, p. 254) for the 2-tailed, 95% confidence interval. |
| Variance of the Mann-Kendall S Statistic, VAR(S) | $= \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right]$<br><br>where $g$ is the number of tied groups, $t_p$ is the number of data in the $p$th group, and $n$ is the number of data values. |
| $C_{0.05}$ | $= Z_{0.975}$ [VAR(S)] |
| Sen's Estimate 95% Confidence Interval | $M_1 = (N' - C_{0.05})/2$<br>$M_2 = (N' + C_{0.05})/2$<br><br>Lower limit of confidence interval is the $M_1$th largest slope, and upper limit of confidence interval is the $(M_2+1)$th largest of the N' <u>ordered</u> slope estimates. |

Table 2

| **Mann-Kendall Test for Sen Slope Significance**, for number of data as small as 10, unless there are many tied values (Gilbert, 1987, p. 211) | |
|---|---|
| Indicator Function<br>$sgn(x_j - x_k)$ | $= 1$ if $x_j - x_k > 0$<br>$= 0$ if $x_j - x_k = 0$<br>$= -1$ if $x_j - x_k < 0$<br><br>where $x_1, x_2, \ldots, x_n$ are the time ordered data ($n$ is total). |
| Mann-Kendall Statistic, S | $= \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$ |
| Variance of S, VAR(S) | $= \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right]$<br><br>where $g$ is the number of tied groups, $t_p$ is the number of data in the pth group, and $n$ is the number of data values. |
| Test Statistic, Z | $= \dfrac{S-1}{[VAR(S)]^{1/2}}$ if $S > 0$<br><br>$= 0$ if $S = 0$<br><br>$= \dfrac{S+1}{[VAR(S)]^{1/2}}$ if $S < 0$<br><br>where positive Z value means upward trend and negative Z value means negative trend. |
| Hypothesis Test<br>$H_0$ = no trend<br>$H_a$ = trend present at 95% confidence | Reject $H_0$ if $Z > Z_{0.975}$<br><br>where $Z_{0.975}$ is obtained from table A.1 in Gilbert 1987, p. 254. |

Table 3

| **Kruskal-Wallis Test for Data Seasonality.** For seasonal mean comparisons for a single well, and also used for comparison of 3 or 4 well means. | |
|---|---|
| $m$ | Total number of data values. |
| $n_j$ | Total number of data in population $j$. |
| $R_j$ | Sum of ranks for population $j$. |
| $K_w$ | Kruskal-Wallis statistic for no tied or ND values<br>$= \left[ \frac{12}{m(m+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j} \right] - 3(m+1)$ |
| $K_w'$ | Kruskal-Wallis statistic with tied or ND values<br>$= \left[ \frac{K_w}{1 - \frac{1}{m(m^2+1)} \sum_{j=1}^{g} t_j (t_j^2 - 1)} \right]$<br>where $g$ is the number of tied groups and $t_j$ is the number of tied data in the $j$th group (Gilbert, 1987, p. 251). |
| $k$-1 | Degrees of freedom, where $k$ is the number of data sets. |
| Test at 95% Confidence | Data set means are not equal if<br>$K_w$ or $K_w' \geq X^2_{0.95,k-1}$<br>where $X^2$ is the chi-square statistic from table A19 of Gilbert, 1987, p.273. |

Table 4

| **Shapiro-Wilk W Test for Normality** | |
|---|---|
| Denominator, D | $= \sum_{i=1}^{n} (x_i - \overline{x})^2$<br>where $\overline{x}$ is the sample mean and $x_i$ are data values ($n$ in total). |
| $X_{(i)}$ | $i$th order data value, where data are arranged smallest to largest. |
| $a_1, a_2, \ldots, a_k$ | Coefficients from Table A6, Gilbert 1987, pp. 259-260, for sample size $n$ where $k$ is approximately $n/2$. |
| Test Statistic, W | $= \frac{1}{D} \left[ \sum_{i=1}^{k} a_i (x_{(n-i+1)} - x_{(i)}) \right]^2$ |
| $w_{0.05}$ | The 5% quantile given in Table A7 of Gilbert, 1987, p. 261. |
| Normality Test at 95% Confidence | if $W > w_{0.05}$, distribution is normal<br>if $W < w_{0.05}$, distribution is skewed |

Table 5

| **Coefficient of Skewness for Normality** assesses data normality and detects left or right skew in data distributions. | |
|---|---|
| Coefficient of Skewness $\alpha_3$ | $= \dfrac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\overline{x})^3}{s^3}$ <br> where $\overline{x}$ is the mean and $s$ is the standard deviation. <br> $\alpha_3 > 0$ for right skew <br> $\alpha_3 < 0$ for left skew, and <br> $\alpha_3 = 0$ for symmetric distribution |

Table 6

| **Student t-test for Mean Comparison** for normally distributed populations of equal variance. | |
|---|---|
| Number of Observations | $n$ |
| Estimate of Standard Deviation, $s$ | $= \sqrt{\dfrac{1}{(n-1)}\sum_{i=1}^{n}(x_i-\overline{x})^2}$ |
| Estimate of Population Mean, $\overline{x}$ | $= \dfrac{1}{n}\sum_{i=1}^{n}x_i$ |
| Estimate of Population Variance, $s^2$ | $= \dfrac{1}{(n-1)}\sum_{i=1}^{n}(x_i-\overline{x})^2$ <br> test assumes that the variances of the two populations are equal. |
| True Mean Concentrations ($\mu$) Confidence Band at 95% Confidence | $\overline{x} - t_{0.975,n-1}\left(\dfrac{s}{\sqrt{n}}\right) \le \mu \le \overline{x} + t_{0.975,n-1}\left(\dfrac{s}{\sqrt{n}}\right)$ <br> where t is from the student t distribution table (Table A2, Gilbert, 1987, p. 255). <br> If the confidence ranges for the two population mean concentrations ($\mu_1$ and $\mu_2$) overlap, the two means are not significantly different. |

Table 7

| **Mann-Whitney Test for Median Comparison,** a non-parametric test for mean comparison (Mendenhall, et al., 1990, pp. 688-690). | |
|---|---|
| $w_A$, $w_B$ | Sum of ranks for samples A and B in the pooled sample set, respectively. |
| $n_1$, $n_2$ | Number of observations in samples A and B, respectively. |
| $U_A$, $U_B$ | $U_A = n_1 n_2 + \dfrac{n_1(n_1+1)}{2} - w_A$ <br> $U_B = n_1 n_2 + \dfrac{n_2(n_2+1)}{2} - w_B$ <br> where $U_A + U_B = n_1 n_2$ <br> for detection of difference in means of samples A and B, use the smaller of $U_A$ or $U_B$ as the test statistic, U. |
| Test at 95% Confidence | Well means are different if $U < U_0$ <br> where $U_0$ is obtained by doubling the $\alpha = 0.05$ value in Table 8, Appendix III of Mendenhall et al., 1990. |

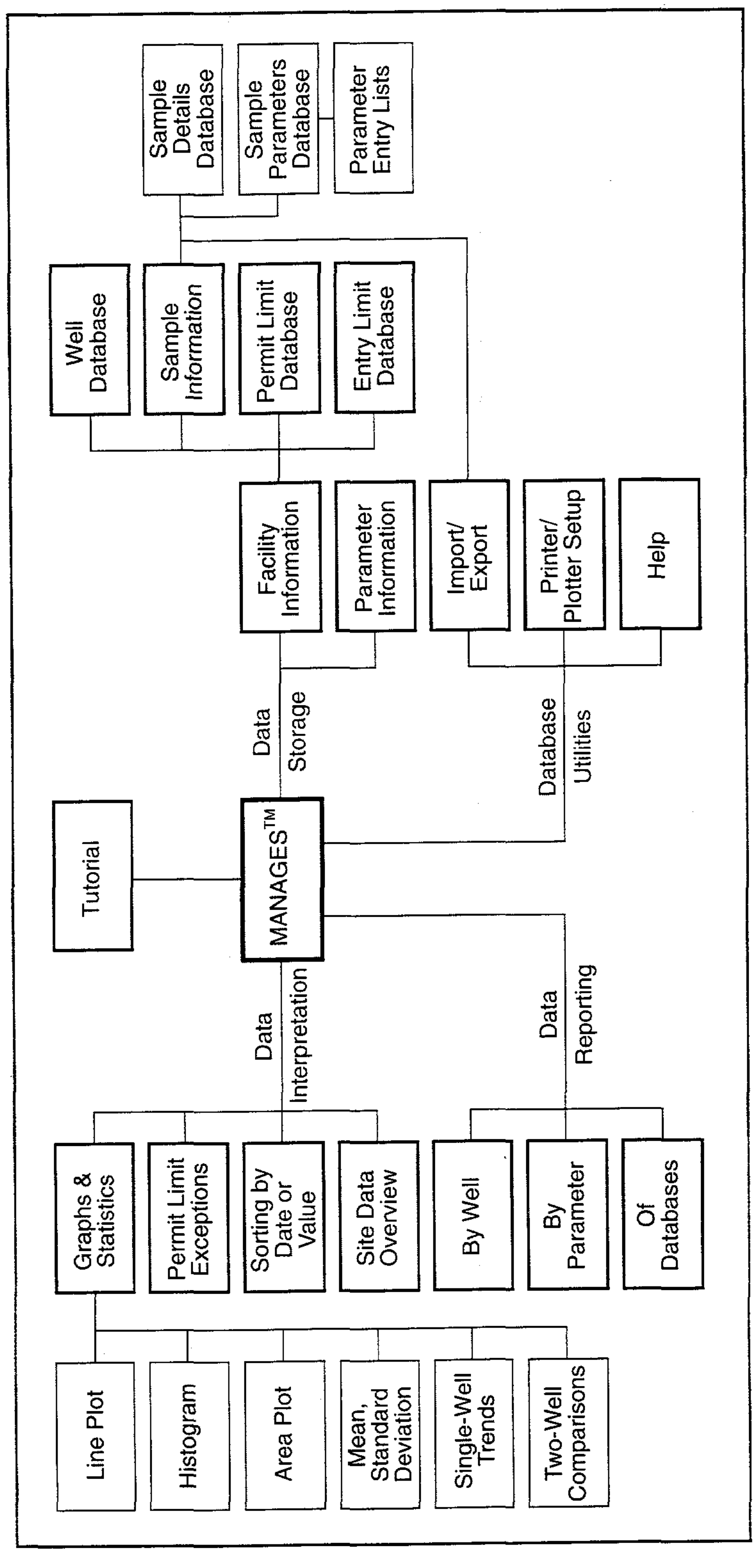



Figure 1. Structure of MANAGES.

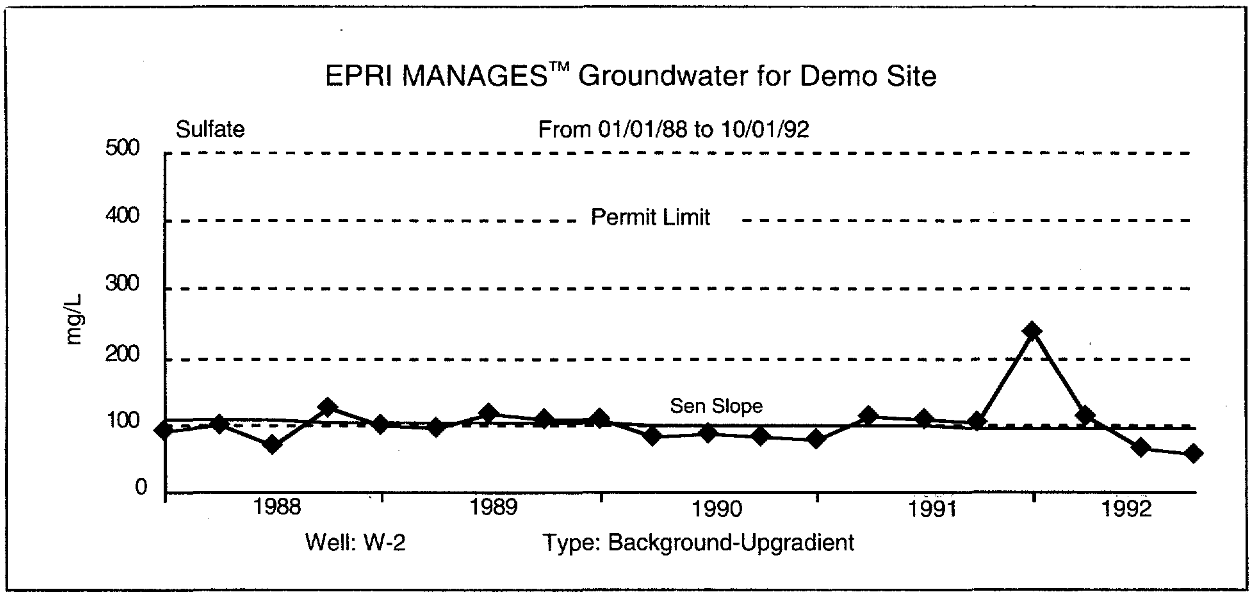



Figure 2. Sulfate trend analysis. The Sen slope estimated trend line is not affected by an outlier point. The Mann-Kendall test indicates that the trend is zero at the 95% confidence level.

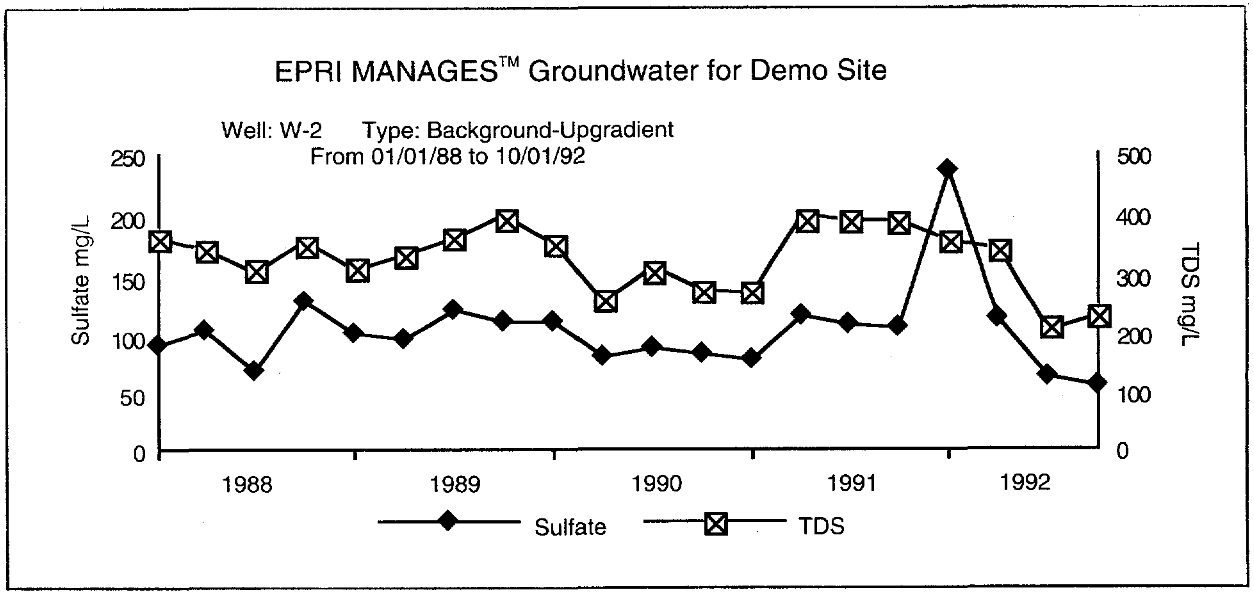



Figure 3. Multiparameter plot with sulfate and TDS. TDS does not have the anomalous high data value that sulfate does, indicating that the high sulfate value is an outlier.

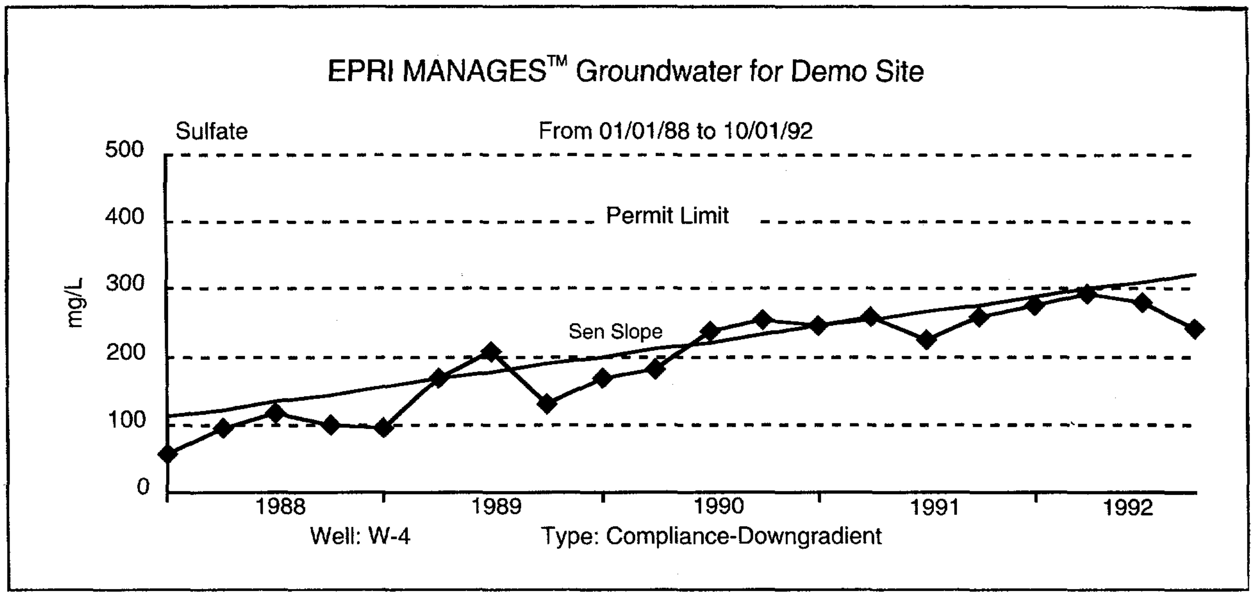



Figure 4. Sulfate trend analysis. The Mann-Kendall test indicates that the sulfate trend is nonzero at the 90% confidence level.

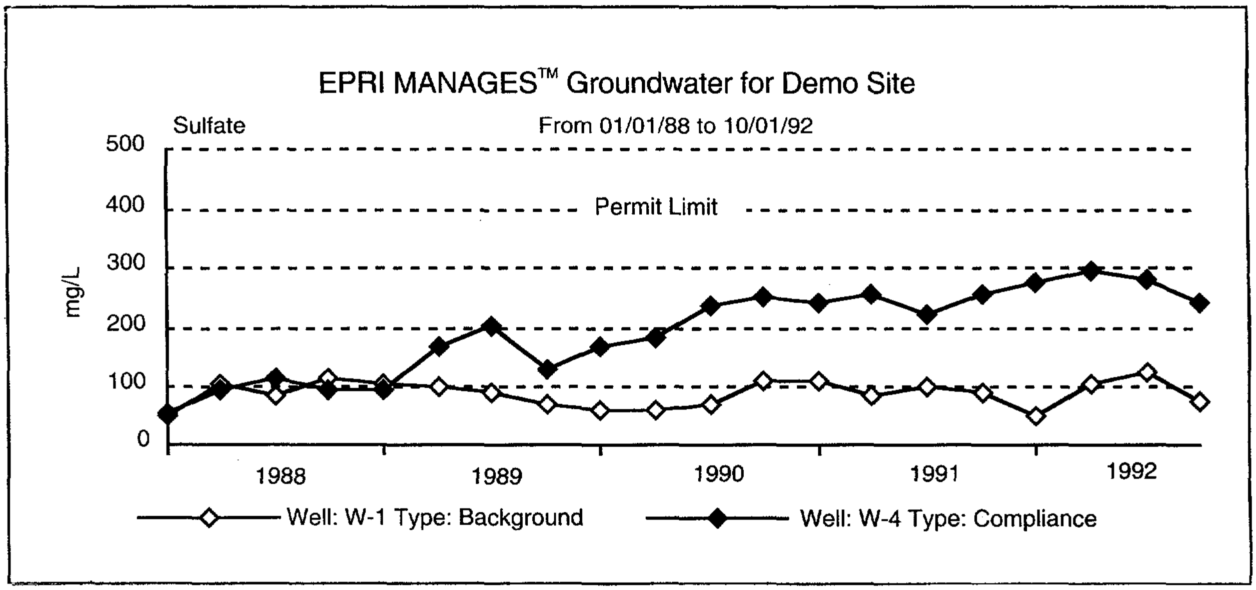



Figure 5. Two-well comparison. The Student t-test and Mann-Whitney test both indicate that the sulfate means are not equal at the 95% confidence level.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Simulation Models for ATES

• Johan Claesson
Dept. of Building Physics
Lund University
Lund, Sweden
• Göran Hellström
Dept. of Mathematical Physics
Lund University
Lund, Sweden
• Thomas Probert
Dept. of Mathematical Physics
Lund University
Lund, Sweden

## ABSTRACT

The paper presents the thermohydraulic models for aquifer thermal energy storage (ATES) developed by the Lund Group for Ground Heat. The basic assumptions are that the aquifer is horizontally homogeneous and that the groundwater flow is two-dimensional without a vertical component. The groundwater flow field is then given by an analytical function, or conformal transformation, which is obtained from the positions of the well, the pumping rates, and the regional flow.

The first set of PC models concerns the groundwater flow and the motion of thermal fronts for any set of wells and a regional flow. The flow field, with streamlines and stagnation points, is presented graphically on the screen. The motion of the thermal fronts is determined by particle tracking. These interactive models have proven to be very convenient and useful design tools.

The complete three-dimensional thermal process is solved in the second set of PC models. The groundwater flow is again given by explicit analytical formulas, while the thermal process is solved numerically. The coupled groundwater and the heat flow process in the aquifer is dealt with using a new entropy-conservation technique.

The models are carefully documented and available on PC. They have been validated against a few field experiments and they are used extensively for design studies.

## INTRODUCTION

Storage of heat (or cold) in aquifers (ATES) involves drilling a few wells to an aquifer stratum for circulation of water between the storage region and the energy system. The aim of the thermal analysis of aquifer heat storage systems is to predict the return temperature from the aquifer for given variations of the injection temperature and fluid flow rate.

The injected warm water will loose heat to colder surrounding parts of the ground by heat conduction. Local inhomogeneities in the aquifer cause a certain amount of mixing of the water (dispersion) that results in further thermal degradation. Convective movements, such as regional groundwater flow and buoyancy flow, can also lead to substantial heat losses.

An understanding of the thermohydraulic processes in the aquifer is necessary for a proper design of an aquifer heat storage system under given thermohydraulic conditions. The main design considerations concern the location of the wells, the loading conditions (injection temperatures and pumping rates), heat losses, temperature quality losses, thermal breakthrough times etc. It is also important to assess the consequences of the uncertainties associated with storage in an underground region beyond detailed investigation.

The thermohydraulic models for warm and cold storage developed by the Lund Group for Ground Heat are presented in this paper. The objective of the first set of models is to visualize the groundwater flow in the aquifer and the movement of the thermal front. The locations of the wells and their pumping rates can be changed interactively.

The second set of models concerns the heat balance of the store. The three-dimensional thermal process with combined groundwater and heat flow in the aquifer and heat conduction in surrounding impermeable layers is solved numerically. The models, which cover the most commonly used well configurations in combination with the presence of one or two hydraulic boundaries in the aquifer, give the temperature of the recovered water.

## CONFORMAL GROUNDWATER FLOW

The thermohydraulic analysis requires a calculation of, or at least a reasonable knowledge of the groundwater flow and the temperatures in the aquifer and the surrounding ground. The groundwater flow is often quite complex. In general, it must be computed numerically for an aquifer with its more or less complicated inhomogeneities. There are, however, many important applications that can be analyzed assuming that the groundwater flow pattern is given by an analytical solution or a so-called conformal transformation (Claesson and Bennet [1]). A requirement is that the hydraulic properties of the aquifer are homogeneous in the horizontal plane of the flow. The most general case that can be treated with use of this conformal technique is an aquifer with an arbitrary number of parallel, homogeneous aquifer strata.

### Thermohydraulic Equations

The coupled groundwater and heat flow processes in the aquifer stratum are governed by the partial differential equations for the mass balance and the energy balance in the aquifer. The darcy velocity $\vec{q}$ is related to the gradient of the pressure $P$ and the gravity force $g$ through the empirical law of Darcy. Compressibility effects are neglected. The divergence of the Darcy velocity $\vec{q}$ then becomes zero at each point. The groundwater flow field is derived assuming that the effect of viscosity and density variations can be neglected and that there is no vertical component of the groundwater flow. The pressure distribution $P$ in the aquifer then satisfies the Laplace equation:

$$\Delta P = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 \qquad (1)$$

The aquifer temperature $T$ fulfills the general equation for convective-diffusive heat transfer:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T - TC_w \vec{q}) \qquad (2)$$

where $t$ is the time. The volumetric heat capacities of the aquifer (matrix plus water) and water, $C$ and $C_w$ respectively, are assumed to be constants. The thermal conductivity is denoted $\lambda$. The last term of (2) is due to the convective heat flux $TC_w\vec{q}$. It gives a convective displacement of the temperature field with the "thermal" velocity:

$$\vec{v}_T = \frac{C_w}{C}\vec{q} \qquad (3)$$

### Buoyancy Flow

The validity of the models presented in this paper assumes that the influence of groundwater flow in the vertical direction is negligible. One important process that may generate considerable vertical groundwater movement is natural convection due to temperature-induced density differences at the thermal front. Here, we will give a criterion by which the influence of this process may be estimated.

The groundwater flow around the wells takes place primarily in the horizontal direction. The interface, or thermal front, between the warm water around the well and the surrounding cold water becomes vertical. The temperature-induced density difference between the warm and cold water causes natural convection, or buoyancy flow, in the vicinity of the thermal front. The buoyancy flow is proportional to the permeability of the aquifer and it depends strongly on the temperature difference between the warm and cold regions. If the buoyancy flow is large, the thermal front tilts and the warm water flows up on top of the cold water. The warm water becomes more exposed to colder surroundings, which increases the heat losses. It will also be difficult to avoid mixing of warm and cold water in the well during the extraction period.

Analytical solutions for the pressure distribution and the flow field have been derived for several idealized situations involving an injection well and a vertical plane or cylindrical interface between two regions of different density and viscosity in an infinite anisotropic aquifer bounded by two horizontal planes (Hellström *et al* [2]). The interface, or thermal front, between the two regions may be either sharp or of finite width. The buoyancy flow induced by the density difference creates a convection cell in the thermal front region and an ensuing tilting of the front. A characteristic time-scale $t_0$ (s) for the buoyancy tilting rate at a sharp thermal front is defined by:

$$t_0 = \frac{HC}{\kappa k C_w} \frac{\pi^2(\mu_0 + \mu_1)}{32G(\rho_0 - \rho_1)g} \qquad (4)$$

The second factor on the right hand side is a function only of the temperatures $T_0$ and $T_1$ of the two regions. The tilting time should not be too short compared to the length $t_c$ of the storage cycle in order to avoid a large tilting of the thermal front. The tilting time becomes longer with increasing width of the transition zone. The tilting-time criterion concerns the case of buoyancy flow in the absence of forced convection. The combined effects of buoyancy flow and forced convection are treated in [3] (Hellström *et al*).

