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AQUIFER THERMAL ENERGY (HEAT AND CHILL) STORAGE

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MASTER

SUMMARY

As part of the 1992 Intersociety Conversion Engineering Conference, held in San Diego, California, August 3-7, 1992, the Seasonal Thermal Energy Storage Program coordinated five sessions dealing specifically with aquifer thermal energy storage technologies (ATES). Researchers from Sweden, The Netherlands, Germany, Switzerland, Denmark, Canada, and the United States presented papers on a variety of ATES related topics. With special permission from the Society of Automotive Engineers, host society for the 1992 IECEC, these papers are being republished here as a standalone summary of ATES technology status. Copies of the complete conference proceedings may be obtained from the Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania, U.S.A. 15096.

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Swedish ATES Applications:
Experiences after Ten Years of Development

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ABSTRACT

During the last 10 years, the general concept of using the subsurface for the storage of energy has been increasingly developed in Sweden. Among the many alternatives, aquifers are one of the most promising options. Potentially they can be used both for seasonal and short-term energy storage at temperatures ranging from 2°C to more than 100°C.

So far, Sweden has had only experimental experience with storage of high-temperatures (>50°C). However, there are several low temperature systems (<25°C) that have been operated for more than two years. In this paper, these ATES plants are overviewed and some general technical problems are identified, as well as measures that have been taken to solve these problems.

The range of problems includes the aquifer system itself, but also problems related to the total system and how it is operated. Further, the economics are briefly described, as well as environmental aspects.

The ATES concept still has some weaknesses that need improvement, but commercialization of the technology should be quite close.

INTRODUCTION

Ever since the first oil crisis in the mid 1970s, the Swedish Council for Building Research (BFR) has supported development of different techniques for energy conservation.

In the beginning it was a thought that solar energy should become a major source of renewable energy with a high potential for replacement of fossil fuel. However, to be effective, solar energy had to be stored from summer until winter and hence this demand gave birth to the seasonal storage concept.

Initially, collected solar energy was stored in large steel tanks, However, this and simular storage techniques resulted in high storage costs and large energy losses. For this reason, soil, rock and aquifers were investigated as storage media.

Within the BFR program for energy storage a large number of different projects have been initiated covering a broad range of underground technologies. The main groups are schematically shown in Figure 1.

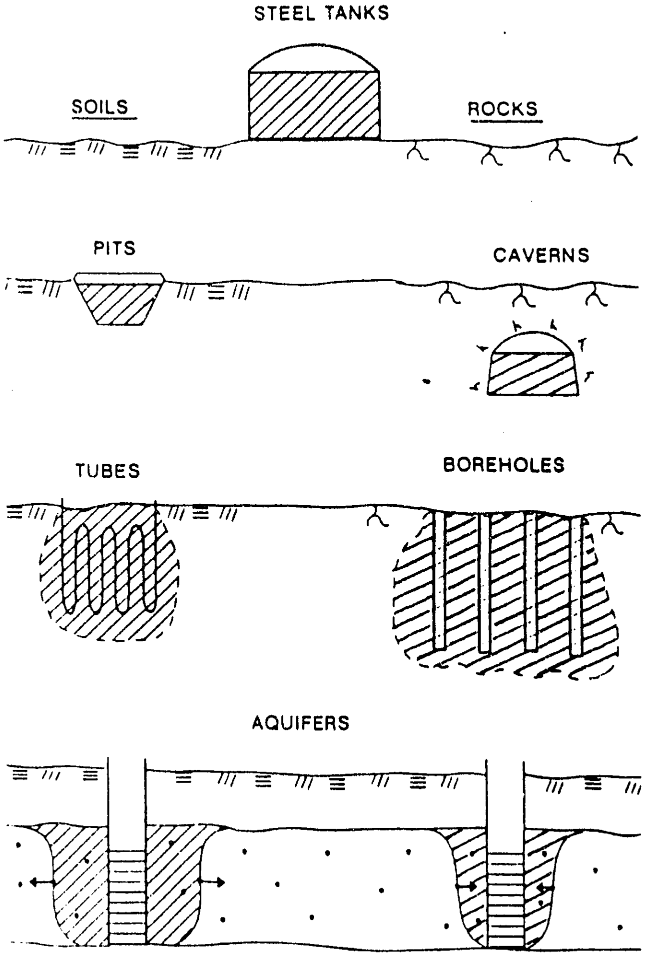

Figure 1 Main groups of seasonal storage techniques demonstrated within the BFR storage program (BFR 1990)

In recent years it has become evident that aquifer thermal energy storage (ATES) is one of the most promising techniques, not only for storage of heat but also storage of cold. The general "Swedish concept" also involves the use of heat pumps in combination with seasonal storage. This allows storage at low or moderate temperatures but still results in effective and profitable systems.

The general concept also states that high-temperature storage is especially suitable for short-term applications. The main reason behind this approach is that energy losses will increase with increased storage temperature and, hence, will decrease the quantity and quality of withdrawn energy. Therefore seasonal storage in aquifers has been focused on low or moderate temperatures. This is shown in Table 1 where eight BFR supported ATES projects are briefly described. Of those, all but one are low-temperature applications (12-25°C). Furthermore the high temperature project (No 8) is pure experimental and includes research on water chemistry problems.

Not pointed out in the table, but still significant, is that all but one of the low temperature projects (No 7) are systems coupled to heat pumps. It is also of interest to note that all systems are quite large and that the typical user is a commercial building owner or a district heating network. A possible lack of technical confidence in the technology combined with extended payback times might explain why more applications are not utilized by the industry. Finally, it shall be noted that during recent years there has been a growing interest in combined heating and cooling systems (four out of seven projects in the table) in the Swedish energy market.

CONFIGURATIONS AND OPERATIONAL EXPERIENCES

In Sweden, the geology and climate are extremely variable and, therefore, the techniques for energy storage are determined by local conditions. As a first step in any ATES project, site investigations have to be carried out and then combined with the users specific requirements.

By considering local geology, geography, climate conditions and general applications several system concepts are possible. They have been divided into four main groups and described below.

STORAGE OF WARM SURFACE WATER - This concept was first tried in Klippan (No 1 in Table 1), then later in Falun (No 3) and quite recently in Lomma (No 6).

In Klippan and Lomma, surface water from rivers is used as a source of energy for seasonal storage. As shown in Figure 2 (the Lomma case), summer heated water is pumped through a heat exchanger to heat groundwater that is pumped from a cool part of the aquifer. The heated water is then stored in a warm part of the aquifer.

The mean storage temperature is roughly 15°C but might go as high as 25°C in the middle of the summer. During winter the stored warm water is withdrawn

No	Name, City	Energy [1] stored/ cycle (MWh)	Mean storage Temperature (°C)		Type of Aquifer	Maximum Flow Rate (m^3/h)	Storage Application			Years in operation (-1992)	**System User**		
			warm side	cold side			Heating only	Heating and cooling	Cooling only		Industry	**Comm. build**	**District heating**
1	Klippan DN, Klippan	2000	15	5	Unconfined sand	70	x			8			x
2	Eriksson Co, Kristianstad	1800	25	10	Semiconfined sandstone	40		x		7	x		
3	Hälsinggårdskolan, Falun	1200	12	4	Unconfined esker	200	x			7		x	
4	SAS Office, Solna	5200	13	5	Unconfined esker	1000		x		5		x	
5	Triangeln, Malmö	2700	12	4	Confined limestone	60		x		2		x	
6	Industrihamnen, Lomma	10000	15	5	Confined sand	350	x			2			x
7	Sparven, Malmö	3200 (4500)[2]	16	8	Confined limestone	150		(x)[2]	x	2		x	
8	ATES Pilot Plant[3], Lomma	200[4]	80[4]	30	Confined sand	30	x[3]			1[3]			x[5]

1) Rough average
2) Under reconstruction for both process cooling and airconditioning
3) Experimental plant under operation 1988-89
4) Last experimental short term cycle
5) Proposed

Table 1 Some characteristics for Swedish ATES plants

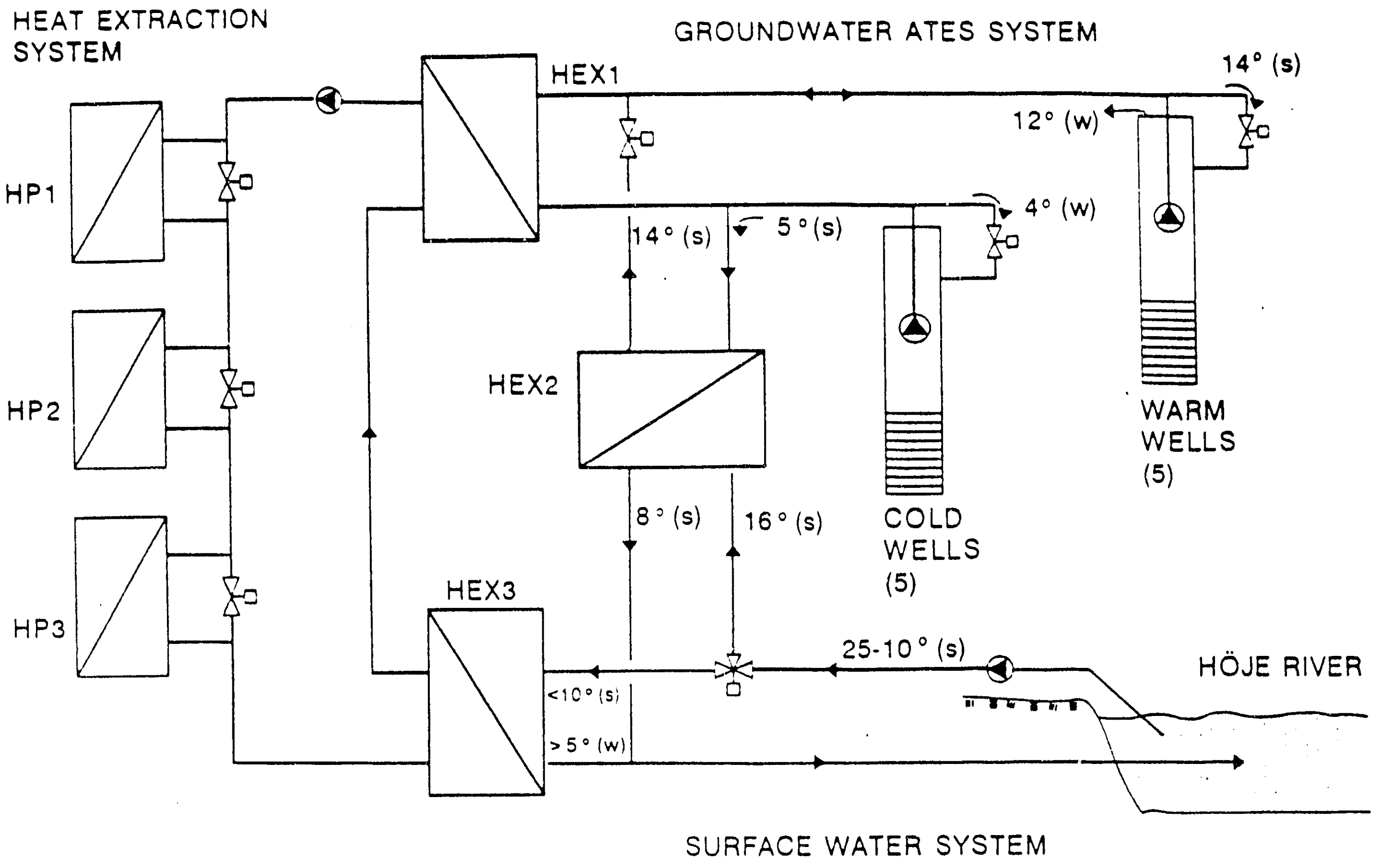

Figure 2 The system for storage of summer warmed surface water at Lomma (s) summer, (w) winter

and used as a source of energy to the heat pump system. The benefits of the ATES systems compared to traditional heat pumps with native groundwater are in both cases

- increased coefficient of performance (COP) for the heat pumps
- shorter distances between wells
- lower flow rates/or increased heat pump capacity
- less risk for thermal breakthrough

The main technical problems so far have been

- biofouling of the surface water heat exchanger (Lomma)
- well clogging of injection wells (Klippan)
- clogging of certain wells during production (Lomma)

In Klippan, the clogged wells had to be abandoned and were replaced with infiltration ponds (Emmelin et al. 1983.

In Lomma, the biofouling problem has been solved by a specially designed air bubble filter, in front of the surface water open-hole inlet. Well clogging is still a problem. However, experimental efforts are being performed to develop a new rehabilitation technique based on biochemical reactions (Andersson 1992).

In Falun, a different storage technique was chosen. In this case, there is a direct hydraulic connection between a lake and a shallow esker aquifer. As shown in Figure 3 three wells are continuously pumped during summer, forcing warm surface water to be drawn

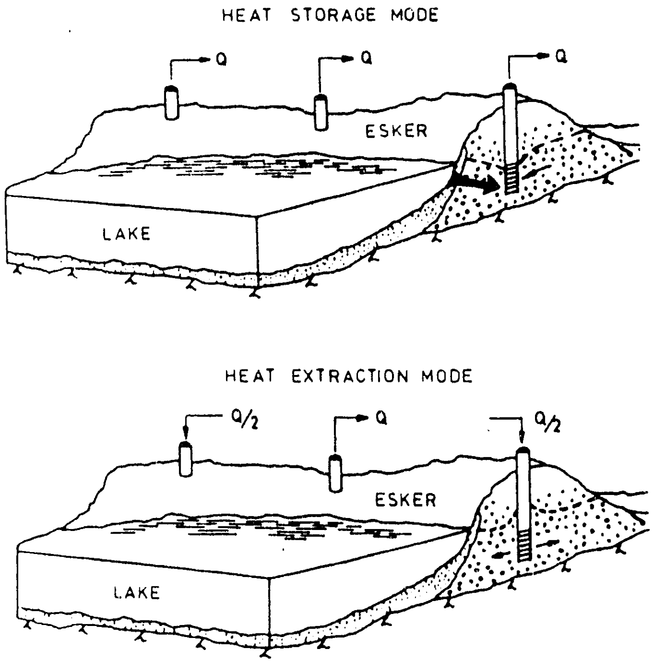

Figure 3 The induced infiltration system in Falun (Gustafson et al. 1989)

towards the wells (induced infiltration). In winter only the center well is used producing an average summer temperature water to the heat pump (Gustafson et al. 1989).

Because natural groundwater temperature in this part of Sweden is low (5-6°C) and much lower considering an influence from the lake in winter, a heat pump application without ATES would not be feasible at this locality. To have the storage functioning with high temperatures in winter, the storage mode has to be seasonally balanced. In this case, a thermohydraulic computer program was used to calculate the distance between the wells and the lake and also the flow rates neccessary to have the system in balance.

The two main problems encountered at Falun are
- flooding, normally in springtime with infiltration of cold water into the aquifer and thermal pollution of the store
- after some years, iron precipitation in the tubes and the heat exchanger.

The flooding is of less importance because the temperature drop in the aquifer is limited. To remedy the iron precipitation problem, the system has to be cleaned frequently, by acid. The source of the iron precipitation problem has been found to originate from the mixing of infiltrated water containing elevated iron with oxidized water (native aquifer water relatively free of iron). The latter water oxidizes the iron rich water when mixed in the center well causing a delayed precipitation in tubes and fittings. To solve this problem, an in situ oxidation of the dissolved iron has been proposed but not yet realized.

STORAGE COMBINED WITH PROCESS COOLING - This storage system is used for industrial process cooling and space heating at Kristianstad (No 2 in Table 1) and for process cooling and combined space heating and cooling at the Sparven telestation in Malmö (No 3).

The prime objective at Kristianstad is to use natural groundwater temperature for process cooling. Most of the heat obtained from the cooling process is directly used for space heating but excess heat is stored in the same aquifer as the cold water. This warm water is then used as a source of energy to a heat pump, serving the space heat demand during cold weather and weekends. When designed, the demand for cooling and heating was assumed to be more or less in balance. However, it was soon found that the cooling demand was much higher than expected and the heating demand much lower. This led to a thermal breakthrough between the cold and warm well and, hence, an increased temperature at the "cold" groundwater. The solution so far has been back-pumping and disposal of warm water. However, for legal reasons a new warm well at a greater distance from the cold well has been proposed (Kronqvist 1991).

The Sparven plant in Malmö, has quite a different lay-out. In this case, electronic telecommunication equipment is chilled constantly with natural groundwater. The groundwater is then reinjected into the aquifer at a distance of approximately 200 m from the production wells. To avoid a thermal breakthrough the water is rechilled in winter prior to injection. This is achieved by pumping the water through a series of fan chillers located to the roof of the station. However, the system is now being expanded. The target is to extend the use of the groundwater to include cooling and preheating of fresh inlet air to the buildings, see Figure 4. Hence the fan chillers will no longer be essential and the economic benefits will increase. The working environment will also be improved by more effective cooling.

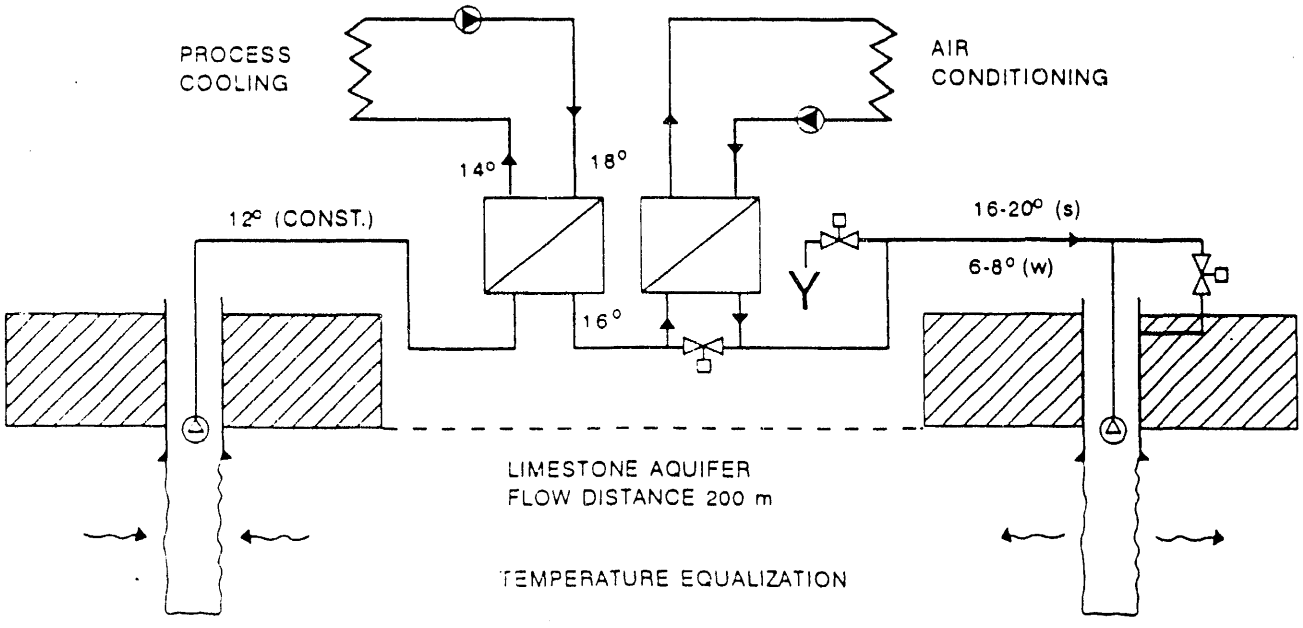

Figure 4 The system for combined process cooling and air conditioning at Sparven, Malmö

The main technical benefits of this system, compared to conventional chillers are
* much better system COP
* less noise
* better cooling security
* less freon handling

Problems encountered so far are restricted to some minor design errors and difficulties with having the controlling equipment working automatically. The latter problem is typically due to the complexity in running the groundwater system in combination with other energy systems. However, corrections have been made step by step to a final successfull system control (Rijpma et al. 1992).

STORAGE FOR COMBINED SPACE COOLING AND HEATING - This category, represented by SAS office in Solna (No 4 in Table 1) and the Triangle Trade Center in Malmö (No 5) is quite similar to the above described system at Sparven. However, at SAS and the Triangle Trade Center, the systems are designed for an optimal space cooling while space heating is covered both by preheating centralized fresh air inlets and by the use of heat pumps. Typically, running the heat pumps in winter also provides cold to be stored for cooling in summer. In contrast to Sparven, which has an unidirectional flow and an equalization of different temperatures within the aquifer, the SAS and the Triangle are designed with separated cold and warm parts of the aquifers. The schematic lay-out of the SAS system is shown in Figure 5. The system in the Triangle looks the same but uses a confined limestone aquifer instead of an esker.

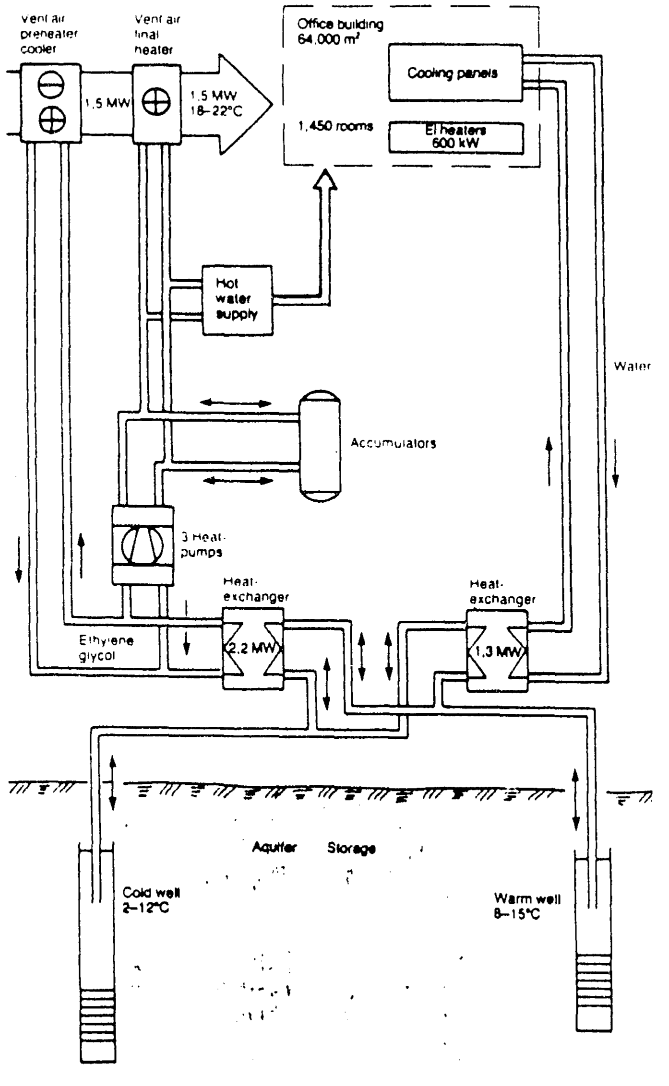

Figure 5 Principal flow diagram for the SAS ATES system in Solna (Johansson 1992)

Both systems suffered from initial operational problems, mainly as a result of the interaction between real energy requirements and the operating strategy. However, the system performance has improved steadily and the plants are now operated more or less as was planned (Johansson 1992. Landberg 1991).

Some long-term concerns have been pointed at. The most important of those are
* unbalance between cold and warm energy stored, caused by extreme climatic conditions or drastic changes in activities within the buildings (both cases)
* potential clogging of wells or corrosion in the groundwater system due to unfavorable water composition (the Triangle only).

HIGH-TEMPERATURE ATES SYSTEMS - Except for the experimental ATES plant in Lomma (No 8 in Table 1) no plants have been constructed. Several projects have been proposed and predesigned, but for different reasons not performed. In some cases, the technical risk has been judged as too high and in other cases, site investigations have shown unfavorable hydrogeological conditions.

The Lomma experimental plant was constructed to study one of the main technical obstacles for this technique, namely scaling caused by oversaturation of carbonates. It was assumed that precipitation of calcium carbonate should occur, especially in the heat exchanger upon heating. Theoretically this would be the case already at a moderate increase of temperature. Strange enough, scaling, corrosion or well clogging did not occur even at temperatures close to the boiling point. It was concluded that the content of phosphonates or dissolved organic matter in the groundwater served as natural inhibitors for growing of carbonate crystals (Banck 1989).

During the recent year and based on the experimental results from Lomma, two new high temperature projects have been studied. Hopefully at least one of these will be built in the near future.

ECONOMICS

According to an official publication from BFR (1990) the storage cost can be compared between systems by dividing the investment cost for the storage system with the energy regained from the store each cycle. This specific storage cost (SEK/kWh) is shown in Figure 6 plotted as a function of storage size.

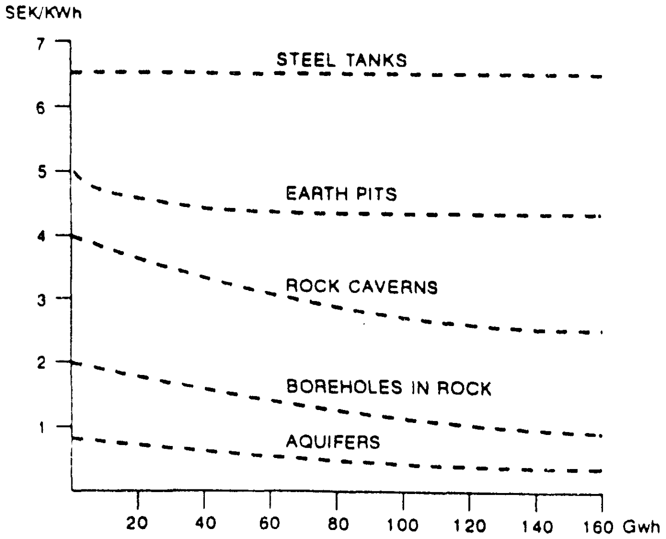

Figure 6 Specific storage cost for different storage systems as a function of size and at temperatures above 50°C (BFR 1990)

As can be seen aquifers are very competitive. This is quite understandable considering that only a few wells have to be drilled compared to hundreds of holes for a borehole storage or excavation of huge rock masses constructing a rock cavern.

The low-temperature ATES systems listed in Table 1 have all been subject to investment and operational cost analyses. Compared to different alternatives the pay-back times have also been calculated. Bearing in mind that the calculations were made at different times and often with different methods, it has to be stated that comparisons between plants are far from being relevant. Still, the calculated pay-back times plotted in Figure 7 show at least one clear indication. Combined systems for both cooling and heating are more profitable than systems for storage of heat only. Apart from that, there also seem to be a tendency within each group that older plants are less profitable than newly constructed ones. This may indicate that a more mature storage technology has been developed in recent years.

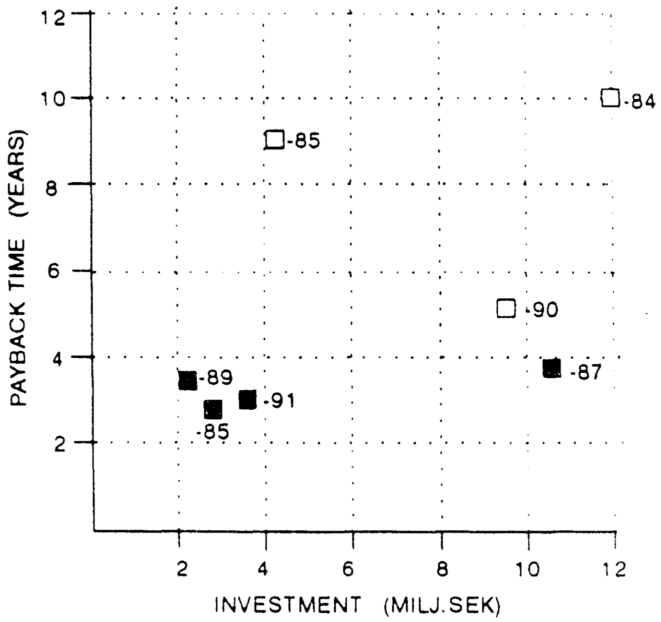

Figure 7 Calculated pay-back for combined cooling and heating systems (filled squares) and systems for heating only (open squares) valid for the low-temperature ATES plants listed in Table 1. Numbers show the first operational year

ENVIRONMENTAL ASPECTS

From an environmental point of view, BFR has performed special studies for energy storage techniques in general (Svensson 1990). Sweden has also participated in such studies within the frame of the International Energy Agency (IEA) cooperation (Greulich 1988).

It can be stated that the main environmental impact is a local temperature change within the aquifer and its close surroundings. How important this disturbance is depends primarily on the storage temperature level, and other interests at the ATES site.

At low-temperature ATES systems in Sweden no negative effects have been reported. However, apart from a thermal impact, there are numerous potential risks (Svensson 1990), e.g.

- leakage of toxic substances like brine, glycol etc
- leakage of heavy metals from tubings and fittings
- emission of CFC gases
- change of water composition in the aquifer due to temperature changes or chemical treatment
- noise and dust during construction

The environmental benefits have not yet been studied in general terms. However, most of the projects listed in Table 1 are to some extent motivated by positive environmental effects. For instance, cold storage applications will decrease the use of CFC refridgerents by replacing conventional chillers. In at least one case a reduction of noise and a better internal environment have been motives for ATES cold store installation.

The most important benefit is the energy conservation that ATES systems provide. Reduction in fossil fuel use and a more effective use of electricity will combine to decrease the emission of carbon dioxide, sulphur, and nitrogen. Hence, ATES is looked upon as an environmentally favorable concept.

CONCLUDING REMARKS

The low-temperature ATES application is one of the most competitive storage systems in Sweden. Research and monitoring aspects of most Swedish ATES systems have been financially supported by BFR. In later years, it has become evident that systems with both cooling and heating capabilities are the most favorable from an economic point of view. Experience shows that the pay-back time for those systems is short enough to make these systems commercially viable. So far the installations have only been made in commercial buildings. However, use of these systems in industrial and residential application is expected in the near future.

Large heat stores connected to district heating systems is another application that looks promising. So far only low-temperature applications with heat pumps have been successfully tested.

For high-temperature applications an experimental plant has been the first step that might develop into at least one full-scale demonstration plant.

Several problems have been identified as development of low-temperature ATES systems has progressed. In most cases solutions have been found and knowledge from the mistakes has been gained. This is indicated by an increase in performance with operational time in most of the existing plants and a reduced specific investment cost for newly built ones.

Remaining problems, not yet completely solved, are

- controlling and operational strategy
- clogging of wells due to precipitates
- long adjustment time due to system complexity and inexperienced management.

Finally it can be stated that in general terms ATES systems would be of benefit for the regional and global environment considering its potential for energy conservation. This would result in less emissions of harmfull gasses like CO_2, SO_x and NO_x. So far BFR has not ascribed an economic value to the environmental benefits. However, this is one item that is planned to be studied and that would be helpfull in bringing the ATES technique to the commercial market.

REFERENCES

Andersson, O., 1992: The development of well efficiency at Lomma ATES plant during the first years of operation. Swedish Council for Building Research, Malmö, Sweden.

Banck, A., 1989: Lomma Pilot ATES Plant. Experiences and results. Lund. Inst. of Techn. Dept. Engineering Geology. LUTVDG (TVTG-3023)/1-81/1989, Lund, Sweden.

BFR, 1990: Thermal Energi Storage - Basis for Research Program 1990-1993. Swedish Council for Building Research, Stockholm, Sweden, G13:1990 (in Swedish).