## NOMENCLATURE

| | |
|---|---|
| $C$ | volumetric heat capacity of aquifer, $J/m^3K$. |
| $C_w$ | volumetric heat capacity of water, $J/m^3K$. |
| $g$ | standard gravity, 9.81 $m/s^2$. |
| $G$ | Catalan's constant (=0.915...). |
| $H$ | thickness of aquifer stratum, m. |
| $k$ | permeability (horizontal), $m^2$. |
| $k'$ | vertical permeability, $m^2$. |
| $\kappa$ | anisotropy factor, equal to $\sqrt{k'/k}$. |
| $\mu_0$ | dynamic viscosity in region 0, kg/ms. |
| $\mu_1$ | dynamic viscosity in region 1, kg/ms. |
| $\rho_0$ | density in region 0, $kg/m^3$. |
| $\rho_1$ | density in region 1, $kg/m^3$. |

## GROUNDWATER FLOW MODELS

The first set of PC models concerns graphical presentation of the groundwater flow and the motion of thermal fronts (neglecting thermal diffusion) for any set of wells and a regional flow. The input data (aquifer data, regional flow magnitude and direction, well locations and pumping rates, and graphical presentation data) are entered interactively in a spreadsheet. The stagnation points and all the stagnation streamlines to and from these are first determined. This gives a direct picture of the character of the flow field between all wells. Any streamlines between the wells and equipotentials of the pressure field may also be drawn. Finally, the motion of thermal fronts is determined by particle tracking along the streamlines. The result, with different colors for areas of water with different temperatures, is presented immediately on the screen in graphics mode (EGA or VGA) for any distribution of wells and pumping rates.

There are two versions of the model. The first one concerns the case of an aquifer with infinite horizontal extensions and the case with a single, straight hydraulic boundary (closed or open). The second version differs in the respect that there are two parallel hydraulic boundaries (closed or open). These models have proven to be a very convenient and useful design tool (where to locate wells, the size of storage volume, analysis of thermal breakthrough, and so on).

Two illustrative examples are taken from projects in southern Sweden. In the first example an aquifer in Malmö is used for heat and cold storage. Figure 1 shows a horizontal, rectangular cross-section of the aquifer with six injection wells (warm wells) marked by solid circles and eight extraction wells (cold wells) marked by open circles. The solid lines are streamlines and they start at an injection well (solid circle) and end up at an extraction well (open circle). The dashed lines are stagnation lines. The point where two stagnation lines intersect is a stagnation point. The groundwater flow is zero at a stagnation point. Stagnation lines are streamlines that connect stagnation points to wells. Figure 2 shows the stagnation lines and the extent of the heated region in the aquifer after one summer. The shaded areas represent the region heated by water injected during this period. In the second example an aquifer in Lomma (a few kilometres north of Malmö) is used for heat storage. In the summer the aquifer is thermally recharged using surface water from a nearby river as a heat source. Figure 3 shows a horizontal, rectangular cross-section of the aquifer after the second summer. Five warm wells (open circles) and five cold wells (solid circles) penetrate the aquifer. Around the cold wells are two sets of thermal fronts. The darkest shade is from cold water injected during the most recent winter (1992), and the lightest shade is from water injected during the winter of 1991. The thermal fronts around the warm wells (open circles) are from warm water injected during thermal recharging in the summer (1992). The cold wells interact slightly while the warm wells seem undisturbed by each other. The solid lines are streamlines and the dashed lines are stagnation lines.

## COMBINED CONDUCTIVE-CONVECTIVE HEAT TRANSPORT MODELS

The second set of models concerns the heat balance of the store. The ground water flow is in each case generated by a conformal transformation. The three-dimensional thermal process with combined groundwater and heat flow in the aquifer and heat conduction in surrounding impermeable layers is solved numerically with use of the explicit finite difference method (FDM). The numerical mesh is generated based on the streamlines and equipotential of the conformal groundwater flow. The calculation is performed in the transformed orthogonal coordinate system, so that the convective transport takes place along only one coordinate axis — the streamlines. This approach, combined with the entropy conservation technique described below, makes the iterative calculation very fast and accurate. A large number of cells can be used in the numerical mesh without excessive execution times. The different versions of the model, which cover the most common well configuration in combination with the presence of hydraulic boundaries, calculate the temperature of the extracted water, the temperature in the aquifer, and the heat balance.

The models have the following characteristics:

- Three-dimensional heat conduction in the aquifer and in the surrounding ground. The thermal properties may vary in the vertical direction.
- Convective heat transport in the aquifer or aquifer layers and crack planes. The layers and crack planes may have different hydraulic properties.
- Thermal dispersion may be accounted for by a anisotropic thermal conductivity in the aquifer.
- The groundwater flow is given by analytical functions (conformal groundwater flow).
- Numerical dispersion minimized by an entropy conservation technique.

### Entropy Conservation Technique

A particular problem in the numerical computation of combined conductive-convective heat flow processes is the so-called numerical dispersion. The effect is an enhanced, apparent heat conduction that causes thermal degradation. A discussion of this problem is given by Lantz in [4] and Claesson in [5].

The heat balance programs listed below use an entropy conservation technique that eliminates the numerical dispersion (Hellström *et al* [6]). The energy and entropy content of each cell in the numerical mesh is then represented by three parameters. This method is used for the convective part of the process, while the diffusive part is calculated with use of the explicit finite difference method (FDM).

## LIST OF COMPUTER PROGRAMS

There are two versions of the PC model for graphical presentation of the groundwater flow, the pressure field, and the motion of thermal fronts:

- CONFLOW – The basic version of the program allows for 25 wells in an aquifer with infinite extension in the horizontal direction or with a single, straight hydraulic boundary (closed or open).
- CFSTRIP – This version has the same features as CONFLOW, except that there are two parallel hydraulic boundaries (closed or open).

Nine models have been developed for simulation of the heat balance in aquifers. The models, which cover the most common well configurations in combination with the presence of hydraulic boundaries, are listed below:

- AST – Heat storage around a single well in an aquifer stratum with infinite horizontal extensions. The groundwater flow is assumed to be in the radial direction from the well.
- RADFAU – Heat storage around a single well located near a closed hydraulic boundary. The groundwater flow field is generated by a conformal mapping.
- RADPER – Heat storage around a single well located between two parallel, closed hydraulic boundaries.
- TWOW – Heat storage with a two well system.
- REG – Heat storage with two wells in the presence of a regional groundwater flow.
- FAULT – Heat storage with two wells located near a closed hydraulic boundary.
- STRIML – Heat storage with two wells located between two parallel, closed hydraulic boundaries. A connecting line between the two wells would be parallel to the boundaries.
- PERPEN – Heat storage with two wells located between two parallel, closed hydraulic boundaries. A connecting line between the two wells would be perpendicular to the boundaries.
- DIPCIRC – This program simulates the thermal process during water flow in a number of circular (disc-shaped) crack planes. There is a central well with a number of symmetrically positioned peripheral wells.

The models are carefully documented and available on PC (Hellström *et al* [6]; Hellström and Bennet [7]). They have been used extensively for design studies and parameter sensitivity studies (Doughty *et al* [8]).

## REFERENCES


1. J. Claesson and J. Bennet 1987, "Thermohydraulics of Conformal Groundwater Flow", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.
2. G. Hellström, C.F. Tsang and J. Claesson 1988, "Buoyancy Flow at a Two-Fluid Interface in a Porous Medium: Analytical Studies", Water Resources Research, Vol. 24, No. 4, pp. 493-506.
3. G. Hellström, C.F. Tsang and J. Claesson 1988, "Combined Forced-Convection and Buoyancy Flow at a Two-Fluid Interface in a Porous Medium: Analytical Studies", Water Resources Research, Vol. 24, No. 4, pp. 507-515.
4. R.B. Lantz 1971, "Quantitative Evaluations of Numerical Diffusion", Soc. of Petroleum Eng. J., p. 315, Sept. 1971.
5. J. Claesson 1978, "Entropy Analysis of Numerical Diffusion", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.
6. G. Hellström, J. Bennet and J. Claesson 1986, "Model of Aquifer Storage System: Radial Ground Water Flow. Manual for Computer Code", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.
7. G. Hellström and J. Bennet 1989, "Model of Aquifer Storage System: Doublet Well. Manual for Computer Code", Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden.
8. C. Doughty, G. Hellström, C.F. Tsang and J. Claesson 1982, "A Dimensionless Parameter Approach to the Thermal Behaviour of an Aquifer Thermal Energy Storage System", Water Resources Research, Vol. 18, No. 3, pp. 571-587.

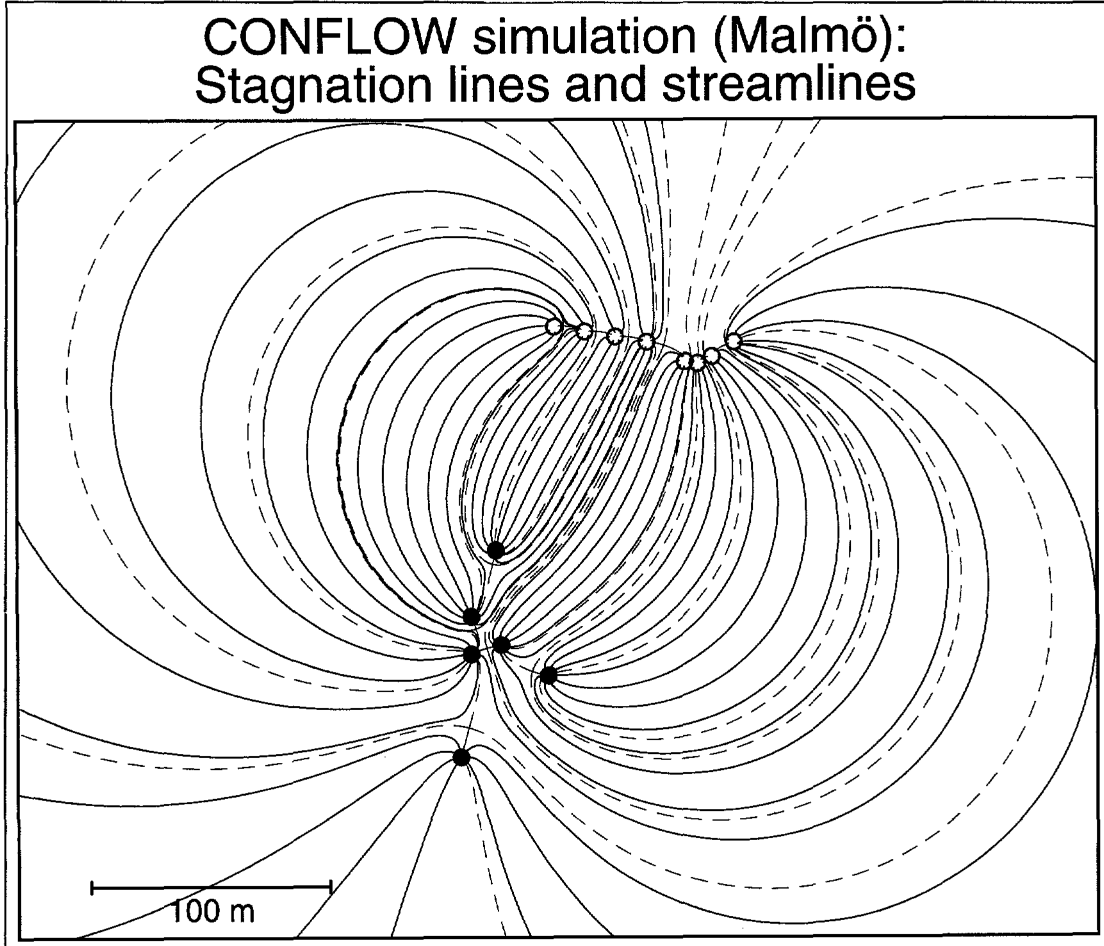



**Figure 1.** A horizontal rectangular cross-section of an aquifer showing stagnation lines (dashed lines) and streamlines (solid lines) for an aquifer thermal energy storage system involving six injection wells (solid circles) and eight extraction wells (open circles) (The Triangel project in Malmö, Sweden).

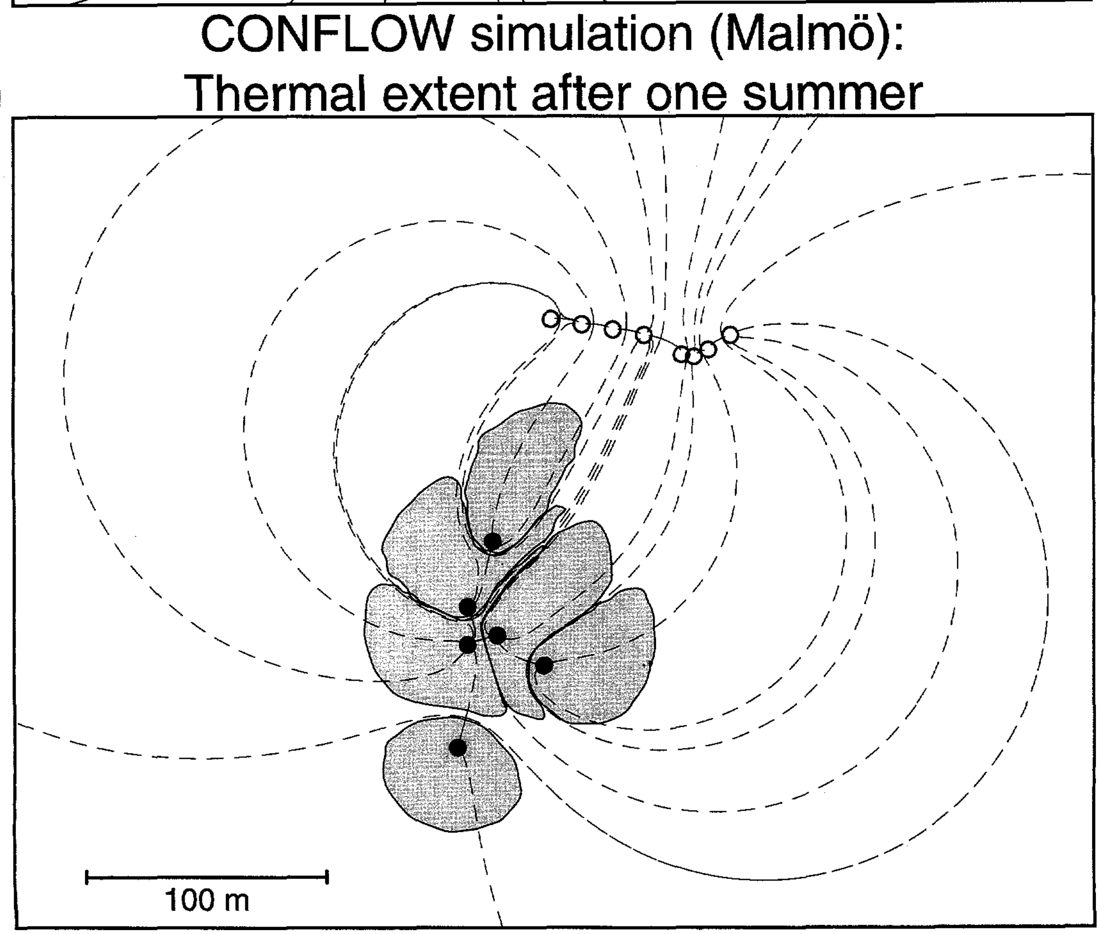



**Figure 2.** Stagnation lines (dashed lines) and extent of heated region (shaded area) after one summer (The Triangel project in Malmö, Sweden). The shaded area represents the region heated by warm water injected during the summer. The irregular (non-circular) shape of the fronts implies that the wells disturb each other.

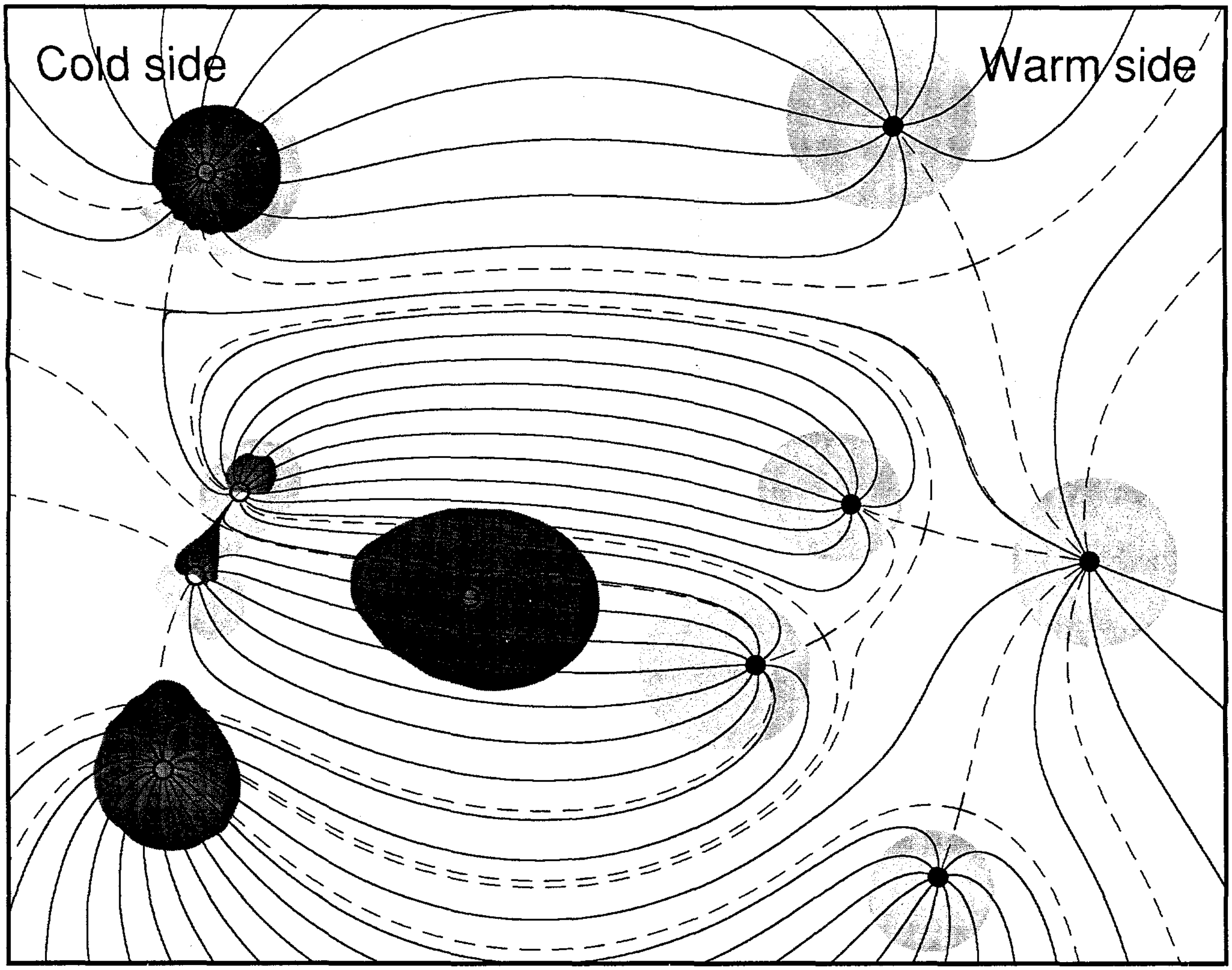



**Figure 3.** A horizontal rectangular cross-section of an aquifer showing stagnation lines (dashed lines), streamlines (solid lines) and extent of heated region (shaded area) for an aquifer thermal energy storage system involving five injection wells and five extraction wells in Lomma, Sweden. The different shades correspond to regions heated or cooled by water injected during the winters of 1991 (lightest shade on the cold side) and 1992 (darkest shade on the cold side), and the summer of 1992 (shaded areas on the warm side). Some of the shaded regions are nearly circular in shape which means that the wells do not interact that much.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

**November 14-15, 1994**
**The University of Alabama**
**Tuscaloosa, Alabama USA**

# Impediments to the Commercialization of ATES Technology in the United States

• C. Everett Brett
Bureau of Engineering Research
The University of Alabama
Tuscaloosa, Alabama, USA
• K. Clark Midkiff Jr.
Department of Mechanical Engineering
The University of Alabama
Tuscaloosa, Alabama, USA

ABSTRACT

Aquifer Thermal Energy Storage (ATES) is a new technology which is unfamiliar to the decision-makers and designers in the HVAC business. Design costs and preliminary testing requirements are greater than for conventional HVAC systems. There are a limited number of existing installations which have adequate operating experience to convince potential users to adapt. Most engineers and designers are unfamiliar with the geohydrologic requirements of ATES systems. Bids for ATES systems are high because the bidders are unfamiliar with them. There is still some uncertainty for recovering the higher first-cost for ATES systems. Although the environmental impacts of ATES systems are now well known, they are still of great concern to potential users who are unfamiliar with the impacts. Although the systems consume very little water, this is still a concern for potential users. Electrical utilities are concerned about the use of the technology even though it has a great potential for load leveling because it significantly reduces the amount of electricity used. Regulation of groundwater use can be an impediment in some states and could require re-evaluation by some state governments before the technology can expand. An integrated infrastructure must be developed combining the three technologies required in designing and constructing an ATES system to maximize its economic use.

HISTORY

In the early history of Aquifer Thermal Energy Storage in the United States, one of the major problems in demonstrating the technology was in finding support to build a field project which could determine cost and demonstrate the viability of the technology. In 1969, Dr. Harold Henry, The University of Alabama, Department of Civil and Environmental Engineering, published a paper demonstrating that a small quantity of hot water could be injected into a shallow aquifer and that a reasonable percentage of thermal energy could be recovered after a period of time [1]. This experiment used one well and a small hot water tank.

Subsequently, Auburn University received support from the U.S. Geological Survey and later from the Energy Research and Development Administration (ERDA), to demonstrate that warm water could be injected into confined aquifers through multiple wells and that a high percentage of the thermal energy could subsequently be recovered [2]. They used much larger quantities of water than Dr. Henry and stored the thermal energy in aquifers for an extended period of time. Most of the Auburn University research took place during the 1970s, at a site near the Berry Steam Plant in Mobile County, the southern-most county in the state of Alabama.

In the later 1970s, Dr. Brett (one of the authors) became interested in storing chilled water in aquifers for air conditioning and space cooling purposes. His interest was generated by the high cost of air conditioning in the warm southern states. The concept was to store winter chill for use during the subsequent summers and to shift electric peakload from summer to winter. In 1976, ERDA was approached by the author with a comprehensive program for Aquifer Thermal Energy Storage combining both heat storage and chill storage. No program was available at that time for research support. In 1977, ERDA funded four major projects to demonstrate the viability of using Aquifer Thermal Energy Storage for commercial applications. Total funding for these activities exceeded $5 million. The University of Alabama applied for this support but was unsuccessful because there was inadequate information concerning the aquifer in the Tuscaloosa, Alabama, area.

Dr. Walter J. Schaetzle and Dr. Brett later received funding to evaluate the use of water-source heat pumps coupled to aquifers for managing both heat and chill storage. This work was funded by the U.S. Department of Energy (DOE), Office of Buildings and Community Systems through Argonne National Laboratory in a program entitled Heat Pumps Centered Integrated Community Energy Systems [3]. The work was completed in the Fall of 1979, and indicated the conditions under which heat pumps, coupled to aquifers, could be practical.

In the meantime, the Parisian Department Store in a local Tuscaloosa shopping mall, decided to install a prototype ATES system for the purpose of air conditioning their business. This decision was influenced by a local engineering company in Birmingham, Alabama which specialized in building energy efficiency. The Parisian store was completed in 1979, and was air conditioned by the ATES system for two years until some problems with the system dictated terminating its use [4].

Partially as a result of encouraging information derived from the Parisian store, a similar system was designed for The University of Alabama's new Student Recreation Center which was placed in operation in the Fall of 1980. The U.S. Department of Energy had taken notice of the Parisian project and had contracted with Dr. Schaetzle to monitor the store's operation for a period of two years. After the completion of the Student Recreation Center Project, DOE, through the Pacific Northwest Laboratories, contracted with The University of Alabama to monitor the operation of the Student Recreation Center. DOE was interested in these two projects because the four major projects previously funded had failed and they were interested in acquiring data on two successful projects [5].

DOE has since been involved in the continuing development and monitoring of the Student Recreation Center system [6] and in the design of systems at the General Motors Radiator plant in Tuscaloosa, Alabama, and at the Veterans Affairs Medical Center (VAMC) in Tuscaloosa. An ATES system is currently under construction at the Veterans Affairs Medical Center in Tuscaloosa and has been paid for entirely by Veterans Affairs with DOE providing support for preliminary design, construction oversight, and system monitoring through the two authors at The University of Alabama.

The ATES system at the VAMC was installed after initial inquiries by the local chief engineer, subsequent review by engineers at Veterans Affairs Headquarters in Washington, DC, and by encouragement from Congressman Claude Harris (deceased) who was a U.S. Representative from the Tuscaloosa area at the time. A major opportunity presented itself when the Veterans Affairs decided to build a new major treatment building as a replacement for other aging treatment buildings at the hospital site.

## UNFAMILIAR NEW TECHNOLOGY

### Introduction

One of the principal impediments to the commercialization of ATES is its newness and the lack of familiarity by architectural engineers, architects, and other designers. At the time the systems in the Tuscaloosa area were being developed, there were no existing installations available as examples and, consequently, the risk in building a prototype system was significant and expensive. Only one related application existed in the northeastern United States in which a theater was cooled by direct heat exchange from a local shallow aquifer. In one location in New York, groundwater had been used to supply large water-source heat pumps and injected back into the ground for a period of time until the groundwater temperature rose making the system uneconomical. The lack of prior experience created a great deal of skepticism amongst architectural engineers. This skepticism is further exacerbated because thermal losses in the aquifer dictate that the smallest ATES system for practical purposes is approximately 350 kW (100 tons). Three hundred and fifty kW of air conditioning is very expensive with proven equipment and even more expensive with ATES equipment which has little history. The risk, then, is significant for the construction of a prototype system and must be offset by an anticipated cost benefit and a reduction in capital costs in subsequent systems based on acquired construction experience.

### Veterans Affairs Medical Center

The pressure of making a risk decision was very evident at the Veterans Affairs Medical Center. In 1987, the resident chief engineer made inquiries to The University of Alabama concerning its ATES system because the Veterans Affairs was planning to renovate some aging buildings. After an initial review, an engineer from Headquarters, Washington, DC, came to Tuscaloosa to look at the Student Recreation Center ATES system and to consider the use of the system in the building renovations. The Veterans Affairs hospitals were under some pressure from Headquarters at that time to practice energy conservation as a means of reducing operating costs. The stations had an incentive to conserve on energy costs because the savings could be transferred to patient care.

The Veterans Affairs ultimately decided that it was more cost effective to build a new treatment building then to renovate the five aging buildings. During the design period for the new treatment building, the authors had several discussions with the Veterans Affairs engineers about energy conserving technologies to use in the building. The Veterans Affairs Central Office had decided to use central chillers (two 1,800 kW [500 ton] units) to air condition the new treatment facility. The chillers would provide cold water piped underground to the building. The U of A team offered several air conditioning alternatives which were markedly cheaper to operate in a life cycle mode than the central chillers, but were turned down because the Central Office engineers were unfamiliar with the new technologies. They elected to continue with the central chillers because they were known to operate reliably in spite of their high cost of operation.

The authors subsequently sought the aid of a local congressman and eventually the Veterans Affairs elected to build a 560 kW (160 ton) aquifer system which would provide 20 percent of the peakload requirement of the treatment building in addition to the central chillers. The system is currently designed so that when there is an air conditioning demand, the ATES system will satisfy the load until the demand exceeds its capacity. At that point, the central chiller system will come on and provide whatever additional air conditioning is required. Since the ATES system can provide 20 percent of the peakload for the building, it will provide 100 percent of the baseload for much of the year, significantly reducing air conditioning costs for the treatment building.

One of the major problems involved in introducing new energy technologies, particularly expensive ones, in Federal government construction, is that there is little incentive for innovation and no incentive for risk taking. For the most part, Federal construction managers will opt for tried and true technology which they know will operate reliably, regardless of long-term costs to the operator. Using proven technologies allows the manager to progress career-wise, whereas, taking a risk with an unsuccessful outcome can damage a manager's future. The risk of using a new technology was removed from Veterans Affairs Headquarters managers and moved to Congress making it possible to evaluate ATES at the VAMC site in Tuscaloosa. Now, the experience at the VAMC site will provide a model for the HVAC industry in the United States and should create an incentive for its application in other Federal installations.