Emmelin, A., Hydén, H. and Lemmeke, L., 1983: Storage of warm surface water in a sand aquifer for usage in the Klippan district heating system - System design. Swedish Council for Building Research, Stockholm, Sweden, R146:1983 (in Swedish).

Greulich, R.H., 1988: Progress in the development of new treatment methods related to ground water storage. Proc. JIGASTOCK 88, Versailles 1988, Paris, France.

Gustafson, G., Ryttar, P-A. and Norbäck, K., Energy Storage through infiltration of surface water. Swedish Council for Building Research, Stockholm, Sweden, R30:1989 (in Swedish).

Johansson, S., SAS Frösundavik, 1992: - An Office heated and cooled by Groundwater. Swedish Council for Building Research, Stockholm, Sweden, D5:1992.

Kronqvist, L., 1991: Energy storage in aquifers - Evaluation of Kristianstad. Swedish Council for Building Research, Stockholm, Sweden, R40:1991 (in Swedish).

Landberg, J., 1991: The Triangle Project in Malmoe. Thermastock '91, 5th Intern. Conf. on Thermal Energy Storage. Novem, Utrecht, The Netherlands.

Rijpma, P. and Andersson, O., 1992: The "Sparven" ATES Plant. Visitor information brochure. Telaris, Malmö, 9204.

Svensson, T., (ed.) 1990: Environmental consequences of using new energy techniques. Swedish Council for Building Research., Stockholm, Sweden, T21:1990 (in Swedish).

Aquifer Cold Storage in The Netherlands: State-of-the-Art, Market Potential, and Future Development

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ABSTRACT

This paper deals with aquifer thermal energy storage (ATES) in the Netherlands. Mainly cold storage is discussed as well as low temperature (< 30°C) heat storage , however only in combination with cold storage. There is an increasing interest in the Netherlands in ATES, not only because the geological conditions are most favorable, but also because of the simplicity and cost-effectiveness of the system. Most of the projects involve institutional and commercial buildings, but the interest in using cold storage for industrial process cooling is increasing rapidly. In this paper, the system concepts and major obstacles to implementation of ATES are described. Furthermore, the market potential is mentioned and the importance of energy storage for future energy supply systems is stressed.

STATE-OF-THE-ART

From a geological point of view, the Netherlands is favorable for ATES. There are aquifers available almost all over the country within an acceptable depth (50-250 m). An active R&D programme on energy storage and a deliberate marketing policy result in the increasing interest in this technology. Figure 1 shows an overview of ongoing ATES projects throughout the country. Of these projects five have been realized, three heat storage projects and two cold storage projects. The other projects are cold storage projects either in preparation or under construction.

SOME EXAMPLES OF ATES

Three typical examples of ATES are cold storage in an office building, air-conditioning of a hospital, and process-cooling for industry. These three examples will be reviewed shortly.

One of the projects under construction is the expansion of an IBM-office building in Zoetermeer. This office is connected to an ATES system that uses two warm wells and two cold wells. The aquifer is 9.40 m below ground level and the maximum aquifer water flow is 100 m^3/h. In this building the old chillers with a total capacity of 1400 kW will be replaced by an aquifer system and a new chiller (225 kW). This new chiller is installed to provide cooling for the computer rooms, which need a lower air temperature than the aquifer can deliver. In the new configuration the stored water will be chilled in wintertime by two new cooling-towers.

Some technical data for the IBM project are:

Storage temperature (°C)	3-5
Production temperature (°C)	max. 7.5
Total cooling/heating capacity (kW_{th})	950
Total cooling/heating requirement (MWh_{th})	1200
Storage cooling/heating capacity (kW_{th})	1050
Amount of seasonal energy stored per cycle (MWh_{th})	1700

The annual energy savings in the IBM building are 440,380 kWh_e. The extra investment costs are Dfl. 780,000,- and the pay-back period is 5.3 years.

A second project involves the seasonal heating and cooling of the Bleuland Hospital in Gouda. The present cooling capacity amounts to 600 kW and is delivered by two chillers. This capacity has to be extended up to a total of 1100 kW. The extra capacity will be delivered by an ATES system, using a doublet configuration at a depth of 75-90 m below ground level. The maximum groundwater flow is 60 m^3/h. The cold for cooling the warm well is extracted from the ventilation system supply

Aquifer Thermal Energy Storage Projects in the Netherlands

State of the art 04-01-92

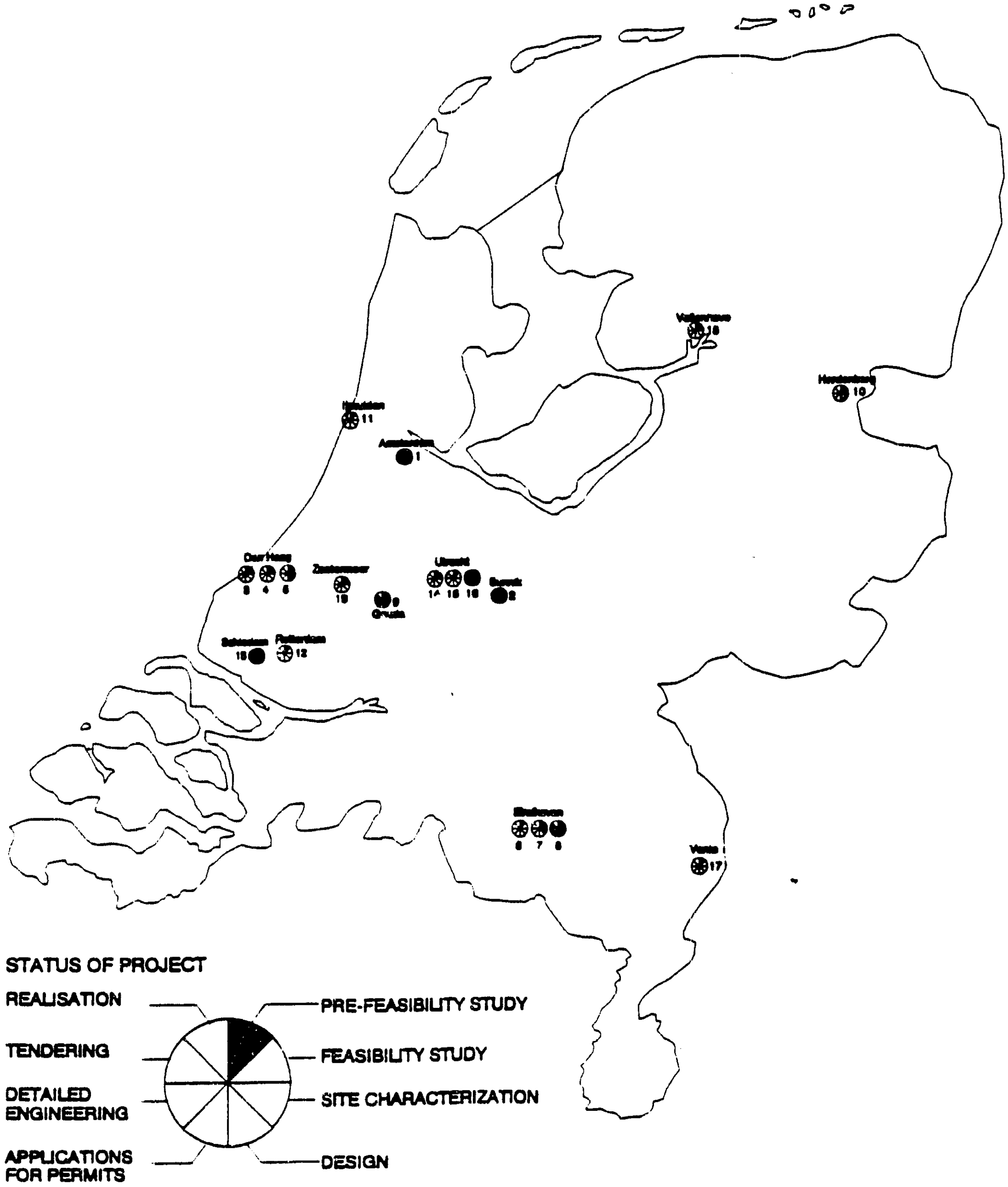

Figure 1

Location and status of projects

project no.	city	name of project	status
1	Amsterdam	Perscombinatie	realized
2	Bunnik	BAM-office	in preparation
3	Den Haag	AEGON	in preparation
4	Den Haag	AEGON	in preparation
5	Den Haag	Stadhuis	in preparation
6	Eindhoven	RABO	in preparation
7	Eindhoven	Univ. of Technology	in preparation
8	Eindhoven	Heuvel galerie	in preparation
9	Gouda	Bleuland Hospital	in preparation
10	Hardenberg	Wavin	in preparation
11	IJmuiden	Hoogovens	in preparation
12	Rotterdam	Erasmus University	in preparation
13	Schiedam	Kantorenhuis	realized
14	Utrecht	IBM hoofdkantoor	in preparation
15	Utrecht	Jaarbeurs	in preparation
16	Utrecht	R.U.	realized
17	Venlo	Andeno (industry)	in preparation
18	Vollenhoven (Ov.)	Coberco	in preparation
19	Zoetermeer	IBM-office	in preparation

air. The ventilation supply air is heated up to 10 to 14°C, depending on the outdoor temperature. In this way the aquifer is used for heating and cooling.

The aquifer is also used for short term cold storage during extremely warm periods or at the end of the summer season, when the cold well temperature is relatively high. The cold is generated by the chillers that run at low cost during the night.

Some technical data are:

	cold storage	heat storage
Storage temperature (°C)	8	17.5
Production temperature (°C)	8-12	14-17.5
Total cooling/heating capacity (kW_{th})	1100	
Total cooling/heating requirement (MWh_{th})	480	
Storage cooling/heating capacity (kW_{th})	800	700
Amount of energy stored (MWh_{th})	550	310

The annual energy savings in the Bleuland hospital amounts to 98,000 kWh_e and 81,000 m^3 of natural gas. The extra investment costs are Dfl. 334,000.-, which means that the pay-back-period is 4.3 years.

The third project involves seasonal industrial cooling. WAVIN at Hardenberg is a huge manufacturer of plastic tubes, crates and building material. Until recently, groundwater was used for process cooling and discharged afterwards to surface water. Because of the high quality of the groundwater, which can be used also for the production of drinking water, the Dutch government has recently legally forbidden the use of this groundwater for cooling only, because of the high quality of the groundwater, which can be used for drinking water. The alternatives for WAVIN are either the installation of chillers or the installation of an aquifer cold storage system, using groundwater but not wasting it.

Some technical data are

	Cold storage	Heat storage
Storage temperature (°C)	7	15
Production temperature (°C)	11	
Total cooling/heating capacity (kW_{th})	2600	
Storage cooling/heating capacity (kW_{th})	2600	

The total cooling demand is 2.6 MW_{th}. If an aquifer cold storage system is installed, there are seven injection wells and seven extraction wells. Each well would have a maximum capacity of 80 m^3/h. The necessary cold is obtained by cooling the hot well in wintertime using surface water. The investment costs for the aquifer system is less than the investment costs for conventional chillers. Furthermore the energy saving for this system would be 1600 MWh_e each year.

GENERAL SYSTEM CONCEPTS FOR SEASONAL COLD STORAGE IN BUILDINGS

Most existing system concepts apply to cooling systems for commercial and institutional buildings. A general approach for the application of seasonal cold storage in the industrial sector can not be defined because of the small number of projects in this sector until now.

The system concepts can be distinguished by the way the chilled water for loading the storage is obtained and the way the total cooling demand of the project is covered. This subdivision of the projects, together with the basic schemes, is shown in Figure 2.

It should be noted that many refinements to the basic schemes are possible, depending on the specific project characteristics, for example,

- new building, extension or retrofit,
- cold demand in summer only or also in winter,
- comfort requirements and back-up systems for cooling.

The concepts shown in Figure 2 will be briefly discussed below.

SYSTEM 1a and 1b - This system applies to projects in which cooling is required for space cooling only. Thus, the cooling demand only occurs in the summer season. All the necessary cooling is supplied to the building by cooling the ventilation air in the air conditioning units ("all air systems"). The cold can be completely delivered by the cold storage system (system 1a) or in combination with one or more chillers (system 1b). The storage is loaded during the winter season with the "cooling" coils in the air conditioning units. These coils then function as conventional (pre)heating coils. When the outdoor temperature is low enough, the warm well water is cooled to the required storage temperature, while the ventilation air is (pre)heated. In this concept the long-term storage system functions as a combined heat and cold storage system. The advantage of this system is that separate chillers do not have to be installed to load the storage. On the other hand, the choice of the temperature levels and the siting of the components require extra attention to obtain a good balance between charging and discharging of the storage. Therefore, this system concept is especially suitable for new construction (building) projects.

SYSTEM 2a and 2b - In this system, the building

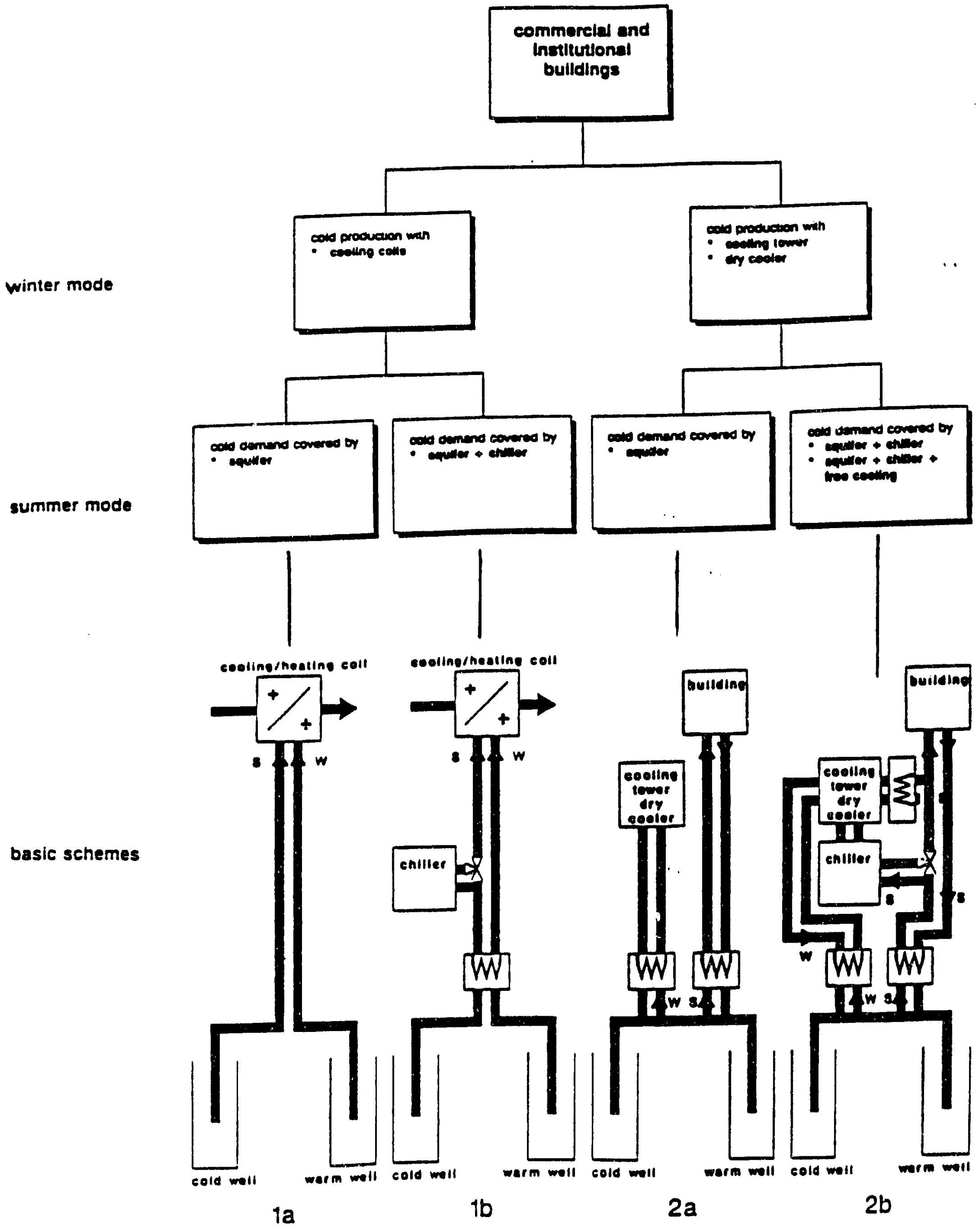

Figure 2 System concepts of aquifer cold storage in the Netherlands.

installation can be considered a black box. Only the maximum cooling load, the demand pattern, the cooled-water flow, and the temperature range have to be known. The stored cold is used for comfort cooling and sometimes to cool equipment (e.g. computer installations). In the latter case, it is common to use free cooling when the outdoor temperature is low enough.

In some projects the cold storage system is combined with one or more chillers, which can be used for additional cooling under extreme conditions. The risk of a cold shortage is reduced in this way. This option is most favorable if extension or retrofit of an existing installation with chillers is planned. If a new chiller has to be installed for additional cooling only, the feasibility of the project will be reduced by the extra investment cost. The need for an extra chiller for additional cooling (as a back-up) also depends on the comfort requirements in the building.

The cold storage is loaded in winter by cooling the warm well water in cooling towers or dry coolers. If cooling is also needed in the building during winter, it is usually possible to apply free cooling and to charge the storage via the same coolers.

MARKET POTENTIAL FOR COLD STORAGE IN THE NETHERLANDS

Potential market sectors for cold storage applications are:

- Commercial and institutional buildings (space cooling)
- Industry (process cooling)
- Greenhouses (space cooling)
- Integrated system

COMMERCIAL AND INSTITUTIONAL BUILDINGS

This market sector refers to government buildings and service industries such as hospitals and business offices.

The potential market is defined as buildings with a floor area greater than 5000 m^2 (new buildings) or 10,000 m^2 (retrofit), > 300 kW cooling power and > 300 MWh cooling demand. In The Netherlands, cold storage is assumed to be (in general) economically feasible for buildings that meet these criteria.

The estimated (gross) market potential for cold storage is about 40 projects per year, from which about 25 projects are newly built offices. The aim is to reach a market penetration of 20% by 1995 (8 projects/year) and 50% by 2000 (20 projects/year).

INDUSTRY

This market sector is defined as the processing industry with present or potential use of groundwater for process cooling, for example the food industry, chemical industry (plastics), paper industry.

The potential market is about 300 industries that presently use groundwater above 50,000 m^3/year and another 300 industries that currently use mechanical cooling.

The total of 600 industries results in an annual gross potential market for cold storage of about 20 projects/year. The aim is to reach a penetration of 10% by 1995 (2 projects/year) and 25% by 2000 (5 projects/year).

GREENHOUSES

A new concept for greenhouse cooling is being developed. The basic idea is a closed greenhouse, with a high level of CO_2-fertilization and forced cooling. The market potential is high, but there are still uncertainties about greenhouse technology and pay-back periods.

INTEGRATED SYSTEMS

The long-term national policy is to reduce the use of fossil fuel energy sources and to limit the environmental effects of energy conversion. This can only be realized if all possible measures - seperate and integrated - are pursued including: physical planning, architecture, installations, unconventional energy sources and re-use of waste energy, i.d.

An example of a future integrated system is the energy-integration of residential and commercial buildings with a combined heating and cooling storage system. Cooling heat of offices and shopping centers can be re-used if (residential) buildings are well insulated, if low temperature space heating systems are being used, and if new technologies (solar energy, heat pumps, geothermal energy, co-generation) are properly tuned within an integrated system. Heat and cold storage is absolutely necessary to meet energy supply and demand. For the prementioned reasons, the main issue of the Netherlands R&D programme "Energy Storage 1990-1994" is to develop and to apply optimized short and long term storage techniques in integrated systems.

The market potential in the Netherlands is determined primarily by the favorable geological conditions. This is not the case for all countries. However, the possible application of ATES in different countries is still underestimated. In many countries, especially in the eastern part of Europe, with a continental climate, ATES is a possible and attractive way of saving energy.

MARKET BARRIERS

There are several barriers that can cause projects to be cancelled, or that may hinder the implementation of projects.

The main barrier is that consulting companies are often not familiar with the technology. The introduction of new technologies consulting companies implies a certain risk, especially the bigger consulting companies do not want to harm their reputation by getting involved in a bad project. So they do not take the risks that are inherent in new technologies. That means that, for the implementation of aquifer energy storage, one is dependent on smaller consulting companies with a limited share of the market. For the smaller companies, it is even a possibility to increase their reputation. These are important considerations because the construction of different projects, in which the new technology is proven, will increase the interest of bigger consultancies and subsequently the market potential.

Another barrier is caused by the consumer. Even if the eventual risks are well known and under control, the average consumer is afraid of new technologies. For the extension of the Amsterdam airport, aquifer cold storage appeared to be very cost-effective. Also the technical risks were well studied and financial consequences investigated. The aquifer storage system would be connected to the existing chillers, so that a back-up facility was available. Nevertheless, conventional chillers were installed instead of the much cheaper aquifer system because of consumer reluctance in relying on the new technology. It is very difficult to deal with this undefined fear for new technologies. Maybe more demonstration projects will encourage consumers to make use of aquifer cold storage.

Another major barrier is governmental policy with respect to licenses. To get a license takes at least 1 year and even then the restrictions could be unacceptable. Now that the implementation of aquifer cold storage is increasing in the Netherlands, the Dutch government is changing their policy. New laws with respect to limiting the use of groundwater clearly declare that energy storage is permitted. Local governmental authorities are even promoting the use of aquifers as storage medium because of their potential of replacing conventional chillers.

FUTURE DEVELOPMENTS

Future development of ATES is not a matter of solving technical problems. There are no unsolved technical problems if the storage temperature is restricted to less than 40°C. If the storage temperature is much higher, water treatment problems may occur. Below 40°C it is a matter of system integration, economy, environmental impact.

Implementation is the ultimate goal and for that reason even more important than the development. Nevertheless national R&D programs are very common and implementation programs are very rare. An implementation program should supply the answers to two questions: "How can one use the developed technology in practice?" (system intregration) and "How can one sell the developed technology?" (marketing). An implementation program in the Netherlands appears to be successful. Maybe this experience can be used in other countries as well.

System integration is very important. Adding aquifer seasonal storage to an existing conventional heating or cooling system is very seldom the most optimal approach and very seldom cost-effective. The storage component should be an integral and essential part of an optimized energy supply system. The importance of optimization was seen early in the Netherlands research program. During the first 3 years, when system optimization was not emphasized, about 90% of the ATES studies were cancelled. During the last 3 years, special attention has been given to system integration and, as a result, less than 40% of the ATES projects have been cancelled. System optimization means that one has to make choices. An ATES system with a 100% back-up facility is not cost-effective. It is either an aquifer system or a conventional system; there is no way in between. That does not mean that the risks are running out of control. Today an ATES supply system can be designed without any unacceptable risks or uncertainties. Risks can be quantitatively calculated very well and there are sufficient system design tools to decrease these risks to a normal level.

System optimization also means that the ATES supply system is a part of the total building concept or industrial process. Building design and the energy supply system are closely related. The possibilities of incorporating an ATES system should be taken into account during the building design. The comfort level of an ATES building need not be less than that of a conventional building. On the contrary, often an ATES system offers a better quality. For example, the total cooling load, and hence the ventilation rate, can increase substantially, without increasing the energy bill. Also in industrial processes the total cooling demand (quantity and temperature) should be considered carefully in relation to the most optimal ATES properties.

There is no general rule regarding how optimized ATES supply systems should look like. The basic system lay-outs used today were mentioned also, combining ATES with a heat pump can be very interesting if heating and cooling is desired. Also combinations can be made from the demand side, for example, waste heat from industries or from cooling equipment in office buildings can be used for residential heating. It is a future challenge to develop energy saving systems by optimizing the supply as well as the demand side. It is certain that optimization, as mentioned above, is very difficult (technical and organizational) but, if done properly, results in a tremendous energy saving.

Overview of Projects with Seasonal Storage for Cooling from Four Countries

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ABSTRACT

This paper presents the results from a review of projects, technologies and applications utilizing seasonal thermal energy storage (STES) primarily for cooling loads. The review covers four countries (Canada, Germany, The Netherlands, Sweden) participating in an IEA R&D collaborative work program. The characteristics of 55 projects are summarized. Projects included in the review include projects with feasibility study only, projects under preparation and completed projects (approximately equal in number in each category). Project load type, system configuration, storage type, size and cost are included. Experience and lessons learned are also summarized.

Assessments of the infrastructure in each country to design and implement such projects are given. Market development characteristics are reviewed in terms of legislation and regulations, and other barriers and drivers.

INTRODUCTION

Energy use for cooling, based primarily on electricity, is rapidly increasing in North America and in Europe. Especially important in both new and existing commercial buildings, cooling is increasingly needed because of heat generation from computers and other appliances. In addition, the emphasis on energy conservation in the past two decades has decreased air infiltration in buildings contributing to an increased requirement for cooling. Increasing awareness of the benefits from improved indoor air quality and occupant comfort also leads to increased demand for cooling.

Thermal storage systems for cooling applications, or for combined cooling and heating applications, can result in energy savings, cost savings and reduced adverse environmental impacts as compared to conventional energy systems.

The Executive Committee of the Energy Conservation through Energy Storage (ECES) Implementing Agreement of the International Energy Agency (IEA) established a collaborative R&D work program (called Annex 7) specifically targeted on thermal storage for cooling (Chant 1991). The primary objective of Annex 7 is to identify, analyze and document such systems and applications which maximize energy savings and environmental benefits from the application of STES for cooling. The ultimate purpose for the results of this work is to encourage the adoption of thermal storage of cooling as a standard design option.

Begun in 1990, this multi-year collaborative R&D work program undertook a review of the state-of-the-art of storage technologies and applications in the participating countries. The review included storage technologies for building and industrial applications, design models for application of these technologies, and methods of predicting subsoil characteristics. As well, national reviews (see list of references) were undertaken 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. This paper summarizes the results of these reviews.

SYSTEM CLASSIFICATION

Figure 1 shows the basic system classification structure developed for the Annex 7 work program. The emphasis in Annex 7 is on *seasonal* applications (that is, with at least three months of storage) which have a defined *charging cycle* for cooling, and which are cost-effective as compared with conventional system designs for the application.

OVERVIEW OF 55 PROJECTS

Data for 55 projects incorporating cooling for storage have been collected and reviewed. The data include actual measurements, as well as estimates from feasibility studies and detailed designs.

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 for each characteristic identified in Column 1.*

Application:	Cooling only	Heating and cooling
Storage technology:	Open (e.g. aquifer, ground source)	Closed (e.g. duct in water bearing soil or rock)
Cold source:	Air (winter cooling) or surface water	Heat pump or system heat exchanger
Load:	Building (residential or commercial)	Industrial process
Size of storage/load:	Storage meets entire load	Additional cooling required

Figure 1: System Classification

PROJECT ACTIVITY - There has been an increasing interest in seasonal cold storage projects in the last decade as illustrated in Figure 2. These projects have been primarily for commercial building applications (83%), while 13% have been for process cooling and 4% have been for residential applications. About one third of these projects have been with closed storage systems (most of which are in Germany).

SCALE OF PROJECTS - Figure 3 illustrates the range of size of projects both in terms of amount of cold energy that is stored per storage cycle and in terms of the cooling capacity of the storage. The size of the projects varies widely from over 10 MW capacity (20 000 MWh stored) to 10 kW (10 MWh stored) and even smaller. The median size is approximately 1 000 kW (1 500 MWh). (All units refer to thermal energy stored or thermal energy flows.)

INVESTMENT COST - Figure 4 plots the additional investment cost due to the storage against the storage cooling capacities. These costs represent a mix of estimates (from feasibilities studies of systems not yet built) and actual costs. There is a definite economy of scale evident in the investment cost relative to the storage cooling capacity. Depending on the inclusion or not of some projects with extreme values, analysis of the data shows that STES project costs vary from about C$400 per kW (for 50 kW systems) to about C$200 per kW (for 10 MW systems) more than conventional designs. Some STES designs cost less than conventional design.

EXPERIENCE

The merits of cold storage systems have been demonstrated in actual operation. Electrical energy consumption and peak demand, and thus energy costs, can be reduced with seasonal cold storage.

Experience gained from realized projects indicates:

- The complexity of the control systems that are required have presented problems in several instances.
- Some problems have surfaced with conventional sub-system components. Existing equipment must be in good working order and be compatible with the cold storage.
- Some aquifer systems have operated without major chemical problems; but high concentrations of dissolved gases such as methane have presented problems in some systems.
- The start up of cold storage projects should be scheduled such that enough cold can be stored before the first cooling season. The fall season appears to be the logical choice.

INDUSTRY INFRASTRUCTURE

The industrial infrastructure required for the implementation of cold storage projects is considered to be in place in all countries participating in Annex 7. In general, all the component expertise and equipment are available; but considerable improvement can be achieved in the integration of the components into an optimal cold storage installation. *Component* expertise and technologies — geological and hydrological site characterization, subsurface installation, and mechanical and control systems — are available. Specific consulting companies exist with experience in designing STES and ground storage systems for cooling applications. Improvement is needed and expected, however, in the design and integration of components and sub-systems comprising a cold storage installation, and in the integration with building energy systems.

REGULATORY ISSUES

The most prominent legal and regulatory issues that can potentially affect the implementation of STES systems are:

- Groundwater withdrawal and well drilling; and
- Reinjection of thermally (and potentially chemically) altered groundwater.

Legislation and regulation which apply to underground energy storage systems are generally the same laws which govern groundwater withdrawal and well drilling for drinking water and for industrial processes. Aquifer thermal energy storage (ATES) systems are addressed specifically in only a few instances. In Sweden, legal permission is required for groundwater energy systems greater than 10 MW, or ATES systems with storage capacities exceeding 3000 MWh/year. Closed systems have minimal regulatory concerns, except in Germany where the same regulations apply.

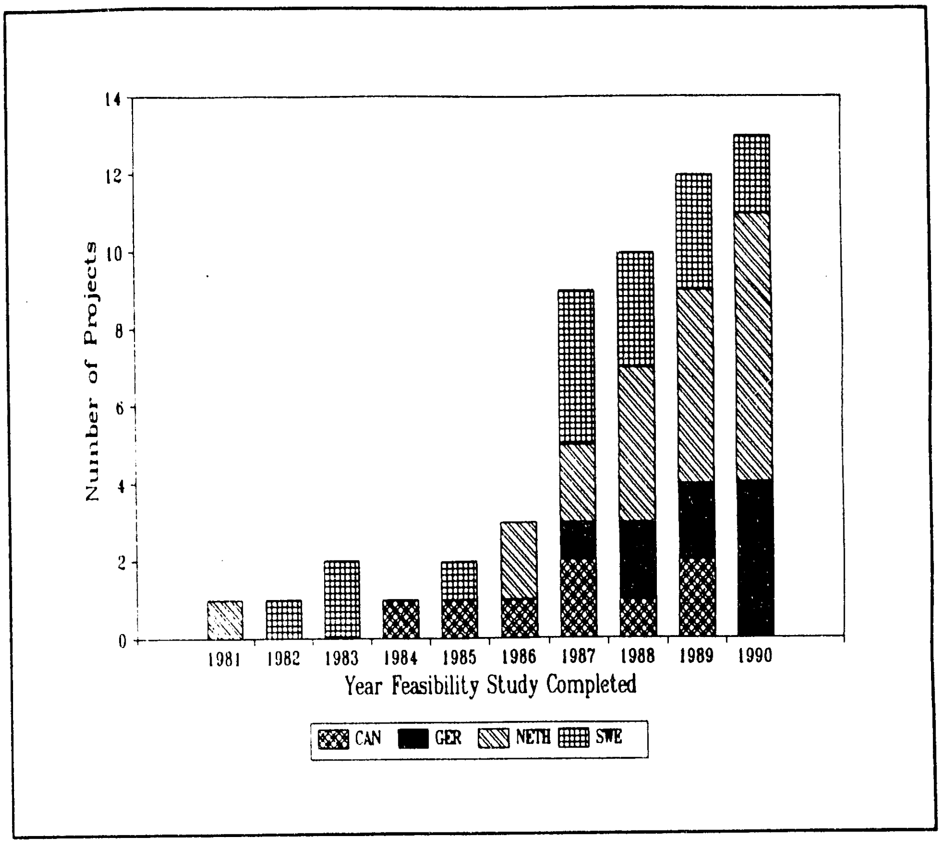

Figure 2: Number of Projects by Year

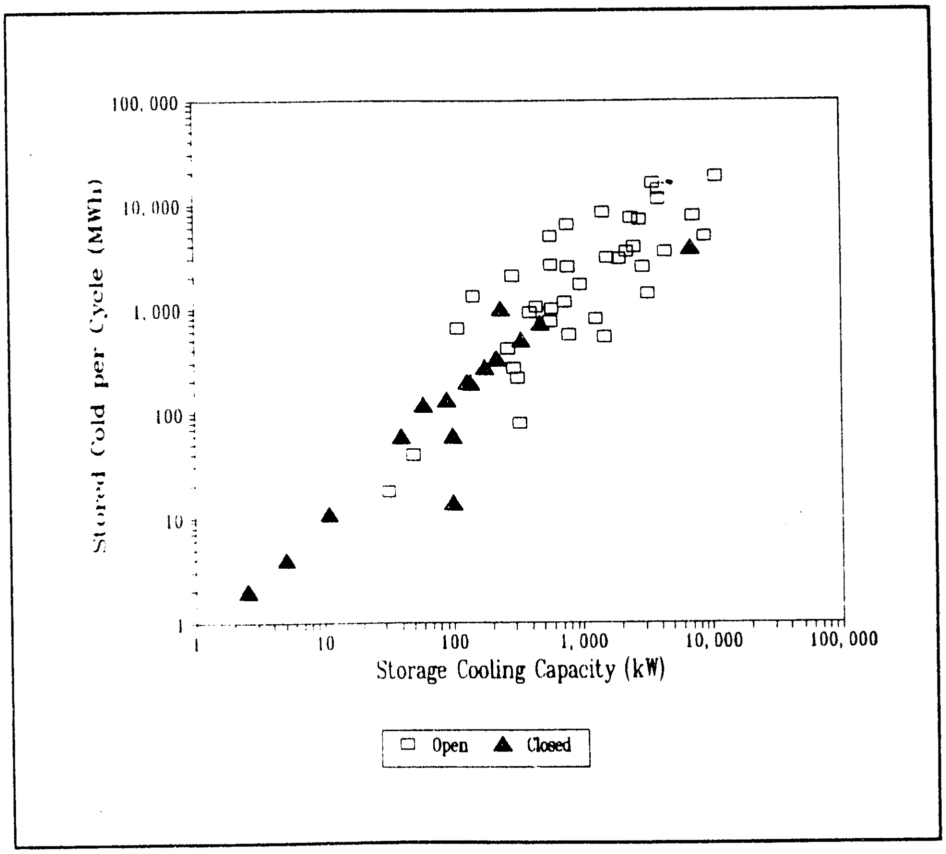

Figure 3: Storage Cooling Capacity by Stored Cold per Cycle

In all countries, the relevant legislation involves two to three levels of governments: federal or national, state or provincial, and local or municipal.

The discharge of groundwater to the surface, and the thermal quality of the returned groundwater, will likely be more rigorously regulated in the future. The complete return of the supply well volume via a return well is already required or strongly recommended in some cases. The installation of seasonal cold storage has the additional advantage of mitigating the warming effects that these industrial cooling processes have on groundwater.

The development of more stringent regulations with respect to the return of groundwater may support cold storage development, particularly in the industrial sector. In many industrial applications, groundwater is simply used for process cooling and then discharged to the surface. The temperature of the water may be changed more than 20°C by the industrial process. The environmental importance of preserving groundwater is increasingly recognized.

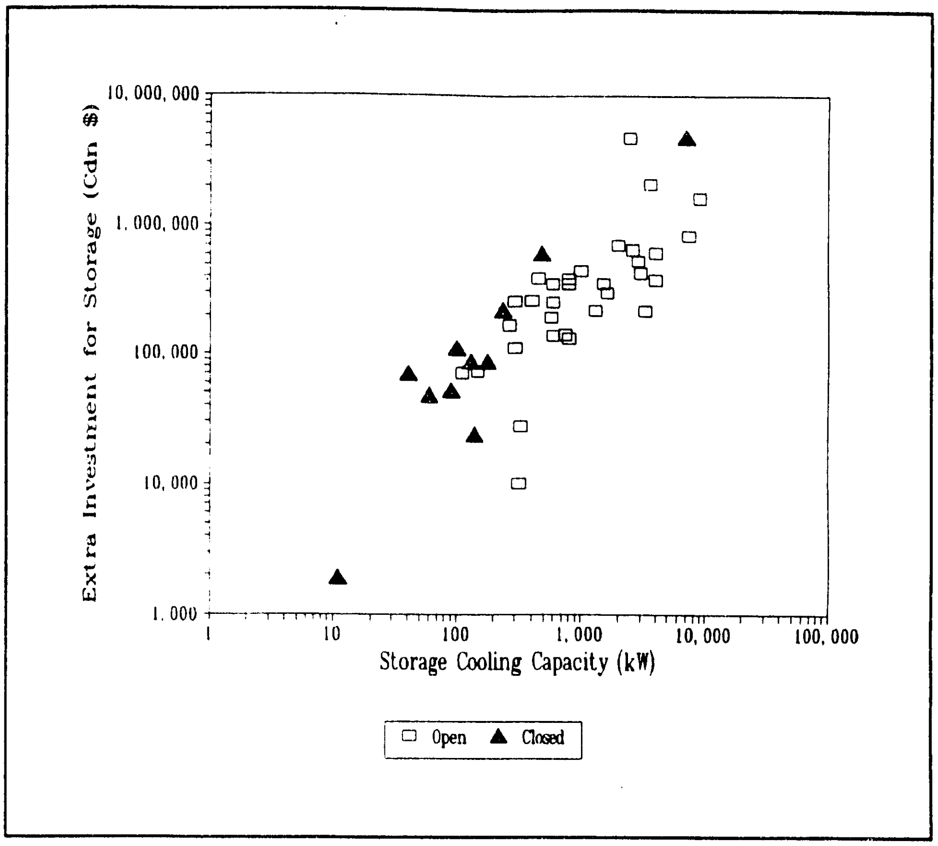

Figure 4: Extra Investment for Storage (Cdn$) by Storage Cooling Capacity

MARKET DEVELOPMENT

The most attractive market sectors identified by the Annex participants are:

- Commercial and institutional buildings (space and equipment cooling);
- Industry (process cooling);
- Residential homes (space cooling); and
- Greenhouses (space cooling).

The commercial and the industrial markets are by far the most important, and they have the best technical and economic viability. Both residential homes and greenhouse applications are less attractive because of technical and economic factors.

Benefits of seasonal cold storage include:

- Energy savings and reduced energy costs through reductions in both energy consumption and in peak demand;
- Environmental benefits (displacement of conventional refrigerants and electricity); and
- Increased security of cooling where full-time cooling is required.

Other relevant factors are the positive public image of adopting an innovative system design which is environmentally friendly and reduced exposure to energy availability and price fluctuations. In some applications, however, the STES design is the least cost.

The most significant drawbacks and barriers to cold storage installations are:

- Higher capital costs with long payback period (most cases examined had payback periods of four to six years, about a quarter were longer than six years with another quarter with payback less than four years);
- Limited energy and energy cost savings, compared with total consumption for the building or process, limits the visible impact of energy savings;
- Increased complexity of design, installation, operation, and maintenance (in some cases); and
- Lack of user confidence in the reliability of cold storage technologies and users making decisions who are not very familiar with cold storage options (more education is required).

The commercial and institutional building market is generally identified as being the most penetrable for the next several years. Although industrial applications represent vast potential, they are viewed as less likely to be developed.

REFERENCES

Chant, V., Morofsky, E., **IEA, Energy Conservation Through Energy Storage, Annex 7 Innovative and Cost-Effective Seasonal Cold Storage Applications: Workplan,** Thermastock '91, Scheveningen, The Netherlands, May 13-16, 1991.

Chant, V., Lovatt, J., Morofsky, E., **Canada Centre Building, Scarborough - Five Year Energy Systems Performance Summary**, Thermastock '91, Scheveningen, The Netherlands, May 13-16, 1991.

Heidemij Adviesbureau, De Wit Adviesbureau, IF Technology, on behalf of: Netherlands Agency for Energy and the Environment (NOVEM), **Annex 7 Innovative and Cost-Effective Seasonal Cold Storage Applications, State-of-the-Art Review in THE NETHERLANDS**, March 1991.

Hickling Corporation, on behalf of: Public Works Canada, **Annex 7 Innovative and Cost-Effective Seasonal Cold Storage Applications, State-of-the-Art Reviews CANADA**, March 1992.

Hickling Corporation, on behalf of: Public Works Canada, **Annex 7 Innovative and Cost-Effective Seasonal Cold Storage Applications, Summary of National State of the Art Reviews - Final Report**, May 1992.

Institute of Applied Geosciences, University of Giessen, on behalf of: BEO, Forschungszentrum Jülich GmbH, **Annex 7 Innovative and Cost-Effective Cold Storage Applications, State-of-the-Art Review GERMANY**, March 1991.

Luleå University of Technology, Studsvik AB, on behalf of: The Swedish Council for Building Research (BFR), **Annex 7 Innovative and Cost-Effective Seasonal Cold Storage Applications, State-of-the-Art Review in SWEDEN**, October 1991.

Long-Term Performance of an Air-Conditioning System Based on Seasonal Aquifer Chill Energy Storage

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ABSTRACT

A nominal 520 kW (thermal) air-conditioning system based on the seasonal storage of cold water in an aquifer has cooled a University of Alabama building since 1983. During cold weather, ambient, 18° C water is pumped from warm supply wells, chilled to about 6° C in a cooling tower, and reinjected into separate cold storage wells. In warm weather, water is withdrawn from the cold wells and pumped through building heat exchangers for air conditioning. Presented here are results of 6 years of study [sponsored by the U.S. Department of Energy through Pacific Northwest Laboratory] of the first successful U.S. application of this technology. This system yields high energy efficiency, with measured annual average COP of about 5 (SEER = 17 Btu/Wh), and energy recovery efficiency ranging from 40 to 85%, shifts utility loads from summer to winter, and no chlorofluorocarbon (CFC) release.

INTRODUCTION

"Cool" or "chill" storage can be used in building cooling to store energy that is more available or less expensive at certain times for use during later periods when energy is more scarce or costly. Diurnal cool storage applications that use off-peak electricity to power mechanical refrigeration equipment and store cold water or ice are becoming quite popular. The electric utility industry is promoting this application of diurnal cool storage because it shifts demand from peak to off-peak periods. From the viewpoint of energy conservation, however, one disadvantage of diurnal cool storage is that electric energy use is usually increased because of losses inherent in any thermal storage and discharge process.

One alternative to the diurnal cool storage systems is seasonal chill Aquifer Thermal Energy Storage (ATES), the subject of this study. Aquifers are natural storage media and only means of access must be constructed, typically a system of wells. Aquifers have been used for diurnal, medium term and seasonal storage of both hot and cold water. A thorough discussion of aquifer thermal storage systems design issues is presented by Schaetzle et al. [1].

The focus here is the seasonal storage and recovery of water chilled by exposure to cold winter air. The primary design objective is to reduce energy costs by minimizing both demand (kW) charges and energy (kWh) charges. Electricity use is reduced, compared to conventional air conditioning with or without diurnal storage, because substantially less energy is required to chill water by exposure to cold ambient outdoor air than is needed to operate a vapor-compression or absorption-type mechanical chiller. Demand charges are reduced because the peak occurs during water chilling on cold winter nights, which typically are periods of low electricity usage in large buildings using fossil fuel heating in southern climates.

In addition to reduced energy and demand costs, chill-ATES-based air conditioning offers several other benefits. ATES system reliability during the air-conditioning season exceeds that of a conventional system because cold water typically can be recovered from several different wells, and the only component required to deliver cold water is a well pump. A conventional system often depends on a single chiller, several pumps, and a cooling tower with fan motors. The failure of a single component disables the entire air-conditioning system.

ATES-based air conditioning offers several major environmental benefits. The possibility of chlorinated fluorocarbon (CFC) release is eliminated because water is the only working fluid. CFC's are both greenhouse gases and are responsible for the chemical destruction of the stratospheric ozone layer. Increased efficiency reduces electricity use, which decreases fossil fuel combustion and its associated air pollution and greenhouse gas release. Southern utilities experience their peak power demands in the hot summer months and would benefit from the reduced peak capacity requirements as load is shifted from summer to winter. An additional benefit of the aquifer chill energy storage system is that the resulting low cost of air conditioning allows new applications, e.g., industrial building cooling.

Aquifers capable of being used for energy storage are available to about 75 percent of the population of the United States [1]. The earliest experimental studies of thermal energy storage in aquifers examined the storage of high temperature water [2,3]. A number of European countries, including Denmark, the Netherlands, Sweden and Switzerland have studied hot water aquifer thermal storage systems, often as sources for heat pumps. Most of the European aquifer storage systems have experienced water treatment problems such as scaling by calcium carbonate or silica [4]. The first test of the feasibility of chilling and storing cold water ("chill" storage) was conducted by Davison et al. [5].

Although chill ATES cooling systems have been used in several other countries, the system at the University of Alabama Student Recreation Center (UASRC) is the oldest operating U.S. installation. The UASRC system was designed and constructed in the early 1980's [6] and began operation in 1983. This paper reports the results of monitoring the performance of the UASRC chill ATES air-conditioning system for six full annual cycles.

SYSTEM DESCRIPTION AND OPERATION

The UASRC facility consists of 5760 m^2 (62,000 ft^2) of conditioned floor space, with 14 handball/racquetball courts, five basketball courts, a running track, a weight room, locker rooms, and offices. The estimated peak cooling load is 520 kW (148 tons) [7]. Using a chill-ATES-based system made air conditioning the gymnasium economically feasible.

The unconfined aquifer at the UASRC lies in an unconsolidated sedimentary layer consisting of alluvial deposits from the nearby Black Warrior River [8]. The aquifer layer lies 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 m is typically saturated with groundwater.

The ATES-based air-conditioning system, shown in Figure 1, consists of three main components: (1) heat rejection, provided by a conventional cooling tower; (2) seasonal chill storage, provided by the aquifer; and (3) heat absorption, provided by conventional cooling coils in the building air handlers. The aquifer system for the UASRC system uses six operating wells, three "warm" wells, numbered 1-3 in Figure 2, and three "cold" wells, numbered 4-6 in Figure 2. The bold rectangle in Figure 2 is the footprint of the UASRC building. The 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 PVC sand screen, are packed with gravel in the 10 m thick saturated zone, cased with solid PVC casing, and grouted with concrete to the surface. Each well contains a three-stage 7.5 kW submersible pump and return riser.

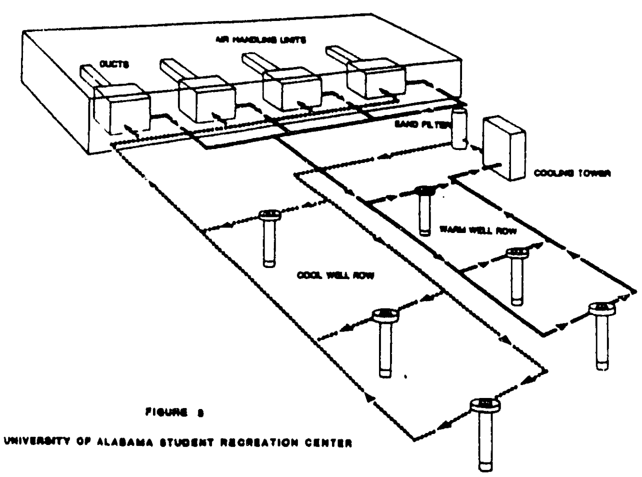

Figure 1. Chill ATES system schematic.

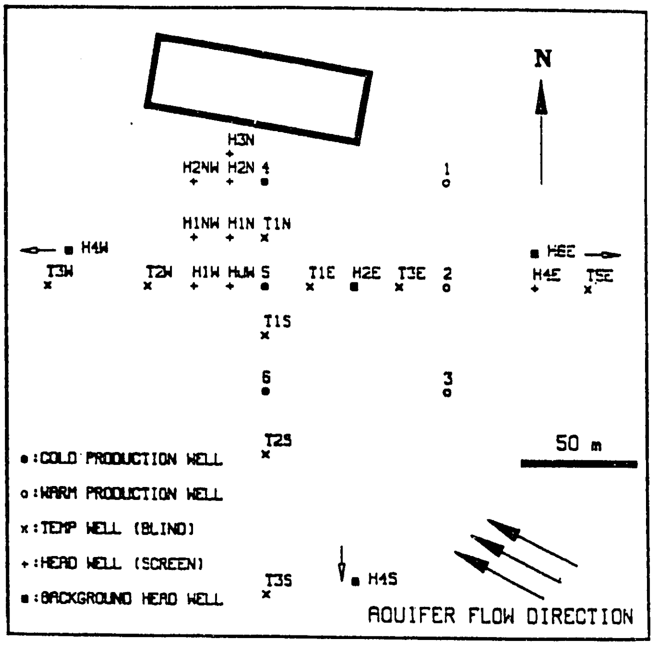

Figure 2. ATES system wellfield layout.

Water chilling is accomplished with a conventional mechanical-draft cooling tower having a nominal water flow capacity of 102 m^3/hr. The tower operates automatically whenever the ambient wet bulb temperature drops below about 6° C. Ambient ($\sim$18° C) aquifer water is pumped from the warm wells to the tower, chilled to below 7° C, and reinjected into the cold wells. In relatively warm weather, this injection temperature is achieved by water recirculation within the tower. For the Tuscaloosa area, there are typically 1200 to 1400 hours below 6° C wet-bulb temperature per year. The chilled water is injected into the cold wells after being passed through a sand filter to prevent aquifer contamination. Cooling tower operation is related only to weather conditions and is not matched to a corresponding cooling load. Chilled water is stored in the aquifer until required for air conditioning, which can be a few hours (a cold night followed by a warm day) to several months.

During hot weather, the cold well pumps withdraw chilled water on temperature demand. Water is pumped from the cold wells and absorbs heat from the air-handler units. The inlet chilled water temperature from the cold wells varies upward from a minimum of 7° C depending on how much water has been chilled the previous winter and how much has been recovered during the current air-conditioning season. The temperature of the warm water leaving the building is typically 14 to 17° C. Warm water exiting the building would ideally be returned to the warm wells, thus creating a system with no net water removal except for minor loss due to evaporation from the cooling tower during winter water chilling. In practice, however, it has been necessary to dump the warm water leaving the building to the storm sewer, and, in addition, to pump water upgradient from the cold storage zone of the aquifer (called back pumping), in order to minimize the loss of chilled water due to adverse regional aquifer water flow.

SYSTEM MONITORING

Data are collected on the performance of the heat rejection (cooling tower), storage (aquifer) and heat absorption (building cooling coils) elements of the chill ATES system. To evaluate the water chilling system, cooling tower inlet and outlet water temperatures, water flow rates and volumes, and power input are measured, as are power inputs to the warm water supply and reinjection pumps. The data acquired to physically define the aquifer performance consist of drilling samples from the monitoring wells, aquifer water head data to determine undisturbed water level and gradient, aquifer water temperature profiles, water flow injection and withdrawal rates and temperatures, and pump power input. Building inlet and outlet water temperatures and flow rates and power input for pumping water are measured to evaluate the building heat absorption system.

To evaluate and monitor the aquifer, 21 monitoring wells have been drilled, as shown in Figure 2. There are three background head monitoring wells far removed from the chill storage activity, three additional head monitoring wells in the operating well field, and fifteen temperature monitoring wells. Four head monitoring wells (H1W, H2E, H4E and H4S) and the temperature monitoring wells are instrumented with thermocouples at 3 m vertical intervals up from the Pottsville formation. The head monitoring wells use 5 cm PVC casing screened through the saturated zone. The temperature monitoring wells use 5 cm blind PVC casing. The monitoring wells are not ground packed.

RESULTS AND DISCUSSION

The chill ATES system, the sole source of air conditioning at the UASRC since 1983, has been monitored for six annual cycles [8-12]. An "annual cycle" is October 1 to September 30 of the following year, which approximately corresponds to an annual charge/discharge cycle.

WATER CHILLING PERFORMANCE - The monthly volumes of water chilled during the six-year period October 1, 1985 through September 30, 1991 are reported in Figure 3 as volume "injected". An operational problem in the 1987-88 water chilling season resulted in the loss of from 6000 m^3 to 15,000 m^3 of chilled water in early January, 1988. The data presented here do not reflect this chilled water loss. Figure 3 shows the relatively short cold season available at the site, with the bulk of the chilling occurring during December through February.

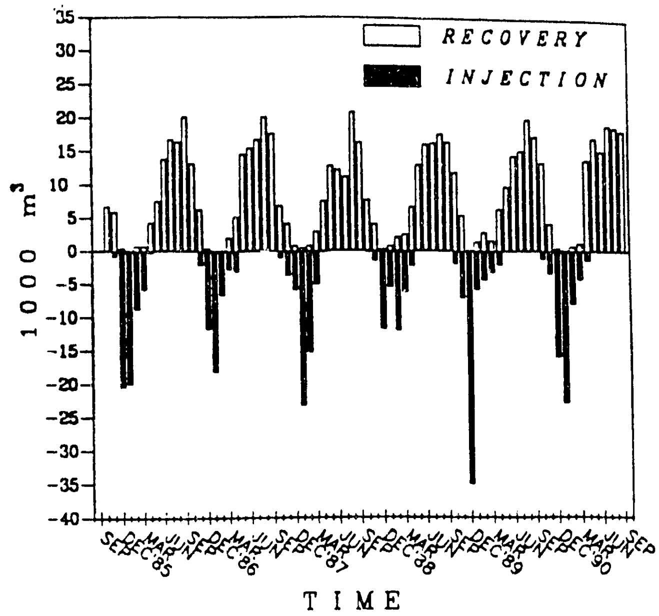

Figure 3. Monthly chilled water injection and recovery volumes.

Average cooling tower water inlet and outlet temperatures, reported as T_{in} and T_{out}, respectively, in the "INJ" (injected) column, and volume of chilled water injected, reported as "1000 m^3" in the "INJ" column, are presented on an annual basis in Table 1. Average annual chilled water injection temperatures vary only slightly from a mean of 5.9° C. Annual injected volumes vary considerably, reflecting large variations in weather conditions. 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. Table 1 also presents annual heat rejection data, reported as "Heat Rej" in the "INJ" column, for the cooling tower, which closely parallels the volume of chilled water injected. The annual electricity use for the cooling tower blower and for the hot well pumps is shown in Table 2.

BUILDING COOLING PERFORMANCE - The monthly volumes of cold water recovered for air conditioning are shown in Figure 3. Water is recovered for building cooling year-round, although little air conditioning occurs December through February. The ratio of volume recovered to volume injected ranges from 1.6 to 2.6, reflecting annual weather variations. This ratio is greater than unity because dispersion of chill energy into both the solid media and the ambient water of the aquifer formation necessitates that more water be withdrawn than was stored in order to recover a substantial fraction of the stored chill energy.

The annual air conditioning provided (heat removed from the building) is presented in Table 1 in the "Heat Rej" row and "REC" column. Air conditioning is calculated as proportional to the difference between the building inlet and outlet water temperatures. At those times when the building inlet water temperature is excessive, the warm water exit temperature, reported as T_{out} under the "REC" column, exceeds the 18° C ambient aquifer temperature.

Table 1 - Overall ATES System Performance Data

	1985-86		1986-87		1987-88		1988-89		1989-90		1990-91	
	INJ	REC	INJ	REC	INJ	REC	INJ	REC	INJ	REC	INJ	REC
1000 m^3	56.4	92.4	44.3	112	54.5	96.9	39.8	103	59.0	109	52.1	122
T_{in} (°C)	18.1	14.5	18.3	14.3	16.9	12.8	17.4	13.9	18.3	13.5	18.2	14.3
T_{out} (°C)	5.7	18.1	6.1	18.9	5.7	17.9	6.1	18.6	5.8	18.2	6.2	18.3
Heat Rej (TJ)	2.89	1.36	2.29	2.15	2.57	2.08	1.89	2.03	3.10	2.15	2.62	2.08
Chill Rec (TJ)		1.18		1.74		1.80		1.64		1.81		1.62
COP	4.1		5.4		4.6		4.9		4.4		4.6	
ERF (%)	40.6		76.0		70.2		36.9		58.6		62	
APF (%)	30.3		32.6		43.9		36.1		38.7		33.2	

Table 2 - ATES System Electricity Consumption

	1985-86	1986-87	1987-88	1988-89	1989-90	1990-91
Total MWh	91.9	111	125	116	135	125
Cold Wells	31.1 %	32.1 %	26.7 %	26.3 %	25.1 %	29.0 %
Hot Wells	11.1	11.7	12.2	8.9	10.9	12.9
Back Pump	0.0	4.6	14.6	22.7	27.5	24.2
Tower	57.8	51.6	46.5	42.1	36.5	33.9
	100 %	100 %	100 %	100 %	100 %	100 %

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 above the ambient aquifer temperature. Thus, "air conditioning" or "total heat rejection" is the sum of the "chill recovery" and the "free cooling."

The actual chill recovery is reported in Table 1. Chill recovery is proportional to either 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 lowest. Total building heat rejection always exceeds the chill recovery, and, in those years where the winter chill storage is small compared to the summer heating load, "free cooling" provides up to 20 percent of the total air conditioning.

The annual electricity usage for building cooling, which is the cold well plus back pumping energy use, is shown in Table 2. Back pumping has proven necessary to counteract the drift of cold water downgradient from the chill storage zone in the aquifer caused by background regional flow greatly exceeding design expectations. Energy use has increased as longer periods of back pumping have been employed. Back pumping lasted about five months the past two annual periods, accounting for nearly a quarter of the annual electricity usage. The effect of back pumping at the UASRC site is further assessed in References 12 and 13.

AQUIFER STORAGE PERFORMANCE - Water levels around the UASRC have been measured at the 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, are used to calculate the undisturbed aquifer hydraulic gradient at the site. The hydraulic gradient, which is proportional to flow velocity, is typically about 3-4 × 10^{-3} in magnitude. The average aquifer flow direction is indicated by arrows at the lower right of Figure 2. For the well field layout employed at the UASRC site, the warm and cold production well rows ideally should be located perpendicular to the aquifer flow.

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

$$V \approx K \cdot \nabla h/\phi \tag{1}$$

where V is the actual regional flow velocity, K is the average hydraulic conductivity, ϕ is the effective porosity, and ∇h is the hydraulic gradient. The hydraulic conductivity has been estimated from recent pumping tests as 25 m/day, and the effective porosity has been estimated as 16 percent at the UASRC site. Using a typical aquifer gradient magnitude of 3.5 × 10^{-3} in EQ (1), a regional flow velocity of about 0.55 m/day is obtained for the site.

The water velocity differs from the thermal front velocity, which is of primary interest for determining aquifer energy storage potential. 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 thermal front velocity, V_{th} can be estimated by [1]:

$$V_{th} \approx V \cdot \phi \rho_w c_w / [\phi \rho_w c_w + (1-\phi) \rho_r c_r] \tag{2}$$

where ρ is density, c is specific heat, and subscripts "w" and "r" refer to water and aquifer solids, respectively. As EQ (2) shows, it is always true that $V_{th} \leq V$. Using ϕ = 16 percent, ρ_r = 1770 kg/m^3, and c_r = 0.84 kJ/kg·K, the thermal front velocity is about 0.19 m/day at the UASRC site.

Only limited information was available prior to the drilling of the UASRC wells and not until after project completion was the existence of a large regional flow discovered. Excessive regional flow causes convection of stored chill energy beyond the potential recovery region surrounding the cold wells. The first measure taken to control the natural flow was to dump 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. Wells 2 or 3 have been used for back pumping because they are located directly upgradient 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 was back pumped in each of the summers of 1989 - 1991.

OVERALL PERFORMANCE - The performance of a chill-ATES-based air-conditioning system can be evaluated in several different ways. A common figure of merit for the gross thermal storage efficiency of the aquifer is the Energy Recovery Factor (ERF) [3], defined as the fraction of the chill energy stored that is recovered during building air conditioning over an annual period. Energy rejection from the building accomplished by heating the building water flow to temperatures exceeding the ambient aquifer water temperature is not included as recovered chill energy. Table 3 reports measurements of ERF ranging from 41 to 87 percent. Note that the recovery efficiency for the 10/87-9/88 period is significantly higher if the loss of chilled water that occurred during that winter is considered.

Table 3 - ATES System Performance Parameters

	1985-86	1986-87	1987-88	1988-89	1989-90	1990-91
%ERF	40.6	76.0	70.2	86.9	58.6	62.0
COP	4.1	5.4	4.6	4.9	4.4	4.6
%ASE	14.0	32.1	33.6	39.0	24.9	22.2
%APF	30.3	32.6	43.9	36.1	38.7	33.2
QI	1.8	2.1	2.8	2.2	2.3	1.9
WSI	0.77	2.37	1.44	2.77	1.28	1.85

The ERF is not an ideal measure of system effectiveness for two reasons. First, the ERF is strongly dependent upon annual weather conditions. Specifically, the water chilling capacity, or availability of cold weather, is unrelated to the air conditioning load, or amount of hot weather. The second weakness of ERF as a performance measure 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, so the ratio of recovered-to-injected cold water volume is large, and a high ERF results. In this situation, the building dehumidification is poor, more of the air conditioning is accomplished by "free cooling", and, although a large fraction of the stored chill energy is recovered, the quality of the building air conditioning is poor. Clearly, a performance parameter less influenced by weather variability is desirable.

From the air-conditioning viewpoint, the average system COP (similar to SEER), defined here as the ratio of air conditioning provided to the electrical energy input required to produce the air conditioning, is a common figure of merit. Comparing the annual air conditioning (Table 1) to the annual electricity use (Table 2), measured annual COP has averaged close to 5 (Table 3). This is approximately double the annual measured COP that is obtained from conventional mechanical air-conditioning equipment of this size. Consequently, the UASRC is being cooled with about one-half the electricity use of a conventionally-cooled building. Note that the COP and ERF have similar problems as measures of system performance. For a cold winter followed by a mild summer, e.g., considerable energy is expended in water chilling, but much of the cold water is not recovered. The ratio of air conditioning provided to electricity input (COP) is low even though building comfort is better than for the case of mild winter followed by hot summer, which results in a higher COP. Back pumping also reduces COP compared to a site with negligible regional flow. The 1989-90 annual COP of 4.4, e.g., could have been as high as 6.1 without back pumping, although building dehumidification would have suffered.