## The University of Alabama Student Recreation Center

The reluctance to evaluate innovative technology even extends to The University of Alabama's own project. In 1979, when the Student Recreation Center Building was being planned, the University was under the guidance of a progressive President, Dr. Howard Gundy. At the recommendation of the facilities manager, Dr. Roy Killingsworth (deceased), who had been advised by Drs. Brett and Schaetzle, the decision was made by Dr. Gundy to redesign the Student Recreation Building based on optimizing for cost-effective energy features and life-cycle costing principles. As a result, the first-time costs for the building rose from an original cost of $1.8 million to $2.3 million which, on a 20-year life-cycle costing base, proved to be the cheapest option. The building was rotated on its site to take advantage of passive solar principles, skylights were added to the roof to take advantage of daylight, special lighting systems were used throughout the building to reduce energy usage, and an ATES system was designed to provide air conditioning for the entire building. The original plans called for most of the building to be cooled by ventilation only. The 520 kW (148 ton) ATES system was provided with a 350 kW (100 ton) conventional mechanical chiller as a backup in the event of failure of the ATES system.

The ATES system has provided air conditioning for the Student Recreation Center since it began operation in 1980. The conventional backup system has been turned on only on rare occasions, primarily when wells in the storage field were being tested (no more than a week) and recently, during an expansion of the Recreation Center which interrupted periods during the winter when chill could have been stored. These short periods of chiller operation gave the authors information on the conventional cost for air conditioning the building which was more than twice the cost for air conditioning using the ATES system.

The expansion of the Student Recreation Center doubled the size of the facility. During the design of the expansion, cost studies were made by an architectural engineering firm to evaluate the use of ATES as compared to conventional technology for the addition.

During the design and evaluation period, there were a number of complaints to the Assistant Vice President for Facilities by Recreation Center users that the existing ATES system did not adequately dehumidify and requested that it not be used in the new addition. They apparently did not wish to perspire while exercising. Partially as a result of these complaints, the decision was made to use a water-source heat pump system to heat and air condition the addition. Wells in the existing ATES system are used to provide water for the water-source heat pumps.

The cost analysis comparing the water-source heat pump with an ATES system showed the water-source heat pump to be more cost-effective than the ATES system. This analysis was based largely on first-cost. One of the major elements of the water-source heat pump analysis was that the water would be supplied from the existing wells in the ATES system and the capital cost for the wells was not included in the analysis. As a consequence, the cost analysis was skewed in favor of the water-source heat pump application.

The new addition, which is about the same size as the older part of the Recreation Center, was opened in January 1993. The Recreation Center continues to be a major research application because with half of the building being air conditioned with a water-source heat pump and half being air conditioned with an ATES system, meaningful comparisons can be made relative to cost of operation and performance. In its present mode of operation, the heat pump uses water from one warm well in the summer time which provides flow control for the chill storage mass and in the winter time chilled water rejected by the heat pump is added to the total chill storage. There have been complications in operating this system because priority for water is given to the water-source heat pump, but these complications are being worked out and should disappear in the future.

The original ATES system used a cooling tower to provide chilled water for storage in the winter time. The cooling tower, along with other components of the system, proved to be too small to provide adequate chill and dehumidification in the latter part of the summer. To correct this, the authors redesigned the system, adding two production wells and a spray cooling pond sized to provide an adequate quantity of cold water for winter chill storage [7]. A spray cooling pond was proposed four years prior to the actual construction of the existing pond. There has been considerable resistance by the University administration to the construction of the cooling pond based on the argument that the pond would create a legal liability in the form of a water hazard and could contribute to damage of the aquifer. Proposals were made to hide it someplace and surround it with a fence to keep animals and people out of it. These proposals persisted even though the University has several open lakes on campus. One of the concepts in building a spray pond is to demonstrate that it can be incorporated as an attractive part of the landscape, whereas a cooling tower is always intrusive machinery. After consideration by a number of standing and ad hoc committees, the decision was made to build a spray pond in its present location in an open area which would provide the option for landscaping. Still the subject of fencing persists even though the presence of a fence would impede the airflow to the pond. At the Veterans Affairs Hospital, where some psychiatric patients are free to wander on the grounds, a similar spray pond has been built as a positive landscape feature incorporating a patio, rock walls and trim and without any fencing.

The Student Recreation Center is surrounded by large playing fields for softball, soccer, and other sports. These fields are maintained with an underground watering system. Several years ago, when the watering system installation was proposed, the authors suggested using groundwater from the ATES system for the water supply. Approximately 760 L/min (200 gpm) of groundwater is discharged to the surface throughout the year as a means of flow control of the aquifer. The watering system was to require 230 L/min (60 gpm). The University's Office of Facilities Management decided to purchase city water for the watering system rather than to use the continuously available groundwater because they felt the city water supply was more reliable and that there was not an adequate quantity of groundwater available to the system. The authors did a cost analysis showing that by using an inexpensive booster pump, essentially free groundwater was available and that the return on investment for installing the groundwater connection was well under one year. City water has been purchased to water the playing fields now for several years.

The success of an ATES system, particularly at this point in history, is predicated in part on the administrative environment in which the system is utilized. With an administration that is willing to take some risk and work its way through problems as they present themselves, a successful ATES system can result. The benefit can be a very long-term cost savings because the operating and maintenance costs are extremely low, reliability is very high, and the life of an aquifer is almost infinite.

## DESIGN COSTS AND TESTING

The design costs and preliminary requirements are significantly higher for an ATES system than a conventional system. In the absence of previous knowledge about the aquifer system at a potential site, testing must be performed to determine the water yield of a well in the formation and the magnitude and direction of regional aquifer flow. This testing is necessary even if water well data is available in the local area. Water wells are designed to produce water for various consumptive purposes and usually are designed only to meet the local demand. ATES water wells have entirely different functions, including both injection and recovery. In an ATES system, the entire saturated zone must be utilized. Testing requires a production-sized well and six smaller bore monitoring wells at a minimum plus additional services of a couple of well servicemen and a hydrogeologist or other knowledgeable professional to perform the tests over a period of approximately one week. An appropriately trained geologist or engineer must interpret the results and, if the initial survey is promising, design a well field layout that meets the application requirements.

Marked progress has been made in the development of simplified field testing methods and in software to facilitate ATES well field layout. Notwithstanding, the professional effort required to design an ATES system will remain sizable, and predicates that the application energy demand be large enough to absorb this additional cost which is significantly greater than the design cost of a conventional system. The minimum size for an ATES system (air conditioning) of approximately 350 kW (100 tons) is driven not only by the potential energy losses in the aquifer itself, but also by the higher testing and design costs experienced in evaluating each application.

## CAPITAL COSTS

At the time that interest in ATES first surged, oil and natural gas prices were escalating rapidly and it seemed apparent that high energy prices would persist in the future. Under those conditions, Aquifer Thermal Energy Storage appeared quite competitive. In today's climate of low energy costs in the United States, the economic advantages of ATES are not so clear.

The results of the work done at The University of Alabama and elsewhere show that operating costs for ATES-based cooling systems are substantially lower than operating costs for conventional air conditioning equipment. A major problematic issue is covering first-costs that typically exceed those of conventional systems with savings in operating costs.

Mechanical engineers who design heating and cooling systems must operate in an extremely competitive environment where following the tried and true solution is cheapest and poses little risk of litigation, while the risks of litigation are high. Consequently, mechanical engineers are suspicious of working with a technology that requires some understanding of geohydrology in addition to their own peculiar expertise. To make it even more complicated, if the customer convinces a consulting engineering firm to design an ATES system, the bids for building the system often are returned at an artificially high price because the contractors are afraid of the novelty of the system, even though all of the components of the system are quite ordinary -- water wells, pumps, piping, valves, cooling towers or ponds, controls, etc.

One way of improving ATES economics and continuing to make the technology more attractive to the marketplace is to further improve the COP so that operating costs are even lower and payback time is shortened. Developing experience in design and construction and unifying the entire activity so that one agency has all of the facilities to bring a project from concept to realization will also lower first-cost significantly making the technology more attractive to the customer.

## INTEGRATED INFRASTRUCTURE

One of the impediments that can be remedied in time is the lack of an integrated infrastructure for building ATES systems. ATES systems involve three separate technologies including geology or geohydrology for evaluating the aquifer system, well drilling which is somewhat different for ATES applications than for conventional well drilling, and HVAC design which is essentially an architectural engineering activity. When there is enough ATES activity, it will be cost-effective for engineering firms to integrate the three technologies, especially for large commercial applications. More experience needs to be accumulated concerning the actual cost for drilling wells, laying pipelines, installing controls, and installing building equipment.

Some attributes of ATES systems will have to be taken into consideration by the design and construction groups because of the nature of water wells and groundwater. For instance, the steel piping used in water wells to suspend the pumps create a wonderful ground which can contribute to the damage and failure of submerged water pumps from electromagnetic pulses and lightning. In addition, most groundwater has sufficient mineral matter to create an electrolytic condition which can cause corrosion in systems with dissimilar metals and mineral fouling. One of the ways to prevent this is to use as much plastic pipe in the system as possible and to install electric isolators in the water lines connecting heat exchanger coils in the building.

Another major problem is to avoid introducing air into the groundwater which will cause minerals to deposit in the water well screens and elsewhere. This is done primarily by eliminating all water-to-air interfaces and putting injection lines into the cold wells which terminate below the static water table.

## ELECTRICAL UTILITY COMPANY ATTITUDES

The electrical utilities could have a major impact on the marketing of ATES systems in the United States. For the most part, electrical power in the U.S. is relatively cheap compared to costs in other countries. This acts as a disincentive because it reduces the pressure to look for energy conserving technologies, particularly ones like ATES which is still relatively novel.

From the utility viewpoint, one of the major disadvantages of ATES air conditioning systems is that they reduce the amount of electricity required on an annual basis by 50 percent or more. Utility companies in the United States are interested in load leveling and would like to decrease peakloads, which an ATES system can do very effectively by shifting the summer air conditioning peak to winter, but they are not interested in reducing the amount of electricity produced. Since ATES systems are not universally applicable to every air conditioning application, they should be viewed as a means of providing a service to a broader base of customers without necessarily reducing the baseload. From another viewpoint, ATES systems can make it possible to expand the customer base without increasing the amount of generation capacity.

## WATER USE AND CONSUMPTION ISSUES

Water use and consumption is a concern to most regulatory agencies and becomes an impediment to the use of ATES systems, primarily through the lack of understanding. Although a typical system may handle in excess of 100 million liters during the course of a season, very little of the water is lost. Except in systems where aquifer flow control is required, most of the losses are from evaporation during the winter cooling period. Evaporative loss of water ranges from 1 to 2 percent of the water flow through the cooling tower or spray pond and is typically smaller in winter than summer because of the cooler air termperatures.

Ideally, all of the water that is chilled in the winter time is re-injected into the aquifer and stored for summer cooling. However, in an aquifer with significant regional flow, some percentage of the water has to be withdrawn to control flow. This water is wasted to the surface and can be considered a consumptive fraction. If possible, a use for the water should be made such, as watering landscape or process cooling in industrial applications. In any event, the water is eventually lost to surface discharge, but can be impounded and returned to the aquifer through percolation. For the most part, ATES systems should have little or no impact on the total water use or consumption of the aquifer to which it is coupled. In most water table aquifers, the rate of recharge would far exceed consumption.

## ENVIRONMENTAL ISSUES

Environmental issues in the United States are a potential impediment to almost any activity that impacts natural water or air. One of the major issues with ATES systems is the potential for damage to an aquifer. With nearly fourteen years of experience operating an ATES system at The University of Alabama, we see little or no negative environmental impacts associated with the operation of the Student Recreation Center system. There has been no clogging of screens or the aquifer itself from injecting chilled water back into the ground. The injection and pumping efficiency of these production wells has actually improved significantly since their installation. For a period of time, silt was collected in the bottom of the cooling tower while the system was new but at the present time there are no sediments being collected in the cooling tower. A sand filter is used to clean the water before it is injected back into the aquifer and apparently is very effective.

One of the major environmental impacts the authors observed is that no human pathogens develop in the cooling tower during operation of the system. Conventional cooling towers, which are used in the summer time, universally develop the presence of human pathogens, including Legionella, and have to be sanitized on a weekly basis. No sanitization is required with the ATES cooling system. When the cooling pond was constructed, there was a concern that students might put chemicals, such as soap, in the spray pond which could potentially damage the aquifer. It was even suggested by some members of the University administration that somebody might dump dangerous industrial chemicals into the spray pond which would cause damage to the aquifer. Although this is theoretically possible, the likelihood seems remote.

As with the cooling tower, all water re-injected into the aquifer from the spray pond passes through a sand filter first. The design revision to the Student Recreation Center ATES system also requires that all water being pumped from the cold wells into the building cooling coils also passes through a sand filter to prevent any damage from the presence of fine silt.

LEGAL ISSUES

In the drilling of wells for water or other substances, most states exercise regulatory control of the operation in one form or another. In Alabama, for instance, to operate an ATES system, there must be a permit to withdraw groundwater and re-inject it or to withdraw groundwater and discharge it to the surface. There are physical and chemical limits to modifications to the groundwater which would allow re-injection or surface discharge. ATES systems easily fall within those regulatory limits. Many states issue drilling permits and require reports upon completion of the well. In states where water is scarce these regulations are stringent, in states where water is plentiful, regulations tend to be less stringent or minimal. In the case of wells drilled for water, there is considerable variation of requirements for state agencies. Most regulations have three functions, first a public health function to assure that wells are so constructed as to provide a safe drinking water supply, another to prevent entry of polluted or mineralized water into the aquifer, and a "consumer protection" function to ensure completion of an efficient well.

Control of the withdrawal and use of groundwater is practiced by many states. Most water-short western states operate under a prior-appropriation doctrine wherein water is allocated on a scale of need and beneficial use. Arizona, California, and Utah are examples of states in which withdrawal and use of groundwater is allocated on the basis of beneficial use. Priority is given to use for domestic and municipal supplies, followed by uses for irrigation, mining, recreation, and so forth. The water-rich states have generally adopted the Riparian-Rights doctrine under which all constraint is placed on the withdrawal and use of surface waters and, for all practical purposes, groundwater is considered personal property of the surface owner. In Alabama, the use of water has not been subject to significant legislation and there is limited control over water usage. The Alabama Water Well Standards Board regulates completion practices and requires that wells drilled for the public be, more or less, automatically granted to the well driller. Florida law is administered by water management districts which issue water-use permits based on availability and maximum reasonable-beneficial use. Georgia requires a permit for the withdrawal for more than 380,000 L (100,000 gallons) of water per day. If there is significant evidence that groundwater is not consumptively used, a permit will be granted without a public hearing.

The state of Mississippi is the only state east of the Mississippi River that has adopted the prior-appropriation system for water rights. Permits for use of groundwater in problem areas are required. Legislation in Iowa states that a permit is required for using in excess of 19,000 L (5,000 gallons) of water per day from any source of supply, but municipal water systems are excluded from the requirement.

Use of aquifers for thermal energy storage is a recent practice. In as much as water withdrawn is returned, for the most part, to the aquifer with essentially no loss, there is not a consumptive use and, therefore, it is envisioned that few problems should be encountered in obtaining a permit for this particular use except in the case of warm water storage. Groundwater with an elevated temperature is considered a pollutant in some states. Building and other local codes may apply to the drilling of water wells. In each case, in every state, local and state authorities should be consulted to determine requirements and restrictions on the use of groundwater. The drilling contractor affords a source of reliable information with respect to all requirements.

Most state laws provide that protective measures be taken to prevent pollution of the water source. A final step in proper well completion is the sterilization procedure which is design to destroy disease producing organisms that may have been introduced into the well during construction operations from drilling fluids, equipment, materials, or by surface drainage into the well.

COMPLEX GEOHYDROLOGY

In most cases, the geohydrology of an aquifer should be relatively easy to diagnose. However, complexities can occur during the site testing activities or during testing while the production wells are being drilled. Complex problems must be anticipated in advance, because if they are not solved they can compromise the performance of the ATES system. At the VAMC, a complex geohydrological problem occurred which required a major effort to diagnose, and resulted in the redrilling of two of the six production wells. Obviously, problems of this sort can be an impediment to the commercial development of ATES systems, and could influence a decision-maker to abandon a site that has such problems. The experience at the VAMC may be of some assistance to future developers.

A field evaluation of the VAMC site was performed in 1989 by Pacific Northwest Laboratories (PNL) and The University of Alabama [8]. Lithium Bromide was used as a tracer to define some of the hydrologic characteristics of the aquifer, along with other conventional pump tests. No unusual problems were detected. Since that time, PNL has developed new instrumentation and more sophisticated techniques for analyzing the hydrologic characteristics of production wells using Lithium Bromide as a tracer.

In early 1994, a followup field evaluation was conducted by PNL and The University of Alabama to confirm the work done in 1989. Two production wells were used so that water could be pumped from one and injected into the second well to evaluate injection characteristics.

A new procedure, using Lithium Bromide, was used to evaluate the flow characteristics of the wells. The production wells were screened throughout the entire saturated zone. A small quantity of Lithium Bromide was placed in the groundwater so that the concentration was uniform from the water table to the bottom of the well. Over a period of several hours, the concentration of the tracer was measured using a new prototype sensor. The test showed that the water in each of the two wells was flowing from the top to the bottom at a rate of 20 cm (0.7 ft) per minute. This vertical flow could seriously compromise the capability of storing chilled water on a seasonal basis.

Driller's logs had been kept on all wells drilled at the VAMC (Figure 1), and it was hypothesized that the bottom 3-6 m (10-20') of the wells, being composed mostly of pebbles and coarse sand, offered an exceptionally porous zone to which the water column in the wells flowed. In most of the wells, there are layers designated as hard rock by the driller which we assume to be limonite layers. Limonite is a mineral oxide of iron and occurs commonly in the terrace gravels around the region through which these wells were drilled. The aquifer itself resides in the bottom portion of these terrace gravels. Limonite was recovered from well cuttings at elevations marked as hard rock by the driller.

We hypothesized that the limonite zone provided a hydraulic barrier between the lower highly permeable sediments and the overlying aquifer. Penetrating the limonite layer would provide communication between the upper aquifer and the lower high porosity zone.

A well servicing company was hired to attempt to plug off the high porosity zone so that additional tests could be performed on the wells. Several unsuccessful attempts were made to plug one of the production wells, but the vertical flow persisted. Apparently, the flow was so great that materials used to plug the wells passed through the screens and into the formation without sealing the packing surrounding the screens. This resulted in one well of a plug of approximately 7 m (23 ft.) but the vertical flow persisted.

After several iterations of dialogue with PNL and other hydrologists around the country, a retired geohydrologist from PNL, Mr. John Raymond, suggested that we might have a perched aquifer at the top of the water column isolated by a clay layer which we identified in the drilling process.

We then redesigned the production wells so that the screens were placed below the clay layer, 18 m (60 ft) versus 24 m (80 ft) as originally designed. The top of the screens were plugged with bentonite to seal off the perched aquifer and the vertical flow was no longer observed.

The time and expense of solving such a problem as described herein can be significant. The authors wish to express their appreciation for the patience and persistance of Mr. John O'Carroll, Veterans Affairs Site Engineer and Mr. G.W. Traywick, Superintendant for the general contractor, Brasfield and Gorrie, Inc. Their patience is especially appreciated because all of the field analyses that were taking place and the redrilling of the two production wells were occurring during the actual construction of the building and required several modifications of the construction schedule. All of the work on the wells was completed without any negative impact on the construction schedule.

CONCLUSIONS

As with any new technology, there are many problems in introducing the technology to the marketplace, not the least of which is skepticism on the part of designers, purchasers, and engineers who might have a need for the new technology. Financial risk is the major impediment for introducing ATES systems into the marketplace. Because their first cost is higher than for conventional HVAC systems, designers and users are reluctant to choose the technology without first being satisfied that they will function well and that they have a favorable return on investment.

One of the other major deterrents for engineers and designers is the unfamiliarity with the geohydrological component of the systems. This adds another risk which increases the uncertainty already existing in the minds of the potential users.

Concerns about the environmental impact of the ATES systems on the aquifers to which they are coupled and to surface waters along with consumptive concerns is also important. These questions are raised immediately in the minds of potential users. Even the regulatory authorities are uncertain about the potential impacts.

The size of these systems can also be of concern because, for practical considerations, they must be very large. An ideal application, from an economic viewpoint, for instance, is the central core of a large city as a part of an integrated community heating and air conditioning system. Designers and decision-makers must have great confidence in the ATES technology before committing to these large systems. The ATES air conditioning system at The University of Alabama Student Recreation Center and at the Veterans Affairs Medical Center, Tuscaloosa, Alabama, can provide models for decision-makers wishing to reduce the cost of air conditioning on an annual basis, for power generation loadleveling, and for reducing the risk of exposure to human pathogens. These systems can also be used to improve landscaping because they eliminate the use of cooling towers if more efficient spray cooling ponds are substituted. The spray cooling ponds can be integrated into the landscape as natural water features.

Information on the performance of the VAMC ATES system will be available to the marketplace in the next year or two along with the experiences of other similar applications in Canada and elsewhere. Many successful applications have been developed in Europe and can provide excellent models for future development in the United States along with the applications in Tuscaloosa, Alabama.

ACKNOWLEDGEMENT

Support for this project by the U.S. Department of Energy through Pacific Northwest Laboratory is gratefully acknowledged.

REFERENCES

1. H. R. Henry, J. R. McDonald and R. M. Alverson, 1971, Aquifer Performance Tests Under Two-Phase Flow Conditions, OWRR Project No. B-020-ALA, The University of Alabama and Geological Survey of Alabama, Tuscaloosa, Alabama.

2. F. J. Molz, J. C. Warman and T. E. Jones, 1978, "Aquifer Storage of Heated Water 1: A field Experiment," Ground Water, Vol. 16, pp. 234-241.

3. W. J. Schaetzle, C. Everett Brett and Marvin S. Seppanen, 1979, "System Development - Final Report," Heat Pump Centered Integrated Community Energy Systems, Argonne National Laboratory, Contract No. 31-109-38-4550, 266 pp.

4. W. J. Schaetzle, C. E. Brett and L. H. Richey, 1983, "Experience with Two Free Cooling Systems Using Aquifer Thermal Energy Storage," Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice, Stockholm, Sweden, June 6-8, 1983, Swedish Council for Building Research, Stockholm, Sweden, pp. 823-828.

5. C. E. Brett and W. J. Schaetzle, 1984, "Experiences with Unconfined Aquifer Chilled Water Storage," ASHRAE Trans., Vol. 2B, pp. 169-181.

6. Y. K. Song, K. C. Midkiff, W. J. Schaetzle and C.E. Brett, 1989,

"Control of Aquifer Flow for Improved Aquifer Thermal Energy Storage System Performance," IECEC-89: Proceedings of the Intersociety Energy Conversion Engineering Conference in Washington, DC, August 6-11, 1989, Institute of Electrical and Electronics Engineers, Washington, DC, pp. 1833-1838.

7. K. R. Gelinas, 1994, "The Applicability of Spray Ponds to Chill Water for Aquifer Thermal Energy Storage Systems," M.S. Thesis, The University of Alabama, Tuscaloosa, Alabama.

8. W. E. Cronin, S. P. Luttrell and S. H. Hall, 1989, Aquifer Characterization at the Veterans Administration Hospital, Tuscaloosa, Alabama, Publication No. PNL-7139, Pacific Northwes Laboratory, Richland, Washington, 21 pp.

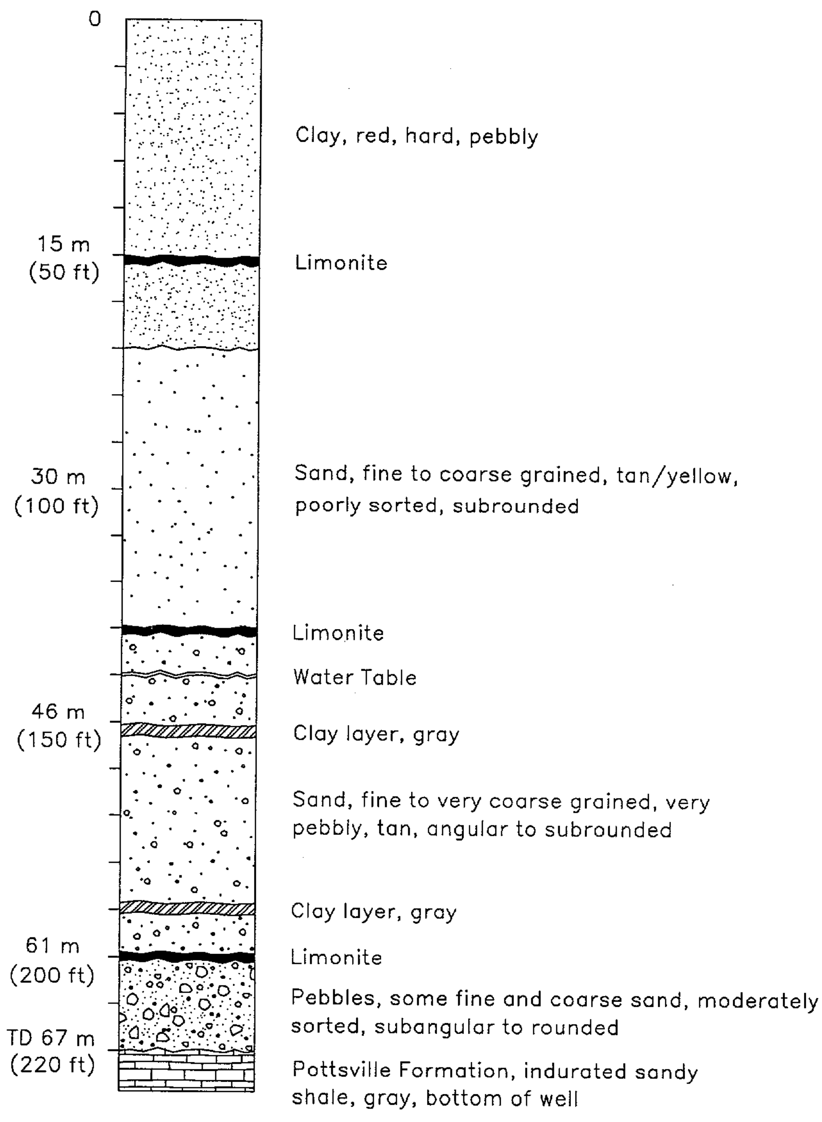



Figure 1 Geological log, typical VAMC, May 9, 1994

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# ATES Project at the University of Utrecht: Recent Experiences and Consequences for Water Treatment

• Martin van de Weiden
Heidemij Consultants BV
Arnhem, The Netherlands

ABSTRACT

The Aquifer Thermal Energy Storage (ATES) project at the University of Utrecht campus in the Netherlands became operational in 1991. The project will extend combined heat and power generation into the summer beyond heat demand periods, resulting in increased electricity generation. The stored heat (90°C) can be used in the winter for space heating of several university buildings. The project is accompanied by a monitoring programme so as to be able to evaluate the project. In this paper special attention is devoted to the energy balance (thermal efficiency of the storage), the effects ((bio-)geochemical reactions) and the underground behaviour (possible clogging). Until now the storage has been functioning in conformity with expectations, although the results of the monitoring programme regularly indicate otherwise. The measurement equipment consequently needs more frequent calibration.

## INTRODUCTION

Because natural energy resources are limited, energy consumption needs to be as low as possible. Consumption can be lowered with aquifer thermal energy storage. To gain insight into the full potential of this technique, research is being done and demonstration projects are being carried out.

One of these demonstration projects is the ATES system at the University of Utrecht campus. The feasibility study for the project was carried out in 1987 [1]. In 1988 two test drillings took place. The second drilling revealed that the third aquifer was suitable for thermal energy storage [2]. Several papers have been published on this project, which became operational in 1991. Some relevant publications are [3] to [6].

The project is being studied through a monitoring programme [7]. The aim of the programme is to determine underground storage behaviour, and to evaluate the system.

This paper will focus on recent experiences with the ATES system as obtained through the monitoring programme (on (bio-)geochemical reactions (chapter four) and on underground storage behaviour (fifth chapter). General information is given in chapter two to familiarise the reader who is not familiar with ATES at the University of Utrecht campus. Moreover the storage system, the monitoring programme and its operation will be explained in the same chapter which for the most part has been taken from the paper of Van Loon and Van der Heide [5]. Chapter three presents the results of the thermal efficiency calculations, which were carried out in 1992 [8].