Another possible index of system performance is suggested by the methods of Second Law analysis. A parameter termed the Availability Storage Efficiency (ASE) can be defined as the ratio of availability recovered for air conditioning to the availability stored, calculated as:

$$ASE = \sum Q_r(1-T_{aq}/T_{bi})/\sum Q_s(1-T_{aq}/T_{te}) \quad (3)$$

where the indicated summations are over an annual period, and Q_r is the chill energy recovered, T_{aq} is the ambient aquifer temperature (which corresponds to the "dead state" temperature), T_{bi} is the building inlet water temperature, Q_s is the chill energy stored, and T_{te} is the chilled water injection temperature, all over a particular subperiod. EQ (3) was used with data for monthly subperiods and a value of T_{aq} = 18° C to calculate values of ASE for the six annual periods, as reported in Table 3. ASE varies considerably from year to year and, as will be demonstrated, also depends significantly on weather.

An alternative parameter for the evaluation of seasonal thermal storage system is the Aquifer Performance Factor (APF), which is defined as [13]:

$$APF = (T_{aq} - T_{bi})/(T_{aq} - T_{te}) \quad (4)$$

The APF does not depend directly on the relative quantities of energy stored and recovered but is indicative of the success of the system in recovering low temperature water. Recovery of low temperature water, as opposed to recovering large fractions of the chill energy, is critical to providing good building comfort and dehumidification.

Building comfort for a given cooling coil configuration is largely a function of entering water temperature. The coils at the UASRC should perform very well with 10° C water entering the building. A parameter termed the Quality Index (QI) can be defined as:

$$QI = (T_{be} - 10)/(T_{bi} - 10) \quad (5)$$

where temperatures are in ° C. Values of QI calculated using EQ (5) are presented in Table 3.

It is of interest to investigate the dependence on annual weather conditions of the various system performance parameters. To quantify the suitability of the annual weather for ATES system operation, a dimensionless Weather Severity Index is defined as the product of the ratio of water volume recovered to volume stored and the ratio of air conditioning provided to chill energy injected. Both of these ratios increase with increasing air-conditioning load and decreasing availability of cold weather for water chilling. The Weather Severity Index is small for annual weather conditions favorable to ease of operating the system— long, cold winters followed by short, mild summers— and WSI increases for less favorable annual weather. Figure 4 shows the annual values of ERF x 5, COP, ASE x 20, APF x 10, and QI x 2 plotted as functions of Weather Severity Index, where values have been scaled as indicated so that they are of approximately the same magnitude. Straight-line, least-squares best fits to the data for each performance parameter are also shown. ASE is most dependent on weather (highest slope), and ERF and COP depend on weather to a lesser degree. API and QI are virtually independent of weather. It should be noted that the Weather Severity Index for 1987-88 (WSI = 1.44) would increase in value if the previously mentioned loss of water were taken into account. This would shift the 1987-88 performance parameters toward increasing WSI.

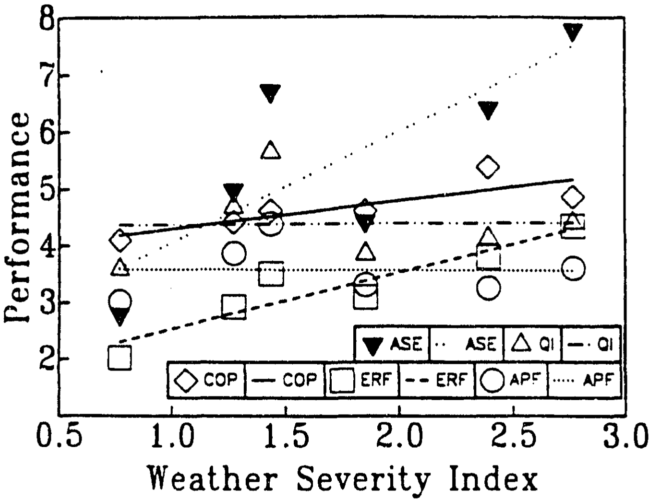

Figure 4. Weather dependence of ATES parameters.

CONCLUSIONS

A chill aquifer thermal energy storage based air-conditioning system has been installed and successfully operated to provide 100 percent of the building air conditioning at the University of Alabama Recreation Center. System monitoring indicates 41 to 87 percent of the stored chill energy is recovered for building cooling, but experience indicates that higher ERF does not necessarily yield better building comfort. Annual COP averages close to 5, about twice that for conventional mechanical air-conditioning equipment of the same capacity. The storage effectiveness of the UASRC ATES system has been improved by back pumping designed to reduce the loss of stored chilled water due to adverse aquifer flow, but at the cost of a reduced COP. Indicators of system performance that allow changes in operating strategies to be evaluated without interference of weather variation have been developed.

ACKNOWLEDGEMENT

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REFERENCES

1. Schaetzle, W. J., C. E. Brett, D. M. Grubbs and M. S. Seppanen, Thermal Energy Storage in Aquifers, Pergamon Press, New York, N.Y., 1980.
2. Henry, H. R., J. R. McDonald and R. M. Alverson, 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., 1971.
3. Molz, F. J., J. C. Warman and T. E. Jones, "Aquifer Storage of Heated Water 1: A Field Experiment," Ground Water, Vol. 16, pp. 234-241, 1978.
4. Kannberg, L. D., Field Experience with Aquifer Thermal Energy Storage, PNL-SA-15449 DE88-007075, Battelle Pacific Northwest Laboratory, Richland, Wash., 1987.
5. Davison, R. R., W. B. Harris and D. L. Reddell, "Texas A&M Cold Water Storage Project," NTIS, CONF-790328-P1, 1979.
6. Brett, C. E. and W. J. Schaetzle, "Experiences with Unconfined Aquifer Chilled Water Storage," ASHRAE Trans., Vol. 2B, pp. 169-181, 1964.
7. Schaetzle, W. J., C. E. Brett and L. H. Richey, "Experience with Two Free Cooling Systems Using Aquifer Thermal Energy Storage," Proc. of the Int'l. Conf. on Subsurface Heat Storage in Theory and Practice, Stockholm, June 6-8, 1983, Swedish Council for Building Research, Stockholm, Sweden, pp. 823-828, 1983.
8. Schaetzle, W. J. and C. E. Brett, The Aquifer Chill Storage Project at the University of Alabama, Tuscaloosa: Progress Report for 1985 and 1986, no. PNL-6797 UC-204, Pacific Northwest Lab., Richland, Wash., 1989.
9. Midkiff, K. C., C. E. Brett, Y. K. Song and W. J. Schaetzle, "Performance of a Chill ATES System," Proc. of the U. S. DOE Energy and Thermal Energy Storage Research Activities Review, New Orleans, La, March 15-17, 1989, no. CONF-890351, U. S. Department of Commerce, Springfield, Va., pp. 294-331, 1989.
10. Song, Y. K., K. C. Midkiff, W. J. Schaetzle and C. E. Brett, "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., 1989.
11. Song, Y. K., "Air-Conditioning Systems Based on Seasonal Aquifer Chill Energy Storage," Ph.D Dissertation, The University of Alabama, 1990.
12. Midkiff, K. C., Y. K. Song and C. E. Brett,"Thermal Performance and Challenges for a Seasonal Chill Energy Storage Based Air-Conditioning System, ASME Paper 91-HT-29, 1991.
13. Song, Y. K., K. C. Midkiff, W. J. Schaetzle and C. E. Brett, "Control of Aquifer Flow for Improved Aquifer Thermal Energy Storage System Performance," IECEC-89: Proc. of the Intersociety Energy Conversion Engineering Conf. in Washington D. C., August 6-11, 1989, IEEE, pp. 1833-1838, 1989.

Experience with a Solar Heating ATES System for a University Building

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ABSTRACT

At Stuttgart University, a solar heating system for an office building with laboratories and lecture rooms was installed in 1985. The heating system consists of 211 m^2 of unglazed solar collectors, a 1050 m^3 water-flooded pebble bed heat store, and a heat pump. This installation is a pilot facility and is included in the activities of the International Energy Agency (IEA). The experimental heat storage contains all heat exchanger systems that are used for ground stores: direct water exchange and a 4853 m long tube for heat exchange. Heat can be supplied to the store from the solar collectors or from a power station (as waste heat). The store and its behavicur are described. The whole system has worked successfully for 5 years under varied strategies.

In the first two heating periods, the heating strategy was aimed to collect as much solar energy as possible. Thus, about 60% of the heat demand could be covered by solar energy; but the yearly heat pump coefficient-of-performance (C.O.P.) was only around 2.76. With an improved heat pump, which was installed during the last 2 months of the second heating cycle, a monthly C.O.P of 3.6 was obtained. Heat losses from the storage amounted to about 20%.

INTRODUCTION

World-wide investigations are performed to learn about storing low-temperature heat in large and cheap storage installations. The price of the store is decisive, therefore all of its components and its construction have to be simple and cheap. There are a great many possibilities for storing heat /1/ and there are also discussions on the use of ground stores /2/. Especially in Sweden, large-scale thermal stores have been built and tested /3/. A thorough investigation of an artificial aquifer is given in /4/. Experience from investigations in many countries is accumulated in the IEA (International Energy Agency) Task VII/XV Program. The German contribution is our flooded pebble-bed store (artificial aquifer). This store has been in operation since December 1985.

THE ITW HEATING AND STORING SYSTEM

A schematic picture of the heating system is shown in Figure 1. The system consists of three main parts: unglazed collectors, a pebble-bed store, and a heat pump. The system is connected with the University cogeneration plant. From this plant, heat can be delivered to the store and directly to the Institute building. The building has a space of 1375 m^2 for offices and laboratories and a calculated heat demand of around 150 MWh/a.

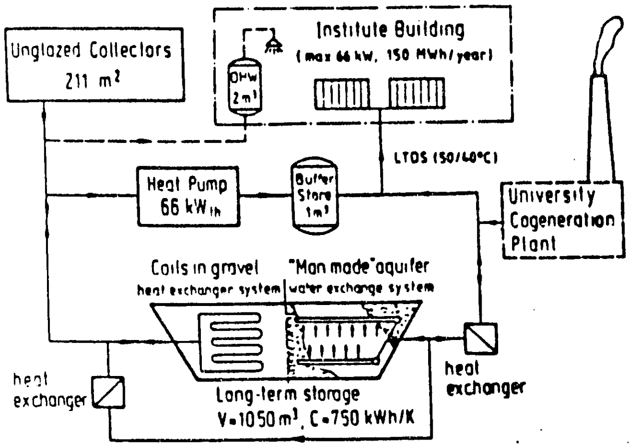

Figure 1: ITW Heating and Storing System

As heat sources we use

- heat from the cogeneration plant
- solar heat from the unglazed collectors.

The heating of the building can be performed

- from the cogeneration plant directly
- from the cogeneration plant indirectly, via the store
- from the unglazed collectors via the heat pump
- from the unglazed collectors via the store and the heat pump.

The store is shown in a cross-section in Figure 2. It has the shape of a truncated cone and is lined with a plastic (high-density polyethylene) foil, 2.5 mm thick. There is no thermal insulation on the bottom or the sides. Only on top, we put a 90 cm porous lava-layer and 60 cm of earth.

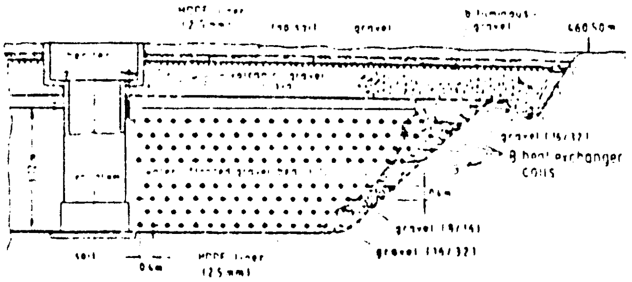

Figure 2: Heat exchanger system (coils)

This arrangement was chosen, because it is cheap and calculations had shown that losses into the surrounding ground can partially be regained. The store is filled with gravel of different size: larger pebbles of 16 to 32 mm diameter form the layers at bottom and top; smaller pebbles of 8 to 16 mm fill the section between these two layers. Thus, a higher hydraulic permeability and smaller flow resistance in the upper and lower layers with a more uniform flow distribution is provided.

The pebbles lie 4 m high, 3.72 m of these are flooded with water. The water portion is 37% or 354 m^3 of the water-filled store volume of 956 m^3. The entire store volume is 1050 m^3, its heat capacity is 750 kWh/K. The store is 5.75 m deep. The groundwater level is only 80 cm below the bottom and may rise after heavy rainfalls. The store provides three different possibilities for being charged and discharged with heat: two systems which allow for a direct exchange of warm or cold water and one heat-exchanger system with 4853 m of plastic coils. One direct water-exchange system is shown in Figure 3.

When the store is charged, warm water enters through the pipes on top and cold water leaves the store through the central header at the bottom. For discharging, the flow direction is reversed.

The heat-exchanger system is shown in Figure 2. Coils of polyethylene tubes (32/26 mm) are arranged in 8 different levels in the store. An antifreeze ethylene-glycol/water mixture flows through these tubes. The flow can be regulated separately for each coil.

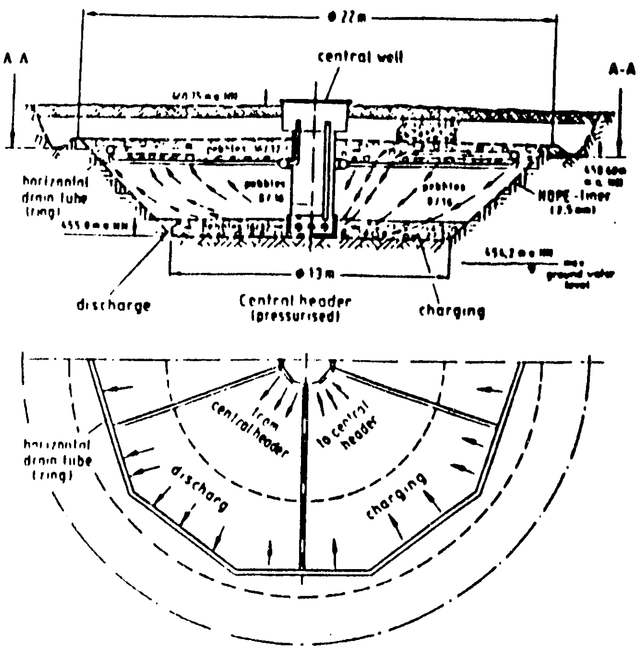

Figure 3: Direct water exchange "ring-system"

With this system the store can be charged in winter from the unglazed collectors and it can be discharged to temperatures below the freezing point of water.

The store was built as a full-scale experiment and is thoroughly monitored. For this purpose 415 thermocouples and 9 heat flowmeters were positioned in, around, and below the store. These probes were arranged in three planes in directions, 120° apart. The water level is controlled by a special well in the store; water probes can be drawn from the store, in order to control the growth of bacteria and possible chemical changes in the water.

HEATING OPERATION

SHORT-TERM TESTS - In two short-term cycles, the behaviour of the store with respect to times of loading and unloading, temperature distribution, and internal mixing was checked.

The store was first charged on Dec. 18, 1985 with heat from the University cogeneration plant. Warm water of 30°C and, finally, 40°C was pumped into the store through the top ring, while cold water was withdrawn at the bottom of the central well. The mass flow was 8000 kg/h. During the four days of charging, a distinct temperature stratification developed, Figure 4, with 36°C on top and 16°C at the bottom (curve 3).

This indicates high heat transfer coefficients to the pebbles: most of the heat is transferred immediately in the top part as indicated by the large temperature increase between curves 1 and 2.

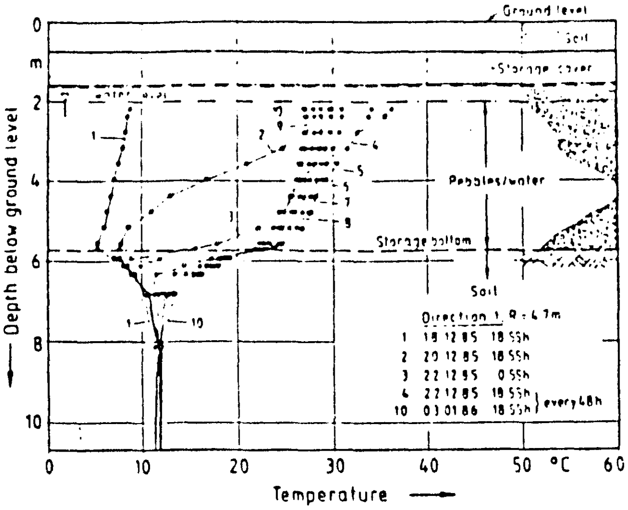

Figure 4: Short-term test: temperature distribution in the store during charging and standby

In the following two days (20.12. to 22.12.), the middle and lower parts of the store gained heat (curves 2 to 3). Altogether 20.4 MWh of heat was supplied to the store, 3.7 MWh of heat was lost to the surroundings. On Dec. 22, at noon, the heating was turned off and the water was circulated through the store until 18.55 h (curve 4), in order to equalize temperatures; a mean temperature of 29°C was reached.

Table 1: Data of Short-term tests

period	operation mode	heat source or sink	data
first cycle			
18.12. - 22.12.85	charging ring system	power station	Q_i = 20.4 MWh $Q_i - Q_l$ = 16.7 MWh $\dot{m}$ = 8000 kg/h ϑ_S = 30 °C
22.12.85 23.12.85	circulation		ϑ_S = 29 °C
23.12. 07.01.86	standby		ϑ_S = 24 °C
07.01. - 24.01.86	discharging heat exchanger	heat pump	Q_e = 5.5 MWh ϑ_S = (14 °C)
second cycle			
24.01. - 04.02.86	charging ring system	power station	Q_i = 34.7 MWh $Q_i - Q_l$ = 26.4 MWh $\dot{m}$ = 4 000 kg/h ϑ_S = (50 °C)
04.02. 13.02.86	discharging ring system	direct house-heating	Q_e = 5.5 MWh ϑ_S = 35 °C
13.02. 20.03.86	discharging ring system	heat pump	Q_e = 12 MWh ϑ_S = 16.5 °C
20.03. 18.04.86	standby		ϑ_S = 15 °C

Subsequently, the store was left alone for a period of 14 days. During this standby period, the temperature dropped by about 5 K. Then heat was extracted for 17 days by the heat exchanger coils via the heat pump and the temperature decreased to 14°C. The various data of this test and of the following one are listed in Table 1.

In the second cycle, the mass flow rate was reduced to 4000 kg/h, but the charging temperature was increased to about 55°C. The temperature distribution for the store and its surroundings is given in Figure 5a.

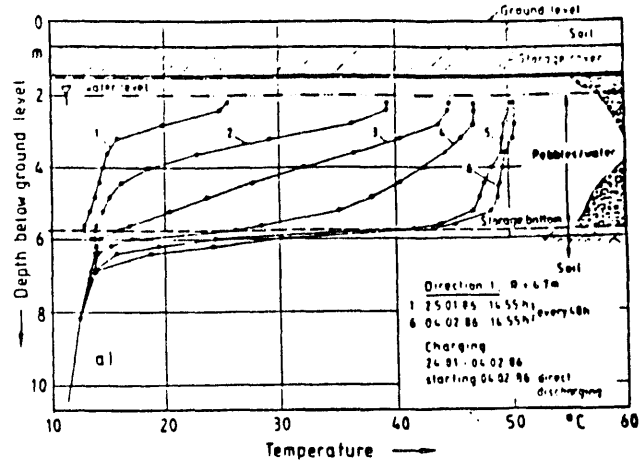

Figure 5a: Short-term test: Temperature distribution in the store during charging

Within 11 days, the store was charged to about 50°C quite evenly distributed (curve 6). Following the charging period, the store was discharged for direct heating of the building for 9 days. This period is shown in Figure 5b.

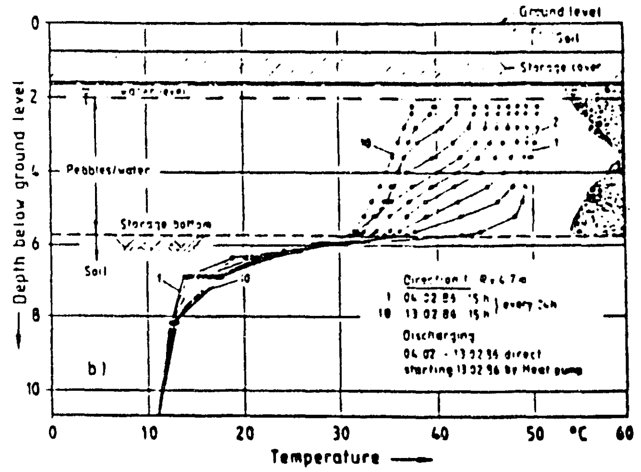

Figure 5b: Short-term test: Temperature distribution in the store during charging

About 5.5 MWh were drawn from the store and its temperature dropped to 35°C. A slight temperature stratification developed as warm water was taken from the top and cold water was fed at the bottom (curve 10). During this period, the ground about 1 m below the store was heated from 14°C to 18°C. Only 5 m below the store, no short-term temperature effects were observed.

In the subsequent discharging period via the heat pump, the stratification becomes more pronounced; this can be observed in Figure 6. The curve 1 gives the temperature distribution when the discharging was ended and a 29 days' standby period began. During this period, experience should be gained on the losses of the store from both internal heat exchange - due to internal convection and thermal conduction - and losses to the exterior. But also heat gains at the bottom of the store can be expected (curve 1 in the ground).

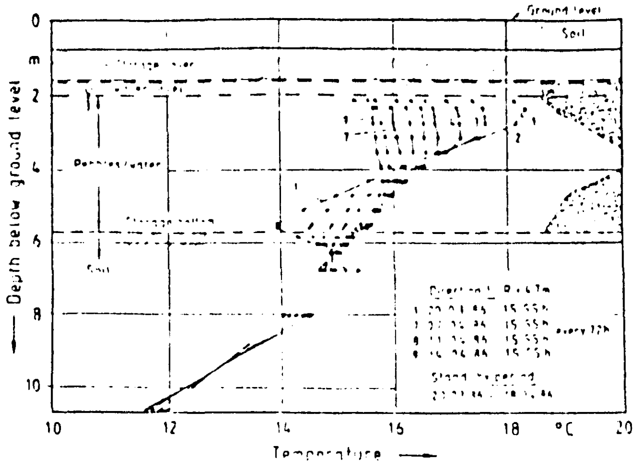

Figure 6: Short-term test: temperature distribution in the store during standby

At these comparatively low temperatures, it takes 25 days to equalize a temperature difference of about 4 K to 1 K throughout the store. The bottom temperature increased from 14 to 15.5°C due to heat gains.

Roughly estimating from Figure 6, there were only small losses to the exterior: the temperature decrease in the upper part of the store is compensated by a temperature increase in the lower part. But the value of the heat - its exergy - has altogether decreased, of course, with temperature changes of about 3/25 = 0.12 K/d, which is still quite small.

LONG-TERM TESTS - In such tests, the possibilities of seasonal heat storage for the solar-assisted heating of buildings was investigated. Detailed heat balances should relate the efficiency and the long-term behaviour of the store with its losses and gains; its impact on the surroundings and its water quality were to be studied.

Starting in April 1986, long-term tests were performed for the two consecutive heating seasons 1986/87 and 1987/88. The tests were performed in such a way that heat is collected from the unglazed collectors and either stored or delivered to the heat pump for house heating. Only when there is not enough heat from the collectors or the store, auxiliary heat is delivered from the cogeneration plant. The control strategy for the heating system is presented in Figure 7. When heating of the building was required at ambient temperatures ϑ_{amb} above -4°C, solar heat was directly supplied to the heat pump if the temperature of the unglazed collectors and their transfer liquid (an ethylene glycol/water mixture) was at least 7 K above the store temperature.

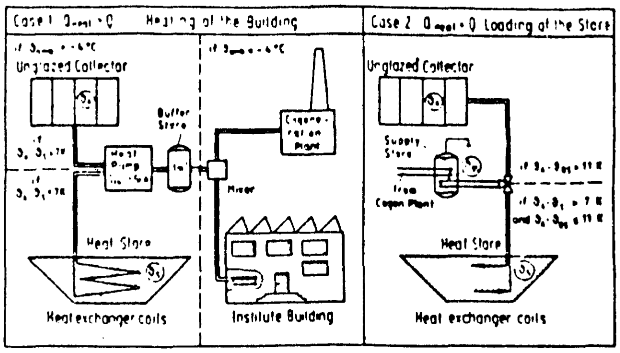

Figure 7: Control strategy for heating and storing

When this temperature difference was not reached, the heat pump obtained heat from the store. This was extracted by the heat exchanger coils so that, if necessary, freezing temperatures can be reached in the store. At low ambient temperatures (below -4°C), the heat pump was backed by the cogeneration plant. When no heating was required, in winter or summer, the solar heat was directed into the store if the temperature difference between the collector outlet and the store exceeded 7 K. This was done by patch-wise operation. It would have been possible to feed the warm water supply store, but the demand for this was small.

The results of the two heating seasons are compiled in an energy flow chart, in Figure 8.

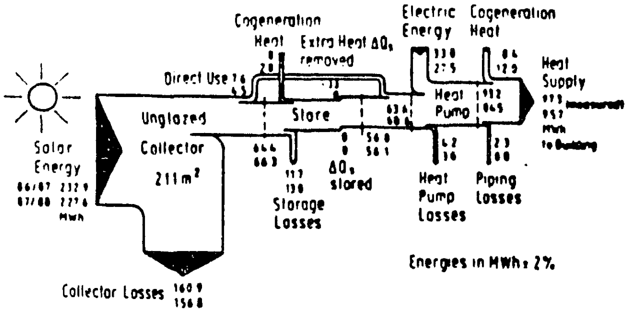

Figure 8: Energy flow chart for the heating system in the seasons 86/87 and 87/88

The solar irradiation of around 230 MWh/a agrees well with the rule of thumb of 1000 kWh/m^2 a for Central European countries. The useful gains, however, are relatively small with only about 340 kWh/m^2 a. But we used only the inexpensive unglazed collectors which cannot collect high-temperature heat, but they suffice in a combination with a heat pump.
The solar fraction f for 1986/87 is

$$f = \frac{\text{heat supplied by sun}}{\text{heat supplied to buildg.}} = \frac{63.6 - 3.3}{97.3} = 0.62$$

and 0.60 for the second cycle. This means that the heating system is 60% assisted by solar energy. Calculations show /5, 6/ that solar fractions between 50 and 60% can result in energy cost of about double the present ones.

The heat pump operation was not so satisfactory in 1986/87: The heat delivered was 93.2 MWh at an electric energy input of 33.8 MWh. Thus, the annual C.O.P. amounted to

$$\text{C.O.P. annual} = \frac{\text{heat output}}{\text{elect.en input}} = \frac{93.2}{33.8} = 2.76$$

The high electric energy input was caused by the heat pump evaporator which was not well adapted to temperatures of 15 to 30°C. These prevailed, when the warm fore-run ethylene glycol/water flow from the store was mixed with the cold return flow from the heat pump. A new heat pump was installed in February 1988 with an improved control of power and refrigerant superheating, and a larger evaporator. For the second heating season an improved C.O.P. of 3.1 was obtained. Most of the heat, which was delivered from the University cogeneration plant, was used to cover the extra heat demand after cold nights in the 86/87 season, when a room-temperature setback during night had been practised. In the 87/88 season most of the auxiliary heat of 12 MWh was used in February when the new heat pump was installed.

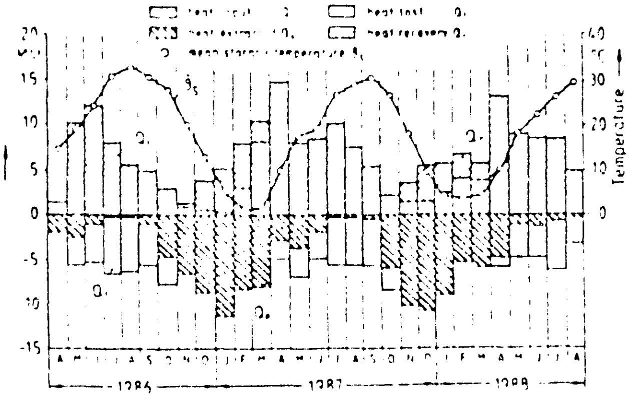

Figure 9: Heat balance and mean temperature of the store

The behaviour of the store and its interdependence with the collectors is presented in a compilation of the monthly heat balances of the store and its temperature in Figure 9.

The biggest heat inputs are found in the spring months when the storage temperatures are still low. In the summer months when the solar gains could be largest, comparatively little heat was stored, because the unglazed collectors were not able to provide heat at temperatures much above 30°C. An extra field of glazed collectors would improve this situation; there is roof space provided for such an extension. With high storage temperature, the heat losses became high in the summer months. A large proportion of these losses is, however, recovered during the winter months.

The fact that the store was only insulated on its top and not at the bottom and sides, caused an outflow of heat of about 40 % in summer, but with most of this heat being recovered in winter, there actually resulted an increase of storage capacity, or a larger store (see Table 2).

Table 2 Heat balance of the store in two heating seasons

in MWh	Heat input Q_{in}	Heat extracted Q_{ex}	Heat to Ground Q_G	Heat recovered Q_r	Heat lost Q_l	Difference in stored Heat ΔQ_s
1986/87	64.4	56.0	27.4	15.7	11.7	3.3
1987/88	69.1	56.1	27.4	14.4	13.0	0

		1986/87	1987/88
Storage Efficiency	$\eta_s = \frac{Q_{in} - Q_l}{Q_{in}}$	82 %	81 %
Capacity Factor	$\kappa_s = \frac{Q_{ex}}{(m\,c_p)_s\ \Delta T} = \frac{Q_{ex}}{750\ \Delta T}$	2.20	2.60
Recovery Factor	$r_s = \frac{Q_r}{Q_G}$	0.57	0.53

The effective storage efficiency was very high with more than 80%. The capacity factor κ_s indicates how often the heat storage capacity was actually utilized during a season. The thermal capacity for the water/pebble compound was calculated as 750 kWh/K. For κ_s in Table 2, a temperature difference of T = 31 K was taken under the assumption that the store could be cooled from its highest temperature to the freezing point. This does not account for the latent heat of formation of ice. Only a little ice was formed in February 87. The recovery factor r_s indicates to what percentage the lost heat could be recovered, it was more than 50% in both cases.

HEAT LOSSES AND TEMPERATURE IMPACT -The heat store affects the surrounding ground with its temperature fluctuations, since these are larger and reach deeper than the natural seasonal fluctuations coming from the ground surface. For an environmental impact (on flora and fauna), the layer 1 m below the surface is the most important. This layer will attain higher temperatures than by natural fluctuation in August, and these reach about 8 m beyond the store rim. In February, the ground temperature around the store 1 m below the surface correspond well with those by the natural impact, so that hibernating fauna should not be irritated too much. In greater depths or below the store, the imposed temperature fluctuations differ very much from the natural ones. Their effect on deep rooting plants should be observed on trees and bushes planted around the store. So far, no effect has been found.

WATER LOSSES AND WATER QUALITY - Within 3 years of operation, we encountered water losses of 13%. There is, of course, evaporation of water on the water surface within the pebble bed. The top surface area is 402 m^2 and if we assume - according to the volume share - an area share o 37% for water, the calculated evaporation rate would be 20 g/m^2h, which definitely appears to be too much. There may be some small leaks in the system. The quality of the storage water and its maintenance was considered a big problem when the store was planned. Luckily, after 6 years of operation, it turns out to be no problem, at all. The water has been regularly monitored for its chemical and biological quality. The evaporation residue has been increasing over the years as an indication that some material dissolves in the water. In the latest check it has decreased. The sulfate (SO_4) is also increasing, while carbonate (HCO_3) and calcium (Ca) remain about constant. The oxygen content of the water decreased rapidly within the first fifty days of operation and stabilized then at a low value of 0.5 mg/l. The existence of oxygen in the water prevents the formation of dangerous anaerobic bacteria and fouling processes. The silicon oxide, which endangers heat exchangers, increased slightly in the first year and decreased thereafter. The biological quality is characterized by the number of colony-forming units (bacteria). Their number has decreased rapidly within the first year and now seems to fluctuate around a low value of 2500 /ml. These fluctuations are likely to be coupled to the heating and cooling cycles; temperatures between 30 and 40°C provide best breeding conditions. The high initial number of bacteria was probably introduced with the pebbles. The water has not been treated, at all, while it is circulated by the various charging/discharging systems, and is in contact with the atmosphere by way of the drainage devices.

CONCLUSIONS

The heating system has worked very satisfactorily. Except for the exchange of the heat pump, there was no interruption or disturbance in the operation for two consecutive heating cycles. Collector size and storage capacity matched well with the heat demand. The addition of some glazed solar collectors to the field of unglazed collectors would bring higher temperatures in the store and thus, improve the solar fraction and the C.O.P. of the heat pump. The water-flooded pebble-bed store exhibited good internal heat-transfer qualities and low internal mixing during standby. All systems of loading or unloading (water exchange or heat exchange) worked properly. No chemical or biological deterioration occurred and no water treatment was necessary.

NOMENCLATURE

A	area	Greek symbols	
C.O.P.	coefficient of	η	efficiency
	performance	ϑ	temperature
c_p	specific heat	ϑ	mean temperature
	capacity	κ_S	capacity factor
m	mass	Indices	
m	mass flow	amb	ambient
Q	heat	S	store
ΔQs	extra heat stored	i	input
	or removed	e	extracted
R	radius	l	lost
r_s	recovery factor	r	recovered

REFERENCES

/1/ Hahne, E., "Thermal Storage - Some Views on some Problems", Proc. of the 8th Int.Heat Transf.Conf. San Francisco, Vol.1, 1986, pp.279-292.

/2/ Lottner, V., "Die Nutzung von Erdreich und Grundwasser für die saisonale Wärmespeicherung und als ganzjährige Wärmequelle für Wärmepumpenheizungen", Z.angew.Geowiss., Heft 7, 1986, pp.5-20.

/3/ Fisch, N., "Internationaler Stand der Saisonalen Wärmespeicherung", Aquifer-Wärmespeicher-Pilotprojekt, Fachkolloquium Stuttgart, 14. Mai 1987, publ. by Forschungsinstitut für Wärmetechnik e.V., Stuttgart.

/4/ Giebe, R., "Ein Kies/Wasser-Wärmespeicher in Praxis und Theorie", Dissertation am ITW Stuttgart, 1989.

/5/ Hahne, E., M. Hornberger, N. Fisch "Solar-assisted district heating plants with long-term heat storage", Clean a. Safe Energy Forever, Proc. ISES Congress 1989 Kobe, Vol.3, pp.1736-1740, Pergamon Press.

/6/ Hahne, E., "System Design: Centralized vs. Decentralized Concepts", IEA Workshop Tutzing 1991 (in press).

Results of the Third Long-Term Cycle at the University of Minnesota Aquifer Thermal Energy Storage (ATES) Field Test Facility

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ABSTRACT

The third long-term ATES cycle (LT3) was conducted between October 1989 and March 1990. Objectives of LT3 were to demonstrate that high-temperature ATES could supply a real heating load and to simplify the water chemistry modeling. For LT3 the Field Test Facility (FTF) was connected to a nearby campus building to demonstrate the FTF's ability to meet a real heating load. For LT3 the wells were modified so that only the most permeable portions of the Ironton-Galesville aquifer were used to simplify water chemistry comparisons and modeling. The campus steam plant was the source for heat stored during LT3.

A total volume of 63.2×10^3 m^3 of water was injected at a rate of 54.95 m^3/hr into the storage well at a mean temperature of 104.7°C from October through December 1989. Tie-in to the Animal Sciences Veterinary Medicine (ASVM) building was not completed until late December. A total volume of 66.0×10^3 m^3 of water was recovered at a rate of 44.83 m^3/hr from the storage well at a mean temperature of 76.5°C from January through March 1990. Highest and lowest temperatures of recovered water were 100.0 and 47.8°C, respectively.

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

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

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

INTRODUCTION

The objectives in building the University of Minnesota ATES FTF were to design, construct, and operate the facility in order to study the feasibility of using ATES in a confined aquifer at temperatures up to 150°C. The FTF is located on the St. Paul campus of the University of Minnesota. The FTF was designed to inject and recover heat at a rate of 5 MW(thermal) using a well doublet spaced at 255 m, operating at an injection/recovery rate of 18.9 L/sec (68.0 m^3/hr). The wells are completed in the Franconia-Ironton-Galesville (FIG) confined aquifer at a depth of from 182 to 244 m and have static water levels about 55 m below land surface. Heat source for the FTF is the St. Paul campus steam plant. Figure 1 is a generalized diagram of the FTF.

Summary results of the experimental ATES cycles conducted at the FTF are presented in Table 1. Results of previous cycles have been reported previously (1-4). For the previous cycles the heating load was a water-to-air radiator located on the storage site (Figure 1).

When the previous cycles had clearly demonstrated that >100°C ATES was feasible, it was determined that one (or more) additional cycle(s) during which the recovered heat would be used on the campus would be desirable. Additionally, it was desirable from a modeling perspective to simplify the configuration of the storage and source wells.

PREPARATIONS FOR LONG-TERM CYCLE 3

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

Permits necessary for operation of the FTF for LT3 required going through the entire permitting process.

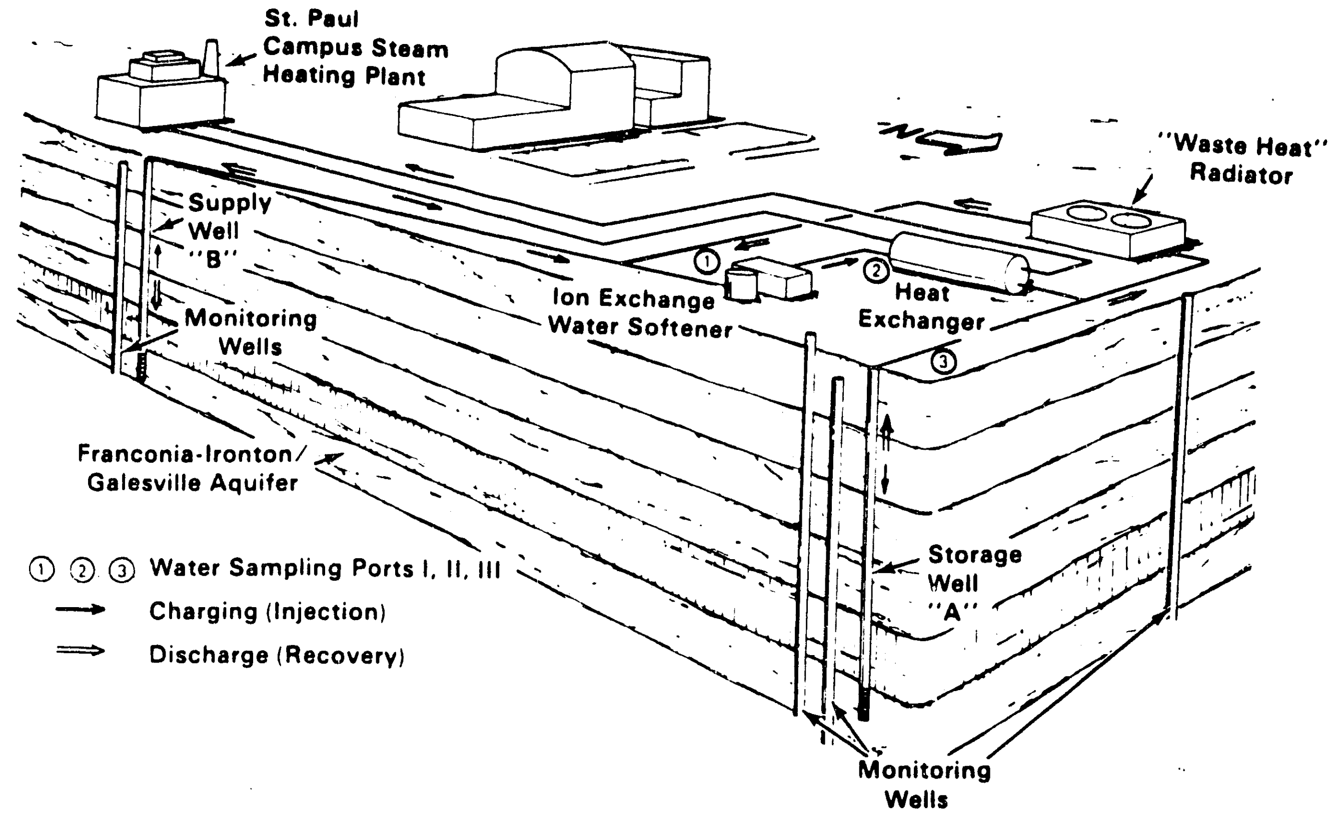

Figure 1. Conceptual Drawing of University of Minnesota ATES Field Test Facility

Table 1. Summary of ATES Cycles at the University of Minnesota FTF

	Short-Term Cycles				Long-Term Cycles		
	1	2	3	4	1	2	3
Duration (days)							
Injection - Pumping	5.2	8.0	7.7	7.7	59.1	59.3	47.2
Injection - Total	17.0	10.0	10.4	12.0	74.7	65.0	47.8
Storage	13.0	90.0	9.7	10.1	64.0	59.1	21.4
Recovery - Pumping	5.2	8.0	7.7	7.7	58.0	59.7	61.2
Recovery - Total	5.2	8.0	8.0	7.7	58.8	59.8	85.8
Temperature (°C)							
Source Water	11.0	20.5	36.1	52.6	19.7	33.1	20.2
Injected Water	89.4	97.4	106.1	114.8	108.5	117.7	104.7
Recovered Water	59.2	55.2	81.1	89.1	74.7	85.1	76.5
Returned Water	29.0	54.4	76.6	75.7	68.0	60.4	68.1
Flow Rate (L/sec)							
Injection	18.4	17.6	18.3	17.9	18.0	18.3	15.3
Recovery	18.1	17.8	17.3	17.8	18.4	17.9	12.5
Volume (10^3 m^3)							
Injection	8.3	12.2	12.2	11.9	92.1	93.9	63.2
Recovery	8.1	12.3	11.8	11.9	92.2	92.1	66.0
Energy Recovery Factor							
(using source temperature)	0.59	0.46	0.62	0.58	0.62	0.62	0.67
(using ambient temperature)	0.59	0.52	0.71	0.75	0.65	0.69	0.70

Necessary permits from the Minnesota Pollution Control Agency, Minnesota Department of Health, and Minnesota Department of Natural Resources for the operation of injection wells, discharge of waste water, and appropriation of ground water for two experimental cycles having no more than 90 days of heated water injection, temperatures no higher than 150°C, and injection rates no higher than ~17.6 L/sec (63.4 m^3/hr) were obtained in September 1989. Site closeout conditions included final temperature of the aquifer and sodium concentration of the ground water. Modeling of the planned cycle(s) and well modifications were significant factors in setting conditions of the permits.

For LT3 the FTF was connected to a nearby campus building to evaluate the high-temperature ATES FTF's ability to meet a real heating load. Several possible nearby buildings were considered for tie-in to the FTF for LT3 (4). Distance to the building, type of building heating system, heating system capacity and cost to tie-in were considerations. The Animal Sciences Veterinary Medicine (ASVM) building was connected to the FTF. The FTF was tied into the reheat system of the ASVM (Figure 2), a relatively constant load. The characteristics of an ATES system, with highest temperature water being recovered initially and relatively complicated startup/shutdown and reversal procedures, strongly suggested that replacing a base load portion of heating need would interface more simply to the FTF. Replacing peak loads would have required much more extensive, and more costly, modification to the FTF. These would probably have included variable speed pumps and a complicated pumping procedure. Replacing a relatively constant demand part of the heating system allowed a nearly constant speed operation and a relatively simple tie-in. No new control systems were required on the aquifer water side of the system. The fine control of the reheat system was taken care of by the already existing ASVM building systems. The FTF was tied into the building system upstream of the building's reheat condensers. The only modification required on the building side besides piping to the FTF and installing a double-wall heat exchanger, was simply adjusting alarm points on the ASVM reheat system. The tie-in was completed in December 1989, after LT3 had begun.

The storage and source wells were originally completed with two screened intervals in the FIG aquifer, the upper Franconia (UF) and the Ironton-Galesville (IG). Modification of the injection/recovery wells consisted of removing the UF well screens and replacing them with blank pipes (Figure 3). This left only the IG part of the aquifer, the most permeable part of the aquifer, screened to the wells. The capacity of the wells was reduced somewhat. This modification simplified modeling of the aquifer because the UF and IG parts of the aquifer have significantly different mineralogy and permeability (1). Additionally, using only the IG part of the aquifer for storage simplified the geometry of the thermal injection/recovery zone around the storage/recovery well, tending to reduce heat loss to the aquifer and adjacent confining beds.

While the wells were being modified, the pumps were removed and inspected. Inspection revealed that the pump in the injection/recovery well required replacement due to wear from the previous experimental cycles. Replacement considerations included the capacity reduction of the wells due to removal of the UF screens

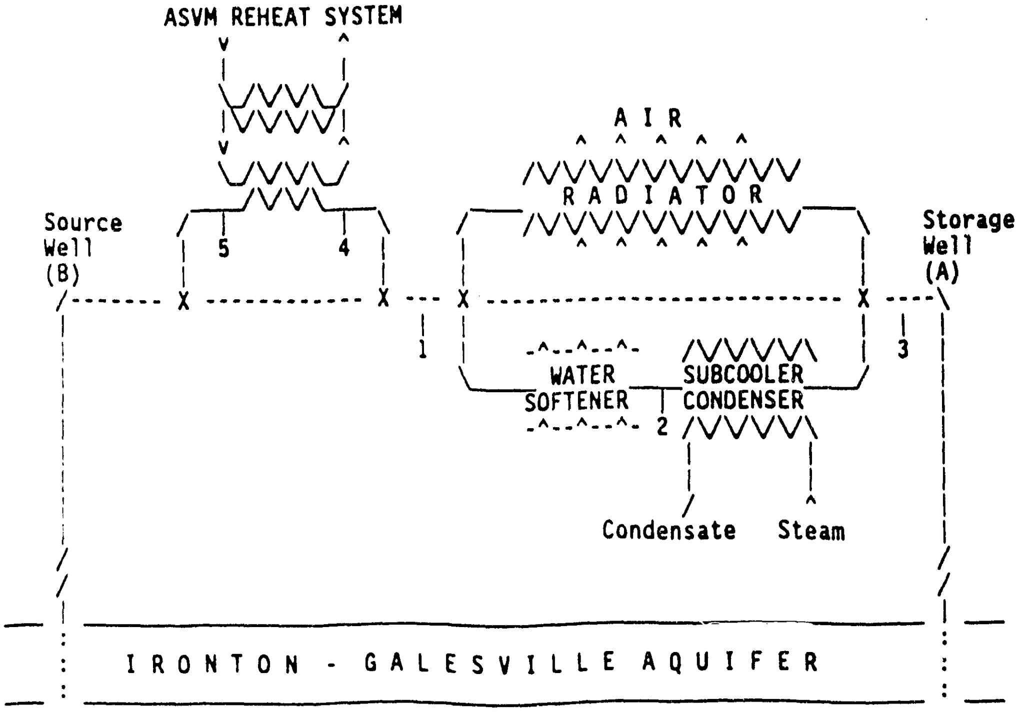

Figure 2. Configuration of the University of Minnesota ATES FTF for Long-Term Cycle 3

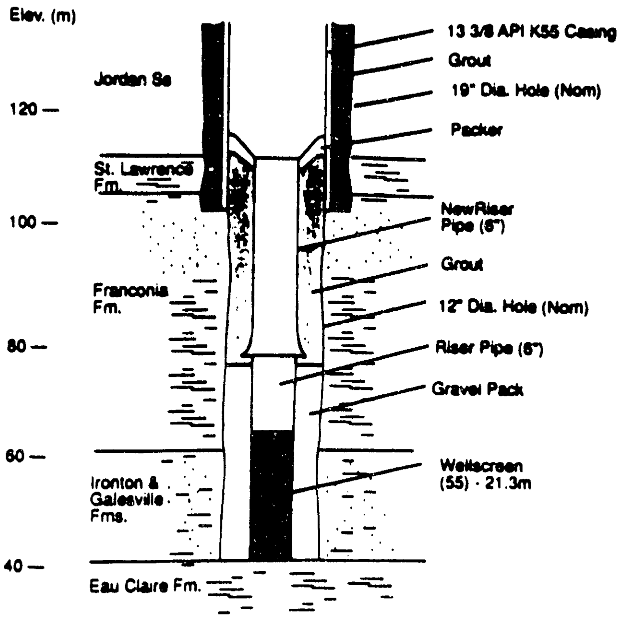

Figure 3. Configuration of the Storage and Source Wells Following Modification

and the required heating need for the ASVM. The required pumping rate for recovery was determined to be approximately 12.6 L/sec (45.5 m^3/hr) instead of the 18.9 L/sec (68.0 m^3/hr) originally installed. The replacement pump in the injection/recovery well was sized for the needed recovery rate rather than the original rate.

LONG-TERM CYCLE 3

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

CHRONOLOGY - LT3 was conducted over 155 days between October 1989 and March 1990. Table 1 summarizes data for LT3 and previous cycles; Figure 4 presents LT3 flows and temperatures. Injection was conducted from October 25 until December 12, when low temperatures (<-18°C) hit the area and the water softener control system froze, causing the system to shutdown. Restarting injection was not feasible at that low an air temperature. Heat recovery was not possible at that time because the ASVM building tie-in was not yet completed. The ASVM building connection was completed and tested in late December. Heat recovery began on January 2. Unseasonably warm weather hit the area, and on January 5 heat recovery was halted and restart of injection was attempted. However, the source well pump did not operate properly and recovery was continued. Each switching of system modes (recovery to injection and injection to recovery) took less than four hours. When the unseasonably warm January weather continued, it was necessary to halt recovery because the attainable temperature drop across the ASVM heat exchanger did not lower the return temperature to less than the maximum temperature for the source well design (85°C). With this interruption, inspection and repairs at the source well were undertaken. Partial repair was not completed until late January when seasonably cold weather had returned. Heat recovery was restarted January 31 and continued through March 29.

PARAMETERS - Figure 4 and Tables 1 and 2 summarize the data and results for LT3. There were only 47.2 days of injection because of problems with the source well pump. Source water temperatures were 20.2°C, a result of the previously completed pumpout to a temperature of ~20°C in 1988 (5). A total volume of 63.2 x 10^3 m^3 of water was injected at a rate of 54.95 m^3/hr into the storage well at a mean temperature of 104.7°C from October through December 1989. A total of 6.21 GWh were added to the source water and stored in the aquifer. Of the total, 2.11 GWh were necessary to raise the water temperature to 49°C, and 4.10 GWh were added to raise the water temperature to 104.7°C.

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

Ion-exchange water softening was used during injection to prevent scaling and blocking of the heat exchangers and the storage well during the cycle. Operation of the softener during injection was nearly troublefree. The major change to the water was from a calcium-magnesium bicarbonate water to a sodium bicarbonate water. Source water had a hardness of 174 mg/L as $CaCO_3$; the injected water had a hardness of <5 mg/L as $CaCO_3$. Sodium concentration was changed from 19 to 101 mg/L by the water softener. Recovered water had an average hardness of 48 mg/L as $CaCO_3$ and a sodium concentration of 87 mg/L.

PERFORMANCE - Table 2 presents the energy performance for LT3. In reporting energy recovery, it must be remembered that the source water was considerably cooler than would be optimal for this system. Approximately 66% (4.13 GWh) of all of the energy added to the water was recovered; approximately 50% (2.07 GWh) of the energy added to the water above 49°C (33% of the total energy stored) was delivered to the ASVM building. Approximately 15% (0.64 GWh) of the usable (10% of the total) energy stored was actually used in the ASVM building. The remainder of the energy recovered, 3.49 GWh (above 20.2°C) or 1.43 GWh (above 49°C), depending upon the base used, was returned to the source well. The useful minimum temperature for recovered water was 49°C. Operations during heat recovery with the ASVM building's reheat

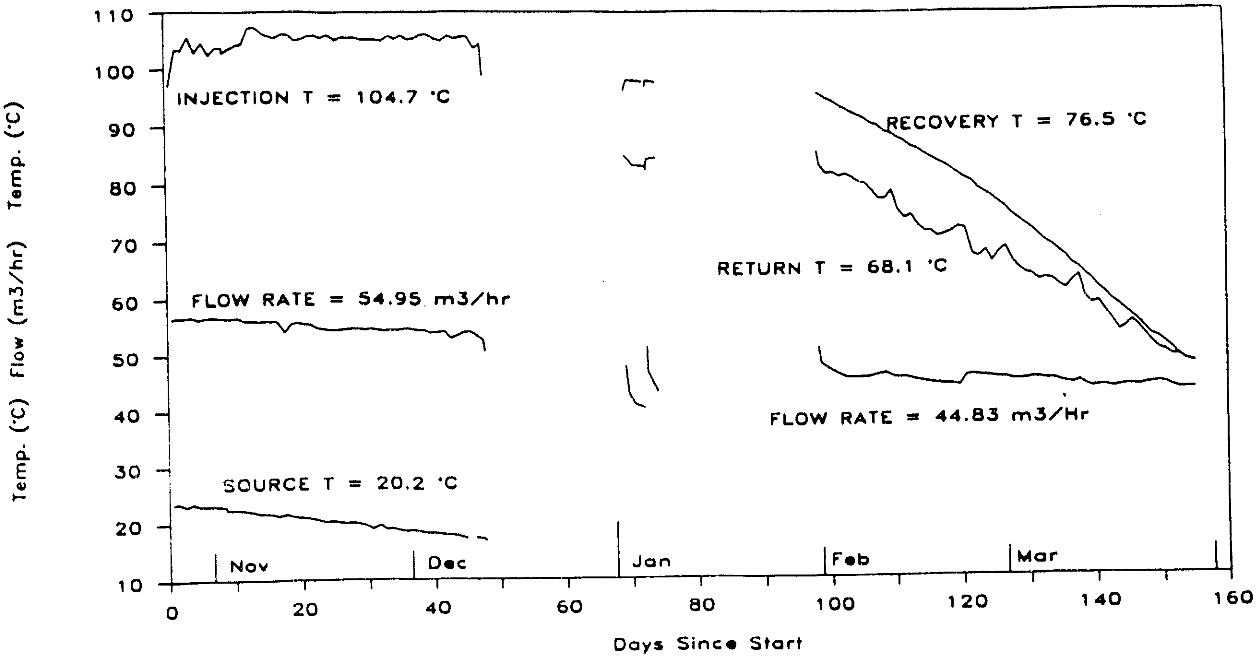

Figure 4. Long-Term Cycle 3 Injection and Recovery Flows and Temperatures

system were troublefree after adjusting the alarm points on the ASVM reheat system.

Temperature drop on the aquifer side of the heat exchangers in the ASVM building averaged 8.4°C, with a maximum drop of 14.7°C. The building reheat side had a temperature rise of approximately double the aquifer side temperature drop. When the heat demand was low and when the recovered water temperature was approaching the lower limiting temperature, the temperature drop was less (Figure 4).

Table 2. Energy Summary of Long-Term Cycle 3

	Added To Aquifer	Recovered From Aquifer	Percentage
ENERGY - GWh			
above 20°C	6.21	4.13	66.5
above 49°C	4.10	2.07	50.5
Energy used in ASVM building		0.64	
Energy used in ASVM / Total energy added			10.3
Energy used in ASVM / Energy added >49°C			15.6
Energy supplied ASVM > 49°C / Total energy added			33.3
Energy supplied ASVM / Energy added > 49°C			50.5

DISCUSSION

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

The ion-exchange water softener reduced hardness to <5 mg/L as $CaCO_3$, allowing successful operation; control of the water chemistry is critical to the operation of the University of Minnesota FTF, or any ATES facility.

CONCLUSIONS

LT3 did demonstrate that ATES in a confined aquifer at temperatures above 100°C can be effectively tied into a conventional building heating system. Although approximately 66% of the energy added and stored was recovered from the aquifer, and 33% was delivered to the ASVM building, only 10% of the total energy added to the water was used in the building. Approximately 50% of the energy added above the usable minimum temperature (49°C) was delivered to the ASVM building. The delivery of heat from the storage system to the targeted use is reasonably predictable if the parameters of the aquifer and operating scheme are well characterized. The system as operated for this cycle would not be cost-effective during an initial cycle, but with continued use and an appropriate interface, it can be cost-effective.

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

REFERENCES

1. Walton, M., and others, 1991, *The University of Minnesota Aquifer Thermal Energy Storage (ATES) Field Test Facility—System Description, Aquifer Characterization, and Results of Short-Term Cycles.* PNL-7220, Pacific Northwest Laboratory, Richland, Washington.

2. Hoyer, M.C., and others, 1991, *University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the First Long-Term Cycle.* PNL-7817, Pacific Northwest Laboratory, Richland, Washington.

3. Hoyer, M.C., and others, 1991, *University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the Second Long-Term Cycle.* PNL-7917, Pacific Northwest Laboratory, Richland, Washington.

4. Sterling, R. L., and M. C. Hoyer, 1989, "Field Testing of a High-Temperature Aquifer Thermal Energy Storage System," pp. 332-347, *in* Hoffman, H.W., and J.J. Tomlinson, eds., U.S. Department of Energy *Thermal Energy Storage Research Activities Review 1989 Proceedings,* U.S. Department of Energy, Washington, D.C.

5. Hoyer, M.C., and others, 1992, *University of Minnesota Aquifer Thermal Energy Storage (ATES) Project Report on the Third Long-Term Cycle.* University of Minnesota, Minneapolis, Minnesota.

Heat Storage at SPEOS (Swiss ATES Pilot Plant): Chemical and Microbiological Aspects and Problems

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ABSTRACT

The Swiss ATES pilot plant, SPEOS, is located in Lausanne near Lake Geneva. The installation consists of a large central well with a network of horizontal drains in each of two successive sandy aquifers. Water goes from one level to the other during the injection and production cycles.

Slight changes in the chemistry of the aquifer have been observed, generally with a low impact. Scaling and clogging by calcium carbonate precipitation are the biggest problem. Many experiments have been performed to find a good solution. Different types of heat exchangers have been tested: tubular, plate, and fluidized bed. Several water treatment methods were also investigated: mechanical, electromagnetic conditioning and injection of chemicals. The fluidized bed heat exchanger is currently running in SPEOS. Continuous injection of HCl (hydrochloric acid) was an effective solution for scaling prevention but it resulted in an increase in chloride concentration and in corrosion of the equipment (including stainless steel). Therefore, a better solution must be chosen, possibly without the use of chemicals, which may lead to environmental impacts.

Microbiological studies were performed to help understand the behaviour of the aquifer microflora to an increase in temperature and possible other changes provoked by the aquifer's exploitation as a thermal storage. Up to now, the hygienic quality of the water has not been altered. But some potentially pathogen microorganisms like Legionella may represent a biological hazard. Therefore, it is necessary to evaluate disinfection methods.

SPEOS PLANT

The Swiss ATES pilot plant, SPEOS (Stockage Pilote d'Energie par Ouvrage Souterrain), was created for scientific researches, within the IEA (International Energy Agency) programme on aquifer thermal energy storage. The researches are sponsored by the Swiss Federal Office of Energy. The plant is located in Lausanne near Lake Geneva. The design of the installation is very unusual and consists of a large diameter central well, from which two networks of six horizontal drains are driven into the soil at the level of two sandy aquifers. During the injection cycle, the water is extracted from the upper level and stored, after heating, in the lower aquifer. During the production cycle, the hot water is taken from the lower level and injected, after heat extraction, in the upper one. At the beginning (1982-1985), the hot aquifer was not the lower but the upper one. Since 1985, the system has been working as described above. SPEOS is linked to a heat producer (waste water treatment plant) and to a consumer (University Sports Centre).

SPEOS characteristics are as follows :

Central well diameter	:	2.2	[m]
Depth of the upper aquifer	:	7	[m]
Depth of the lower aquifer	:	24	[m]
Length of each drain	:	25	[m]
Drain diameter	:	0.2	[m]
Storage volume	:	100,000	[m3]
Aquifer's texture	:	silt and sand	
Upper aquifer permeability	:	1xe-4	[m/s]
Lower aquifer permeability	:	5.7xe-4	[m/s]
Injection temperature	:	40 - 80	[°C]
Flow rate	:	5 - 20	[m3/h]

Moreover, numerous measuring points were set up for checking and regulation :

- 43 piezometers (aquifers level and pressure, water sampling),
- 10 thermometric tubes (temperature reading),
- 6 vertical microwells (to increase the permeability through the two aquifers).

Figure 1 shows a schematic of the working process of SPEOS.

CHEMICAL ASPECTS AND PROBLEMS

SPEOS WATER - Initial quality of SPEOS water has been analyzed since 1979. Water from the upper and lower aquifers were quite similar.

Main parameters were as follows :

Temperature	: 12	[°C]
pH	: 7.2 - 7.6	[/]
Alkalinity	: 250 - 300	[mg/l] as $CaCO_3$
Calcium	: 62 - 100	[mg/l]
Magnesium	: 15 - 33	[mg/l]
Sodium	: 9 - 16	[mg/l]
Silicon	: 4 - 9	[mg/l]
Sulphate	: 36 - 100	[mg/l]
Chloride	: 25 - 35	[mg/l]
Dis. oxygen	: 3 - 6	[mg/l]

Preliminary "in vitro" tests involving SPEOS water and sand showed that, during the loading cycle, calcium carbonate precipitation and clay weathering occured. Then, during the cooling cycle, silica gel reprecipitation was expected.

WATER TREATMENT METHODS TESTED - Scaling and clogging have occured several times, particularly during injection. Silica gel precipitation did not occur inside the equipment during production. Many experiments have been performed to find the best solution to avoid scaling. Three types of heat exchangers have been tested : tubular, plate and fluidized bed. Several water treatment methods were also investigated : mechanical, electromagnetic conditioning, and injection of chemicals such as HCl (hydrochloric acid) and NaOH (sodium hydroxide). Some of these experiments have been combined. Table 1 provides a summary of the systems tested from 1982 through 1992.