## ATES UNIVERSITY UTRECHT

### General Information

The 'De Uithof' campus of the Utrecht University was constructed in the mid-sixties. The building area is 335,000 $m^2$ and energy consumption is 37,000,000 kWh electricity and 10,000,000 $m^3$ natural gas per year. The heat required to heat the buildings of 'De Uithof' is generated in two central plants and a number of decentralized plants. In each central plant there are heat-power co-generation units. The capacity of these co-generation units is 3.75 MW in the one plant, and 4 MW in the other. Until 1991, heat demand dictated production. Excess electricity was sold to the Public Utility Services.

Since 1991, electricity has also been generated in summer, and excess heat stored for re-use in the winter season.

### Storage System

At 'De Uithof' heat is stored in an aquifer, a water bearing sand layer between two clay layers, at a depth of 210 to 260 m below ground level. The principle of the system can be seen in the artist's impression in Figure 1.

In summer the aquifer is charged by pumping up water from the relatively cold well (the well on the right in the picture), heating this water with the residual heat from the co-generation units and injecting it into the warm well at a temperature of some 90°C. The warm water replaces the cold water and thus a warm bell is created around the warm well. When the heating season commences, the warm water is extracted and transfers its heat to the buildings at 'De Uithof' via a heat exchanger, after which it is injected into the cold well.

In Figure 2 it can be seen how the excess heat from the central plant for the Veterinary Medicine Faculty and from the central plant for the Mathematics and Physics Faculty is transferred via two heat exchangers and transported underground to load the aquifer.

During discharge, the return water from the two buildings first passes the heat exchanger which is connected to the heat store; subsequently it may be heated additionally by boilers.

In order to prevent wells and the heat exchanger becoming clogged by lime deposits, the groundwater is treated, for which a water treatment unit (Ca-Na exchange) has been installed.

The groundwater flow rate is changed by speed controlling the pumps and by control valves. To avoid carbon dioxide being degassed when the pressure in the system becomes too low, injection pipes are geared to a specific flow rate.

More details about the system design are given by Van Loon and Paul [3]. A summary of the key technical figures is given in table 1. Thermal and chemical environmental effects have been reported by Willemsen and Van der Weiden [4].

### Monitoring Programme

The ATES system is being studied in a monitoring programme during a period of five years (1991-1995). The aim is to determine the underground storage behaviour and to evaluate the energy balance and the economic results.

Altogether, there are six wells. One warm well, a cold well and four wells only for monitoring purposes. Seventy temperature sensors have been installed in these wells. The groundwater level is recorded and groundwater samples are collected with the aid of 25 observation tubes. These samples are analyzed for numerous substances, mainly ordinary components such as calcium. Furthermore, bacteriological activity is also measured. Expansion and subsidence is measured at the wells and in the wide vicinity of the storage. Two water meters have been installed to measure the volume of displaced groundwater. In the above-ground system ten heat sensors, eight gas meters, twelve kWh meters, two pressure transmitters, eleven temperature sensors, a hardness meter and turbidity meter are used to monitor the system behaviour and to establish the energy balance. The data are recorded for a large part automatically by the 'building automatisation system'.

### Operation

The aquifer storage was tested under natural temperature conditions in late 1990. After installing the water treatment equipment, the system was started up on March 14, 1991.

After several charge and discharge tests (15, 40°C), the system commenced complete automatic operation on May 13, 1991 at a maximum temperature of 65°C. From August 29, 1991, the injection temperature was increased to 90°C. Since then the injection temperature has been kept constant at 90°C.

During discharge, water is extracted from the cold well until the temperature drops to 50°C. At this moment the system has accomplished three cycles of charge and discharge. During the fourth cycle only small amounts of thermal energy could be stored because the co-generation units were temporarily out of order.

## THERMAL EFFICIENCY

### SWIP and HST-2D

In 1992 the thermal efficiency of the ATES was recalculated with the computer programs SWIP and HST2D-PC [8]. SWIP [9, 10] and HST2D-PC [11] are heat and solute transport programs. SWIP is a 3-dimensional and HST2D-PC is a 2-dimensional (horizontal, vertical or radial symmetrical) program. SWIP is the predecessor of HST3D (the 3-dimensional version of HST2D-PC).

The models made with HST2D-PC and SWIP were calibrated with measured data of the first cycle (1991/1992). The program HST2D-PC and the ATES were evaluated with the measured data and the efficiency calculations.

### Calculations

Three earlier studies have been carried out in which efficiencies were estimated or calculated. These studies were all based on design data. An efficiency of 65-75% was estimated in 1987 for the third cycle [1]. In 1988 efficiencies of 20, 45, 55 and 60% were calculated for the first, second, third and fourth cycle, with a combination of (2-dimensional) horizontal and radial symmetrical SWIP-models [2]. Based on additional soil data obtained during the realization of the ATES in 1989, new (radial symmetrical) calculations were performed and efficiencies of 13, 38, 48 and 52% were determined for the first four cycles [12].

The measured efficiency for the first cycle (1991/1992) was 16.8% [7]. After calibration of the (newly-made) 3-dimensional SWIP-model in 1992, the calculated efficiencies for the second, third and fourth cycle were 40, 51 and 56,5%. Calculations with the calibrated HST2D-PC-model revealed efficiencies of 41,5, 58,5 and 67% for these cycles. It is assumed that the calculations with SWIP (in 1992) are more reliable, since with SWIP the complex 3-dimensional groundwater situation has been 3-dimensionally modelled. This was not possible with HST2D-PC. The model made with HST2D-PC was a 2-dimensional horizontal model because the groundwater situation is not radially symmetrical. The thermal efficiencies from all studies are presented in Figure 3.

Figure 4 presents the temperature distribution in the storage at the end of the fourth charge period as calculated with SWIP.

### Evaluation of HST-2D

HST2D-PC can be seen as an 'engineering tool', that can be used for efficiency calculations for ATES in situations in which:

- the permeabilities in the aquifer differ less then one order of magnitude;
- the wells are fully penetrating.

Exceptions are radial symmetrical groundwater situations (2-dimensional groundwater problems). In these cases HST2D-PC can also be used for efficiency calculations if the wells are not fully penetrating and the permeabilities differ more then one order of magnitude.

### Evaluation of the ATES

Less heated water was injected in the first cycle then was planned. Moreover, the temperature of the injected water was less then 90°C in the first months of the injection period because of the start up procedure. Hence the efficiency of 16.8% was less then it would have been with the design quantity (100,000 $m^3$) and temperature level (90°C).

During the second cycle the measured efficiency was 36%. This is slightly lower than the calculated efficiency (40%) because less water was injected than had been planned for the first two cycles (116,000 instead of 200,000 $m^3$). Less water was injected due to technical problems which had no direct bearing on the ATES. These technical problems were solved during the third cycle.

With SWIP the calculated efficiency for the third and fourth cycles is 51 en 56,5%. since the efficiency of the ATES is increasing less with every cycle, it is expected that the efficiency will stabilize at 60% when thermal equilibrium is reached. For an ATES system this is a good result.

## (BIO-)GEOCHEMICAL REACTIONS

### Relevant Reactions

The ATES initiates (bio-)geochemical reactions in the aquifer. The most relevant reactions are the precipitation of lime, the dissolving of silica and the exchange of cations. The precipitation of lime is the most threatening one for the ATES system. Hence the water is treated before injection by a Ca-Na exchanger. These reactions and the water treatment change the water composition in the aquifer.

To monitor this effect, water samples are taken every two months and analyzed for all major components. The hardness of the water is measured every week during charge so that water treatment can be adjusted.

### Water treatment parameters versus hardness

The watertreatment results in lower values for the saturation index of calcite ($SI_{calcite}$) and in higher values for the sodium adsorption ratio (SAR). The SIcalcite is defined as:

$$SI_{calcite} = Log\left(\frac{IAP_{calcite}}{K_{calcite}}\right) \qquad (1)$$

In which:

$SI_{calcite}$ = Saturation index of calcite
$IAP_{calcite}$ = Ion activity product of calcite
$K_{calcite}$ = Solubility product of calcite

$SI_{calcite}$ values at 90°C have been calculated with WATEQP [13].

The SAR is defined as:

$$SAR = \frac{[Na]}{([Ca] + [Mg])^{0.5}} \qquad (2)$$

The concentrations are expressed in mmol/l.

The split of the treatment during the first cycle was 60 % (which means that 60 % of the water is treated; 40 % is not treated). During the next cycles the split was adjusted because otherwise the water would have been over-treated (once treated and injected water is produced during discharge, and is used again during the next charge). If the water is treated too much, clays can swell in the storage and cause clogging.

To avoid clay swelling the Sodium Adsorption Ratio (SAR) needs to be below 11. To avoid precipitation of calcite the $SI_{calcite}$ should be below 0.3.

The SAR and SIcalcite are plotted versus the hardness of the water in Figure 5.

Hardness is chosen because this parameter is directly influenced by the water treatment. The hardness is expressed in German degrees (DH). The graph indicates the clogging criteria. The optimum lies between 6 and 7 DH. During the cycles after the first one, the split of the water treatment was adjusted so that the hardness came within this range.

### Components versus Time

The components analyzed can be presented in graphs plotting the component concentration versus time. For example, in Figure 6 the Ca, Mg and Na concentrations are plotted versus time.

The influence of the water treatment is obvious during charge: the Ca and Mg concentrations decrease while the Na concentration increases. During discharge the Ca and Na concentrations increase while the Mg concentration stays constant. In the same way the Cl, $HCO_3$, $SO_4$ and 'total inorganic carbon' (TIC) concentrations were investigated. $SI_{calcite}$, too was plotted in this way. The following observations and interpretations were made:

- The Cl concentration increased, probably as a consequence of the inflow of deeper water;
- The $HCO_3$ concentration during discharge is higher than during charge, perhaps also because of the inflow of deeper water, but possibly due to $CO_2$ production as a result of the decomposition of organic matter;
- The $SO_4$ concentrations are low and stay low;
- During charge, the $SI_{calcite}$ value is lowered by the water treatment to about 0.6. During discharge the value increases.

The $SiO_2$ concentration and the temperature correlate with each other. An elevated temperature leads to elevated $SiO_2$ concentrations. The highest measured $SiO_2$ concentration was 39 mg/l. In Figure 7 the $SiO_2$ concentration is plotted versus time.

The components analyzed revealed no other relevant reactions.

The low concentrations of COD and $PO_4$ are worth mentioning. As a consequence the precipitation of lime will hardly be inhibited by these components.

Moreover, the dissolved gas concentrations of $CO_2$ and $N_2$ are low. $CH_4$ and $H_2S$ concentrations are near the detection limit. The total gas pressure of the water at 90°C was calculated to be $2 * 10^5$ Pa. To avoid clogging by gas bubbles the pressure in the system needs to be at least $2 * 10^5$ Pa.

## UNDERGROUND STORAGE BEHAVIOUR

The aquifer thermal energy storage is designed to function for some 20 years. Clogging could shorten the lifetime of the ATES system. To prevent clogging the water is treated (see second and fourth chapter). However, clogging remains a possibility. To detect any clogging in good time, the hydraulic head in the wells is monitored.

### Hydraulic Head in Wells

The hydraulic head in the wells is a function of temperature and of flow. A theoretical hydraulic head can be calculated for each temperature and flow combination. The calculated values for the warm well are presented in Figure 8 [14].

The hydraulic head can also be increased by clogging. This increase should not be too high. The increase can be expressed as a pressure difference which is defined as:

$$\Delta_P = \frac{((P_m - P_{ref}) - (P_c - P_{ref}))}{(P_c - P_{ref})} * 100\% \qquad (3)$$

In which:
- $\Delta_P$ = Pressure difference (%)
- $P_m$ = Pressure measured at the well head (kPa)
- $P_c$ = Pressure calculated at the well head (kPa)
- $P_{ref}$ = Pressure calculated at the well head (kPa) without injecting or producing water (kPa)

Well cleaning is needed if $\Delta_P$ increases above 100 %.

### No Clogging of Warm Well

The 'building automatisation system' keeps a continual ecord of all relevant parameters. $\Delta_P$ was calculated with the available data. Since the ATES became operational, $\Delta_P$ would appear to have increased steadily for both wells.

In 1993 the calculated $\Delta_P$ values indicated that the warm well was clogged within the third cycle. Hence preparations were made to clean the warm well, but because of the water's high temperature (90°C) it was decided that it was more practical to wait until the storage was discharged. In the meantime, the available data were thoroughly checked. This check revealed that the flow meter which measures the amount of water injected into the warm well, was not functioning optimally. The meter gave values which were too low. The meter started disfunctioning in 1992 and the deviation increased from a few % to some 30 % by 1993 !

With the available data it was possible to correct the flow values and the $\Delta_P$ values were recalculated with these corrected figures. They are plotted versus time in Figure 9.

During the second cycle, the $\Delta_P$ values are still close to 100 %, however, during the third cycle they are between zero and 50 %, so that the warm well is not clogged.

When the meter was dismantled, it was found to be covered with small amounts of sulphide, probably iron sulphide which had precipitated on the meter. This precipitate caused electrical short circuit in the meter. This short circuit had led to the low flow values. Once the meter had been cleaned, the flow values restored to normal.

### No Clogging of Cold Well

The flow meter for the cold well was also checked. The meter appeared to function correctly. The calculated $\Delta_P$ values for the cold well were above 100 %. At that moment the high values for the hydraulic head could only be explained by clogging, probably caused by particles or chemical precipitation (sulphides). Hence the well needed cleaning.

In June, 1994 the cold well was cleaned. The pumping tests before and after the cleaning operation indicated, however, that the well was not clogged. The only possible explanation for the high $\Delta_P$ values is an error in recording the hydraulic head at the cold well, perhaps caused by gas accumulating under the well head. What is certain is that the system of measuring the hydraulic head needs regular calibration.

## CONCLUSIONS

### Thermal Efficiency

The thermal efficiencies were calculated with a calibrated model. For the first to the fourth cycle these efficiencies are respectively: 16.8, 40, 51 and 56.5 %. Efficiency is expected to stabilize at 60% once thermal equilibrium has been reached. For an ATES system this is a good result. Until now, the measured thermal efficiencies of the storage are almost in conformity with the forecasts, though less heated water was injected during the first and second cycles, than was planned.

### (Bio-)geochemical Reactions

The water treatment led to a decrease in Ca and Mg concentrations and to an increasing Na concentration. These changes are in perfect balance. As a consequence, the sodium adsorption ratio (SAR) is close to 11 (no clogging by clay swelling), and the saturation index of calcite ($SI_{calcite}$) at 90°C is close to 0.6 (possibly clogging by lime).

The Cl concentration increased, probably as a consequence of the inflow of deeper water.

The total inorganic carbon (TIC) concentration increased, possibly due to $CO_2$ production resulting from the decomposition of organic matter.

A geochemical reaction in the aquifer which also led to a measurable effect was the dissolving of silica. The $SiO_2$ concentration correlates very well with the temperature.

### Underground Storage Behaviour

The water treatment is functioning well as there are no indications of clogging by carbonates.

Small amounts of sulphide precipitation on the flow meter of the warm well caused too low flow values and too high relative pressure values ($\Delta_P$ values) falsely indicating clogging of the warm well. After correction of the flow values and recalculation of the $\Delta_P$ values, there was no further indication that the warm well was clogged.

The flow meter of the cold well is functioning correctly. The $\Delta_P$ values indicated that the cold well was clogged. Pumping tests, however, indicated that the well was not clogged. The only possible explanation is an error in recording the hydraulic head at the cold well.

## RECOMMENDATIONS

The ATES system is being monitored by several measuring devices. It is of great importance to check and calibrate them frequently.

Until now, the water has been treated so as to avoid the ATES being clogged by the precipitation of lime. The treatment has been successful so far. However, high SAR and $SI_{calcite}$ values mean that there is still a chance that the system will eventually become clogged. To prevent this, water treatment has to be optimized. Optimization experiments are needed for this. These experiments should produce maximum values for SAR and $SI_{calcite}$. These values will be are unique to the ATES project in Utrecht.

ACKNOWLEDGEMENTS

The monitoring programme is financed by the Dutch Agency for Energy and Environment (NOVEM). Heidemij Consultants BV worked on this programme in conjunction with Bredero Energy Systems (the main contractor) and FBU-engineering (the owner of the ATES).

Thanks are due to L.J.M. van Loon for his valuable suggestions for improving this manuscript.

REFERENCES

1. Bredero Energy Systems, Rijksuniversiteit Utrecht en Heidemij Adviesbureau BV, 1987 "Haalbaarheidsstudie seizoenopslag van restwarmte uit de WKK-installaties van de Rijksuniversiteit te Utrecht", Arnhem, Heidemij Advies BV.

2. Heidemij Adviesbureau, 1988b, "Resultaten 2[e] Proefboring in 3[e] aquifer", Arnhem, Heidemij Advies BV.

3. L.J.M. van Loon and A. Paul, 1991, "Aquifer thermal energy storage at the state University of Utrecht, The Netherlands", in Proceedings Thermastock '91, p. 1.3-1 - 1.3-7.

4. A. Willemsen and M.J.J. van der Weiden, 1991, "Heat losses and groundwater chemistry of the Utrecht University ATES", Proceedings Thermastock '91, p. 4.12-1 - 4.12-7.

5. L.J.M. van Loon and K. van der Heide, 1992, "High temperature ATES at the University of Utrecht, the Netherlands", in Proceedings of 27th Intersociety Energy Conversion Engineering Conference, San Diego, IECEC, Volume 4, P-259, p. 4.73 - 4.76.

6. K. van der Heide en M.J.J. van der Weiden, 1992, "De warmte-opslag van het complex "De Uithof" van de Universiteit Utrecht", Klimaatbeheersing (21) nr. 11: 341-350.

7. Heidemij Adviesbureau BV, 1993, "4[e] voortgangsrapportage meetprogramma warmte-opslag Rijksuniversiteit Utrecht; ondergrondse deel", Arnhem, Heidemij Advies BV, 63 blz., Rapportcode 638/AA93/A053/45619W.

8. Heidemij Adviesbureau BV, 1992, "HST2D-PC- en SWIP-berekeningen voor warmte-opslag Universiteit Utrecht", Arnhem, Heidemij Advies BV, Rapportcode 638/AA92/A415/05910T.

9. U.S. Geological Survey Water-Resources Investigations (U.S.G.S.), 1976, "A model for calculating effects of liquid waste disposal in deep saline aquifers", Houston, Texas, U.S.G.S. Water-Resources.

10. U.S. Geological Survey Water-Resources Investigations, 1979, "Revision of the documentation for a model for calculating effects of liquid waste disposal in deep saline aquifers", Houston, Texas, U.S.G.S Water-Resources.

11. Hagoort & Associates, 1992, "HST2D-PC (version 2.0): Heat and solute transport simulator for personal computers", Delft, Hagoort & Associates.

12. Heidemij Adviesbureau, 1989, "Rendementsberekeningen warmte-opslag Rijksuniversiteit Utrecht", Arnhem, Heidemij Advies BV, 2 blz., Interne Mededeling met kenmerk 630/45617/6769/Nyl.

13. Appelo, C.A.J., 1988, "WATEQP: A computer program for equilibrium calculations of water analysis", Amsterdam, The Netherlands, Vrije Universiteit, june 1988.

14. Heidemij Advies BV, 1994, "Onderhoud bronnen warmte-opslag Universiteit Utrecht; Deel 1: Verwerking GAS-gegevens", Arnhem, The Netherlands, Heidemij Advies BV, 84 blz., rapportcode 672/BA94/A042/07728W.

Table 1: Key technical figures in fourth cycle.

| | **Charge** (summer) | | **Discharge** (winter) | |
|---|---|---|---|---|
| Heat capacity | 6.0 | MW | 2.6 | MW |
| Energy amount | 21,600 (6,000) | GJ (MWh) | 13,000 (3,600) | GJ (MWh) |
| Temperature warm well | 85-95 | °C | 90 -> 50 | °C |
| Temperature cold well | max. 50 | °C | max. 50 | °C |
| Flow rate (max) | 100 | m³/uur | 50 | m³/uur |
| Water displacement | 100,000 | m³ | 130,000 | m³ |

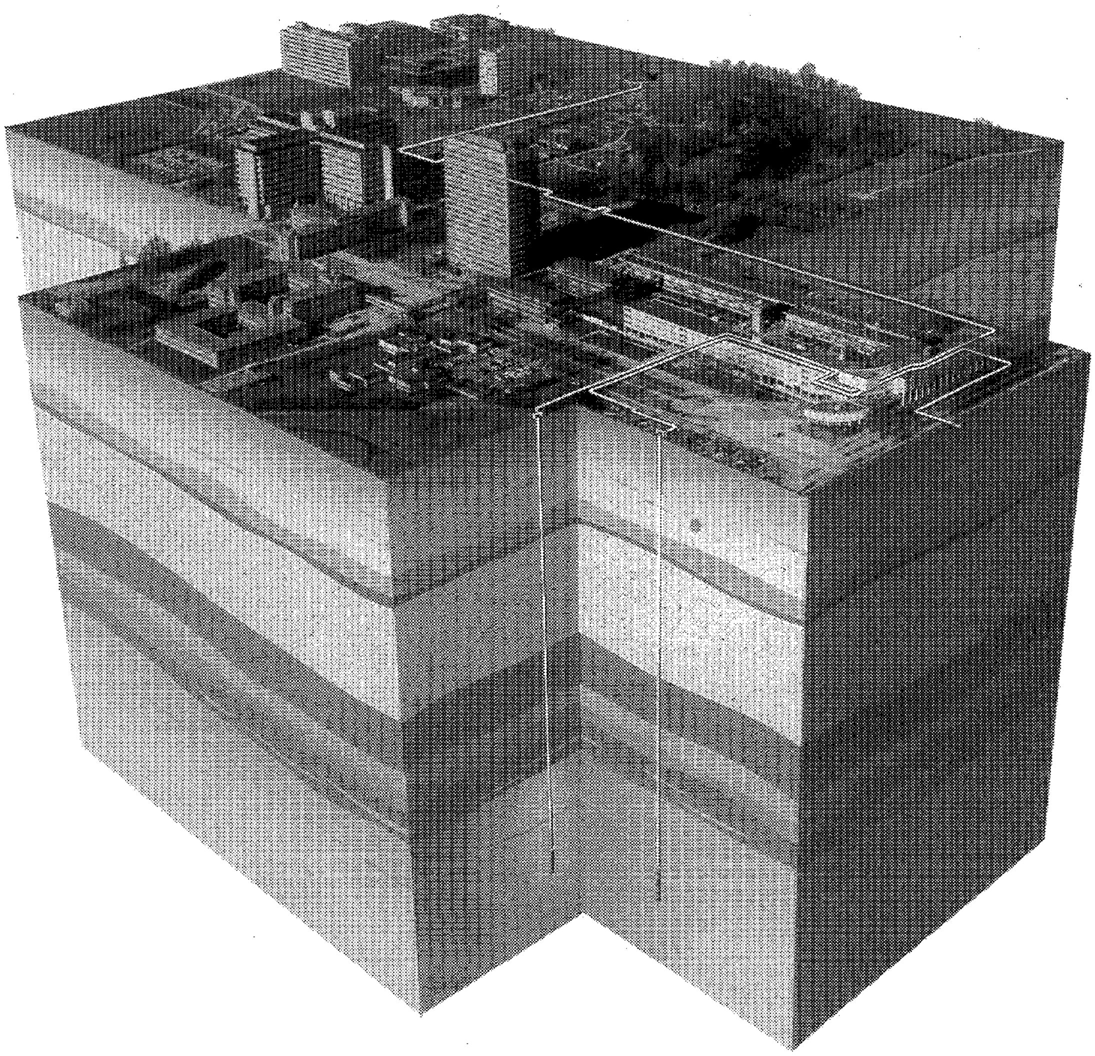


Figure 1: Artist's impression.

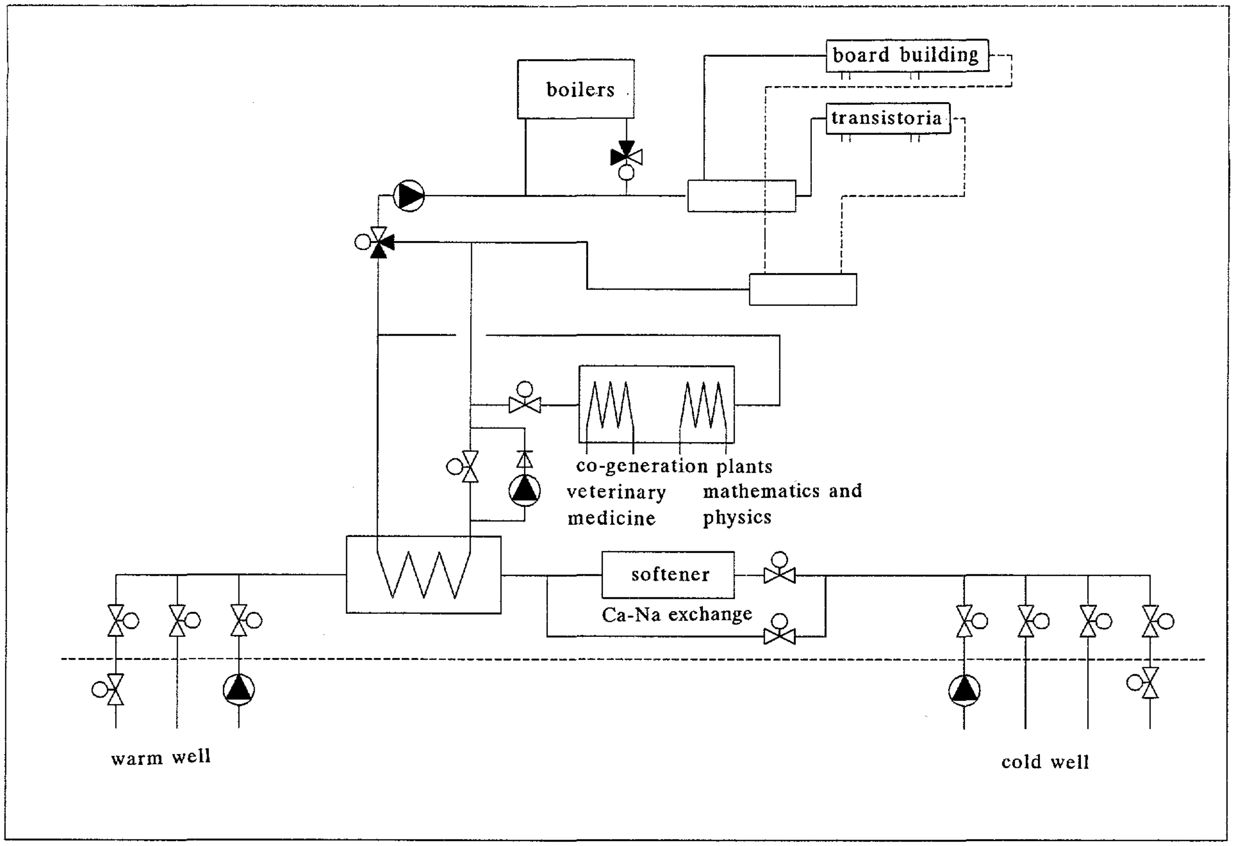



Figure 2: Simplified diagram of the principle of the system.