Tubular Heat Exchanger - Tubular heat exchangers (eight in parallel) with a periodic washing process by HCl in a closed circuit, were tested first. Washing processes became too frequent. The exchangers were blocked with deposits containing calcite (calcium carbonate), iron oxides-hydroxides, manganese oxide and other fine particles due to the weathering of clays (Miserez, 1989). Moreover the permeability of the drains decreased, also due to scaling.

Plate Heat Exchanger and HCl - After that, it was decided to continuously inject HCl into the water before heating. The resulting pH was about 6.5 to 6.8. This method was very successful in keeping the exchanger clean and maintaining a good permeability in the drains. But it resulted in an increase in chloride concentration in the aquifer and in corrosion of the equipment. Even plates of the heat exchanger made of stainless steel (V4A) were damaged by pitting corrosion (Miserez, 1989). Therefore, a better solution must be chosen, possibly without the use of chemicals, which may lead to environmental impacts.

Electromagnetic Conditioning - Several types of physical conditioning like electromagnetic field, permanent magnets outside or inside the tube were tested at the inlet of the plate heat exchanger. The formation of macromolecules of calcium carbonate, which do not form deposits, was not observed with any of these devices.

Plate Heat Exchanger and Self-Scrubber Balls - The self cleaning system is a mechanical one and consists of polystyrene microballs, which recirculate continuously inside the exchanger. Turbulence and erosion destabilize the deposits and remove them. A barrel with two baskets is used to guide the balls inside the exchanger and filter them from the outlet. The results with hard deposits such as calcite were not as good as with soft deposits like organic matter. The balls were very often blocked inside of scale, particularly in dead zones. Moreover, scale taken out from the exchanger can clog the equipment downstream and the aquifer.

Fluidized Bed Heat Exchanger - The fluidized bed heat exchanger is based on the same principle. It consists of a tubular exchanger with a fluidized bed (quartz sand) outside the tubes. Sand particles increase turbulence and avoid the growth of deposits in the exchanger by breaking them. The exchanger system works without scaling or clogging. Peeled off deposits of calcium carbonate are partially held in a cyclone device. The problem is that aquifer permeability tends to decrease by clogging. Thus, it is necessary to wash the drains periodically with HCl (Miserez, 1990).

Heat Exchanger with Special Coating - A tubular heat exchanger with PTFE (polytetrafluoroethylene) coating was tested with hard water similar to the water found at SPEOS. Scaling did not occur inside the exchanger because of the antiscaling effect, but small flakes were observed downstream. This could surely result in clogging of the drains within SPEOS. In addition, heat transfer coefficient is so low that the volume will become prohibitive for a high outlet temperature (Jollien, 1991).

Fluidized Bed Heat Exchanger and NaOH Injection - NaOH was injected at the exchanger inlet to increase the precipitation rate of calcium carbonate, so that the scale will grow inside the fluidized bed on the surface of the particles (quartz sand). The pH of the exit water increased to about 8.5 to 9. Calcium carbonate precipitated quantitatively not only in the exchanger but but also in the aquifer. Clogging was observed. However the scale contains more aragonite than calcite. Vaterite formation was also observed but not systematically.

Tubular Heat Exchanger and CO2 - Within the IEA Annex VI programme, Subtask F, the German group is currently performing field experiments with CO_2 (carbon dioxide) injection in SPEOS. CO_2 is used instead of HCl to acidify the water, keeping it in equilibrium after heating and thus avoiding scaling. The first results are quite promising.

WATER TREATMENT METHODS AVAILABLE - To date at SPEOS, only a few methods can be used while injection cycles are operating. (Production cycles do not need water treatment):

- Heat exchanger with continuous hydrochloric acid injection.
- Fluidized bed heat exchanger with periodic washing of the drains by HCl.

Neither method is perfect, but the disadvantages can be overcome easily. The second method is running at the moment in SPEOS.

The method using NaOH injection can not be applied without an additional device, which can quantitatively capture the flakes of carbonate at the exchanger outlet, for example, by using centrifugal force.

EVOLUTION OF THE AQUIFER CHEMISTRY - Slight changes in the chemistry of the aquifer were observed, generally with no effect on the aquifer. More significant was the increase in chloride concentration because of the continuous injection of acid, with the resulting evolution of the pH and hardness (oversaturation for calcium carbonate). However, since about 1989, continuous injection has been stopped and these parameters are gradually returning to the initial values. Degradation of clay minerals has not been as strong as expected; dissolved sodium and silicon concentrations still tend to increase. Figure 2 shows the evolution of the main parameters of the water chemistry, since 1982.

MICROBIOLOGICAL ASPECTS AND PROBLEMS

Microbiological studies were performed to help understand the behaviour of the aquifer microflora to an increase in temperature and possible other changes provoked by the aquifer's use as a thermal storage. Up to now, the hygienic quality of the aquifer, such as attested by microbiological tests and analyses, has not been altered. "In vitro" (using SPEOS water and sand) and "in situ" (using drain simulators) studies on the different flora do not show a critical situation within the context of SPEOS environment, which is very poor in nutrients. Mesophilic and saprophytic bacteria, as well as allochthonous bacteria of fecal origin, tend to decrease because of the high temperatures, almost near-sterilization. However, in this environment, the thermophilic flora appears to be able to dominate the other species and thus, to provoke a modification of the microbial ecology.

Biocorrosion and bioclogging did not occur during SPEOS operation, although some types of iron bacteria were detected at the beginning of SPEOS exploitation (Miserez, 1989). Moreover the presence of dissolved oxygen in the aquifer avoids an extensive development of the bacteria responsible for biocorrosion, such as sulfate reducers.

Ubiquitous thermotolerant and potentially pathogenic microorganisms, like Legionella, were also studied. These organisms may represent a biological hazard in an ATES system, for example, near the main well of SPEOS and in plumbing fixtures, if specific physiochemical and biological conditions are found, (temperature from 30 to 50 °C, for example). Legionella spp. survive quite well in sterilized and unsterilized SPEOS water (Montandon, 1991). These organisms can compete with indigenous microorganisms, if temperature is lower than 45 °C. Therefore, it is necessary to evaluate disinfection methods (chlorination of stored water and/or superheating at 70 °C).

BIBLIOGRAPHY

All the following papers are IEA restricted and can be obtained from the Federal Office of Energy, OFEN, 3003 Berne, Switzerland.

(1) CHYN, IENER (1983) - SPEOS, IEA Annex III- Premier cycle d'exploitation de l'installation pilote SPEOS, rapport 1983. N° 703.217, Lausanne, Switzerland.

(2) International Energy Agency, Annex III, third Expert Meeting on energy storage (Lausanne, January 1983). Summary of presentations, CHYN, Neuchâtel, Switzerland.

(3) CHYN, IENER (1984) - SPEOS, IEA Annex III- Deuxième cycle d'exploitation de l'installation pilote SPEOS, rapport 1984. N° 703.220.

(4) B. Saugy, J.-J. Miserez, B. Mathey (1988)- SPEOS, a seasonal aquifer heat store, Results after five years of tests and running. Proceedings of JIGASTOCK 88, Versailles, France. IHE, Lausanne, Switzerland.

(5) B. Saugy, IHE, (1988) - SPEOS, IEA Annex III- Suivi scientifique de la deuxième étape, rapport intermédiaire au 31.12.1987. N°703.265c, Lausanne, Switzerland.

(6) J.-J. Miserez (1989) - IEA Annex VI- Phase I, Final Report : Researches performed in Switzerland. La Chaux-de-Fonds, Switzerland.

(7) B. Saugy, IHE, (1989) - SPEOS, IEA Annex III- Rapport final SPEOS, deuxième étape. N°703.293, Lausanne, Switzerland.

(8) F. Miserez, (1990) - IEA Annex VI - Rapport de la phase intermédiaire, groupe suisse. ICC SA, La Chaux-de-Fonds, Switzerland.

(9) L. Jollien, S. Remonnay (1991) - IEA Annex VI phase II - Test d'efficacité d'un échangeur de chaleur à revêtement anti-adhérent. ICC S.A., La Chaux-de-Fonds, Switzerland.

(10) L. Jollien, F. Miserez (1991) -IEA Annex VI phase II- Traitement de l'eau par élévation du pH par injection de soude.

(11) P.-E. Montandon, (1991) - IEA Annex VI phase II- Expert Meeting La Chaux-de-Fonds November 1991 - Survival of thermotolerant and potentially pathogen microorganisms in conditions of an ATES. La Chaux-de-Fonds, Switzerland.

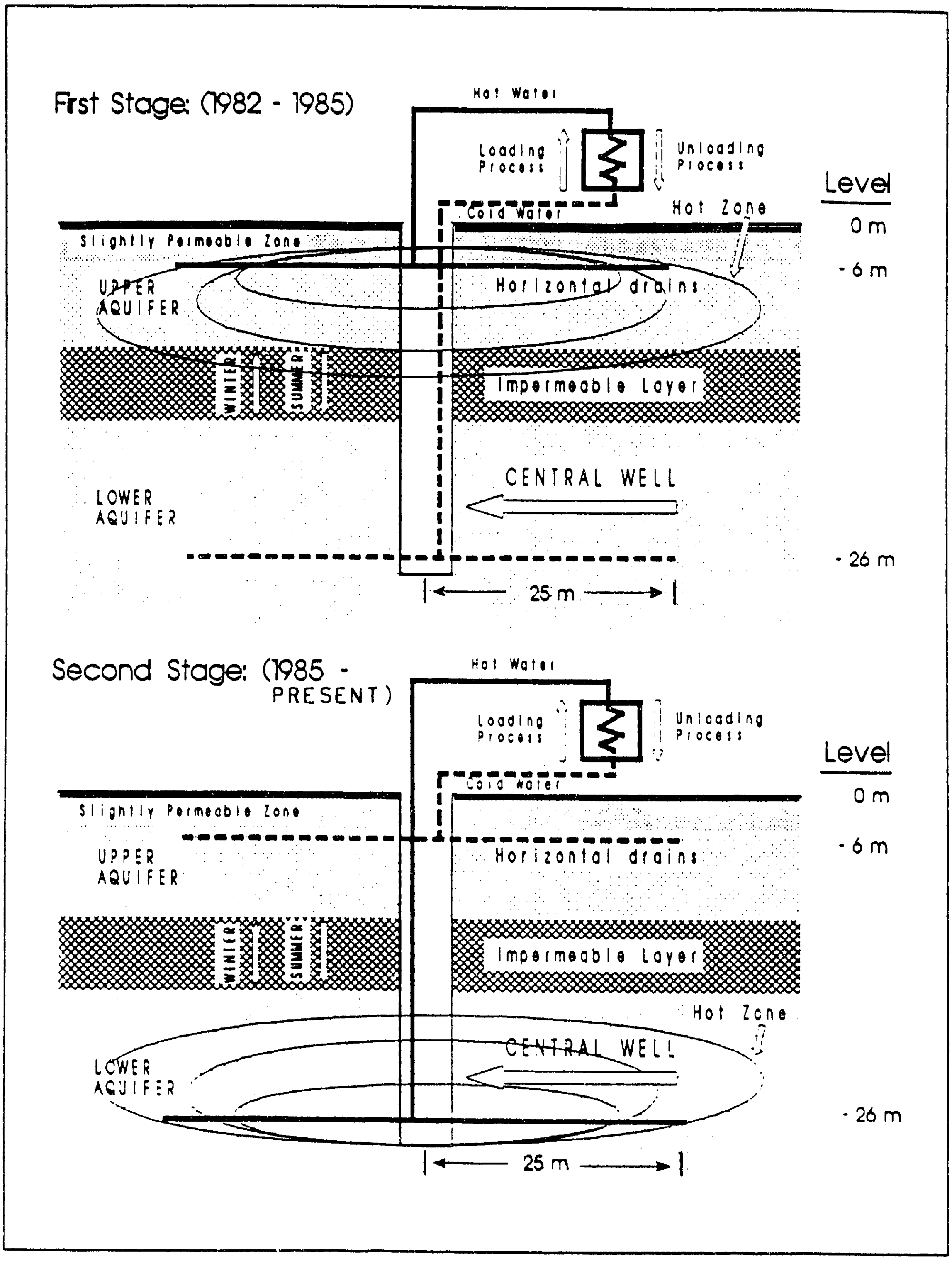

Figure 1. The Dorigny ATES (SPEOS, Stockage pilote d' énergie par ouvrage souterrain) System - Loading and Unloading Cycles

Cycle (injection and production)	1	2	3	4	5	6	7	8	9	10
Operating period	1982 - 1983	1983 - 1984	1984 - 1985	1985	1986 - 1987	1987 - 1988	1988 - 1989	1989 - 1990	1990 - 1991	1991 - 1992
Storage aquifer	UPPER LEVEL			STAND - BY	LOWER LEVEL					
Temperatures [°C] Injection Production	60 19 - 37	70 20 - 45	50 50		80 50	70 - 80 40 - 60	70 45 - 60	50 30 - 40	80 40 - 60	70 - 75 40 - 60
Inj. Flow rate [m3/h]	5 - 10	7 - 10	10		20	20	20	5 - 20	20	20
Heating system	8 Tubular Heat Exchangers				Plate Heat Exchanger				Fluidized Bed Heat Exch.	
Water treatment	Periodic Washing of HE * with HCl	Continuous HCl injection pH = 6.5 to 6.8 (about 5,000 [l] HCl 18 % used).			Continuous HCl injection pH = 6.5 to 6.8 (about 9,000 [l] HCl 32 % used)			Mechanical Self-Scrubber Recirc. of Microballs	Mechanical by the action of the fluidized bed particles (quartz sand)	
Results	-HE clogged -Decrease of the drains permeability (Rehabilitation with HCl.)	- No clogging inside HE and drains - Corrosion of the equipment - Increase in aquifer Cl concentration			- Neither clogging nor scaling inside the heat exchanger and drains. - Corrosion of the equipment . - Increase in chloride concentration in the aquifer.			-Heat exchanger blocked by scale and and microballs. -Low inject. temperature.	- No clogging inside the exchanger. - Decrease of drains permeability. (Rehabilitation with HCl)	
Other tests					Short experiments with several electromagnetic conditioning devices.			HE with PTFE overcoating	Injection of NaOH (to pH 9) with fluidized bed HE	
Results					- No influence on calcium carbonate precipitation and thus clogging			-Less scaling -Clogging downstream -Low heat transfer.	- Scaling and clogging inside heat exchanger and downstream	

* HE : Heat Exchanger.

TABLE 1 : Summary of the systems tested at SPEOS (Swiss ATES pilot plant, Dorigny, Lausanne) from 1982 through 1992.

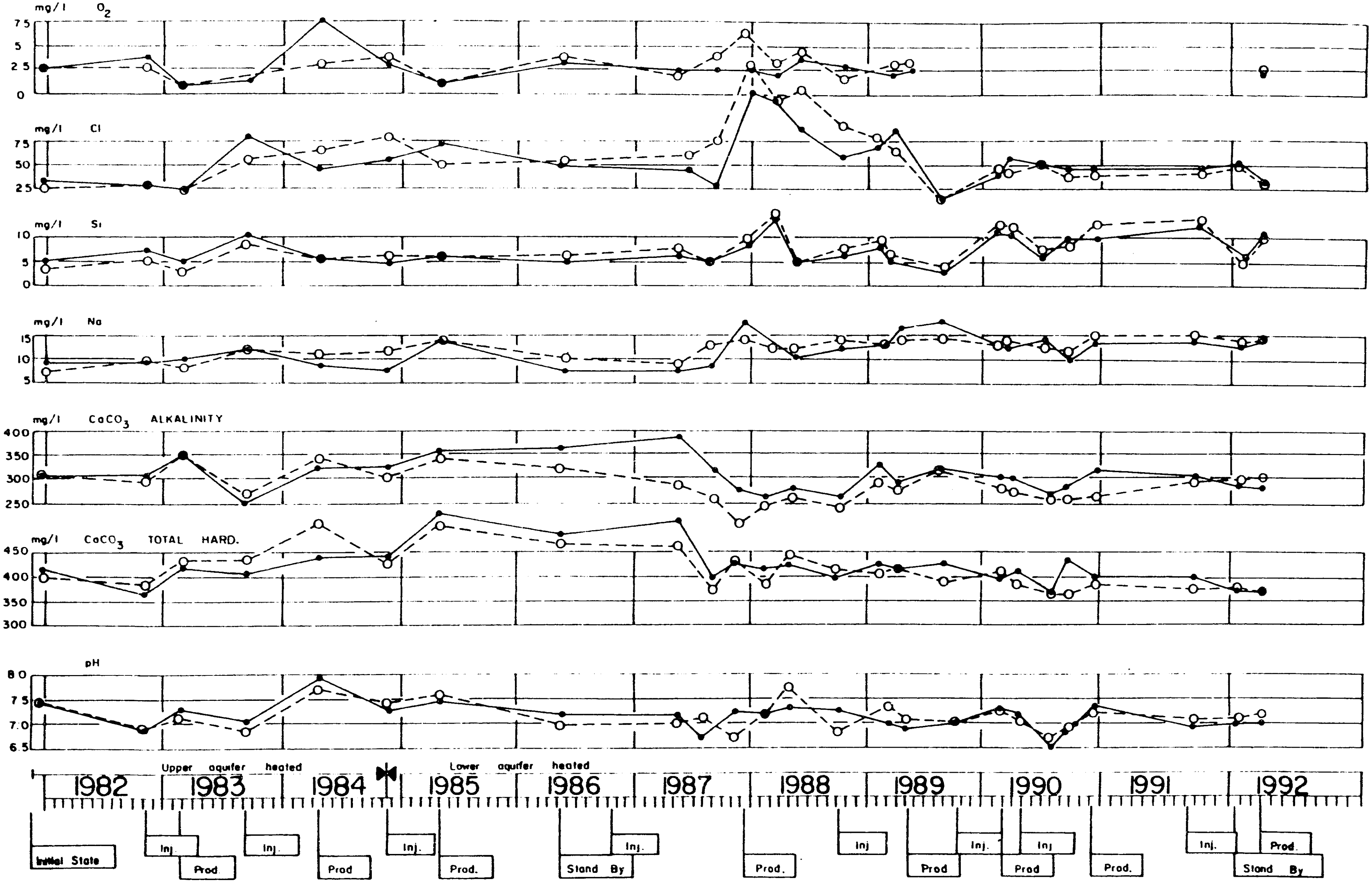

Figure 2 SPEOS Water Chemistry-
Evolution of the Main Parameters

High Temperature ATES at the University of Utrecht, the Netherlands

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ABSTRACT

A long-term thermal energy storage system has been implemented at the University of Utrecht campus in the Netherlands. The project will extend co-generation operation into the summer beyond heat demand periods, resulting in increased electricity generation. The stored heat (90 °C) is used in winter for space heating of several university buildings. In this demonstration project experience is being gained, among others, with groundwater treatment and flow-rate control in an aquifer thermal energy plant.

The storage system has been in full operation since May 13, 1991. In this paper a short review is presented of the technical problems that were met during the design stage and one year of operation.

The general conclusion is that during the first operational period too much water had been treated so that there was a risk of clay-swelling. This problem was caused by a technical failure of the spit-control for water treatment. Since the control system has been altered the high temperature ATES has been functioning perfectly.

PROJECT DESCRIPTION

GENERAL INFORMATION - The "De Uithof" campus of the University of Utrecht was constructed in the mid-sixties. The building area is 335 000 m2 and energy consumption is 37 000 000 kWh electricity and 10 000 000 m3 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 Utilities Services.

However, since 1991, electricity is also generated in summer, and excess heat is stored for re-use in the winter season.

Project engineering and realisation was done by Bredero Energy Systems and Heidemij Consultants, with support from the Netherlands Agency for Energy and the Environment.

STORAGE SYSTEM - At "De Uithof", heat is stored in an aquifer, a water-bearing sand layer between two clay layers, at a depth of 210-260 m below ground level. The principle of the system can be seen in the artist's impression (figure 1).

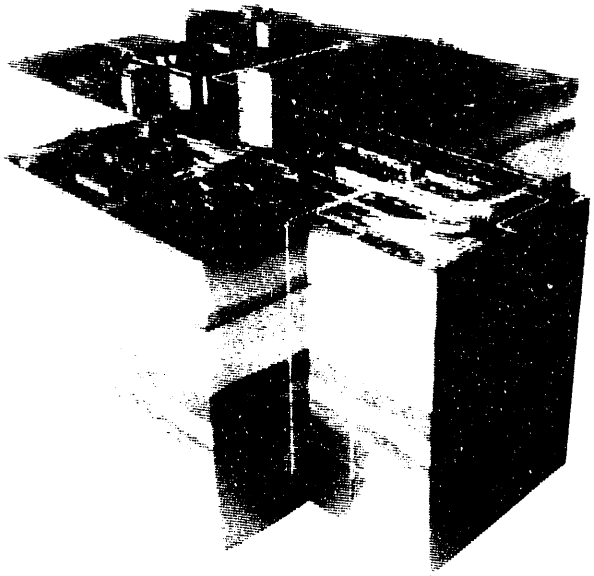

Figure 1: Artis's impression

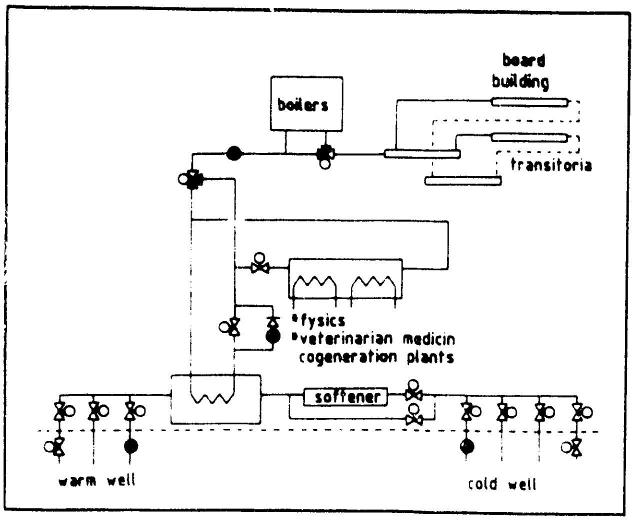

Figure 2: Simplified diagram of the principle of the system

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 residueal 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 two buildings at "De Uithof" via a heat exhanger, after which it is injected into the cold well.

In figure 2 it can be seen that 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 heat exchangers 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 drops too low, injection pipes are geared to a specific flow range, as discusses below.

More details about system design are given by van Loon and Paul (1991). A summary of key technical figures is given in Table 1. Thermal and chemical environmental effects have been reported by Willemsen and van der Weiden (1991).

Table 1: Key technical figures in 4th cycle (precalculated)

	charge (summer)	discharge (winter)
heat capacity	6.0 MW	2.6 MW
energy amount	21 600 GJ (6000 MWh)	13 000 GJ (3600 MWh)
temperature		
warm well	85 - 95 °C	90 -> 50 °C
cold well	max 50 °C	max 50 °C
flow rate (max)	100 m^3/h	50 m^3/h
water displacement	100 000 m^3/a	130 000 m^3/a
storage depth	210-260 m	210-260 m

MONITORING PROGRAMME - The ATES-system is being studied in a monitoring programme during a period of two years (1991-1993). The aim is to dertemine underground storage behaviour and to evaluate the energy balance and economic results.

Altogether, 70 temperature sensors have been installed in the four monitoring wells. With the aid of 25 observation tubes, the groundwater level is registered and groundwater samples are collected. These samples are analyzed with regard to numerous substances including heavy metals; furthermore, bacteriological activity is measured. Possible expansion or subsidance is measured at all wells and in the wide vicinity of the storage. To measure the volume of displaced groundwater, two water meters have been installed. In the above-ground system 10 heat sensors, 8 gas meters, 12 kWh-meters, two pressure transmitters, 11 temperature sensors, a hardness meter and turbidimeter are used to monitor the system behavior and to establish the energy balance. The data are recorded in a logbook in which maintenance and experience can also be registered. A final report is expected in 1993.

OPERATIONAL - The aquifer storage was tested under natural temperature conditions late 1990. After installation of the water treatment equipment, the system was started up on March 14, 1991.

After several charge and recharge tests (15, 40 °C) the system started complete operation (automatic) on May 13, 1991 at a maximum temperature of 65 °C. From August 29, 1991, the injection temperature was increased to 90 °C.

DESIGN PROBLEMS

WATER TREATMENT - Heating groundwater before injection means that calcite scaling can be expected: the Saturation Index for calcite (SI_{cc}) tends to increase at this location from 0.47 at 15 °C to almost 1.0 at 90 °C. For environmental reasons Ca/Na exchange treatment prior to heating was chosen (Figure 3). However, this technique implies a risk of clay swelling and conseqeuntly an increase of flow resistance. From calculations by Willemsen and van der Weiden (1991) it was concluded that a split-treatment of 60% is the maximum value that can be used without a risk of clay swelling. This split is probably safe enough to prevent calcite precipitation.

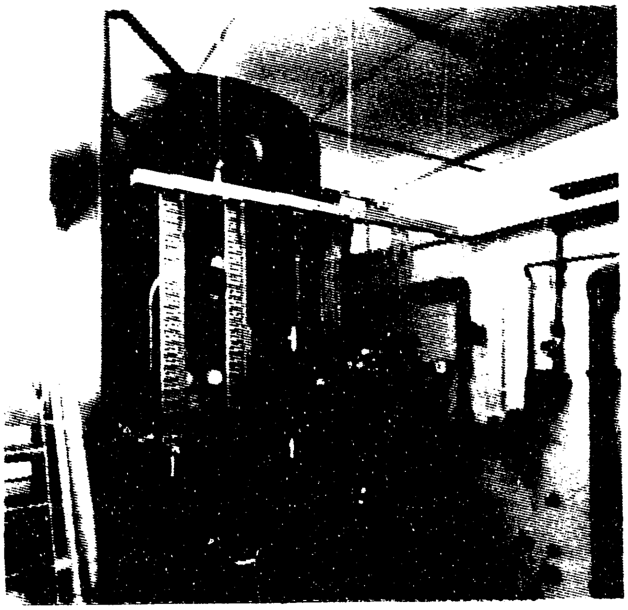

Figure 3: Water treatment installations

FLOW AND PRESSURE CONTROL - The temperature is fairly constant when charging the store, but the injection rate is variable. To maintain a constant injection temperature of 90 °C in the secondary (aquifer) circuit, the groundwater flow requires stepless control in summer.

When discharging the store, the temperature gradually drops from an initial 90 °C to 45 °C at the end of the heating season. However, the temperature demanded in the building fluctuates greatly with ambient outdoor temperatures, so that the groundwater flow in winter also requires stepless control. This is achieved by means of frequency control panels. At low flow rates, flow resistance diminishes considerably, so that O_2, CO_2 or CH_4 gas bubbles may form as a result of under pressure. It is absolutely necessary to prevent this because gas bubbles can cause acute well clogging.

The concentrations of soluble gases in the aquifer are: N_2 16.3 mg/l; CH_4 0.08 mg/l; CO_2 3 mg/l.

According to chemical-physical equilibrium calculations, an absolute pressure of 2 bar is necessary at 90 °C throughout the secondary (groundwater) circuit. This pressure is regulated in the most critical part of the system (injection well) by using several injection tubes with varying diameters and thus resistances.

At a decreasing flow rate, smaller injection tubes are used and at a very low flow (about 10 m^3/h when charging) there is a throttle valve at the end of the smallest injection tube in order to maintain overpressure.

There are 3 injection tubes in the cold well and 2 in the warm well.

MATERIAL SELECTION - In order to limit heat losses, insulation is needed throughout the system. It is difficult to insulate well-tubing at 200 m depth. A material had to be found with acceptable and fairly constant thermal resistivity, a strength of (200 m) 20 bar pressure, strong adhesion force (expansion), and iwich is constructable and sufficiently economic.

Materials with high thermal resistivity contain air and they are generally not strong enough nor constructable at a depth of 200 m. After a pre-study of cements, foams, fibres and double-tubings, an optimum was found in spherelight-cement insulation, thermal conductivity 0,12 W/mK. During construction, no problems were encountered.

MONITORING RESULTS AND OPERATIONAL PROBLEMS

ENERGY BALANCE - The first loading cycle is not complete, because of a gradual starting-up procedure. At the end of the summer season (week 43, 1991) 78 257 m^3 of water and 18 170 GJ of energy was stored with a maximum temperature of 90 °C. Of this amount, 3 030 GJ (17%) hade been discharged during the first winter season at temperatures of 83 to 51 °C. This result is fairly good, compared with previous calculations. It is expected that the thermal efficiency will increase to about 55% in the fourth cycle.

WATER TREATMENT - Water chemical composition was monitored on several dates. Some of the results have been published by Willemsen (1992). The Saturation Index calculated for calcite are presented in Table 2. The SI values are calculated before treatment ("before"), after treatment ("after") and within the warm well (aquifer).

From the results on 13-06-1991 may be concluded that far too much water has been treated during the first two months of operation.

After some research, it was found that the split-control did not function properly during the first two months. Instead of 60%, 100% of the water appeared to have been treated. This problem was caused by an incorrect signal from the flow meter to the split-valve. When this

problem was discovered, the split was changed. In the near future the split will be controlled by a water-hardness meter.

Tabel 2: Saturion index SI for calcite during operation

	13-06-91	29-07-91	30-09-91	05-12-91
Before	+0.28	+0.30	+0.42	- 0.40
After	- 0.05	- 0.08	+0.10	- 0.29
Aquifer	- 1.37	+0.23	- 0.12	- 0.22

Since then, the Saturation Index has been within the proper range, and salt consumption by the softener is according to previous calculations.

A more detailed interpretation of the water chemistry is given in Willemsen (IECEC, 1992).

HYDRAULIC PRESSURES - The hydraulic pressure in the injection well depends on flow rate and temperature. If water is stored with 100 m^3/u (maximum flow rate) and 90 °C, the hydraulic (over)pressure in the warm well is expected to be 1.7 ato. Monitoring results are presented in Table 3.

Table 3: Measured hydraulic pressure in injection well W, when charging the storage.

	01-07-91	29-07-91	29-08-91
Flow rate m^3/h	50	35	45
Temperature °C	70	65	90
Calculated pressure (ato)	0.95	0.75	1.25
Measured pressure (ato)	1.1	0.6	1.1
Difference (ato)	+0.15	-0.15	-0.15

These results indicate that in the first two months of operation a higher flow resistance did occur.

This phenomenon disappeared after some time (see conclusions).

OTHERS - During operation, some minor problems did occur concerning one pump, pipe leakage, and frequency control problems.

During the summer period, the concentrations of soluble gases did not change.