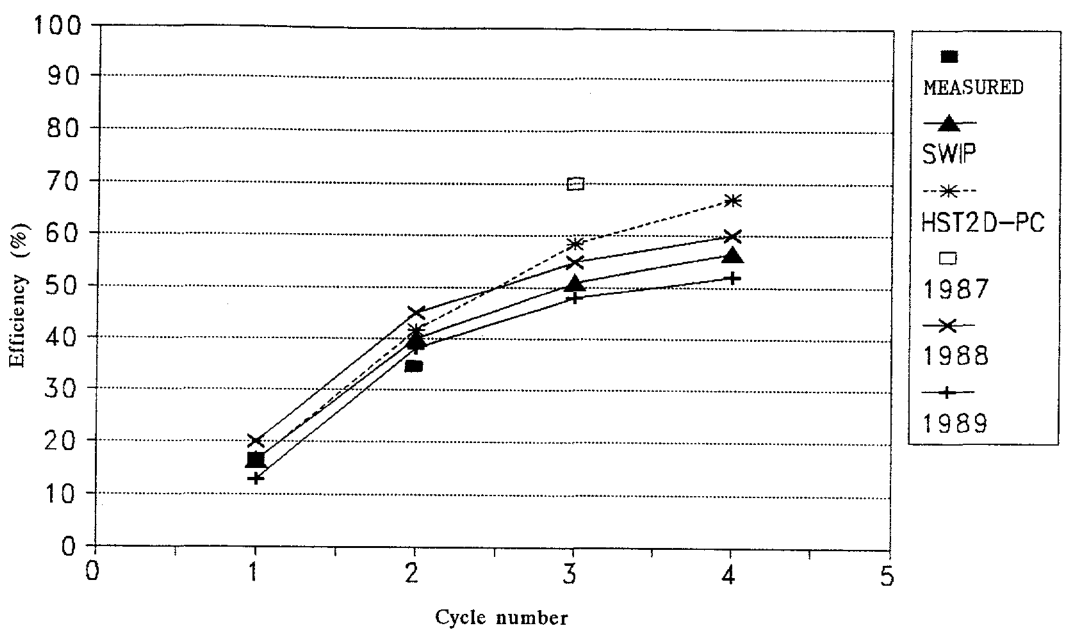



Figure 3: Thermal efficiencies.

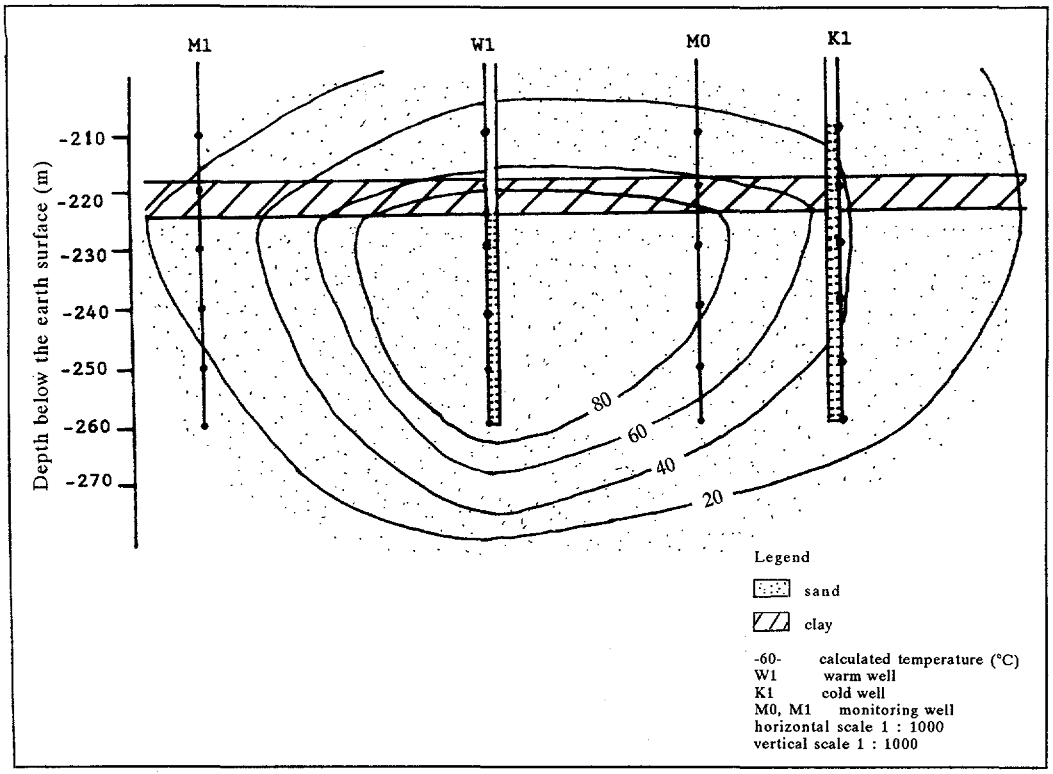



Figure 4: Temperature distribution in the storage at the end of the fourth charge period.

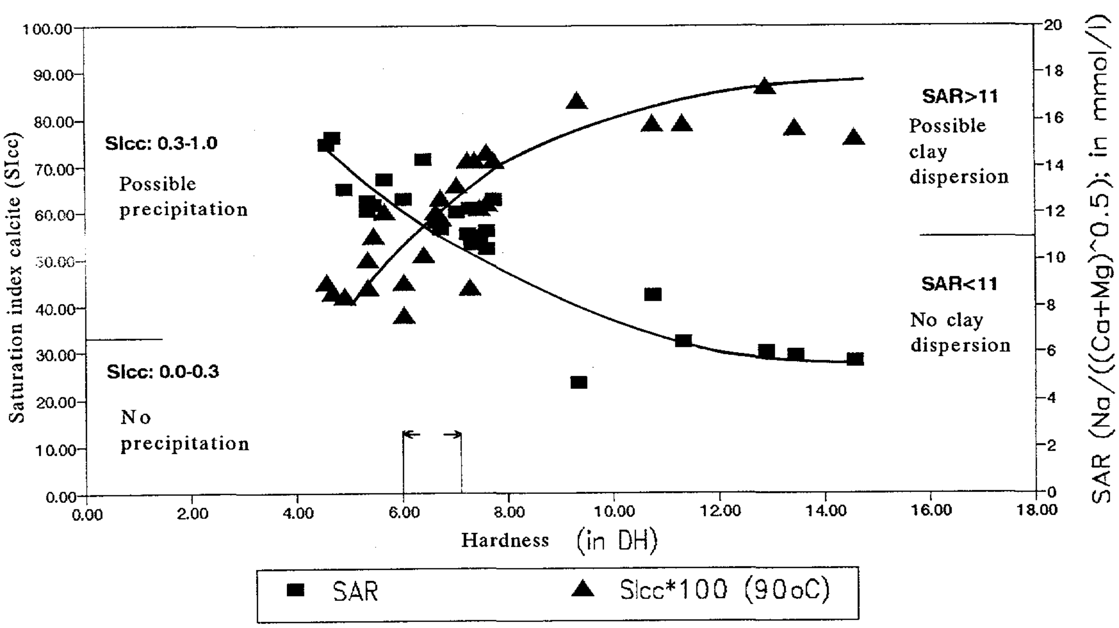



Figure 5: SAR and $SI_{calcite}$ versus hardness.

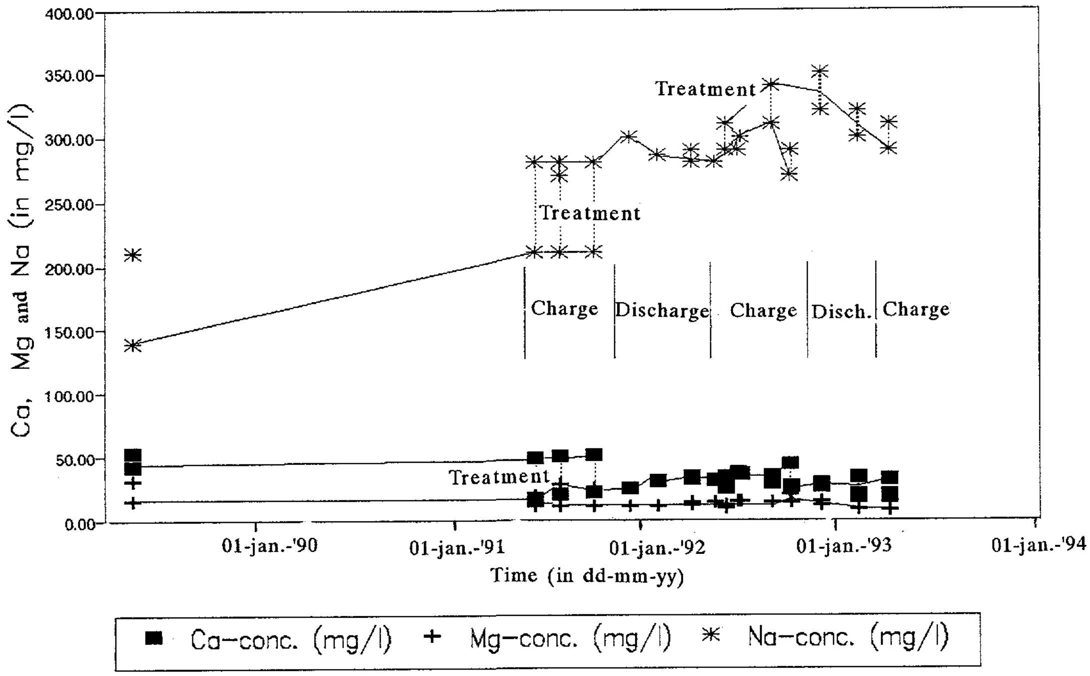



Figure 6: Ca, Mg and Na concentrations versus time.

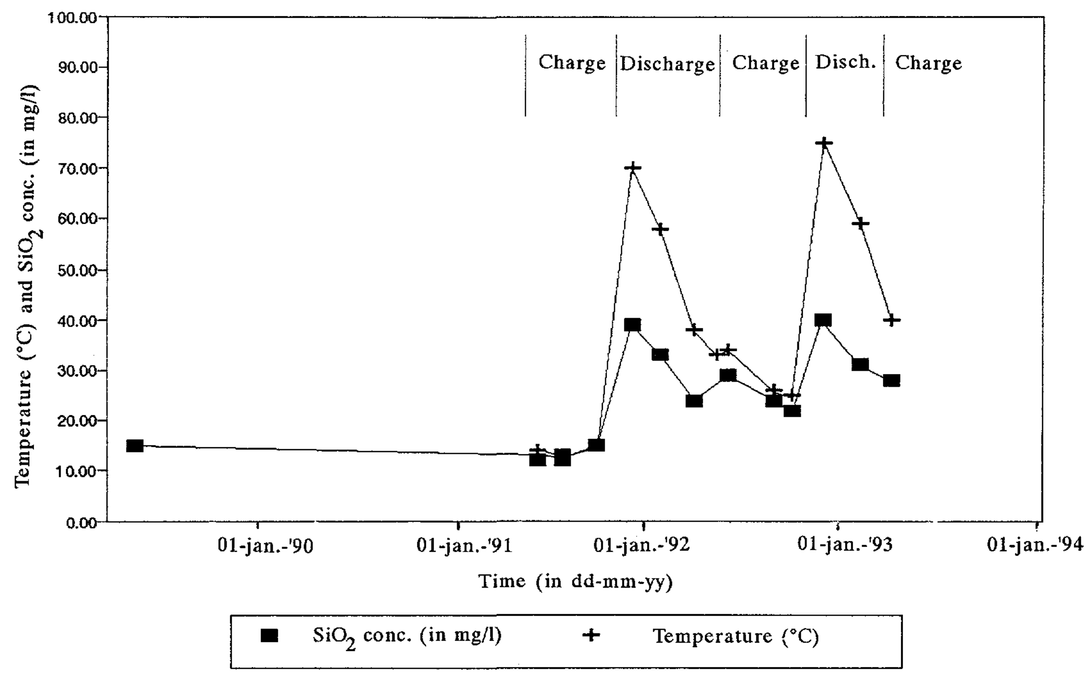



Figure 7: $SiO_2$-concentrations versus time.

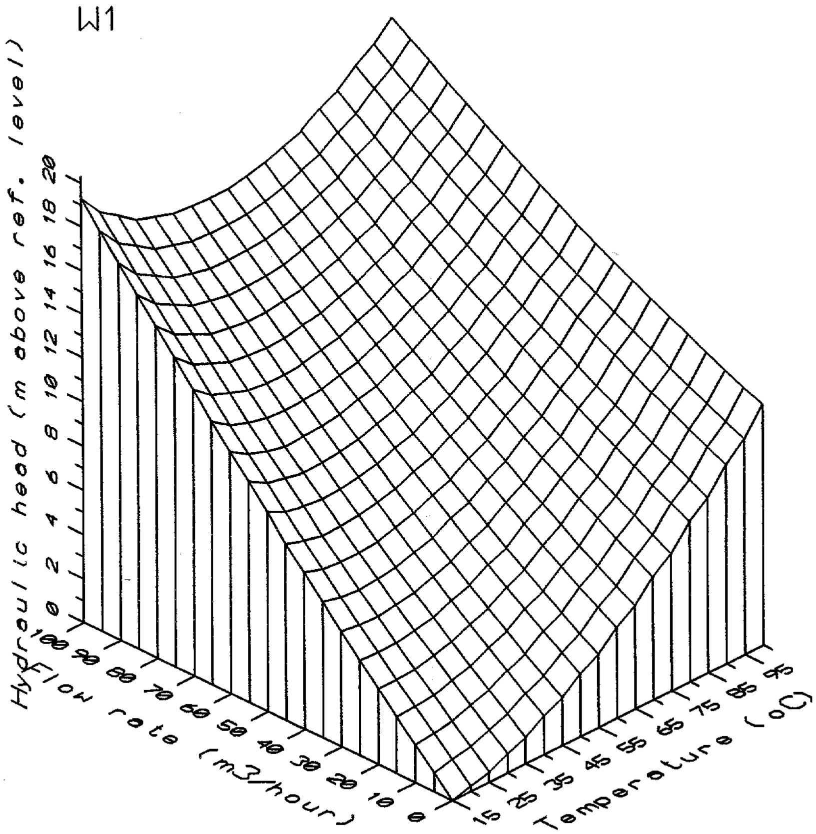



Figure 8: Theoretical hydraulic head at the warm well.

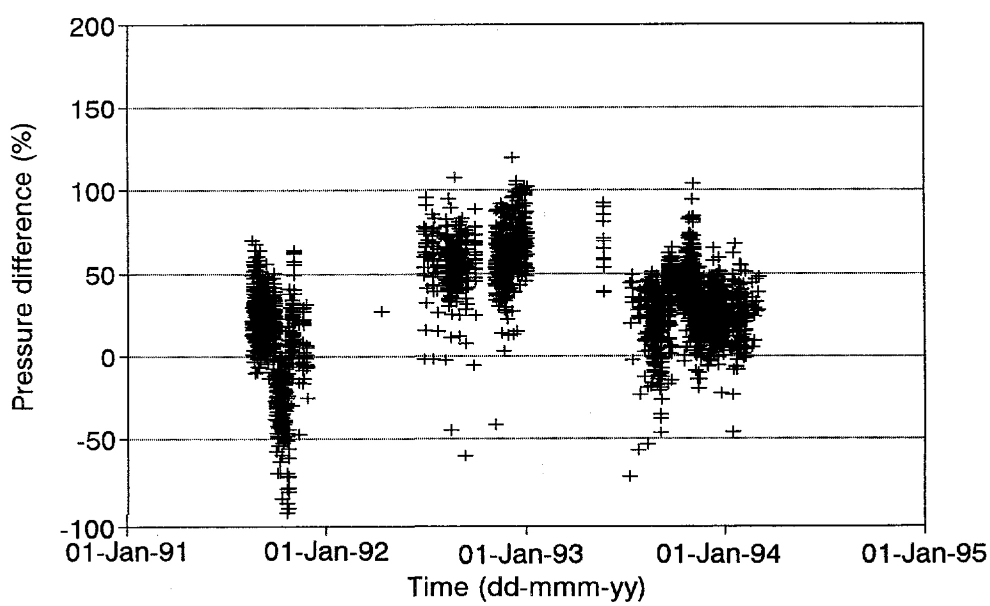



Figure 9: Relative pressure of the warm well versus time.

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Aquifer Thermal Energy Storage: A Building Block in Integrated Energy Systems

Douglas A. Wilke
Architect-Engineer
Glen Head, New York, USA

ABSTRACT
AQUIFER THERMAL ENERGY STORAGE
A BUILDING BLOCK
IN INTEGRATED ENERGY SYSTEMS

An operational ATES System is a key segment in the 258,000 square foor USPS/MPF integrated systems installation at Melville, New York. The potential for annual cycle groundwater storage to support space conditioning systems and reinforce energy conservation processes was identified in 1982, designed in 83-84, constructed and brought fully on line in 1989. Extensive on site monitoring was conducted through 1992. This project represents a step by step documentation of ATES implementation through conceptual selection, design, construction, on line operation and maintenance of a system keyed into a total building energy concept involving: Desiccant dehumidification, air cleaning and zoned air distribution within an energy conservation building design; integrally programmed to serve a twenty-four hour per day, seven day a week mail process operation.

The primary subjects of this paper will be:

Preliminary Systems Selection Based On

* Energy requirements, cost and availability
* User requirements, time of day, annual
* Annual climatic conditions
* Site geology
* Regulatory requirements
* Budget
* Availability of hardware

Design Criteria and Implementation

* Integrated system development
* Selection of hardware
* Projected use/maintenance factors

Construction Phase

* Contract limitations
* Field construction problems
* Modification and corrective actions

Post Construction

* On line corrections and balance
* Operational scenarios - developed/implemented
* Modifications
* Maintenance
* Monitoring
* Hardware evaluation

Final Concept and System Evaluation and Recommendations

The intent of this paper is to summarize for the industry those factors and conditions that will support the economically institutional application of ATES, identify potential problem areas and list parallel supportive technologies to be used in tandem with the groundwater system under specific geological, climatic and energy economic conditions.

INTEGRATED SYSTEMS SELECTION

Mid-Island USPS/MPF was first designed as a standard Postal Service building operating twenty-four hours per day to service a population of over one million persons daily. Of paramount importance was the requirement that all systems have secondary backup because the mail sorting process had to always operate continuously. The first design was rejected by USPS as using excessive energy.

USPS ordered a separate design team to develop a totally objective plan incorporating the best possible combination of systems for use for process operation within the environment of the site and the economics of off site energy.

CLIMATIC

Mid-Island at latitude 40 degrees North is in an area of 5,000 heating degree days with winter design temperatures of 5°F and summer peaks exceeding 95°F with high humidity. The cooling/humidity loading dominated energy requirements.

ENERGY

At the time Mid-Island was studied, 1982, the energy picture on Long Island, New York was very unstable. Concerns of high oil prices ($32+/bbl) and shortages, i.e., the 73 embargo, dominated consideration of oil usage in this area of very high petroleum dependence. Natural gas use was refused USPS by the serving utility, the Long Island Lighting Company. An 800 megawatt nuclear plant, Shoreham was under construction by LILCO and also under severe public attack. Electric rates were to become the highest in the United States, rising to $.21/KW all inclusive in 1994. Co-generation was not a viable alternative because atmospheric and micro area pollution yielded a negative Environmental Impact Study. The reference of the USPS was for off site electric energy plus maximum use of on site renewable energy. The selection was based on the guarantee of an uninterrupted energy source for uninterrupted postal operation.

AQUIFER (Figure 1)

The best source of natural energy on Long Island is the Magothy Aquifer. Cooling by drawing from the upper Magothy had been practiced since 1936. The groundwater on early systems yielded a 53° to 55°F source. Temperatures in high use areas had risen as a result of warm recharge. EPA/DEC regulations allowed continued use if wells did not exceed 200 feet in depth and recharge was within 50 vertical feet of the supply.

SYSTEMS COMBINATIONS

- The application of the ATES system was judged to be optimized if used for thermal control, heating and cooling only. Cooling would be at water temperatures of 50°F.
- Dehumidification was to be provided by a liquid desiccant system, tri-ethylene glycol in the form of a spray which would also serve to reduce paper-dust and dirt from the air of the workplace. The desiccant was to be purged of water at the rate of 500 lbs/hr using propane as a source. The application allowed for trial application of air solar collectors at 135°F to purge water. Propane was to be available for fueling Postal vehicles and operating a trial 50 KW fuel cell for electric generation. Final selection for construction retained only the conventional desiccant/propane system.
- The cleansed and tempered air was zoned and subzoned to meet operational needs of different segments of the workroom at differing time intervals as required by the mail sorting process. Of particular concern was the operation of future computerized BAR-CODE mail sorting equipment that required low humidity in the summer and moderate humidity in the winter and temperatures not to exceed 80°F. The tailored zone approach also swept dust from the air with multi station-multi level air returns for desiccant cleansing. Multi zones also reduced peak loading, for all areas of the facility were never on line at the same time.

BUILDING SHELL AND CONCERVATION

- The building shell is of insulated concrete mass to reduce peak demand during the day.
- Multi level high pressure sodium subzoned within 337 luminaires linked to 384 skylights. Interior colors supported the lighting.
- The roof is of highly reflective white Hypalon.
- The total package was to support the use of high temperature 50°F cooling water.

CONSTRUCTION DESIGN

The final product 1984 design was:

| | |
|---|---|
| DESIGN | - 1982-1984; 260,000 SF single story. |
| CONSTRUCTION | - 1984-1987; single General Contract, \$22 million. |
| OCCUPANCY | - September 1987; 1,200 employees, 24 hour, seven day/week. |

INTEGRATED SYSTEMS - TOTAL BUILDING CONCEPTS

| | |
|---|---|
| Thermal Conditioning (Figure 2 & 3) | - Aquifer thermal energy storage. Closed $H_2O$ loop/ closed circuit roof cooler. Wells - six 412 GPM 180 feet (3 cool, 3 warm). Two 100 ton chiller/heat pumps. |
| HUMIDITY CONTROL (Figure 4) | - Seven desiccant dehumidifer/ humidifiers. Central glycol concentrator - propane fired. |
| AIR CIRCULATION | - Twelve work zones/work station distribution. Mid height & floor sweep returns. Mechanical and desiccant filtration. |
| CENTRAL CONTROLS | - Mechanical and desiccant filtration. Honeywell/PC monitor/24 hour program. |
| RADIANT HEAT | - Mail deck gas radiant heat. |
| LIGHTING DAYLIGHT | - 384 - 4'x4' triple dome skylights. |
| LIGHTING ARTIFICAL | - 337 HPS luminaries variable 150-450 watts. Daytime pyronameter control, 24 hour/ 15 minute. Program computer base/radio signal control. HPS lighting reflective painted surfaces. Reflective floors and machinery. |
| ENERGY CONSERVATION | - Roof Plane: White Hypalon; insulation. Walls: Insulated precast concrete, light gray. Berms: Selected West, North and East elevations. Work Doors: Infiltration reduction double doors. |
| INTEGRATED CONCEPTS | - Desiccant coupled with closed aquifer system allows use of higher temperature cooling water eliminates bacteriological pollutants, reduces electric peak loading and summer usage. |
| TECHNICAL VALUE AQUIFER/DESICCANT SYSTEM | - Combination cost effectiveness. Actual electric peak reduction. Operation learning curve. |

OPERATING ENERGY CONCEPT

I. THERMAL CONDITIONING

A. Ground Water System

Cold Water Storage Wells - Three 412 GPM wells supply cold water during the summer at 45-50°F these wells are recharged in the winter through heat pumps and the closed circuit cooler at 40-45°F.

Warm Water Storage Wells - Three 412 GPM wells supply warm water during the winter at 63-68°F These wells are recharged in the summer through the building at 68-73°F.

B. Heat Pumps - Two 100 ton chillers operated in series reduce well water temperature as required to 49°F (825 GPM) for summer cooling. Condensor water is used for winter heating at 120°F (300 GPM).

C. Closed Circuit Cooler - A roof top closed circuit cooler is used to reduce well water temperatures in the winter to 40°F prior to introduction to ground storage. This additional cooling capacity is required to offset heat loading generated by the mail processing operation in order to balance heating and cooling ground water storage.

D. Radiant Gas Heaters - Perimeter mail platforms are heated during cold periods with overhead propane gas radiant heaters.

E. Modular Boilers - Back-up heating is accomplished through the application of modular propane boilers.

F. Process Heat - Operating USPS equipment generates internal heat.

G. Domestic Hot Water - Hot water for domestic use is heated in a separate propane fired boiler and storage tank.

II. Humidity Control

A. Desiccant Dehumidification - A desiccant spray of Tri-ethylene Glycol is passed over the unit cooling coils through which zoned workroom supply air passes. Humidity is removed as required to 50% RH±. The application enables the cooling/humidity process to operate with 49°F well water. Water is removed from the Glycol at a central concentrator serviced by the modular boilers.

B. Desiccant System Humidity Addition - The desiccant system adds water to the air stream during the winter period to maintain the relative humidity at 45%.

III. Air Quality Control

A. Air Quality Dust Areas - Airbone dust control areas have been established for:

1) General workroom.
2) Computerized mail sorting equipment room.
3) Office and service areas.
4) Loading platform.

B. Airborne Particulate Removal - Dust, paper dust and other airborne particulates are removed from the air by:

1) Mechanical roll filters.
2) Desiccant spray - filter bags remove collected particulates from the desiccant.
3) Screens at all desiccant conditioning coils
4) Air returns - workroom air returns are located at the floor and at intermediate levels to remove dust at a low level in the workroom.

C. Air Cleaning - The desiccant, Tri-ethylene Glycol is capable of germicidal reduction up to 99% and thus purifies air at the time of conditioning.

IV. Lighting

A. Natural Lighting - 364 four foot square triple domed skylights with diffusing interiors make up 3.5% of the workroom ceiling.

B. Artificial HPS Lighting - The workroom is serviced by variable high pressure sodium lighting (150 watts - 450 watts). Each luminaire is controlled by a central computer generated radio signal. The luminaire wattage is governed by the USPS work program needs and reduced as allowable by the natural light level achieved through skylighting.

V. Energy Conservation

A. Roof - The roofing is of a white Hypalon membrane mechanically fastened over R-30 polyiscyanuarate insulation. The white surface is reflective to an extent that the surface is as much as 55°F lower in temperature than the surface of a black roof. In addition reflected light on low angles is deflected into the building through the curvature of the skylights.

B. Mass Walls - Insulated mass concrete walls reduce the impact of exterior solar energy flow on the East and West. Earth berms add additional protection on the West.

C. Energy Recovery - Mechanical energy recovery units are employed for the North Service areas of the building.

D. Workroom Surfaces - Walls, ceiling, equipment, ductwork, and structure in the workroom are all of a white 70%± reflective to high pressure sodium lightwaves. The flooring is 35% reflective.

E. Loading Platform - The mail platforms have all doors fitted with truck door seals. Double self closing doors separate the platforms from the workroom.

VI. Zoning

A. Workroom - The workroom is divided into two enclosed spaces forming twelve work zones serviced by seven HVAC units. The zones are serviced for thermal/humidity requirements through forced air locally supplied according to the needs of the mail processing 24 hour day program. Lighting is separately programmed to serve individual process equipment areas as required by the program. Manual overrides for special application is provided throughout.

B. Platforms - The platforms are zoned separately because of the relationship to exterior non-conditioned air.

C. Load Shedding - Computers operating HVAC and lighting are capable of manual electric power load shedding.

DESIGN/CONSTRUCTION BARRIERS

Scheduling

The USPS required the building without delay. The time for detailed groundwater investigation was to be following the bid process with allowance made for modification during construction. The initial hydrology investigation made for the study became basis for design. Following the bid USPS did not follow-up with the required detailed investigation.

Operational Security

The USPS, to assure operation under all conditions required 100% redundancy for all systems including the well system in the event EPA/DEC disallowed the well system in the future.

Bid Process

The low bidder was awarded the construction contract. Said bidder was not at all versed in sophisticated mechanical systems.

Construction Management

The USPS turned construction implementation over to a Construction Manager who had no knowledge of mechanical systems of the type used at Mid-Island. The Engineers input at the site was very limited.

Required Completion

Mid-Island was ten months behind schedule. Poor mechanical workmanship was noted, at one stage the contractor was defaulted. The building was occupied without systems being completed. Wells were fouled and the cooling tower frozen.

Remedial Work

During occupancy over a two year period systems were rebuilt under the supervision of Engineers. Work included:

- Well purging via backflushing for three months.
- Reconstruction of one well with a destroyed gravel pack. A new well pack and tremi pipes were inserted into the existing well.
- The auto filter was rebuilt and brought on line
- The closed circuit cooler serving the ATES was rebuilt with additional freeze proof controls.
- The desiccant system was studied and readjusted over a two year period.