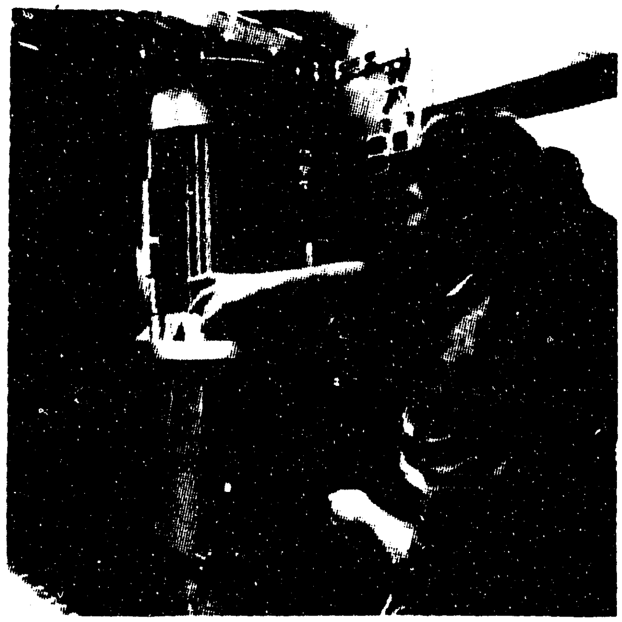

Figure 4: The groundwater engine

CONCLUSIONS

During the design of the high temperature ATES at the University of Utrecht many potential problems were studied and safety measures were taken. During operation, a serious problem was traced by monitoring chemical and hydraulic features. Too much water proved to have beent reated by a Ca/Na exchanger, entailing a danger of clay swelling. High hydraulic pressures on 1-7-1991 indicate that flow resistance was increasing and danger for clogging might be starting. The correlation between Saturation Index and hydraulic pressures have not yet been evaluated.

After solving the technical problem of split-control, the ATES has been functioning without problems, up to 90°C. The project will be evaluated early 1993 in a final report.

LITERATURE

Loon, L.J.M. van, and A. Paul (1991)
Aquifer thermal energy storage at the University of Utrecht, the Netherlands
Proc. Thermastock '91. pp. 1.3-1 to 1.3-7.

Willemsen A., and M.J.J. van der Weiden (1991)
Heat losses and groundwater chemistry of the Utrecht Univesity ATES.
Proc. Thermastock '91. pp. 4.12-1 to 4.12-7

Willemsen A. (1992)
PHREEQM-2D A Computer Model to Calculate Geochemical Reactions During Transport of Ground-water: Model Description and Application to the Utrecht University.
Proceedings IECEC Conference San Diego.

Well, Hydrology, and Geochemistry Problems Encountered in ATES Systems and Their Solutions(1)

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Abstract

In aquifer thermal energy storage (ATES) systems, wells provide the interface between the energy storage and use. Efficient operational wells are, therefore, essential for the system to run at maximum (design) efficiency. Adequate test drilling to accurately predict aquifer properties is essential in the design phase; proper construction and development are crucial; and proper monitoring of performance is necessary to identify the early stages of clogging and to evaluate the adequacy of well rehabilitation. Problems related to hydrology, well, and aquifer properties include 1) loss of permeability resulting from gas exsolution, chemical precipitation, and dispersion and movement of fine-grained particles; 2) loss of recoverable heat caused by excessive regional ground-water gradient, hydrodynamic mixing of injected and native ground water, buoyancy flow (because of temperature-induced differences in water density); 3) leakage up along the well casing; and 4) "fracturing" of a shallow upper aquiclude as a result of an injection pressure greater than the hydrostatic pressure on the aquiclude.

The predominant geochemical problems encountered are precipitation of carbonates in some areas and iron plus manganese oxides in others. These precipitation problems can be anticipated, and thus avoided, via geochemical calculations. The likelihood of iron carbonate ($FeCO_3$) precipitation is less certain because of the lack of adequate research. Corrosion is a frequent problem.

Most of the hydrochemically related clogging and corrosion problems that have been encountered in ATES systems can be predicted and avoided by appropriate design, construction, and operation of new ATES systems, assuming that a comprehensive and careful site investigation that includes appropriate hydrologic and geochemical modeling is carried out in advance. Because of local variations in hydrology and water chemistry, each project must be carefully examined and the installation planned based on a knowledge of the kind of problems that could be encountered and site conditions. It is prudent to carefully consider the need for water treatment and to anticipate that there will be some increase in injection pressure and decrease of specific capacity over time. Therefore, the design should include 1) the capability to monitor the specific capacity, 2) an injection pressure control, 3) a permanent backflush system, and 4) a safety valve.

INTRODUCTION

Aquifer thermal energy storage (ATES) systems make it possible to achieve large storage volumes, hence a large potential energy transfer, and obtain economy of scale, particularly if local ground-water gradients are small. A driving force for alternative energy forms is Europe's quest for energy self sufficiency (Rybach et al. 1988, Louwrier et al. 1988).

During the early studies of Iris (1979) and colleagues at the Ecole des Mines de Paris, the concept of seasonally recharging a solar/geothermal doublet was developed and commercialized for an urban area containing 200 housing units near Paris, France (Hadorn et al. 1990). Since then the majority of ATES systems involve the doublet concept. However, because of the loss in recoverable heat caused by buoyancy flow experienced at Colombier, near Neuchatel, the second Swiss ATES site (known as SPEOS) utilized a novel radial drain design in separate but adjacent aquifers.

China clearly leads in utilization of chill storage having had "several years of experimentation" by 1965 (Yan and Woo 1981), with as many as 500 wells in Shanghi province alone (Lundin 1990). There are various other heat and/or chill storage sites not included in this review because they were not reported in our primary sources.

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Many ATES systems have storage temperatures in the range of 12 to 40°C, but there have been only six with temperatures of >85°C (Horsholm, Mobile, Plaisir, SPEOS, St. Paul, and Utrecht; Lundin 1990, Molz et al. 1983, Willemsen 1992).

The objective of this paper is to review the technical design and implementation problems encountered to date in ATES systems worldwide, examine the extent to which these problems are unique to ATES as opposed to generic problems known to the applicable disciplines, and identify the solutions exploited to resolve these problems so that they can be avoided in future ATES systems.

The scope of this review includes those ATES systems that have been recorded in the Seasonal Thermal Energy Storage (STES) newsletter, the JIGASTICK'88 and THERMASTOCK'91 conference proceedings, or are included within International Energy Agency (IEA) Annexes III, VI, and VII and for which enough information was found to make a meaningful entry into the Appendix table. Thus, the review is not all-inclusive but does include the majority of all experimental and commercial ATES sites. Economic and environmental aspects of ATES systems are not considered in this paper. The information collected on problems and solutions has been summarized in the Appendix along with selected key information pertinent to the problem encountered. In the following text, ATES sites are referred to by their identification in the table (acronym, company, or city).

WELL DESIGN AND CONSTRUCTION

In ATES systems, wells provide the interface between the energy store and the remainder of the system; therefore, they are critical for the successful operation of the total system. Thus, wells need to be carefully designed, drilled, and completed to prevent operational problems.

DESIGN CONSIDERATIONS - In a storage system, individual wells are generally used both for production and injection. Thus, they are operated under both hydraulic drawdown and pressure buildup conditions. For the latter case, this normally means a tight well-head construction to avoid gas escape and a pressure relief device to avoid excessive pressure. On the other hand, if the water level is low, a negative pressure can occur. In this case, airtight construction is necessary to avoid oxidation of Fe^{II} by atmospheric oxygen; either a set of injection tubes of different diameters and/or a down-hole throttle may be necessary during the injection phase to prevent exsolution of dissolved gas and clogging of the aquifer with gas bubbles and/or precipitates.

Because water almost always contains some particulates, most injection wells will clog with use. However, it has been shown that well performance after clogging from silt and sand-sized particulates can easily be restored by backflushing (Andersson 1988). However, specific capacity may be only partially restored if the clogging is due to clay-sized material or amorphic precipitates that may result from water clarification. If it is expected that frequent backflushing will be needed, it is advisable to design wells with a permanent backflushing system.

CONSTRUCTION ASPECTS - Even drilling a well in an unconsolidated formation involves a risk of clogging, especially if a non-biodegradable mud is used as a drilling fluid. In this case, clogging is caused by fine-grained sediment entering the more permeable parts of the formation and lodging there (Glenn and Slusser 1970).

A loss of gravel pack permeability can occur while the screen and the gravel pack are being emplaced. If these components are not carefully installed, formation sediment may be admixed with the gravel pack, resulting in a permanent loss of permeability. Particle migration and bridging of pores during well operation, especially at high flow rates, may also result in clogging (Andersson 1988).

Short-circuit flow along a casing may have been the cause of the breaching of the upper confining at the Mobile site, allowing the mixing of the thermally altered water with native ground water (Molz et al. 1978). This occurs as a result of an inadequate seal above the gravel pack and upwards along the casing.

It is obvious that inadequate well design, improper drilling, or inadequate well construction can cause severe damage to the total ATES system. Therefore, adequate test drilling to accurately predict aquifer properties is essential in the design phase of the project. It is then up to the engineer and the well driller to carry out their work skillfully. To reduce potential drilling and well construction errors, some simple but important "guidelines" can be stated (Andersson 1990): 1) use biodegradable polymers instead of clay minerals (e.g., bentonite) in the drilling fluid, 2) before setting screen and gravel pack, circulate water until the hole is clean, 3) design screen slot size and gravel pack carefully to avoid sand production or clogged gravel pack, 4) spot weld down-hole pipe connections so that they cannot loosen and allow air entry, and 5) develop the well (e.g., by airlift) until the water is free of particulates and no sand is circulating.

HYDROGEOLOGY

FREE CONVECTION OR BUOYANCY FLOW - Buoyancy flow is the flow in the aquifer that is driven by the difference in density between hot and cold water (or between saline and fresh water). Buoyancy flow occurred at all sites where storage occurred at relatively high temperatures in aquifers with a high permeability, i.e., Bunnik, Colombier, Horsholm, Dorigny (SPEOS), Campuget, and Mobile. Buoyancy flow can not be prevented for given hydrogeologic and storage conditions, such as thickness and permeability of the aquifer on the one hand, and temperatures and amounts of water on the other hand. However, the amount and effect of buoyancy flow within a cycle can be reduced and the effect of buoyancy flow on the storage efficiency can be greatly minimized by implementing one or more of the following design measures:

- Inject warm water over the full height of the aquifer and produce water only over some upper part of the aquifer as was done at Mobile, Horsholm, and Delft. The results from tests at Mobile and theoretical calculations on the subject by Buschek et al. (1983) show that this can significantly increase the thermal efficiency of the store.
- Drill horizontal instead of vertical wells as was done at Dorigny (SPEOS). When there are two levels of wells and the "warm" wells are above the "cold" wells, there will be a layered store, as with short-term storage in tanks. In such a situation, the density difference will cause a stable situation when the lighter water is above the heavier, colder water. At Dorigny (SPEOS), it was subsequently found that there was a low-permeability layer between the hot and the cold wells and that heat loss to the surface could be lowered significantly by switching the cold wells and warm wells.
- Prevent vertical flow through the (vertical) wells when pumping is stopped. At Bunnik, it was found that vertical flow through wells occurred and contributed significantly to the buoyancy flow. Vertical flow was subsequently prevented by placing a packer in the warm well, which was manually closed when the store was not used. In practice it was found, however, that the packer leaked the nitrogen gas used to close the packer. This gas caused high pressures at the top of the warm well.

BREACHING OF CONFINING LAYER - When the injection pressure becomes higher than the minimum pressure required to lift the confining layer, the confining layer will breach and the water will flow to the surface. This phenomena is known from artificial recharge (Olsthoorn 1982) and from injection carried out to minimize subsidence caused by a lowering of the groundwater table (Rijkswaterstaat 1986). In general, the rule can be used that the injection pressure in meters of water head above the surface level should not be larger than 0.2 times the depth of the top of the screen below land surface. For the final design of an injection well, an accurate calculation of the allowed injection pressure should be made, taking into account the weight of the total column of rock and water above the top of the screen or above the top of the aquifer (whatever is the most critical point) and the angle under which the matrix is likely to start to move. Breaching of the confining layer occurred at Horsholm and may have occurred at Mobile. At Horsholm, a pressure transducer that should have shut down the system before too high an injection pressure was reached did not function properly. This is not an isolated occurrence, as pressure transducers at St. Paul also failed.(2) At Mobile, it was speculated that the failure may have been caused by piping along a improperly sealed well casing rather than breaching the aquiclude (Molz et al. 1978).

In general, breaching of the confining layer can be prevented by an adequate design of the storage system. Account should be taken of the necessary injection pressure during maximum flow and of possible clogging. Also, safety measures should be taken such that the system shuts off above a certain injection pressure. These safety measures should not depend on a single pressure transducer.

THERMAL BREAKTHROUGH - The injection and production wells should be at an optimum distance from each other that should allow for the maximum required amount of energy to be stored. Whether any influence of one side on the temperatures at the other side is desired depends on the injection temperatures with respect to the natural ground-water temperatures. If the injection temperatures at the "warm" and "cold" sides of the store are such that the natural ground-water temperature is between those temperatures, then thermal breakthrough is undesirable. Undesirable thermal breakthrough occurred, for example, at Kristianstad. If, on the other hand, "warm" and "cold" sides have injection temperatures that are both below or above the natural ground-water temperature, then some thermal breakthrough is wanted. Kowalczyk and Havinga (1991) performed calculations on the thermal efficiency of a store as a function of well distance. They showed that the optimum well distance depends on the type (heat, cold, or combined) and the temperatures of the store. In case the injection temperatures are on both sides of the natural ground-water temperature, the radius of influence of cold and warm well (Rth) should not reach each other (well distance larger than 3 times Rth). In the other case the wells should be in each other's range of influence (well distance approximately 1 to 2 Rth). The potential for thermal breakthrough depends of course also on the regional flow, the direction of this flow with respect to the locations of the wells and on the existence of preferential flow paths.

PREFERENTIAL FLOW PATHS - Aquifers normally exhibit higher permeability in some layers than in others, resulting in a greater volume of water being injected into the higher permeability layer(s). The effect of variable permeability layers is to increase the surface area of the store and, therefore, the thermal losses. The flow of thermally altered water to a greater distance in some layers than other, cannot be prevented, but the following countermeasures can be taken to prevent excessive losses caused by preferential flow paths.

- If feasible, use (screen) only the part of the aquifer exhibiting similar permeability values.
- Contrary to the standard practice with water production wells of using the maximum slot size and gravel pack grain size that is allowed by the grain size in the aquifer, for ATES wells an (small) increase in resistance to flow across the screen and gravel pack may be beneficial by causing the injected water to be distributed more uniformly over the various aquifer

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(2) M. Hoyer, Oral Communication.

layers. This approach will, of course, reduce the specific capacity.

REGIONAL FLOW - Where regional gradients in pressure head in the aquifer are relatively large and the permeability of the aquifer is high, there will be a significant regional flow that will cause part of the stored energy to be lost. Significant losses from regional flow occurred at Bunnik, Dorigny (SPEOS), and Tuscaloosa (Schaetzle and Brett 1989). The losses caused by regional flow can be minimized by altering the upstream head or effective permeability by developing

- An active gradient control or "bypass" for the regional flow wherein the upstream head is reduced by pumping from one or more wells upstream of the store to one or more downstream wells (transfer to surface water as is now done at Tuscaloosa). Willemsen and Groeneveld (1989) showed with computer calculations that such a bypass can effectively reduce the effect of the regional flow on the thermal efficiency of the store to zero.
- Passive gradient control wherein the impact of regional flow is minimized by judicious control of pumping schedules can be effective if the regional flow is not too great (Schaetzle and Brett 1989).

Both of these methods to decrease the extent of the regional flow through the aquifer store require significant investments, and care must be taken to ensure that they are cost effective. A low-permeability screen is only feasible in shallow aquifers. Other methods that may be used to reduce the loss in the efficiency of the store without actually reducing the regional flow itself are to

- Inject into the store upgradient of the recovery well. This requires that the quality of the energy in the upstream part is higher, the wells are in line with the regional flow, and that the warm and cold sides are both higher or lower than the natural ground-water temperature. Otherwise, steps must be taken to minimize thermal breakthrough, which means that the wells have to be placed orthogonal with respect to the regional flow.
- Inject more water in the upstream than downstream well and/or produce more from the downstream than in the upstream well. This implies that the wells on each side have to be placed in the direction of flow.

However, application of these methods may also involve significant cost.

GEOCHEMICAL SCALING AND CLOGGING

As is evident from the Appendix table, scaling of heat exchangers and clogging of wells, gravel pack, adjacent aquifer caused by chemical precipitates has been frequently encountered in existing ATES systems, especially the precipitation of carbonates in the systems operating above 85°C and Fe and Mn oxides in low temperature (<40°C) systems.

CARBONATES - Scaling (i.e., precipitation within the above-ground portion of an ATES system) and precipitate-induced aquifer clogging (i.e., reduced aquifer permeability caused by precipitation within the aquifer) results from carbonate and Fe plus Mn oxide precipitation. Problems with carbonates has occurred at St. Paul, Dorigny (SPEOS), Horsholm, and Plaisir (Appendix). Extensive clogging occurred at St. Paul because the engineers and geologists involved were unaware of the inverse solubility of carbonate minerals with temperature. Subsequently, the quantity of carbonate available for precipitation was underestimated; hence, precipitation cylinders clogged within a day or so because of the extensive precipitation that occurred. A Na-ion exchange system was subsequently installed that has been essentially trouble-free. At Dorigny (SPEOS), carbonate precipitation was prevented by adding acid for some years; but, the acid addition was terminated because of increasing Cl concentration and hardness levels of the water. Since then, there has been continuing experimentation with a variety of physical approaches ("non-sticking heat exchanger coatings," recirculation of plastic balls), alkali addition to raise the pH, and fluidized bed heat exchangers. However, these treatments resulted in fine-grained carbonate precipitates that have frequently clogged the well/aquifer interface. At Horsholm, as at Dorigny (SPEOS), acid addition was used to prevent carbonate scaling. Aquifer clogging at Plaisir occurred when the treatment control system failed. In the later stage of this project, a cation exchanger was installed and no further carbonate clogging was encountered.

Thus, Na-exchange resins provide a trouble-free method of avoiding carbonate scaling and clogging, as long as care is taken to ensure that clay swelling and/or dispersion does not occur and the disposal of the acid or salt used to recharge the resin is not a problem. The likelihood of clay swelling/dispersion can be estimated from the sodium adsorption ratio and used in conjunction with the salinity of the water. An environmental consequence of the cation exchange method is that sizable amounts of either salt or acid, used in recharging the exchange resin, must be discharged to surface or ground water.

Although not yet implemented in other than an experimental mode, a fluidized bed heat exchanger with an in-line activated carbon column to remove dissolved organic carbon has recently been successfully tested.(3)

IRON AND MANGANESE HYDROXIDE PRECIPITATION - The precipitation of Fe and Mn oxides is caused by a change in water chemistry. Precipitation of Fe^{III} oxides can be induced by increasing either the redox potential (Eh) or the pH. As illustrated in the Fe stability field diagram shown in Figure 1, if either the Eh or pH of a slightly reduced water (point A in the diagram) is increased, precipitation of Fe oxides is likely. Not shown on this figure is the effect of Fe concentration; as Fe concentration increases, its oxide will precipitate at progressively lower Eh and pH values. In practice, there

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(3) A. Willemsen, Unpublished Data.

are at least three processes involved to create the Eh and pH changes. Those are (Andersson 1990) 1) oxygen is added from some source and the Eh value is increased (displacement from A to B in Figure 1); 2) waters differing in their Eh status are mixed upon entering the well causing either an increase or decrease in Eh and possibly pH (A to B or B to A); or 3) carbon dioxide escapes from the water, increasing the pH-value (A to C). The latter process is also believed to be one of the main factors causing the precipitation of carbonates in a production well with little or no scaling in the heat exchanger. Where there are significant Fe concentrations, Fe carbonate rather than Ca carbonate may precipitate. Although definitive information is not yet available, the precipitation of Fe carbonate is suspected at several locations in Sweden (e.g., Lomma). The Fe carbonate precipitate in these cases is not readily solubilized by acid treatment of the well.

Shallow, unconfined aquifers generally have levels of Fe and Mn that are likely to yield oxyhydroxide precipitates if air is allowed to enter the ATES system. Some Fe oxide, along with pyrite, was found on the heat exchanger at Horsholm, presumably the result of partial oxidation of dissolved sulfides caused by air leaking into the system. An air leak in the ATES system at Bunnik caused Fe and Mn scaling of the well screen. Iron oxide precipitation was presumed to be the cause of clogging at Klippan.

However, none of the processes causing Fe oxide precipitation need occur during injection if the system is airtight, and the aquifer is selected or the hydrology is controlled to eliminate the mixing of dissimilar waters near the well. For these reasons, the likelihood of Fe oxide clogging during injection is low in a properly designed system. If for any reason an airtight system is not feasible, any one of a number of iron removal methods may be used (Vail et al. 1992). The principal processes leading to a greater likelihood of clogging in production and injection wells with water containing elevated levels of Fe are illustrated in Figure 2.

CLOGGING BY MICROBIAL GROWTH - Clogging by biofilm or microbial slime is a well-known phenomena in the water-well industry (Driscoll 1986). The most frequent biologically caused well clogging is that associated with iron bacteria, especially the ones belonging to the Gallionella family. However, in a highly reduced environment, clogging can also be associated with sulphur bacteria. In ATES applications, clogging by iron bacteria slime will is a potential risk mainly in low-temperature systems (less than 25° C) and in waters with an iron content of at least 1 mg/L. Other conditions that favor major bacterial growth are Eh values between 200 and 400 mV and pH values between 5.5-7.5.

GAS CLOGGING - Gas clogging may occur as a result of the exsolution of gases present in excess of the amount that would be present at equilibrium with the lowest pressure in the system. This occurred at Delft because of the methane overpressure in the source/storage aquifer, and presumably at Scarborough (see Appendix), but did not occur at Utrecht, because a total pressure sufficient to maintain the dissolved gas in solution was maintained at the latter site.

CLAY DISPERSION - Swelling and dispersion of clays contained within the aquifer sediment occurs when the Na saturation exceeds an amount determined by the ionic strength (i.e., conductivity) of the water (Willemsen 1992). Clay swelling and dispersion are unlikely to pose a problem in consolidated or silica-cemented aquifers even when the water is passed through a Na ion exchanger repetitively, as at St. Paul. However, it is the suspected cause of the last clogging problem encountered at Plaisir.(4) Clay swelling and/or dispersion has been avoided at Utrecht, by treating the minimum fraction of the water necessary to prevent carbonate scaling; no scaling is observed at a calcite saturation indices of 0.6 to 0.7 (Willemsen 1992). A large amount of sediment was recovered at Mobile (Molz et al. 1983). The amount of suspended sediment may have been increased by the use of a foreign water (i.e., local surface water) into the aquifer and/or the inadequacy of the gravel pack.

CORROSION

Both chemical and electrochemical corrosion occur in ATES systems. Chemical corrosion is induced by constituents such as CO_2, O_2, H_2S, dissolved sulfide, chloride, and sulphate. Sites that have used HCl to remove or prevent carbonate precipitation, e.g., Dorigny (SPEOS) and Horsholm, have experienced significant corrosion. Corrosion was also experienced when a pipe connection was not sufficiently tight and allowed a small amount of water to seep through the threaded joint and react with air in the annulas between the riser pipe and the well casing. This leakage water with its dissolved Fe partially oxidized was drawn down to the submersible pump inlet causing Fe precipitation and promoting corrosion (Andersson 1990). Electrochemical corrosion appears to be more frequent than chemical corrosion. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials but electrochemical corrosion also occurs on monometallic components that have been stressed, e.g., welded joints, cut surfaces or damaged coatings. Further, it seems that electrochemical corrosion causes loss of material only on parts of well screens and casings. Usually it occurs in water that is slightly acidic and with total dissolved solids greater than about 1000 mg/L (Driscoll 1986).

Protection against corrosion is in most cases dependent upon the choice of materials for each specific system. For instance, different steel alloys may cope with expected corrosion, as well as plastic materials, ceramics, or corrosion-resistant coatings. A world-wide method for galvanic corrosion protection of wells is to use a cathodic protection system, normally accomplished by connecting a sacrificial anode to the well casing (Driscoll 1986).

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(4) A. Vinsot, Personal Communication.

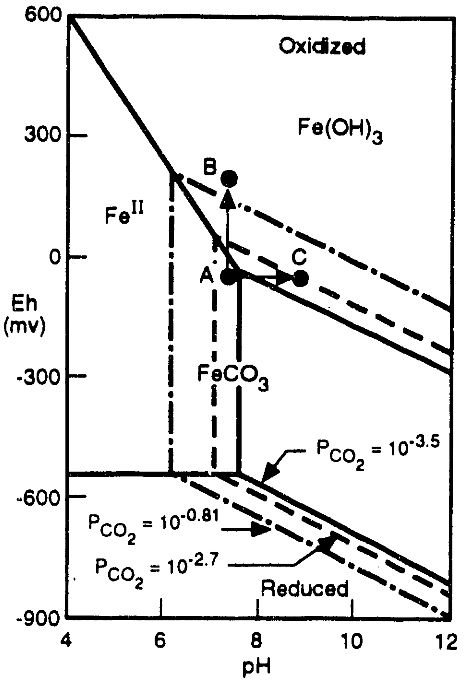

Figure 1. A portion of the Eh versus pH stability field for iron illustrating the likely precipitation of ferric hydroxide and/or ferrous carbonate (siderite) as result of a change in EH or pH (a_{Fe} = 10^{-4} M, temperature = 25°C; after Jenne 1968).

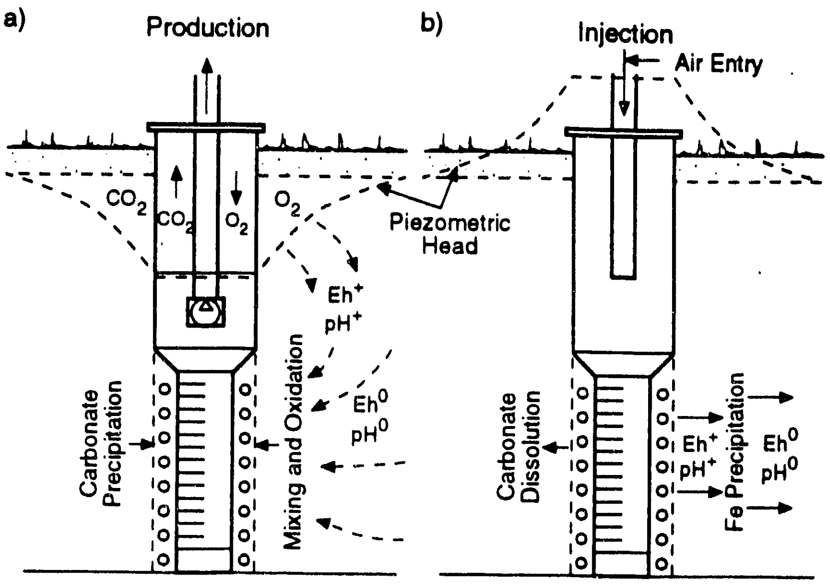

Figure 2. Illustration of hydrologic and geochemical processes that facilitate the precipitation or dissolution of carbonate and/or Fe and Mn oxides in or close to (1) production well in an unconfined aquifer (carbonate and Fe/Mn oxide precipitation) as contrasted to (b) a well where oxygen-containing water that is undersaturated with respect of Fe oxides (e.g., surface water or treated ground water) and carbonate is injected into a confined aquifer.

CONCLUDING DISCUSSION

Most of the hydrochemically related clogging and corrosion problems that have been encountered in ATES systems can be predicted and avoided by appropriate design, construction, and operation of by performing a comprehensive and careful pre-investigation. Because of local variations in hydrology and water chemistry, each project must be carefully examined and the installation planned on the basis of a knowledge of the kind of discussed in this paper that could be encountered and specific site conditions.

Virtually all common hydrologic and geochemical problems have been encountered at one or another of the ATES sites (e.g., buoyancy flow, breaching of confining layer, gravel pack failure, particle clogging, air clogging, methane clogging, precipitation Fe and Mn oxides), in addition to carbonate precipitation which is somewhat unique to ATES and geothermal systems. It is prudent to anticipate some build-up in injection pressure and decrease of specific capacity over time and therefore, to include in the design 1) the capability to monitor the specific capacity, 2) an injection pressure control with more than one transducer, 3) a permanent backflush system, and 4) a safety valve.

Clogging is the most frequent problem encountered in ATES systems. Rapid filtration (e.g., sand, fiber filters) and frequent backflushing is effective against particle clogging. Backflushing may need to be done as frequently as twice daily, as in the chill storage wells in Shanghai province during charging (Lundin 1990). Bacterial biofilms or slime are rarely a problem unless the water being stored is a surface water or has been enriched in nutrients and/or energy substrates. It is presumably for this reason that the water used to cool the cotton mills in Chanzhou is not only filtered three times but is chlorinated twice (Shen 1988, Yong-Fu et al. 1991). Where Fe precipitation is a potential problem, confined aquifers are preferred and care should be taken that CO_2 is not allowed to form a separate gas phase nor to escape. It is also desirable to limit the drawdown to the minimum extent possible.

Iron oxide and Ca carbonate solubility, as well as clay swelling and dispersion calculations have been found reliable in predicting when these problems will not occur. However, not enough experience has yet been gained to allow the prediction of Fe carbonate precipitation. Research on this problems, as well as on the effects of kinetic inhibitors (e.g., DOC, PO_4, Mg) on Ca carbonate precipitation and complexation with dissolved organic carbon on the apparent oversaturation of Fe oxides is underway within Annex VI of the IEA.

Steps to detect and avoid corrosion include 1) not allowing contact between metals or alloys with different electrochemical potentials, 2) not allowing oxygen to enter the system at any point, and 3) avoiding the use of acid to prevent scaling and clogging, and 4) installing a corrosion detector.

CONCLUSIONS

- There is an acute need for greater use of multidiscipline experience in the design and implementation of ATES because most technical problems encountered to date could have been avoided if they had been anticipated in the design, construction, and implementation stage and the appropriate steps taken to prevent their occurrence.
- From a hydrogeological point of view, confined aquifers are strongly preferred over unconfined aquifers, because the potential for mixing of reduced and oxidized waters is much reduced.
- Minimize buoyancy flow losses by injecting thermally altered water over the full height of the aquifer but produce only from the upper part of the aquifer, or drilling horizontal instead of vertical wells.
- Use best available hydrologic modeling to optimize distance between warm and cold wells.
- Losses from excessive regional flow can be minimized through lowering the upstream head by pumping an appropriate distance upgradient of the recovery well and/or by injection at an appropriate distance downgradient.
- Multiple pressure transducers should be included in the design to shut down the system before excessive pressures can cause a breaching of the confining layer.
- Closed and over-pressured systems are generally essential to avoid loss of carbon dioxide and entrance of air.
- Where the ground water contains considerable dissolved gases, a sufficient overpressure must be maintained to avoid the exsolution of these gases to form a discrete gas phase, which can clog the aquifer.
- The drawdown of an aquifer containing significant Fe concentrations during production should be limited to the extent possible, to avoid local degassing and a possible pH rise, by using highly permeable aquifers or additional wells.

REFERENCES

AJ91 Abyhammar, T., S. Johansson, S. Berglung, and A. Eriksson. 1991. The Aquifer Energy System at SAS Main Office in Solna - Evaluation. R14:1991, Swedish Council for Building Research, Stockholm, Sweden (in Swedish).

Andersson, O. 1988. "Injection Well Designing Requires Special Concerns." In Geohydrology in Practice Symposium. VIAK AB, Stockholm, Sweden (in Swedish).

Andersson, O. 1990. "Scaling and Corrosion in Subsurface Thermal Energy Storage Systems." In J.C. Hooghart and C.W.S. Posthumus (eds), Hydrochemistry and Energy Storage in Aquifers. TNO Technical Meeting 48, Ede, The Netherlands.

An92a Andersson, O. 1992a. "Evaluation of the Well Development at Lomma ATES Plant." Swedish Council for Building Research. Stockholm, Sweden.