SUMMARY (Figure 6)

Concept

The ATES/desiccant combination provided a good working environment with 50°F water cooling and the desiccant dehumidifying and cleaning the air. During 1991 and 1992 the system operated on high winter groundwater supply temperatures of 60°F, and cooled the water within a very mild winter and was capable of cooling the building without the 100 ton chillers for the majority of the summer months. A special study of micro dust showed a high reduction 26%+ in the workroom.

Operational Problems

- Wells - had to be continually back flushed as a result of pressure build up. The well rebuilt with a factory assembled gravel pack and tremi pipes operated successfully.

- The Desiccant - system required excessive amounts of propane for purging water.

- Factory Maintenance - was unable to meet the system needs. The system did not operate up to design expectations. Excessive Glycol was lost despite modification of controls and the addition of a second storage tank.

Economics

- The First Cost - of the system was within the budget for the total facility cost of the original base building cost prior to design changes. Redundancy of systems required by USPS and fail safe systems yielded a system more costly than a base line package HVAC system building.

- Energy and Operating Cost - exceeded the design estimated 38,000 BTU/SqFt/year energy usage. Three areas were responsible for high energy usage and operational cost.

  1) Propane for purging water caused the energy overrun above 38,000 BTU/SqFt. The concentrator could not be properly controlled for low energy, glycol retention operation.

  2) Glycol replacement cost was excessive.

  3) Operating motors were overdesigned to assure building operation. Modified operation reduced motive power requirements by up to 25%.

CONCLUSION

- The ATES system operation in a humid temperate area is more effective when operated at higher cooling temperatures while supported by a dehumidification system.

- The Glycol dehumidification system maintains a good programmed indoor environment and further acts to cleanse the air. With all systems operational professionals and workers both judged the working environment superior to that in similar facilities.

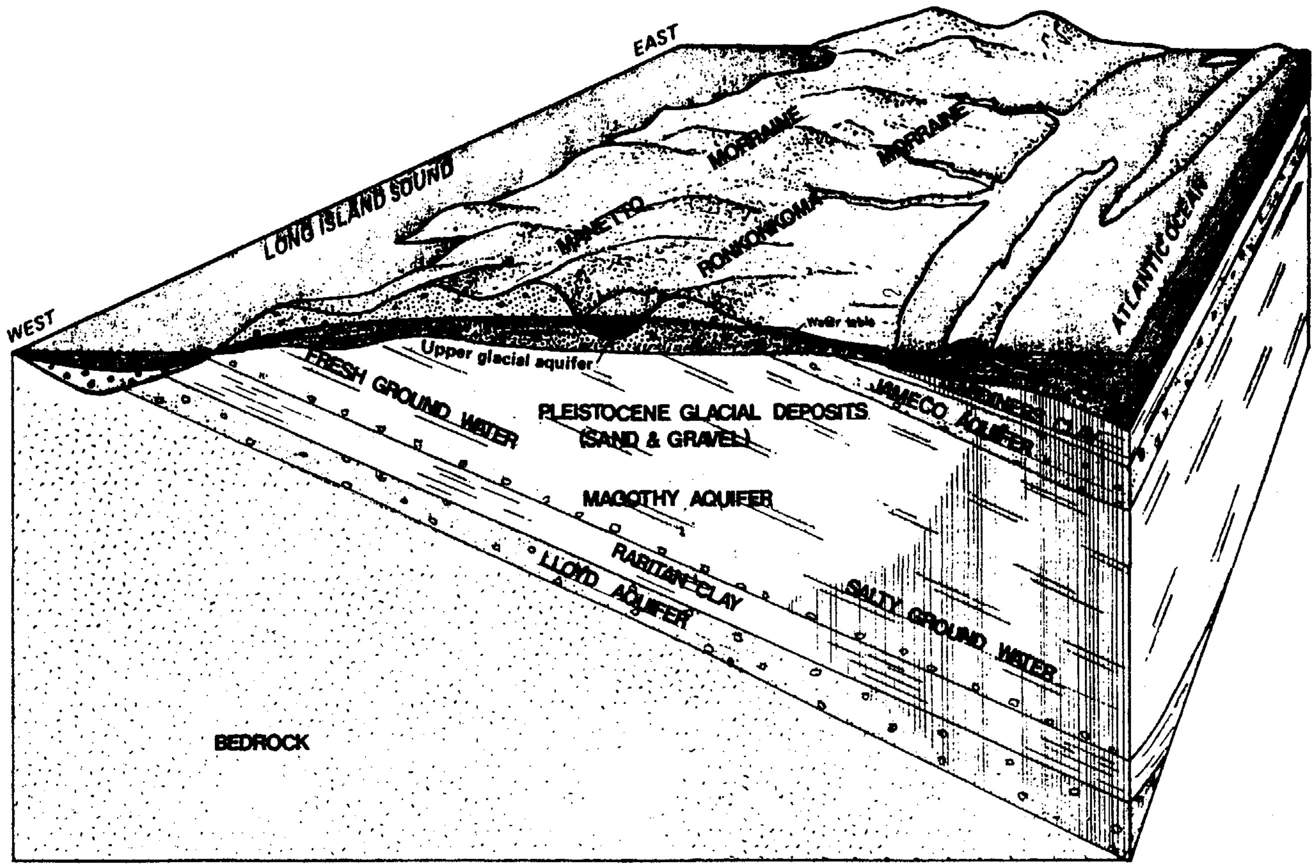
- Well technology should address recharge with tremi piping to eliminate the introduction of excessive air. The well so modified displayed marked performance improvement.

- The desiccant system as installed was not manageable and did not meet manufacturers performance levels. Desiccant system investigation should be continued. Systems employing desiccant wheels should be reviewed for integration with ATES. Low temperature desiccant systems should be studied for operation with air solar systems at 125°-135°F.

- Building air delivery systems should be tailored to the exact application to allow for a high quality work environment with even marginally tempered cooling water.

- The building shell, mass and color and area planning should be designed for high energy conservation and reduction in peak loading to allow for a high quality work environment with marginally tempered cooling water.

- The basic ATES technology is excellent for application in areas such as Long Island, N.Y. having a fine water supply, and a high electric rate structure. Desiccant technology now emerging is a natural fit in humid areas. What is needed is a basic understanding and acceptance of the process. This can be achieved best in projects where the ATES application is introduced at the start of the project and is encompassed as an integral part of the design. Government should encourage ATES application and should consider the total building concept when evaluating such installations.




Not to scale; large vertical exaggeration

TYPICAL GEOLOGICAL SECTION, Long Island

# FIGURE 1

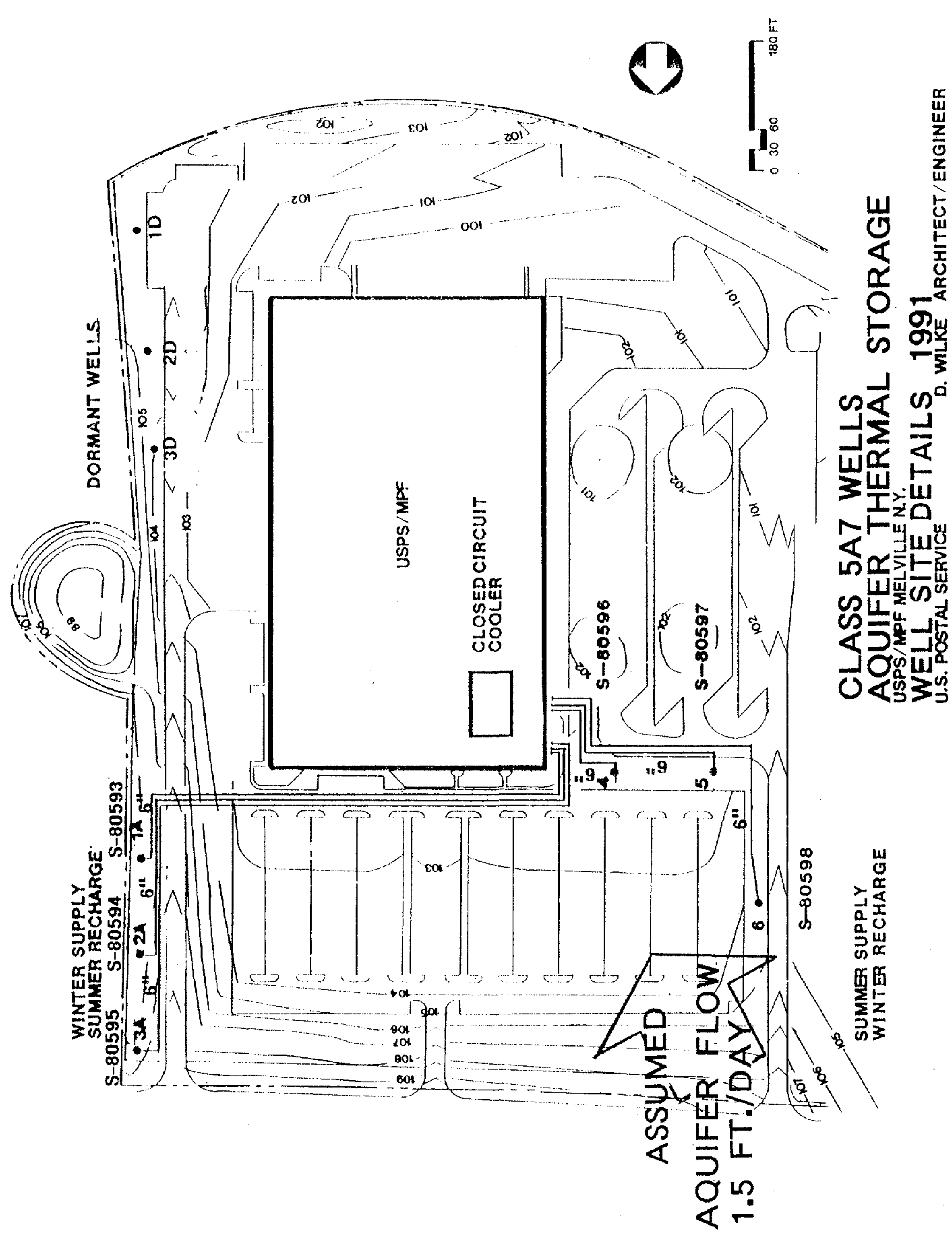

DORMANT WELLS
WINTER SUPPLY
SUMMER RECHARGE
S-80595
S-80594
S-80593
3A
2A
1A
1D
2D
3D
USPS/MPF
CLOSED CIRCUIT COOLER
S-80596
S-80597
S-80598
SUMMER SUPPLY
WINTER RECHARGE
ASSUMED
AQUIFER FLOW
1.5 FT./DAY
0 30 60 180 FT
CLASS 5A7 WELLS
AQUIFER THERMAL STORAGE
USPS/MPF MELVILLE N.Y.
WELL SITE DETAILS 1991
U.S. POSTAL SERVICE
D. WILKE ARCHITECT/ENGINEER

FIGURE 2

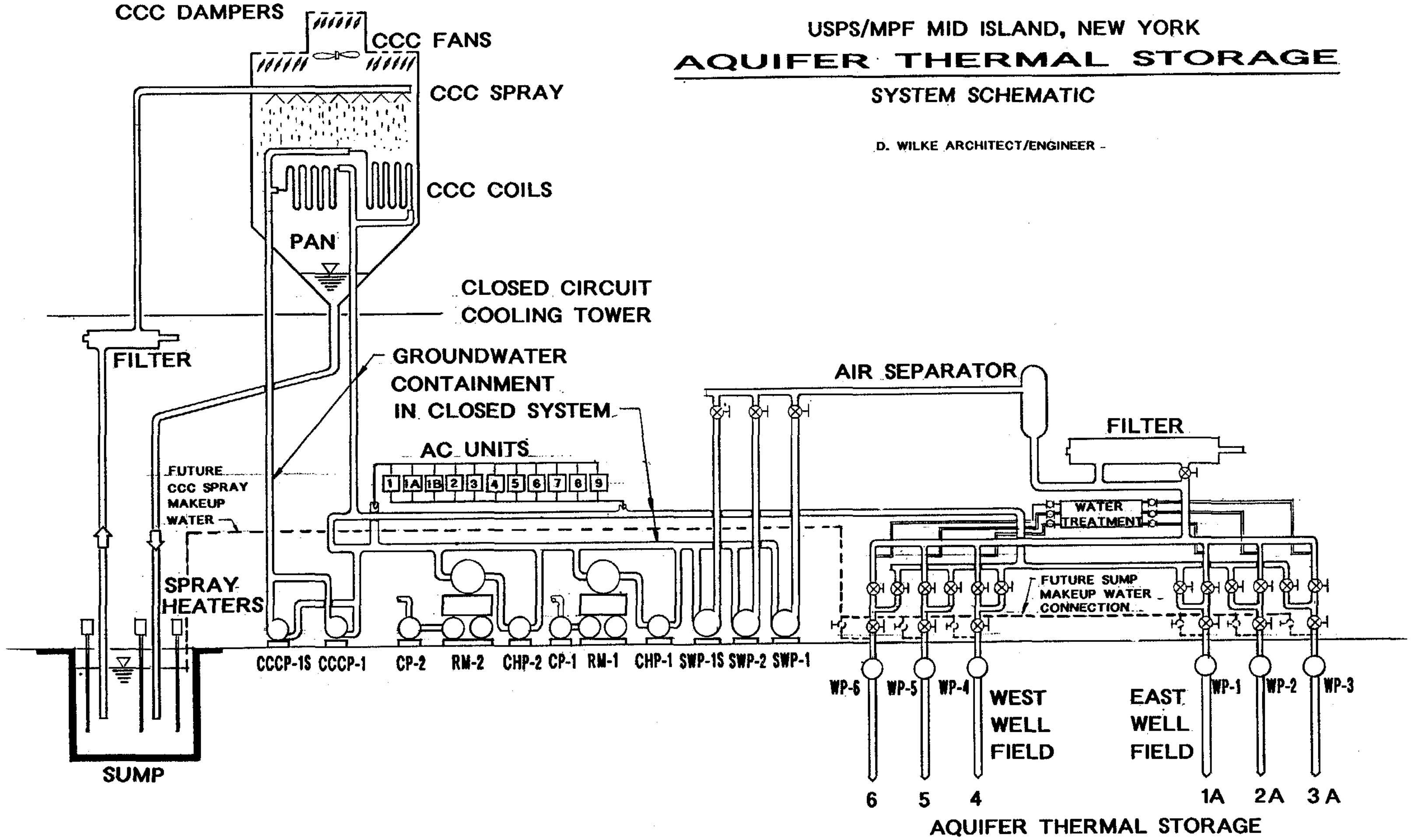
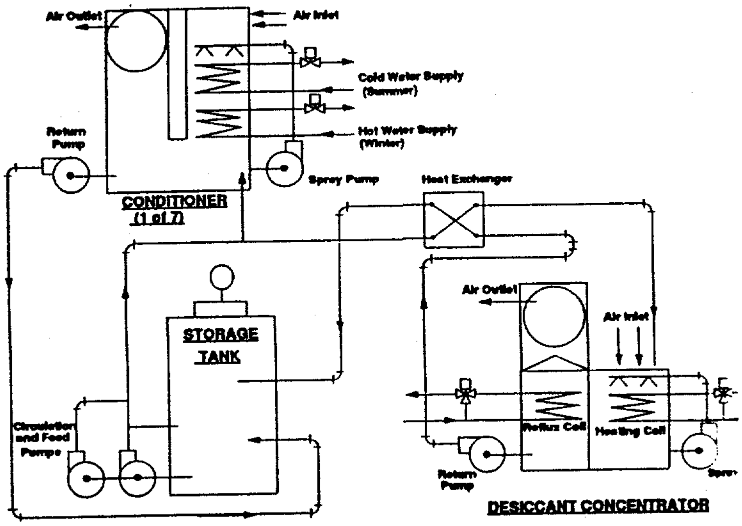
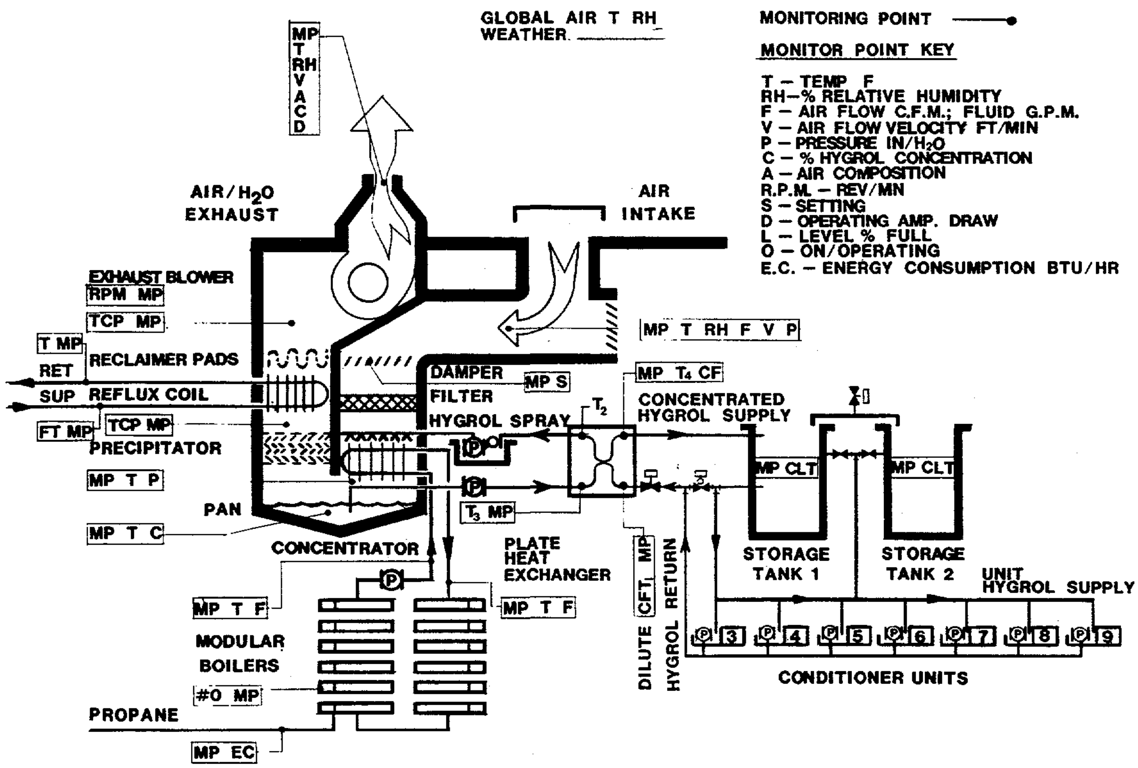

USPS/MPF MID ISLAND, NEW YORK
AQUIFER THERMAL STORAGE
SYSTEM SCHEMATIC
D. WILKE ARCHITECT/ENGINEER
CCC DAMPERS
CCC FANS
CCC SPRAY
CCC COILS
PAN
CLOSED CIRCUIT COOLING TOWER
FILTER
GROUNDWATER CONTAINMENT IN CLOSED SYSTEM
AIR SEPARATOR
FILTER
AC UNITS
1
1A
1B
2
3
4
5
6
7
8
9
FUTURE CCC SPRAY MAKEUP WATER
SPRAY HEATERS
WATER TREATMENT
FUTURE SUMP MAKEUP WATER CONNECTION
SUMP
CCCP-1S
CCCP-1
CP-2
RM-2
CHP-2
CP-1
RM-1
CHP-1
SWP-1S
SWP-2
SWP-1
WP-6
WP-5
WP-4
WEST WELL FIELD
EAST WELL FIELD
WP-1
WP-2
WP-3
6
5
4
1A
2A
3 A
AQUIFER THERMAL STORAGE

FIGURE 3

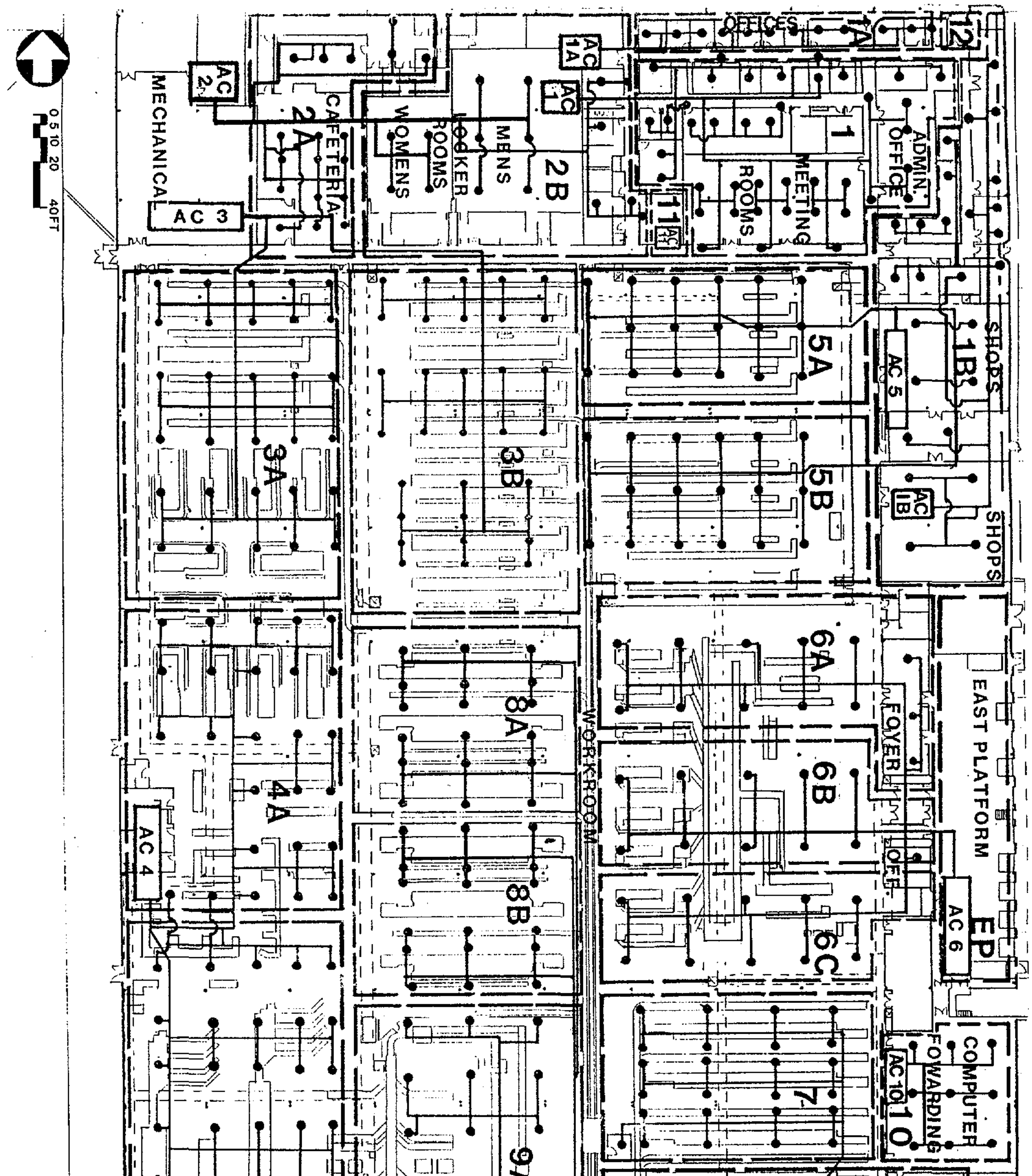



Liquid-Desiccant System Schematic



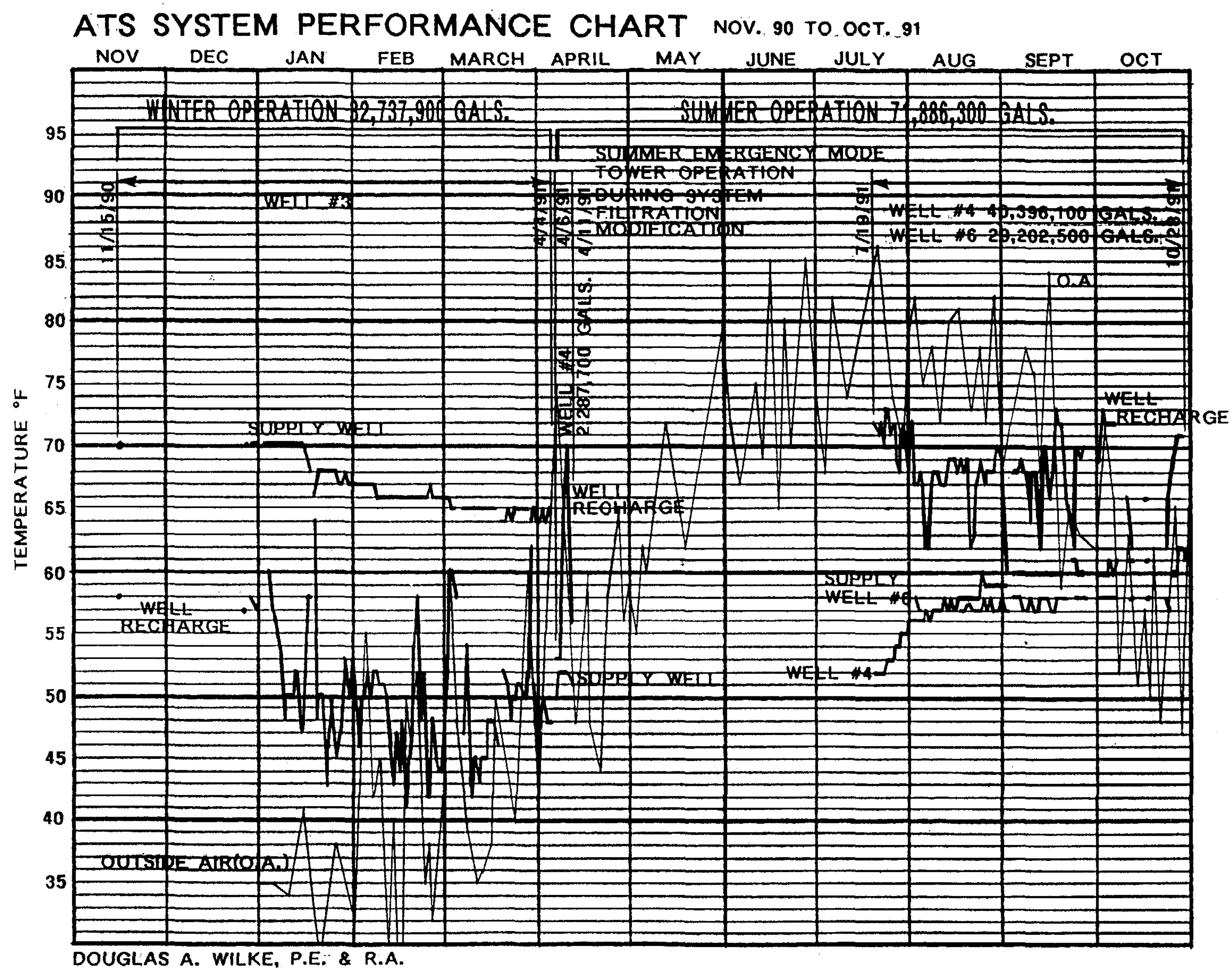

USPS/MPF MID ISLAND
**DESICCANT CONCENTRATION MONITOR**
D. WILKE ENGINEER/ARCHITECT

# FIGURE 4



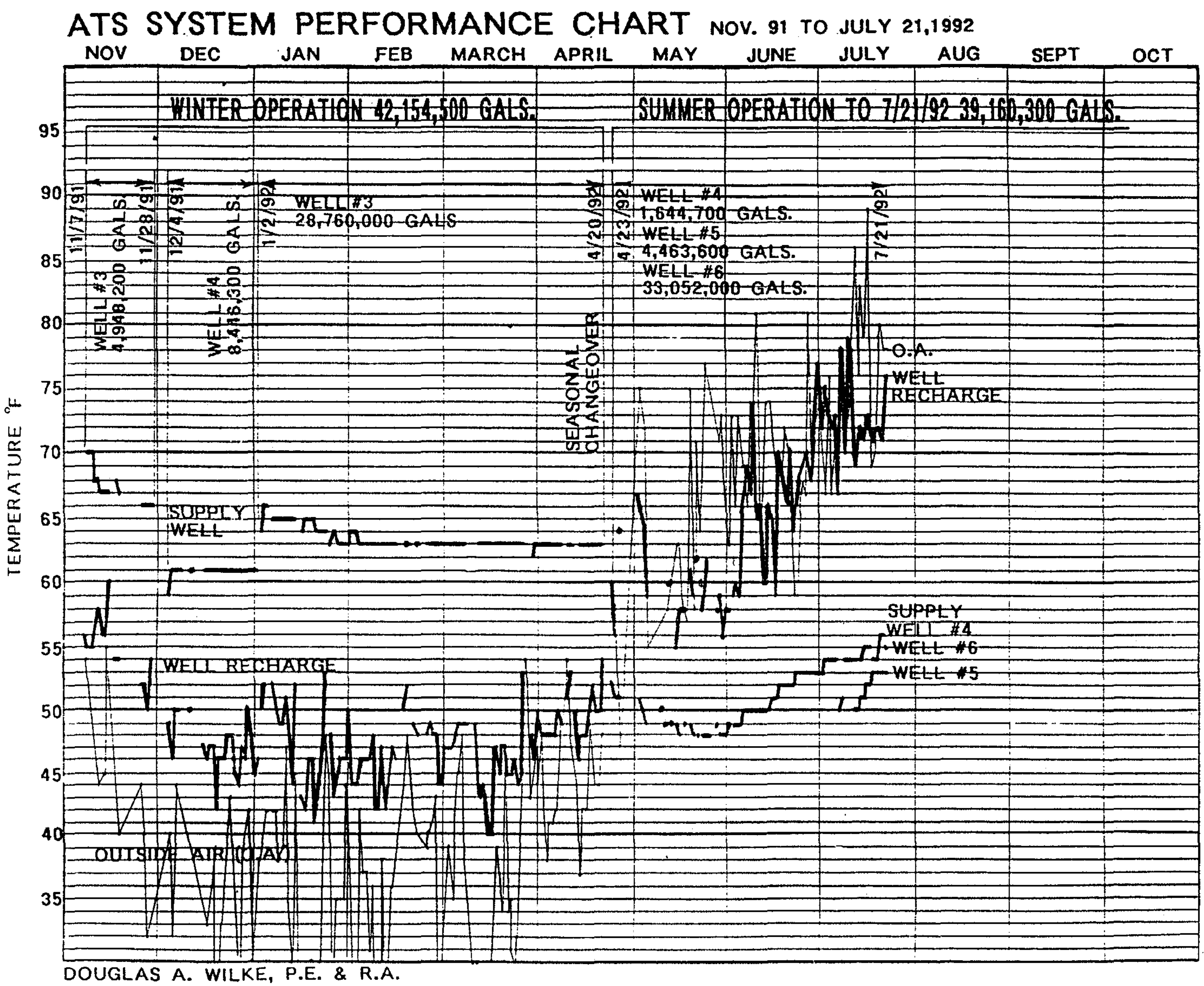
0 5 10 20 40FT
MECHANICAL
AC 2
AC 3
CAFETERIA
2A
WOMENS
LOCKER ROOMS
MENS
2B
AC 1A
AC 1
OFFICES
1A
12
1
MEETING ROOMS
ADMIN. OFFICE
11
AC 11
3A
3B
5A
5B
AC 5
1B
SHOPS
AC 1B
SHOPS
4A
AC 4
8A
8B
WORKROOM
6A
6B
6C
FOYER
OFF.
EAST PLATFORM
AC 6
EP
7
AC 10
10
COMPUTER FOWARDING
4B
9A
9B
SHOPS
MEDICAL
8C
FOYER
AC 8
AC 9
AC 7
SOUTH PLATFORM
SP


FIGURE 5



ATS SYSTEM PERFORMANCE CHART NOV. 90 TO OCT. 91
NOV
DEC
JAN
FEB
MARCH
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
WINTER OPERATION 82,737,900 GALS.
SUMMER OPERATION 71,886,300 GALS.
SUMMER EMERGENCY MODE
TOWER OPERATION
DURING SYSTEM
FILTRATION
MODIFICATION
11/15/90
WELL #3
4/4/91
4/6/91
4/11/91
WELL #4
2,287,100 GALS.
7/19/91
WELL #4 40,396,100 GALS.
WELL #6 29,202,500 GALS.
10/28/91
O.A.
WELL
RECHARGE
SUPPLY WELL
WELL
RECHARGE
SUPPLY
WELL #6
WELL #4
WELL
RECHARGE
SUPPLY WELL
OUTSIDE AIR(O.A.)
TEMPERATURE °F
95
90
85
80
75
70
65
60
55
50
45
40
35
DOUGLAS A. WILKE, P.E. & R.A.


# FIGURE 6



ATS SYSTEM PERFORMANCE CHART NOV. 91 TO JULY 21,1992
NOV
DEC
JAN
FEB
MARCH
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
WINTER OPERATION 42,154,500 GALS.
SUMMER OPERATION TO 7/21/92 39,160,300 GALS.
TEMPERATURE °F
95
90
85
80
75
70
65
60
55
50
45
40
35
11/7/91
WELL #3
4,948,200 GALS.
11/28/91
12/4/91
WELL #4
8,416,300 GALS.
1/2/92
WELL #3
28,760,000 GALS
SEASONAL
CHANGEOVER
4/20/92
4/23/92
WELL #4
1,644,700 GALS.
WELL #5
4,463,600 GALS.
WELL #6
33,052,000 GALS.
7/21/92
O.A.
WELL
RECHARGE
SUPPLY
WELL
WELL RECHARGE
SUPPLY
WELL #4
WELL #6
WELL #5
OUTSIDE AIR (O.A.)
DOUGLAS A. WILKE, P.E. & R.A.


FIGURE 7

INTERNATIONAL SYMPOSIUM

AQUIFER THERMAL ENERGY STORAGE

November 14-15, 1994
The University of Alabama
Tuscaloosa, Alabama USA

# Microbiology of a Chilled-Water Aquifer Thermal Energy Storage System (ATES) Operating at The University of Alabama Student Recreation Center

• Alvin L. Winters
Biological Sciences
The University of Alabama
Tuscaloosa, Alabama, USA

• Freda Sue Allison
Biological Sciences
The University of Alabama
Tuscaloosa, Alabama, USA

• James A. Neville
Animal Resources
The University of Alabama
Tuscaloosa, Alabama, USA

• Catherine Shea
Biotechnical Research Department
Tennessee Valley Authority
Muscle Shoals, Alabama, USA

• C. Everett Brett
Bureau of Engineering Research
The University of Alabama
Tuscaloosa, Alabama, USA

ABSTRACT.

Aquifer thermal energy storage (ATES) systems that use unconfined groundwater aquifers can interact with the above ground environment through water exposure in conventional cooling towers, and in specialized cases, through exposure to water ejected from the aquifer. These systems have an inherent potential to create problems in public health, environmental impact, and/or heat-tranfer engineering by acting as a source of infectious diseases, modifying the indigenous microbiota of the aquifer environment, and/or promotion of biofouling/biocorrosion within the ATES system. A chilled-water ATES system had been operating at the University of Alabama Student Recreation Center five years prior to microbiological investigation. The bacterial content of water in this system was examined for a period of 80 weeks to determine whether any conditions detrimental to public health were generated. Water samples were obtained from relevant sites throughout the system and analyzed for bacteriological content. The study focused on the presence of water-borne bacterial pathogens (disease-causing microorganisms), including *Legionella pneumophila*. Heterotropic bacteria, which are indicative of the general state of the water quality, were quantified also. Pathogens were not detected and heterotrophic bacterial populations did not change significantly. Thus, the operation of the ATES system did not contribute to infectious disease transmission and did not adversely affect the environment. Biofouling or biocorrosion were not observed during the study period.

INTRODUCTION.

Overview

The storage of thermal energy, either heat or chill, in natural aquifers has demonstrated the potential for notable energy savings as compared to currently used energy-consuming technologies [1]. A cold water aquifer thermal energy storage (ATES) system has been operating at The University of Alabama Student Recreation Center (UA-ATES) since 1983 (Figure 1) [2]. The system pumped approximately 40,000 $m^3$ of water from the Tuscaloosa aquifer (winter season), chilled the water to ≤ 7°C by passage through a conventional mechanical-draft cooling tower, and returned the chilled water to the Tuscaloosa aquifer at a different site for thermal storage. Cold water (approximately 103,000 $m^3$) was then recovered from the stored plume of chilled aquifer and passed through air handlers (summer season) to provide cooling (Figure 2).

Background

Hicks and Stewart published a comprehensive analysis of the potential effects of ATES on groundwater microorganisms [3]. The presence and transmission of human pathogens in ATES systems was recognized and identified as a major possibility in the development of ATES technology. As a direct result of their assessment microbiological monitoring of the UA-ATES system aquifer water was initiated.

The local changes of the surface and subsurface environment that are associated with chilled water ATES systems have the potential for creating four broad microbiological problems. These problems directly affect design, development, and operation of ATES systems. The investigation of the UA-ATES system addresses the first and second areas. Problems in the third and fourth areas were not observed.

- Human disease caused by human interaction with ATES system water obtained from a microbiologically contaminated aquifer or cooling tower.
- Modification of aquifer normal flora by ATES operation with adverse environmental impact.
- Biofouling of air handling units and aquifer porosity during ATES system operation.
- Scaling and/or corrosion caused by microbiological activity during ATES system operation.

Characteristics of the Tuscaloosa Aquifer

Wells were drilled near the University of Alabama Student Recreation Center for water production and storage, monitoring of the aquifer during ATES system operation, and sediment analysis of the aquifer (Figure 3). Approximately 30 m of alluvial material overlies the Pottsville formation at the UA-ATES site [2]. The Tuscaloosa aquifer is approximately 10 m in depth and lies just above the indurated Pottsville formation, which acts as an aquiclude and limits the downward migration of groundwater. The lower zone in the formation is siliceous sand and clay. The alluvial deposits become more gravelly and less sandy toward the surface. The surface consists of mostly red clay. The geological structure is represented by a fence diagram derived from analysis of sediments during the drilling of the wells

(Figure 4). The west-east profile illustrates three sand and clay layers in the porous sand mass of the aquifer (scan wells 4 to 1, 5 to 2, and 6 to 3 in Figure 4). Only the lower sand and clay lens appears to be in a position to have a major influence on the distribution of temperatures in a cold water storage plume. The analysis of sediments indicated the greatest porosity in the bottom 8 - 9 m, and the coldest water was found at 6.10 m above the Pottsville formation after chilled water injection. The depth of the water-saturated zone was relatively stable throughout the year with only minor seasonal variations; however, there is a relatively small lateral movement (0.64 m/day) of the aquifer water with respect to the UA-ATES system. This resulted in a shift of the cold aquifer plume (0.26 m/day) from the site of chilled water injection (Figure 5).

The ATES system was designed to activate one, two, or three of the warm water (ambient aquifer temperature) production wells depending on the cooling rate obtained with a given atmospheric temperature. Water was pumped from the aquifer with submersible three-stage pumps at a rate of 1.2 $m^3$ per min per well or up to 3.6 $m^3$ per min. total, if a very low atmospheric temperature created a cooling tower demand. The warm water from Wells 1, 2, and/or 3, was chilled in a conventional cooling tower with a temperature-controlled flow valve that recycled the water through the sprayers for additional chilling, if the first chilling cycle failed to reach a sump water temperature of $\leq$ 7°C. The water was then injected into the aquifer (usually through well 4) for storage. This system stored approximately 40,000 $m^3$ of chilled water during the winter season and recovered approximately 103,000 $m^3$ of chilled water during the air-conditioning seasons.

### Microbiological Problems Associated with Cold Water ATES System Operation.

Aquifer thermal energy storage (ATES) systems using natural unconfined aquifers inherently impinge on the microorganisms indigenous to the aquifer by creating a local perturbation in the environmental characteristics of the aquifer. An ATES system also creates an artificial two-way communication between the aquifer penetrated by ATES system wells and the surface environment near the ATES system site, especially where a conventional cooling tower with an open-air heat exchange is used for chilling the water. In addition, an accidental, unidentified contamination of the groundwater might occur as the result of aquifer penetration by ATES system wells. A variety of groundwater pollution sources have been identified by Keswick [4]. Groundwater polution is usually linked with the disposal of sewage, animal manure, and septic tanks where the sources of pollution contain extremely high enteric bacteria and virus counts. The UA-ATES system had been operating at the University of Alabama for five years, and although general observations of the system indicated the probability was small, the UA-ATES system might pollute the aquifer or spread infectious agents from a polluted aquifer.

The conventional cooling tower used to chill the UA-ATES water has the potential for changing the microbial content of the water during transit through the tower (Figure 2). Consequently, the chilled water injected into the aquifer for storage could contain air-borne microorganisms that would modify the microbiological populations in the aquifer. An immediate concern is the dispersion of microorganisms with pathogenic potential for humans, since the UA-ATES system operates in close proximity to a large student, faculty, and staff population that uses the recreation center. Two possible routes apparent. Formation of aerosols by the cooling tower during the water chill process could lead to respiratory infections, such as legionellosis. A second route of transmission from contaminated water could occur by ingestion or skin exposure; however, the current design of ATES systems reduces the opportunity for transmission by injection of the water into the aquifer or ejection of the water from the system into a small stream that is not used for recreational purposes. A secondary concern, but just as important in an ecological sense, is that operation of the ATES system may modify the "normal" flora of the aquifer. Although this does not appear to present an immediate problem, the long term use of an aquifer and the construction of ATES systems with ten- to one hundred-fold larger capacities than the UA-ATES system would amplify the problem and might lead to a serious environmental impact.

## MATERIALS AND METHODS

### Water testing laboratory

A microbiology laboratory was organized in Nott Hall (Figure 1) for the specific purpose of isolating and identifying potential water- and air-borne pathogens in the UA-ATES system aquifer water. This laboratory within the University of Alabama Animal Care Facility was chosen to ensure security for handling of a variety of human pathogens and to take advantage of immediate access to the loading dock for specimen transport and shipment The laboratory was patterned after a hospital-based clinical microbiology laboratory (Microbiology Procedure Manual (compiled by S. B. Nix, E. Comer, and S. S. Polt), Department of Pathology, Division of Clinical Pathology, University of Alabama Hospitals, University of Alabama at Birmingham) and a water testing laboratory. Laboratory procedures for quality assurance were developed and performed using the Standard Methods for the Examination of Water and Wastewater, 16th edition, 1985 and the National Committee for Clinical Laboratory Standard: PSC3, Specification for Reagent Water Used in the Clinical Laboratory. In addition, procedures for quality assurance were developed and performed to be in compliance with the Standards for Accreditation for Medical Laboratories, (Commission on Laboratory Inspection and Accreditation) College of American Pathologists, Skokie, Ill, 1988. These standards are similar to those required by the Joint Commission for Accreditation of Health Care Organizations and Medicare Regulations as outlined in the Code of Federal Regulations (10-1-90), Title 42, Chapter 4, Subpart K, 1201-1227. These procedures documented and assured proper operation of the laboratory equipment critical to the growth, isolation, and identification of potential human pathogens, while following standard laboratory safety guidelines to protect laboratory personnel. The quality control of all microbiological media was documented to assure proper cultivation and detection of potentially pathogenic bacterial species. These precautionary efforts in documentation were performed to address possible legal aspects in the future development of ATES systems.

### Collection of water from the ATES system piping

Collection sites were chosen to examine the water at different stages of water processing in the UA-ATES system circulation (Figures 6 and 7). Comparison of the microbial content of water upstream and downstream from the major mechanical components in the circulation would allow identification of potential sources of contamination with human pathogens (Table 1). Comparison of the microbial content of warm (ambient) aquifer water and the ejected water after passage through the Recreation Center air handling units should reflect the overall effect of ATES system operation on microbial populations.

The piping in the UA-ATES system was modified for collection of the appropriate water specimens during the pumping process. Stainless steel valves and spigots were added to pre-existing pipe-plug fittings or the pipe-plug fitttings of pressure gauges on the UA-ATES system. Sterilized medical grade silicon rubber tubing was attached aseptically to the stainless steel spigot. The spigot valve was opened, samples of water were collected by inserting a wide mouth polypropylene bottle into the stream, and the pH and conductivity was measured with a hand-held pH and conductivity meter. Water was discarded until the pH and conductivity stabilized. The pH and conductivity usually stabilized after 10 - 12 min of flushing the spigot. A sample (8.0 L) was then collected aseptically. This sample was subsequently subdivided for the designated microbiological procedures. Collection of water specimens was attempted at biweekly intervals over a complete seasonal cycle of 80 weeks (10/07/88 - 04/09/90). Sites A, B, and C were generally sampled during the active winter cycle of operation, and Sites D and E were generally sampled during the active summer cycle of operation. It should be noted that during the transition periods of atmospheric temperature during the spring and fall seasons, aquifer water might be chilled at night and early morning and chilled aquifer water might be used to cool the recreation center during the afternoon and early evening of the same day. Some specimens collections were not completed because the pumps would automatically shut off in the middle of the collection. In general, specimen collection from the UA-ATES system was initiated at 7:00 - 8:00 A.M. on Tuesday of alternate weeks. This collection schedule permitted one day of last-minute preparation of equipment and materials, one day for specimen processing and shipping by air, and three days for incubation of cultures and observations of results. A basic physical and chemical characterization of each water specimen was performed also.

The sampling of the circulating water in the ATES system should be placed in the perspective of the entire ATES system. Two hundred and eighty liters were collected for microbiological analysis in the study, while approximately 140 x $10^6$ liters of chilled water passed through the ATES system.

### Bacteriology

Standard diagnostic microbiology procedures were used to detect specific pathogens and opportunistic pathogens that historically are associated with water-borne infectious diseases (Table 2). Circulating aquifer water in the UA-ATES system was tested for heterotrophs, fecal coliforms, and pathogenic bacteria. The study period included two winter chill storage cycles to confirm the reproducibility of the procedures. Each group of microorganisms had a specific procedure for isolation and identification (Table 3). In addition, the sump water of conventional cooling towers at Buildings 2 - 6 (Figure 1) were tested for *Legionella* species to establish the efficacy of the isolation procedure.

## RESULTS AND DISCUSSION

### Physical and Chemical Characteristics of UA-ATES water

The pumping patterns in the ATES system circulation are illustrated in Figure 8. The climate in the Tuscaloosa region resulted in intermitent thermal storage and use during the winter and spring seasons. In contrast, thermal energy use was essentially steady through the summer and fall seasons. Physical measurements and chemical analyses of water specimens are summarized in Table 4. The ATES system did not appear to modify the aquifer water chemistry during the study period.

### Bacteriological Characteristics of UA-ATES water

The concentrations of heterotrophic bacteria were varied in water samples from sites A, B, and C (Figure 9) during times of intermittent pumping (winter and spring). In comparison, the concentrations of hetertrophic bacteria in water samples from sites D and E were relatively constant during times of steady pumping (summer and fall). There are two possible explanations for the variable heterotrophic bacteria counts. The aquifer-air interface in the immediate area of the production well cycles up and down as the pumps turn on and off during the periods of intermittent pumping. Sweeping of the aquifer sand and gravel with this interface as the production well pump turned on and off would tend to dislodge adherent microorganisms, and they would then appear in water samples taken from a production well. Alternatively, the bacteria might grow in small clumps. As these clumps pass through the cooling tower, the relatively violent action of passing through small orfices at high velocity to produce water droplets for heat exchange might break up the clumps into individual cells, and thereby increase the colony counts. The concentration of heterotrophic bacteria in the UA-ATES system water was similar to the concentration observed in an ATES system using an impounded aquifer at the University of Stuttgart [5].

The concentrations of coliform bacteria were varied in water samples from sites A, B, and C (Figure 10) during times of intermittent pumping (winter and spring). In comparison, the concentration of coliform bacteria in water from Sites D and E was essentially below detectable levels during the period of steady pumping. The coliform bacteria make up approximately 0.01% of the heterotrophic population of bacteria. Fecal coliforms were not detected in 70 separate samples from the UA-ATES system. The chilled aquifer plume that develops in the operation of the UA-ATES system would probably decrease the probability of infection with some of the most common water-borne enteric pathogens, i.e., *Salmonella* and *Shigella* species.

Overt pathogens were not detected in the UA-ATES system (Table 5). Standard control cultures were included in the isolation and identification procedures as a quality control for the bacteriological media and procedures. Two opportunistic pathogens were isolated, but were present in low numbers. *Pseudomonas aeruginosa* was detected three times in water from site B. *Mycobacterium chelonae* was detected one time in water from site D and four times in water from site E. In all cases of isolation the CFU/ml was extremely low, i.e., < 0.01 CFU/ml. *Legionella* species were not detected in 72 samples of water from the UA-ATES system. This negative observation is notably significant, since *Legionella* species were readily detected during the summer season in five conventional cooling towers located nearby on the University of Alabama campus (Figure 11).

SUMMARY

Operation of the chilled water UA-ATES system did not contribute to the growth of pathogenic bacteria or fecal coliforms. The numbers of coliform bacteria appear to be reduced in the chilled aquifer plume. The numbers of heterotrophic bacteria do not appear to be affected by chilling of the aquifer. This study minimizes the potential of pathogenic bacteria for an adverse impact on the continued development of chilled water ATES. However, the ubiquitous nature and multifaceted biological and biochemical activities of microorganisms dictates that microbiological surveillance is an integral element in the continuing development of ATES technology. Future studies should be more limited in scope and focus on heterotrophic and coliform bacteria to assess the general water quality of the aquifer.

NOMENCLATURE

**Adherent bacterium**. a bacterium that is attached to a surface by specific biological/biochemical interactions; the microorganism may be found free in water, if a surface is perturbed by water flow.

**Antibody**. a protein present in the serum that combines specifically with components of the microbial cell. The specific binding can be used to identify microorganisms.

**BCYE medium**. Buffered charcoal, yeast extract medium used specifically for the isolation of *Legionella* species.

**Campylobacter thioglycolate medium**. an enrichment medium for *Campylobacter* species.

**CampyPak Plus**. A commercial system that generates special gas concentrations necessary for isolation of *Campylobacter* species

**Clinical microbiology**. microbiology pertaining to observation, diagnosis, and treatment of infectious diseases.

**Coliform bacteria**. aerobic and facultative anaerobic, gram-negative, nonsporeforming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35°C and produce a golden-green metallic sheen on a suitable medium. These bacteria are a subset of hetertrophic bacteria.

**Enrichment medium**. a liquid medium designed to favor the growth of a few bacterial cells of one or two specific species to higher numbers in relation to other bacteria and thereby ensure detection of the specific bacterium by routine procedures.

**Enteric bacteria**. gut-associated bacteria. These bacteria are usually transmitted by the oral-fecal route. The microorganism obtained in either feces-contaminated food or water.

**Fecal coliform**. A subset of coliform bacterium that are specifically associated with the gut of various warm-blooded animals, e.g., the human. They are separated from coliform bacteria by biochemical testing.

**GPAV medium**. glycine-polymixin B-anisomycin-vancomycin supplemented BCYE medium. The antibiotic supplements inhibit overgrowth of low numbers of *Legionella* species by high numbers of other microorganisms.

**Heterotrophic bacteria**. bacteria that require organic carbon for energy and growth.

**Indigenous**. descriptive of a microorganism that occurs or lives native to the local environment, and is not introduced by human activity.

**Infection**. the process of transmission, entry, spread of a microorganism in the human.

**Lowenstein-Jensen medium**. a coagulated egg-based medium used for the isolation of *Mycobacterium* species.

***m* Endo agar LES medium**. a medium specifically designed for the counting coliforms.

**Middlebrook 7H10 medium with OADC**. a defined medium supplemented with oleic acid, albumin, dextrose, and catalase. The medium is used for the isolation of *Mycobacterium* species.

**Mitchison 7H11 medium**. an antibiotic-supplemented (carbenicillin, polymyxin B, amphotericin B, and trimethoprim) defined medium. The medium is used for isolation of *Mycobacterium* species.

**MPA medium**. a medium for the membrane filter technique used for isolation of *Pseudomonas aeruginosa*.

**Opportunistic pathogen**. a microorganism that is usually noninfectious, but under certain conditions the microorganism will cause disease.

**Pathogen**. a microorganism that usually infects and produces disease.

**Pathogenic**. descriptive of a microorganism that is capable of producing disease.

**R2A medium**. a low nutrient medium designed specifically for counting heterotrophs.

**TCBS medium**. Thiosulfate, citrate, bile, sucrose medium designed for the isolation of *Vibro cholerae* and *Vibrio parahaemolyticus*.

**Transmission**. the process by which a microorganism passes from an infected host to a second susceptible host.

**XLD medium**. Xylose-lysine-desoxycholate medium designed for the direct isolation of *Shigella* and *Salmonella* species.

ACKNOWLEDGEMENTS

The contributions, expertise, and technical assistance of Tammy E. Thompson and Catherine E. Walker are gratefully acknowledged. This work was supported by Pacific Northwest Laboratory Contract 005383-A-M.

REFERENCES CITED.

1. R. W. Reilly, 1980, "A Descriptive Analysis of Aquifer Thermal Energy Storage Systems," PNL-3298, Pacific Northwest Laboratory, Richland, Washington.

2. K. C. Midkiff, Y. K. Song, and C. E. Brett, 1991, "Thermal Performance and Challenges for a Seasonal Chill Energy Storage Based Air-Conditioning System," 91-HT-29, American Society of Mechanical Engineers, New York, New York.

3. R. J. Hicks and D. L. Stewart, 1988, "Environmental Assessment of the Potential Effects of Aquifer Thermal Energy Storage on Microorganisms in Groundwater," PNL-6492/UC-94e, Pacific Northwest Laboratory, Richland, Washington.

4. B. H. Keswick, 1984, "Sources of Groundwater Pollution", in G. Britton and C. P. Gerba (eds), Groundwater Pollution Microbiology, pp. 39-64, John Wiley and Sons, New York.

5. A. L. Winters, 1992, "Summary of Research on Microbiological Processes," International Energy Agency SubtaskD Final Report, PNL-7980/UC-202, Pacific Northwest Laboratory, Richland, Washington.

Table 1. Overview of sample collection from the UA-ATES system.

| Location of Sample Collection | Rationale for Collection of the Sample |
|---|---|
| Site A | Aquifer water before entry into the conventional cooling tower. This water was pumped directly from the aquifer and would potentially contain nonadherent bacteria and previously adherent bacteria dislodged from aquifer sand and gravel by the physical action of pumping , and possible perturbations of the air-water interface. The microbial content should provide a baseline for comparison with Sites B, C, D, and E. |
| Site B | Chilled aquifer water after passage through the conventional cooling tower. It should be noted that the resident time of aquifer water in the cooling tower was at most a few minutes and generally the water was not recirculated in the cooling tower. Sampling at this site should detect the introduction of air-borne bacteria into the chilled aquifer water before storage. |
| Site C | Chilled aquifer water after filtration through a sand filter and immediately before injection into the aquifer. The sand filter may provide enrichment of microbial growth by serving as an "incubator" and introduce high numbers of bacteria into the chilled aquifer water. |
| Site D | Chilled aquifer water before passage through the airhandling units in the Student Recreation Center. This water was pumped directly from the chilled aquifer and would potentially contain free-floating, nonadherent bacteria and previously adherent bacteria dislodged from aquifer sand and gravel by the physical action of pumping , and possible perturbations of the air-water interface. |
| Site E | Chilled water after passage through the air handling units and immediately before ejection from the ATES system. Although the current UA-ATES system operation entails ejection of the water from the system, comparison of the bacterial content from Site E with the bacterial content from Site A should illustrate the overall impact of the UA-ATES system operation on aquifer microbiology. In addition, examination of this water sample will document the safety of ejecting this water to a surface drain. Comparison of bacterial populations from Sites A and E should provide an evalulation of the overall impact of the UA-ATES system on aquifer microbiology. |

TABLE 2. Water-associated bacteria targeted for isolation and identification in the UA-ATES system.

| Microrganism or Group of Microrganisms Targeted for Detection | Rationale for Choosing the Pathogen |
|---|---|
| *Salmonella*, *Shigella*, and *Vibrio* species (pathogens) | the most common enteric pathogens derived from human and animal fecal contamination of water, the procedures also detect fecal coliforms and coliforms that may be opportunistic pathogens. |
| *Campylobacter jejuni* (pathogen) | a specific enteric pathogen derived from human fecal contamination of water. |
| *Yersinia enterocolitica* (pathogen) | a specific enteric pathogen derived from animal fecal contamination of water. |
| *Pseudomonas aeruginosa* (opportunistic pathogen) | a pathogen that is usually associated with skin disease after exposure to contaminated water. However, immunocompromised individuals may develop serious systemic infections. |
| *Mycobacterium* species, nontuberculosis (opportunistic pathogens) | a group of opportunistic pathogens associated with skin, soft tissue, and lung disease following exposure to contaminated water. |
| *Legionella* species (opportunistic pathogens) | a group of opportunistic pathogens associated with lung disease following exposure to aerosols of contaminated water. The contaminated water is usually found in a conventional cooling tower, but shower heads and other sources have also been implicated in dissemination of the microorganism. |
| Coliforms (opportunistic pathogens) | a group of opportunistic pathogens associated with a wide variety of infections. The infections range from mild to severe. The presence of fecal coliforms indicates fecal contamination of the water, thus water-borne transmission of *Salmonella*, *Shigella*, and *Vibrio* species may occur. |
| Heterotrophs | a group of microorganisms that are not pathogens or usually not opportunistic pathogens. Their number reflects the general quality of water, i.e., low numbers indicate water with a low organic content. |

TABLE 3. Outline of procedures for isolation and identification ot the targeted bacteria.

| Microorganism or Group of Microorganisms Targeted for Detection | Procedure |
|---|---|
| *Salmonella*, *Shigella*, and *Vibrio* species (pathogens) | The microorganisms in a 1.0 L water sample were captured by filtration through a diatomaceous earth pad and cellulosic membrane. The filter and pad were divided, and placed in tetrathionate broth and alkaline peptone water. The target microorganisms were enriched by an 18 h incubation at 35°C. The enrichment cultures were streaked on XLD agar plates and TCBS agar plates and incubated for 18 h at 35°C for presumptive identification, respectively. Confirming identification was obtained with biochemical tests and serotyping. |
| *Campylobacter jejuni* (pathogen) | The microorganisms in a 1.0 L water sample were captured by filtration through a cellulosic membrane. The filter was placed in Campylobacter thioglycolate broth. The target microorganism was enriched by a 48 h incubation at 42°C in a CampyPak Plus GASPAK jar. The enrichment culture was streaked on Campylobacter blood agar plates and incubated 48 h for presumptive identification. Confirming identification was obtained with biochemical tests. |
| *Yersinia enterocolitica* (pathogen) | The microorganisms in a 1.0 L water sample were captured by filtration through a cellulosic membrane. The filter was placed on a Yersinia selective agar plate with antibiotic supplement CN and incubated 18 - 24 h at 25°C for presumptive identification. Confirming identification was obtained with biochemical tests. |
| *Pseudomonas aeruginosa* (opportunistic pathogen) | The microorganisms in a 1.0 L water sample were captured by filtration through a cellulosic membrane. The filter was placed on a modified M-PA agar plate and incubated 72 h at 41.5°C for presumptive identification. Confirming identification was obtained with biochemical tests. |
| *Mycobacterium* species, nontuberculosis (opportunistic pathogens) | The microorganisms in a 1.0 L water sample were captured by filtration through a cellulosic membrane. The filter was decontaminated with 1.0% formaldehyde and placed on a Mitchison 7H11 Selective agar plate and incubated 3, 6, and 14 d at 30°C. Acid-fast colonies were streaked sequentially on Middlebrook 7H10 agar plates with OADC enrichment and Lowenstein-Jensen medium for presumptive identification. Confirming identification was obtained by the Alabama State Laboratory, Montgomery, Alabama. |
| *Legionella* species (opportunistic pathogens) | The microorganisms in a 1.0 - 10 L water sample were captured by filtration through a polycarbonate membrane. The microorganisms were resuspended in 10 mL of sterile water and 1.0 mL of the suspension was placed on a BCYE agar plate with cysteine and incubated 48 h at 35°C. Suspect colonies were patch inoculated on BCYE biplates with and without cysteine for presumptive identification. Water samples from conventional cooling towers were treated with acid and plated on GPAV agar plates to reduce background flora. |
| Coliforms (opportunistic pathogens) | The microorganisms in a 1.0 L water sample were captured by filtration through a cellulosic membrane. The filters were placed on an *m* Endo agar LES plate and incubated for 24 h at 35°C. The concentration of coliforms was derived from counting colonies with a green sheen and subsequent biochemical testing representative colonies. Fecal coliforms were distinquished by biochemical testing. |
| Heterotrophs | Water samples from Sites D and E were diluted 1:20 (v/v) and 1:50 (v/v) in 0.1% peptone water. Water samples from Sites A, B, and C were diluted 1:50 (v/v) and 1:100 (v/v) in 0.1% peptone water. The microorganisms in the dilutions were captured by filtration through a cellulosic membrane. The filter were placed on R2A agar plates and incubated for 5 d at 25°C. The concentration of heterotrophs was derived from colony counts. |

| Table 4. Physical and chemical characteristics of specimens collected. | | | | | |
|---|---|---|---|---|---|
| Characteristic | Range of Values | | | | |
| | Site A | Site B | Site C | Site D | Site E |
| Water temperature (°C) | 13.3 - 17.6 | 4.2 - 10.6 | 6.1 - 9.0 | 11.6 - 18.0 | 15.1 - 21.1 |
| pH | 4.14 - 5.31 | 4.52 - 6.90 | 4.53 - 6.34 | 4.16 - 6.76 | 4.06 - 6.81 |
| Conductivity (μSiemens/cm) | 73 - 84 | 65 - 75 | 65 - 74 | 69 - 81 | 72 - 82 |
| Inorganic Carbon (mg/L) | < 5.0 | < 5.0 | < 5.0 | < 5.0 | < 5.0 |
| Total Organic Carbon (mg/L) | < 5.0 - 11.0 | < 5.0 - 14.2 | < 5.0 - 5.2 | < 5.0 - 7.2 | < 5.0 |
| Dissolved Organic Carbon (mg/L) | < 5.0 | < 5.0* | 5.0 | < 5.0 | < 5.0 |
| $NH_4^+$ (mg/L) | 0.1 - 2.7 | 2.2 - 3.4 | < 0.05 - 4.0 | < 0.05 - 1.9 | < 0.05 - 2.6 |
| $NO_3^-$ (mg/L) | < 0.05 - 16.9 | 0.44 - 16.4 | < 0.05 - 15.4 | 4.0 - 15.5 | 4.0 - 14.4 |
| $NO_2^-$ (mg/L) | < 0.05 | <0.05 | <0.05 | < 0.05 | < 0.05 |
| $SO_4^{-2}$ (mg/L) | <0.05 - 0.68 | 1.5* | < 0.05 - 0.33 | < 0.05 - 2.8 | < 0.05 - 2.2 |

* Single assay

| Table 5. Summary of Attempted Isolations of Pathogenic Microorganisms. | | | | | |
|---|---|---|---|---|---|
| Targeted Microorganism(s) | Samples with isolates/Total samples tested | | | | |
| | Site A | Site B | Site C | Site D | Site E |
| *Yersinia* species | 0/12 | 0/12 | 0/9 | 0/16 | 0/16 |
| *Pseudomonas aeruginosa* | 0/14 | 3/14# | 0/10 | 0/16 | 0/16 |
| *Salmonella* species, *Shigella* species | 0/14 | 0/14 | 0/11 | 0/16 | 0/16 |
| *Vibrio* species | 0/14 | 0/14 | 0/11 | 0/16 | 0/16 |
| *Campylobacter* species | 0/14 | 0/14 | 0/10 | 0/16 | 0/16 |
| *Mycobacterium* species (Nontuberculosis) | 0/14 | 0/14 | 0/10 | 1/16* | 4/16* |
| *Legionella* species | 0/14 | 0/14 | 0/12 | 0/16 | 0/16 |

\# Detected only with enrichment culture. The low concentration of *Pseudomonas aeruginosa* in UA-ATES system water precludes it as a biohazard, except in the case of an immunocompromised individual.

* *Mycobacterium chelonae* was isolated. The low concentration of *Mycobacterium chelonae* in the UA-ATES system water precludes it as a biohazard, except in the case of an immunocompomised individual.

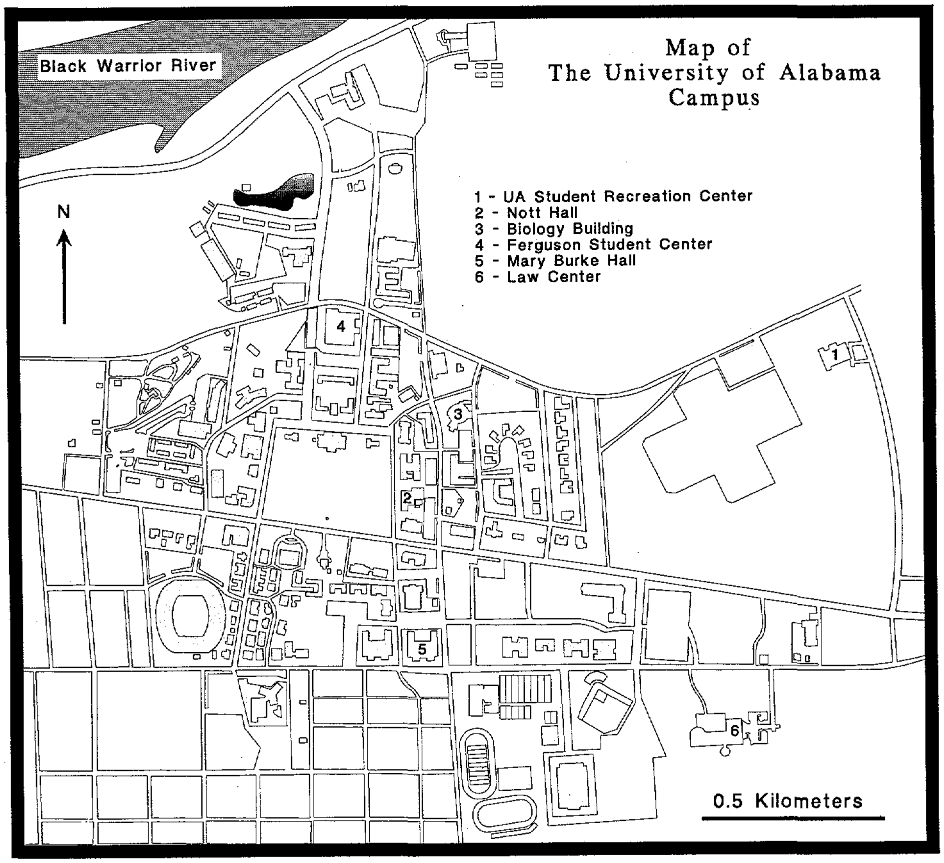



Figure 1. Location of the UA Student Recreation Center and Other Sampling Sites.

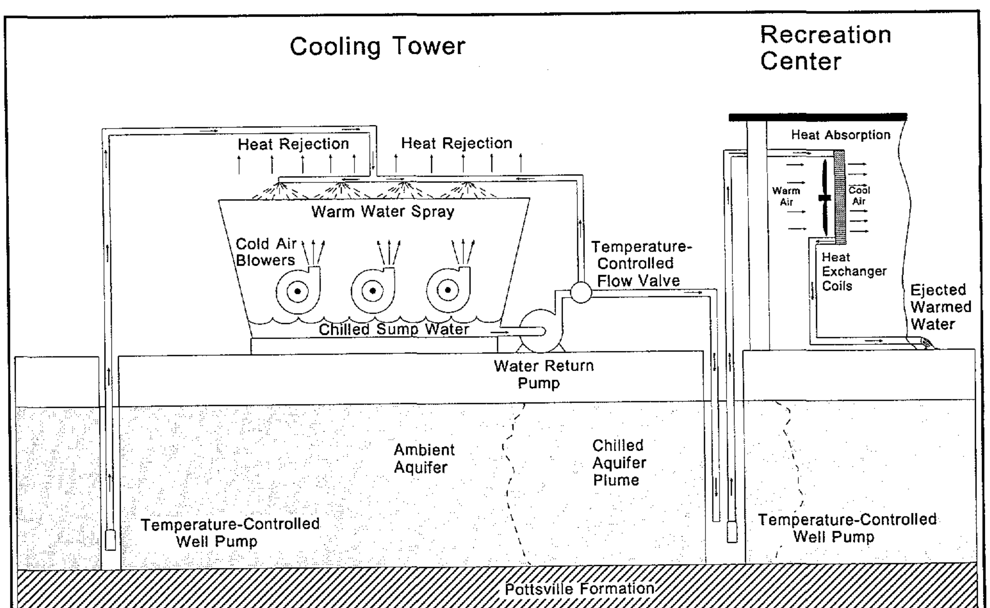



Figure 2. Generation of Chilled Aquifer in the UA-ATES system.

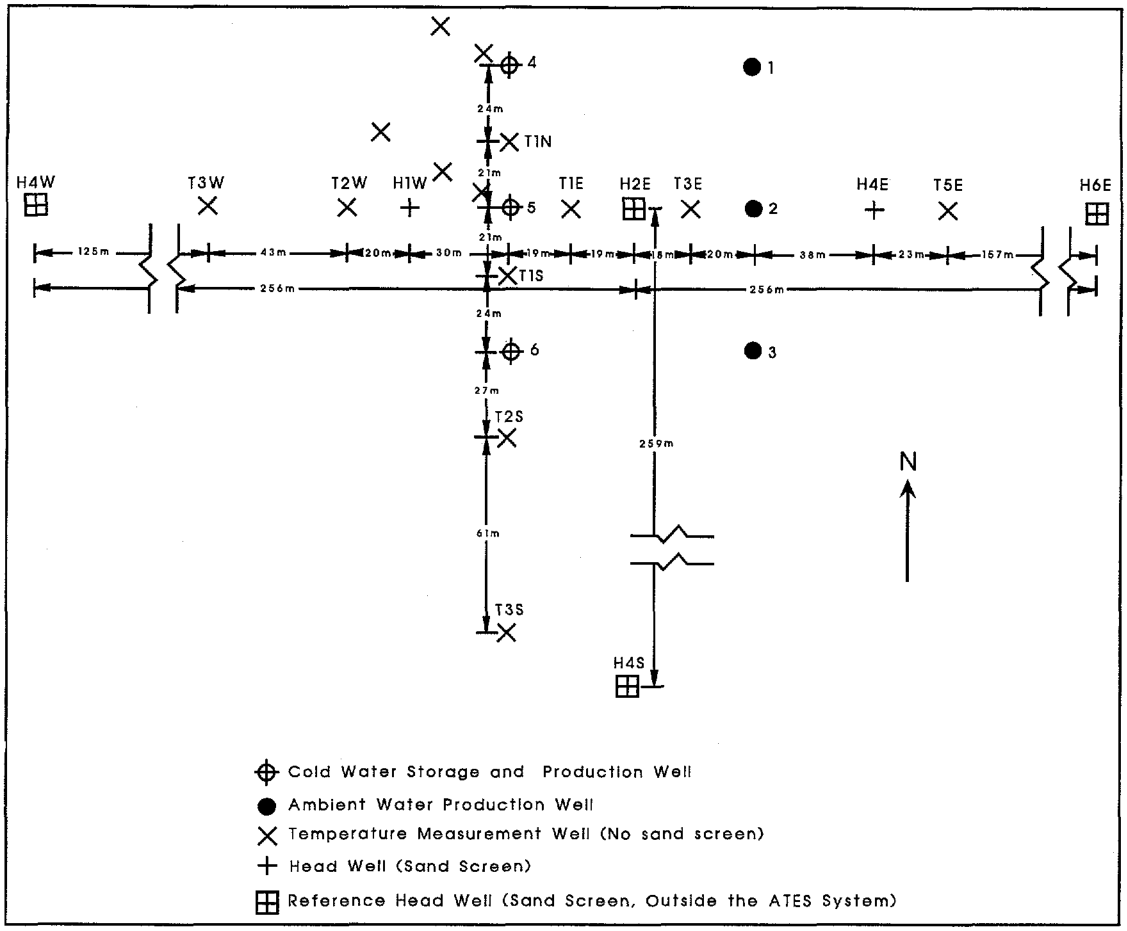



Figure 3. Map of the UA-ATES system well field. Water from Wells 1 - 6 were sampled in the investigation. Production wells (1 - 6) were drilled to the Pottsville formation (depths ranging from 24.4 to 30.5 meters), lined with 20.3 cm PVC pipe. Slots were cut in the bottom 10 m of the pipe to serve as sand screen.

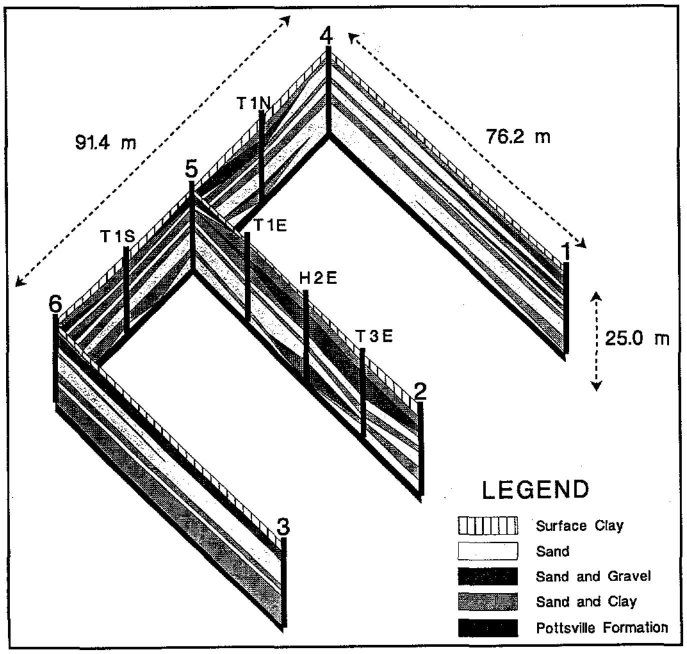



Figure 4. Fence diagram of the sediment layers in the UA-ATES well field.

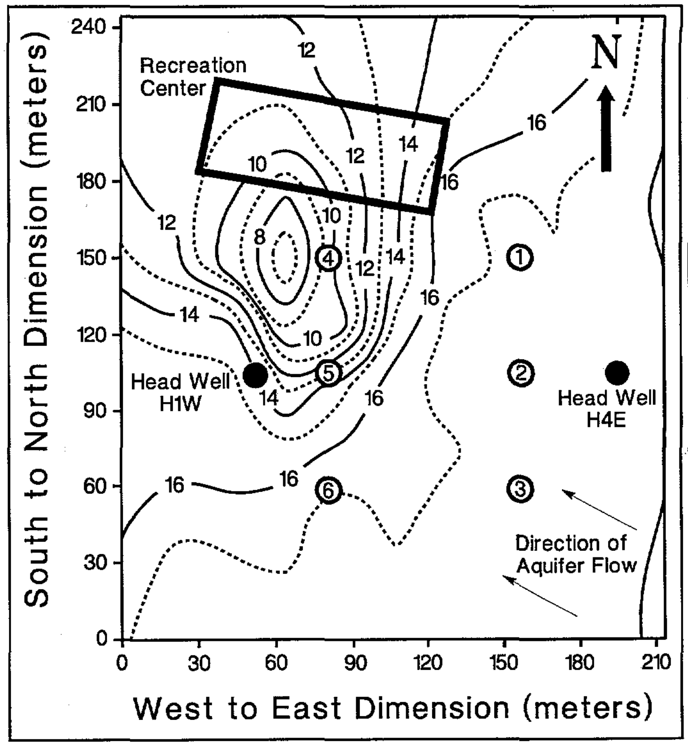



Figure 5. Isotherms in the chilled aquifper plume near the end of the chilled water storage cycle. Chilled water was injected for storage in production well 4.

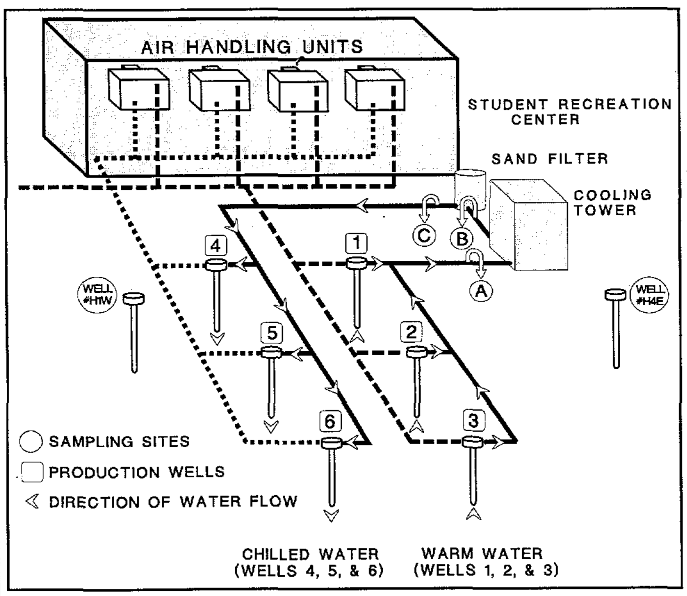



Figure 6. Location of sampling sites during generation and storage of chilled water in the UA-ATES system.

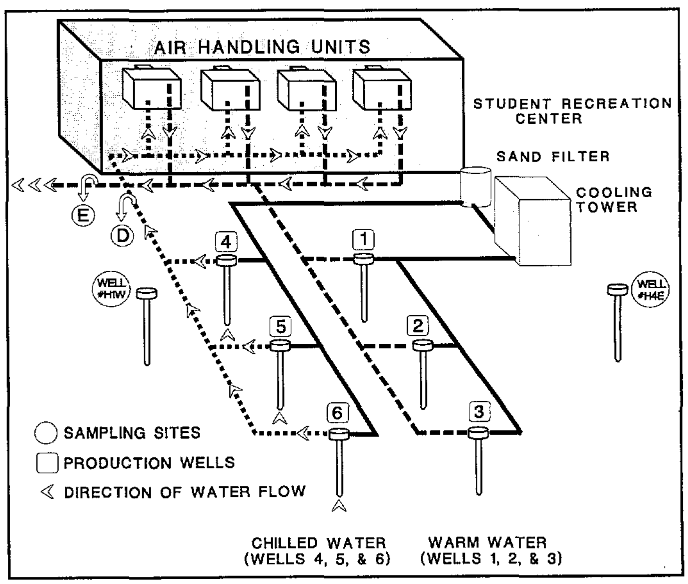



Figure 7. Location of sampling sites during recovery of cold water from the UA-ATES system for air conditioning of the Student Recreation Center.

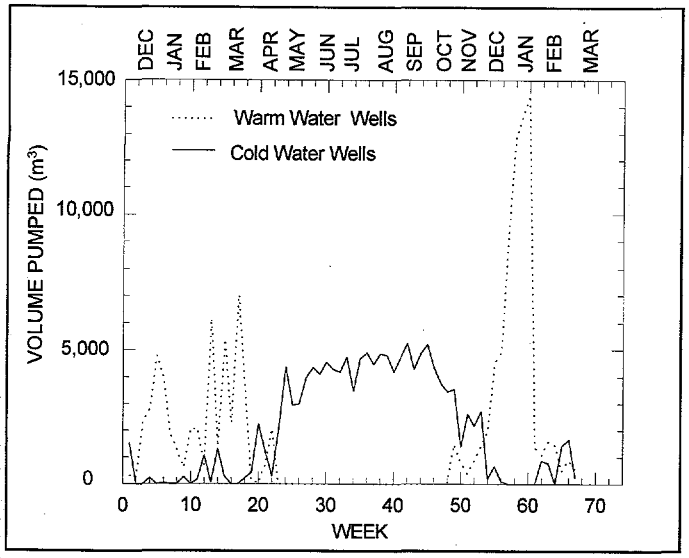



Figure 8. Pattern of UA-ATES water pumping during a seasonal cycle.

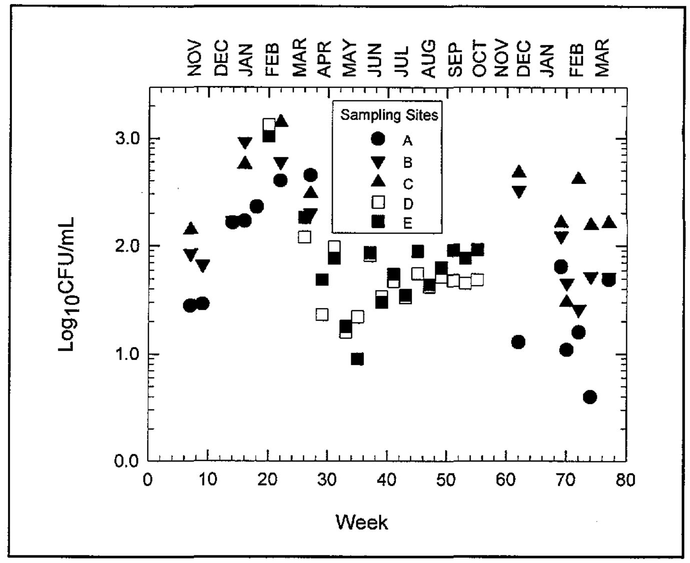



Figure 9. Concentration of heterotrophic bacteria in the UA-ATES water during a seasonal cycle. Limit of detection was $< 1.0 \times 10^{-3}$ CFU/mL.

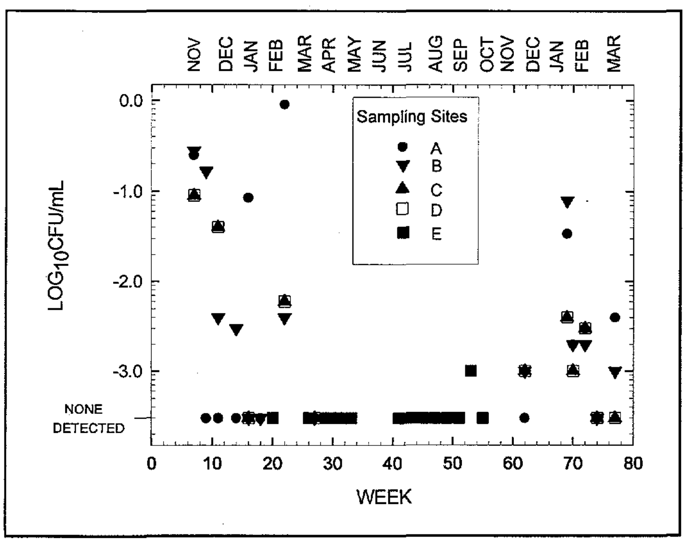



Figure 10. Concentration of coliform bacteria in UA-ATES water during a seasonal cycle. Limit of detection was $< 1.0 \times 10^{-3}$ CFU/mL.

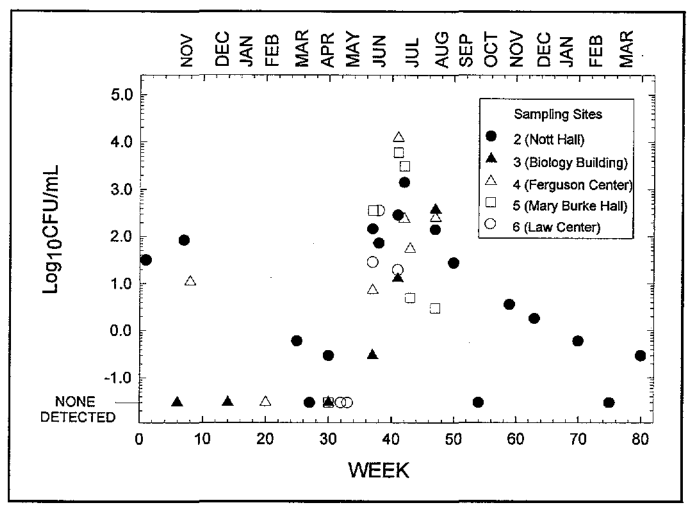



Figure 11. Concentration of *Legionella* species in sump water of conventional cooling towers on the UA campus.