An92b Andersson, O. 1992b. Operational Monitoring of the Sparven ATES Plant. Consultant Commission Report on Behalf of Telaris, Malmö. VBB VIAk AB, Malmö, Sweden.

BS85 Bruggen, R.J.A. van der and A.L. Snijders. 1985. "Heating of an Office Building Using Solar Energy in Combination with a Heat Pump and Seasonal Heat Storage." In Proceedings ENERSTOCK'85. Public Works Canada, Ottawa, Canada.

BD83 Buschek, T.A., C. Doughty, and C.F. Tsang. 1983. "Prediction and Analysis of a Field Experiment on a Multilayered Aquifer Thermal Energy Storage System with Strong Buoyancy Flow." Water Resources Res. 19:1307-1315.

Da91 Dalton, M. 1991. Questionnaire for Review of Cold Storage Projects within IEA-Annex 7. Hickling Corp., Ottawa, Canada, February 1991.

Driscoll, F.G. 1986. Groundwater and Wells. Second Edition. Johnson Division, St. Paul, Minnesota.

EH83 Emmelin, A., H. Hydén, and L. Lemmeke. 1983. Storage of Surface Water in a Sand Aquifer for the District Heating System in Klippan. R146:1983. Swedish Council for Building Research, Stockholm, Sweden (in Swedish).

Glenn, E. and M. Slusser. 1970. "Factors Affecting Well Productivity." Series of Articles in Well Completions, Petrol. Trans. Reprint, Series No. 5, Soc. Petrol. Eng., Dallas, Texas.

GR89 Gustafson, G., P-A. Ryttar, and K. Norback. 1989. Storage of Heat by Induced Infiltration of Surface Water. R30:1989. Swedish Council for Building Research, Stockholm, Sweden (in Swedish).

HM91 Haak, A.M. and B. Minnema. 1991. "National Testing Facility for Cold and Heat Storage in Aquifers, The Netherlands. First Experience: Well Injectivity Potential." In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

HC90 Hadorn, J-C., D. Chuard, P. Jaboyedoff, and P. Chuard. 1990. Guide to Seasonal Heat Storage. SIA, Swiss Federal Energy Office and Swiss Association of Engineers and Architects, Zurich, Switzerland. (Originally published in Switzerland in 1987, Translated into English in 1990 by J. Boake for Public Works Canada.)

HE91 Hoyer, M.C., S.J. Eisenreich, N.L. Holm, T.R. Holm, R. Kanivetsky, M.A. Jirsa, H.C. Lee, H.L. Laure, R.T. Miller, J.L. Norton, and H. Runke. 1991. The University of Minnesota Aquifer Thermal Energy Storage (ATES) Field Test Facility - System Description, Aquifer Characterization, and Results of Short-Term Test Cycles. PNL-7220, Pacific Northwest Laboratory, Richland, Washington

IQ91 Ibsen, L., B. Qvale, and C. Boesen. 1991. "Windup of the Danish Aquifer Thermal Energy Storage Plant. Answers Gained and Questions Remaining," In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

Iris, P. 1979. "Héliogéothermie à faible profondeur avec pompe à chaleur associée." Expe'rimentation de stockage de chaleur interaisonnier en nappe phre'atique a' Campuget (Gard) Rapport Plan Construction, Pairs (Cited in Hadorn 1990).

Ir80 Iris, P. 1980. "Experimental Study of Heat Storage in Aquifer," in C. den Ouden (ed) Thermal Energy Storage of Solar Energy. Martinus Nijhoff, The Hague, The Netherlands.

IV88 Iris, P. and P. Viennot. 1988. "An Example of Heat Pumps on Aquifer for Collective Dwellings: Comments After 5 Years of Operation." In Proceedings JIGASTOCK'88. AFME, Paris, France.

IV85 Iris, P., P. Viennot, J.Y. Ausseur, and J.P. Sauty. 1985. "Heat Storage and Heat Pumps on Aquifer - Two Case Studies," In Proceedings ENERSTOCK'95. Public Works Canada, Ottawa, Canada.

Jenne, E. A. 1968. "Controls on Mn, Fe, Co, Ni, Cu, and Zn Concentrations in Soils and Water - the Significant Role of Hydrous Mn and Fe Oxides." Advances in Chemistry 73:337-387. American Chemical Society.

KL91 Kooiman, L. and L.J.M. van Loon. 1991. "Demonstration Project: Perscombinatie NV Amsterdam: Cold Storage in Aquifer." In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

Kowalczyk, W. and J. Havinga. 1991. "A Case Study on the Influence of the Distance Between Wells on a Doublet Well Aquifer Thermal Performance." In Proceedings THERMASTOCK'91 NOVEM, Utrecht, The Netherlands.

Kr91 Kronqvist, L. 1991. Aquifer Energy Storage - Evaluation of Kristianstad. R40:1991. Swedish Council for Building Research, Stockholm, Sweden (in Swedish).

LH92 Loon, L.J.M. van, and K. van der Holde. 1992. "High Temperature ATES at the State University of Utrecht, The Netherlands." (this proceedings).

LP91 Loon, L.J.M. van, and A. Paul. 1991. "Aquifer Thermal Energy Storage at the State University of Utrecht, The Netherlands." In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

Louwrier, K., E. Staroste, and J.D. Garnish. 1988. "Geothermal Research in the European Community." In Proceedings JIGASTOCK'88 1:37-43. AFME, Paris, France.

Lu90 Lundin, S-E. 1990. "Heat Storage in Aquifers." In Proceedings JIGASTOCK'88 3:971-975. AFME, Paris, France.

Mi92 Mirza, C. 1992. Aquifer Thermal Energy Storage System Canada Center Building, Scarborough, 1992 Well Efficiency Testing. File S•92•331 (dated 1992•04•13). Strata Engineering Corp., Don Mills, Ontario, Canada.

MM83 Molz, F.J., J.G. Melville, O. Guven, and A.D. Parr. 1983. Design, Performance and Analysis of an Aquifer Thermal Energy Storage Experiment Using the Doublet Well Configuration. PNL-4849, Pacific Northwest Laboratory, Richland, Washington.

ML85 Molz, F.J., J.C. Warman, and T.E. Jones. 1978. "Aquifer Storage of Heated Water: Part I - A Field Experiment." Ground Water 16:234-241.

Olsthoorn, T.N. 1982. Clogging of Recharge Wells. KIWA, Rijswijk, The Netherlands (in Dutch; short English version available).

PD91 Pfiffer, M. M. Durin, J. Despois and B. Fritz. 1991. "The Heat Storage Project at Plaisir-Thiverval-Grignon (France)." In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

Rijkswaterstaat. 1986. Groundwater Infiltration in Bored Wells. Rijkswaterstaat, The Hague, The Netherlands.

Rybach, L., A. Feur, and D. Roux. 1988. "The Swiss System of Government Risk Coverage for Geothermal Drilling." In Proceedings JIGASTOCK'88 1: 19-21. AFME, Paris, France.

SG91 Saugy, B., O. Graf, S. Ward, S. Germano, E. Recordon, R. Crottaz, F. Favrat, J.M. Colomb, P.A. Riedo, and J.P. Baraben. 1991. "Project SPEOS5-Recent Developments." In Proceedings THERMASTOCK'91 1.17, 6 p. NOVEM, Utrecht, The Netherlands.

SG82 Sauty, J.P., A.C. Gringarten, H. Fabris, D. Thiery, A. Menjoz and P.A. Landel. 1982. "Sensible Heat Storage in Aquifers - Part II: Field Experiments and Comparison with Theoretical Results." Water Resour. Res. 18:253-265.

SB89 Schaetzle, W.J. and C.E. Brett. 1989. The Aquifer Chill Storage Project at the University of Alabama, Tuscaloosa: Progress Report for 1985 and 1986. PNL-6797, Pacific Northwest Laboratory, Richland, Washington.

Sh88 Shen, G.J. 1988. "Research on Energy Storage In the Underground Water and its Quality in Changzhou City." In Proceedings JIGASTOCK'88 1:337-341. AFME, Paris, France.

ST85 Shen, G.J., Y. Tang, and B.Q. Pang. 1985. "Research on Energy Storage in the Underground Water and its Quality in Changzhou City." In Proceedings IIIrd International Conference on Energy Storage for Building and Cooling. Public Works Canada, Ottawa, Canada.

SZ88 Shen, G.J. and Y. Zheng. 1988. "The Characters of Land Subsidence and Mechanism Analysis of Changzhou City." In Proceedings JIGASTOCK'88 2:843-846. AFME, Paris, France.

SS82 Supkow, J. and J.A. Shultz. 1982. "Analysis of Reinjection Problems at the Stony Brook ATES Field Test Site." STES Newsletter IV:5.

Vail, L.W., E.A. Jenne, and L.E. Eary. 1992. "H2O-*TREAT*: A Software Aid for Evaluating Water Treatment Requirements for Aquifer Thermal Energy Storage. (this proceedings).

VC91 Vinsot, A. and A. Coudrain-Ribstein. 1991. "Geochemical Impact of A Seasonal Heat Storage in an Aquifer in Trappes, France: Field Measurements and Mathematical Modelling." In Proceedings THERMASTOCK'91. NOVEM, Utrecht, The Netherlands.

Wa84 Walton, M. 1984. "Status of St. Paul Minnesota Energy Storage Project." In Summary of Presentations Fifth Expert Meeting, IEA Energy Conservation Through Storage Annex III, p. 115-135. Lausanne, Switzerland.

Willemsen, A. 1992. "PHREEQM-2D: A Computer Model to Calculate Geochemical Reactions During Transport of Groundwater - Model Description and Application to the Utrecht University ATES." (this proceedings).

WG89 Willemsen, A. and G.J. Groeneveld. 1989. "Environmental Impacts of Aquifer Thermal Energy Storage (ATES): Modeling of the Transport of Energy and Contaminants from the Store." In G. Jousma et al. (ed), Groundwater Contamination: Use of Models in Decision Making. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Yan, Q.-S. and T.-F. Woo. 1981. "The Development and Application of Aquifer Storage in China." STES Newsletter III:4-5.

YQ91 Yong-Fu, S., L. Qin-fen, and W. Ji-hong. 1991. "The Experiment of Storing Cold and Warm Water in Aquifer in Shanghai, P. R. China and Its Effect." In Proceedings THERMASTOCK'91, 1.1, 7 pp. NOVEM, Utrecht, The Netherlands.

APPENDIX

Key Aspects of Experimental and Commercial Aquifer Thermal Energy Systems from Selected Literature Sources (as of May 1992; C = Commercial, E = Experimental; Alphanumeric reference designations are given at left margin of Reference section.)

Site, Country	Years Operated/ C or E	Recovery Temperature Range Warm	 Cold	Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
		------°C-------						
Carlton, Canada	1/C	14/11	7/8	Sandstone/Confined	Not given	None	None	Da91
Scarborough, Canada	5/C	50/20	3/10	Glacifluvial sand/ Confined	7.8/1.0/90/3	None	Degassing of methane clogged aquifer and building explosion danger caused pump shut down (mechanical and acid treatment planned)	Mi92
Winpak, Canada	6/C	15/4	7/9	Limestone/Confined	Not given	None	None	(1)
1st National Cotton Mill, Chanzhou, China	3/C		16/12	Fluvial fine to coarse sands/ Confined	--/0.08/--/--	Filtered (3 times), chlorinated (3 times)	Clogging near well caused presumably to Fe and Mn dissolution and reprecip-itation (minimize O_2 in stored water, back flush frequently)	Sh88 SZ88
Shanghai, China	Several/C	40/20	_/1	Quaternary sand & gravel/Confined	"semi-salty"	Use tap water	Corrosion (fill store with tap water, pressure-filter before reinjection)	YQ91
Hoorsholm, Denmark	6/E	100/65	50/70	Glacifluvial sand/ Confined by boulder clay	7.2/4.0/80/30	Acid + degassing	Clogging of central well due to delayed carbonate precipitation (acid treatment); Leakage through confining clay aquilide due to excessive pressure (used alternate well); Severe corrosion caused by acid treatment (reduce acid usage); Heat exchanger scaling and clogging of injection well caused by Fe oxidation (restored by mechanical cleaning and acid treatment)	IQ91
Aulnoy sous bois, France	5/C	13	7	Sand/Confined	--/--/0.6/ --	None	Some clogging of injection well due to aeration and Fe precipitation (closed system with respect to air and acid treated well)	IV88 IV85
Bonnaud, France	1/E	33		Sand/Confined		None		SG82
Campuget, France	1/E	33/16		Sand + gravel/Unconfined		None	Buoyancy flow and/or preferential flow lowered thermal efficiency; Aquifer polluted with bacteria from above ground greenhouses (plan to close system and/or use disinfectants)	Ir80
Montruell sous bols, France	2/C	26/20		Sand/Confined	None		Clogging of injection well, possibly due to migration of fines (Lowered maximum flow by changing the on/off regulation to frequency regulation of the pump)	IV85

Site, Country	Years Operated/ C or E	Recovery Temperature Range Warm ------°C	Recovery Temperature Range Cold -------	Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
Plaisir (Thiverval-Grignon), France	3/E	120/80		Sand with clay layers/Confined	"Soft"	1. Precipitation with lime, Al, and $FeCl_3$ 2. Na exchange	Clogging of wells and corrosion due to aeration in the lime treatment (changed treatment to Na exchange); Clogging of aquifer possibly due to clay dispersion resulting from Na treatment	PD91
Trappes, France	3/C	50/25		Sand/Confined	--/160/--/70	NCl-addition	Clogging of well (add acid)	VC91
Amsterdam, Netherlands	5/C	10/12	5/8	Sand + gravel/Confined	7.1/450/7/5000	None	None	KL91
Bunnik, Netherlands	5/C	26/18	10	Sand + gravel/Confined	7.2/140/10/50	Injection of soft Fe-free tap water	Recovery efficiency decreased by regional and buoyancy flow enhanced by buoyancy flow between wells during shut down (Install packer in store well); Minor clogging of injection well by Fe due to leakage of air into the system (made system air tight)	BS85
Delft, Netherlands	2/E	12	7/12	Sand + gravel/Confined	6.7/290/30/1200	None	Clogging of wells due to exsolution of CH_4 gas due to pressure drop (degas before injection or keep pressure on system)	HM91
Utrecht, Netherlands	1/C	90/50	45/30	Marine silty sand/ Confined	8.0/50/1/400	Na exchange	None	LP91
Falun, Sweden	6/C	14/8	2/4	Esker/ Unconfined	6.8/3.5/30/20	None	Scaling of heat exchanger by iron (frequent acid flushing)	GR89
Klippan, Sweden	8/C	17/9	5/11	Glacial outwash/ Unconfined	8/4/50/40	None	Clogging of warm wells by iron (abandoned and replaced with infiltration ponds)	EH83 (2)
Kristianstad, Sweden	8/C	25/22	10/16	Sandstone/ Semiconfined	8.0/0.2/80/20	None	Thermal breakthrough to cold well (less warm water injected)	Kr91
Lomma, Sweden	4/C	20/12	3/5	Glacifluvial sand/ Confined	7.3/6.5/85/130	None	Clogging of wells during production (acid treatment with limited success; experimental treatment planned)	An92a
SAS Office, Sweden	5/C	15/8	2/12	Esker/Unconfined	7.0/<0.1/170/140	None	Iron clogging of one well (acid treated); Leak in suction pipe to well pump (repaired)	AJ91
Sparven, Sweden	1	15/13	2/5	Limestone/ confined by boulder clay	6.9/0.5/220/2000	None	Corrosion on well pumps caused by air entrance (made system air tight); Leakage caused by excessive pressure (removed constricting backflow valve)	An92b
The Triangle, Sweden	2/C	15/13	2/5	Limestone/ Confined by boulder clay	7.7/0.5/170/250	None	Unreliable control valve (replaced); Heat exchanger clogged by gravel (changed pump)	(3)

Site. Country	Years Operated/ C or E	Recovery Temperature Range Warm ------°C-------	Cold	Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
Columbier-Robinson, Switzerland	1/E						Low recovery efficiency caused by buoyancy flow (abandoned)	HC90
SPEOS, Dorigny (Lausanne), Switzerland	10/C	80/35		Glacifluvial sandy; clay layer between 2 aquifers	7.4/--/80/30	Acid	Carbonate scaling and clogging. (1982-85: wash exchanger and store with HCl. 1986-89: lower pH with HCl); Increasing HCl concentration and corrosion (1990: fluidized bed heat exchanger); aquifer clogging (1991: acid wash)	SG91
Mobile, Alabama, U.S.	5/E	56/36 54/29 52/39		Confined	7/<0.1/4/20		Bouyancy flow (changed screened depth); Clogging from >5 µm suspended solids in surface water (use aquifer water); Clogging from suspended solids (sand filtration, periodic back pumping with surging) and gas (vent gases); Leakage through upper aqnuclide (avoid excessive injection pressure)	MM83
Melville (Long Island), New York, U.S.	2			Glacial Outwash/ Unconfined	--/20/15/27		Air and iron clogging (drill new wells in area where aquifer contains less Fe); gravel pack failure (repacking will be required); Low chill recovery efficiency due to high regional flow rate	(4,5)
St. Paul, Minnesota, U.S.	11	97/39		Cemented sandstones/ Confined	8/2/50/2	Na exchange	Carbonate scaling of heat exchanger and aquifer clogging (water treatment)	Wa84 HE91
Stony Brook, New York, U.S.	1/E	50/45		Glacial outwash/Unconfined but "Leaky"	7/1/2/6	None	Clogging from suspended sediment (filter water); Iron clogging (add Na sulphite and back flush)	SS82
Tuscaloosa, Alabama, U.S.	10/C		7			None (sand filter)	Chill recovery efficiency low as a result of high regional groundwater flow (modify well operations pump ground water to surface water to counteract regional flow)	SB89

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(1) Martin, J. 1991. Personal communication. MCW Consultants Limited, Vancouver, British Columbia, Canada.
(2) Lemmeke, L. 1992. Oral communication.
(3) Landberg, J. 1992. Evaluation of the Combined Warm and Cold Storage at The Triangle, Malmö. Swedish Council for Building Research, Stockholm, Sweden. (In preparation).
(4) H.F.H. Fu. 1991. Unpublished data.
(5) L.W. Vail. 1992. Personal communication.

Injection of CO_2 for the Inhibition of Scaling in ATES Systems

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ABSTRACT

A new water treatment method for the prevention of carbonate scaling is described. This method uses carbon dioxide for adjusting the water to fulfill Tillmans Equilibrium. The pH is lowered and therefore no scaling occurs.

The experimental plant used in the experiments is sketched and results of a field test in a Swiss ATES system are presented. This water treatment method proved to be economical, effective and environmentally beneficial.

INTRODUCTION

Scaling in heat exchanger and piping systems due to the precipitation of carbonate minerals is a problem in many ATES systems with high temperatures (Wagner et al., 1988). As a 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 German working group developed a new water treatment method for the prevention of this scaling. The objective of ATES is the saving of energy and therefore protection of the environment. If a conventional water treatment method is needed to prevent carbonate scaling, this goal is endangered at least partially. The water treatment method using CO_2 was developed to avoid negative effects to the environment.

PRINCIPLE

Difficulties with chemical precipitation in heat exchanger and piping systems are mainly caused by displacements of Tillmans Equilibrium.

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2\ HCO_3^-$$

Shifting this equilibrium to the left will cause precipitation of calcium carbonate ($CaCO_3$); shifting to the right leads to the tendency to dissolve $CaCO_3$ from deposits. With increasing temperature, the equilibrium also will change and $CaCO_3$ will precipitate. The basic principle of the new water treatment technology is to control the carbon dioxide content of the water. It was well known from water supply technology, that it is possible to adjust water chemistry to fulfill Tillmans Equilibrium by adding or stripping carbon dioxide (CO_2).

During the loading cycle of the ATES system (heating of the ground water), the addition of CO_2 lowers the pH, but this should be done only to such an extent that no excessive carbonic acid is formed, which could destroy the protection coatings of the pipes. Therefore injection of CO_2 must be controlled. The necessary amount of carbon dioxide depends on the temperature difference, the water hardness, and the flux. Because of frequent changes in flux and sometimes in temperature, online measurement and controlling are absolutely necessary.

EXPERIMENTAL PLANT

As a first step a small-scale experimental plant was constructed for the loading cycle of an ATES system (about 1 m^3/h water). This plant consists of

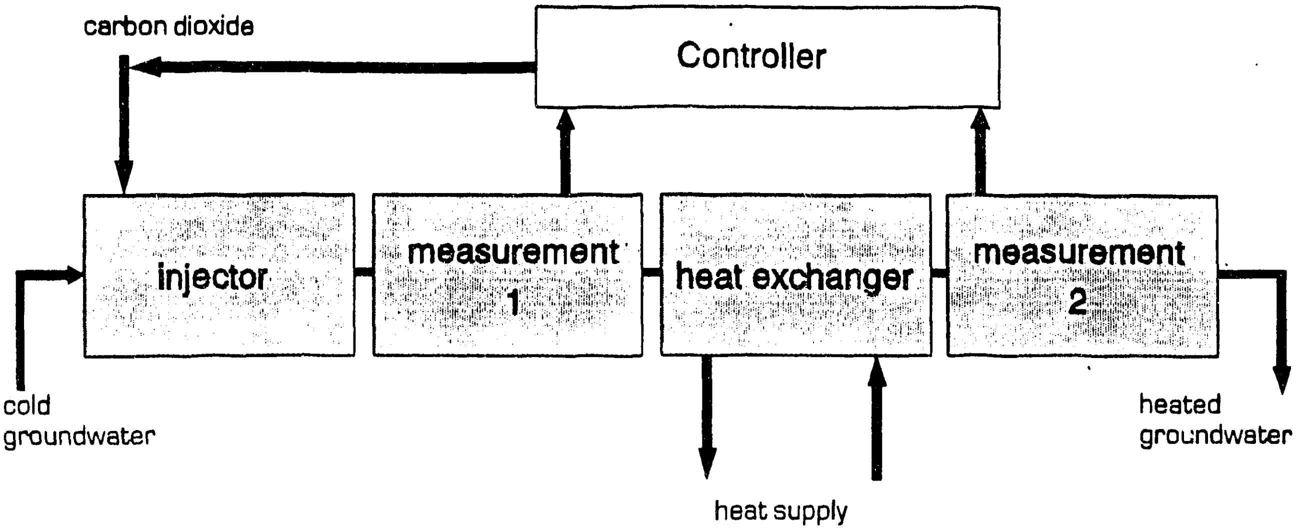

FIG. 1: Principle of an ATES carbon dioxide water treatment plant

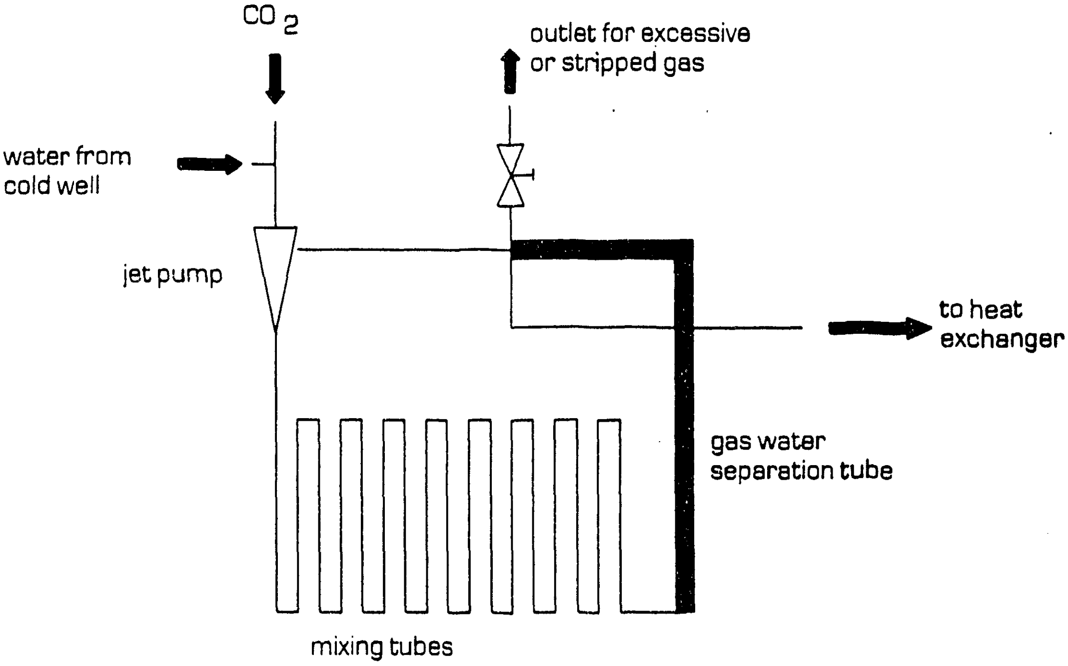

FIG. 2: Schematic of the injector

three parts:

- injector for CO_2
- measurement devices
- control unit

In Fig. 1 the principle of a water treatment plant is depicted.

INJECTOR - The CO_2 has to be vigorously mixed with the water. Fig. 2 shows a schematic of the injector used. A jet pump installed in the injector had various functions:

- mixing gas and water
- increasing the flow velocity in the mixing tubes
- recirculation of eventual undissolved CO_2.

The mixing tubes (½" in diameter) increase the turbulence and allow time for the dissolution of the gas. The separation tube (2" in diameter) lowers the flow velocity and enables the separation of gas bubbles. A valve is placed on top of the injector as an outlet for excess gas, primarily stripped nitrogen and oxygen. The material of the injector should be resistant to corrosion caused by CO_2-aggressive water. In the experimental plant stainless steel was used, but plastic tubes would also be sufficient.

MEASUREMENT - A key factor for measurement is pH. There are two possibilities. On one hand, the necessary pH after the injection can be calculated from the temperature after the water exits the heat exchanger and from the calcium and hydrogencarbonate content. In Fig. 3 the calculated pH for a water with a calcium ion content of 2.87 mmol/l, hydrogen carbonate content of 3 mmol/l, and ion strength of 11.95 mmol/l is plotted versus the temperature.

Measurement 1 in Fig. 1 provides the actual pH and temperature after the injection. This signal can be obtained very fast and therefore can be used for controlling of the CO_2 dosage.

Another possibility is to take a small part of the heated water and pass it through an analytical column filled with calcite (measurement 2, Fig. 1). In this column the dissolution or precipitation reactions are accelerated (Axt, 1965). The result is a change in the pH-value. This pH difference is a direct measure of the scaling or dissolving tendency of the water. Although this signal would be the best method to control the water treatment, it's not suitable for direct controlling because of the time delay before the corresponding signal is available. However, it seems feasible to use it as a master controller to regulate water treatment. Fig. 4 shows a schematic of the necessary measurement 2 device.

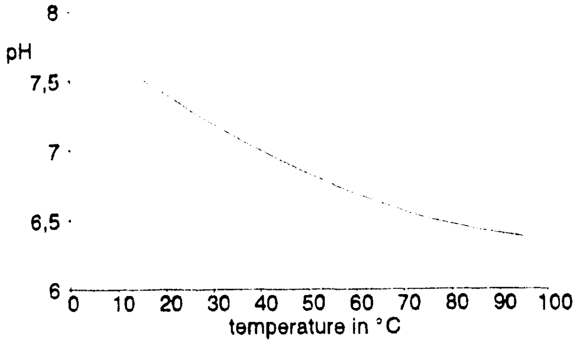

FIG. 3: Example for calculated pH versus temperature ($[Ca^{2+}]$ = 2.87 mmol/l, $[HCO_3^-]$ = 3 mmol/l, ion strength = 11.95 mmol/l)

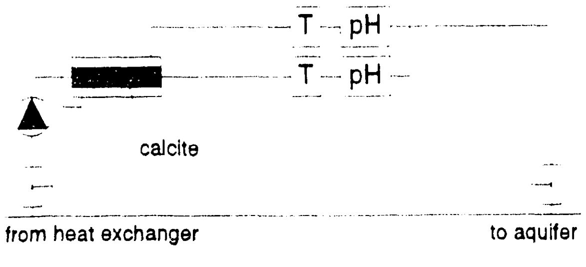

FIG. 4: Schematic of the measurement 2 device

CONTROLLING - A computer was installed for data logging, calculation and controlling. The flow of carbon dioxide was adjusted with a mass flow controller. For an upscaled version of the treatment method, an automatic calibration of the pH electrodes is planned.

FIELD TEST

With the equipment described above, two field experiments with a total duration of 5 weeks were carried out in the ATES plant SPEOS (stockage pilote d'énergie par ouvrage souterrain) (Saugy, 1990) in Lausanne, Switzerland. A tube heat exchanger with stainless steel pipes and a glass outer wall was used. So scaling on the hot tubes could be inspected visually. In addition, it was possible to clean the heat exchanger with formic acid and analyze the Ca^{2+} content of the cleaning solution. From this, the total amount of precipitated minerals could be calculated. The water was heated from 25°C to about 75°C using heat from the district heating system. The temperatures of this primary circuit were about 105°C and 80°C respectively.

During the tests, temperatures and pH-values were measured every 3 seconds and the mean values were recorded each minute. The pH after the injector was set automatically to the calculated value (see above). To this, a term (pH_{add}) was added. The term was varied for each test to change the saturation state of the water according to Tillmans Equilibrium. A positive pH_{add} means that the amount of CO_2 injected will be less and the saturation index of the water will increase. On the contrary a negative pH_{add} means a surplus of CO_2, so the saturation index will decrease. In addition, blind tests without injection were carried out.

The experiments were started with an overpressure of about 0.5 bar in the heat exchanger. At this pressure many gas bubbles could be seen in the heat exchanger and the following sand filter. Analysis of the gas showed that only about 20% of the gas was CO_2. Nearly 80% was nitrogen and oxygen from the water. So, in the second phase of the experiments the overpressure was increased to about 2 bar. After that, all gas bubbles disappeared and all of the air and the CO_2 were kept in solution.

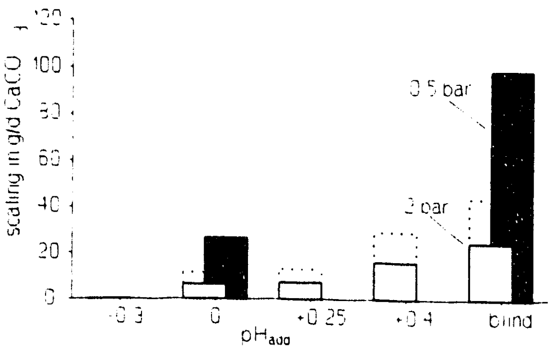

FIG. 5: Scaling rates versus pH_{add} during various test periods at SPEOS, Lausanne

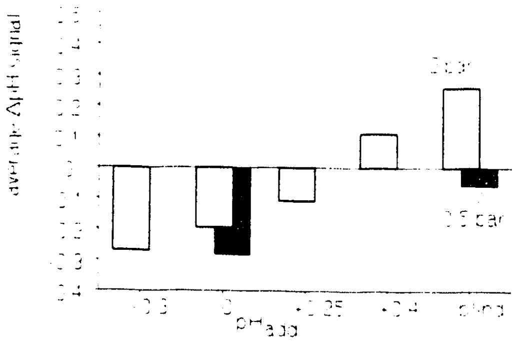

FIG. 6: Average ΔpH-signal of the second measurement device versus pH_{add} during the field test at SPEOS, Lausanne

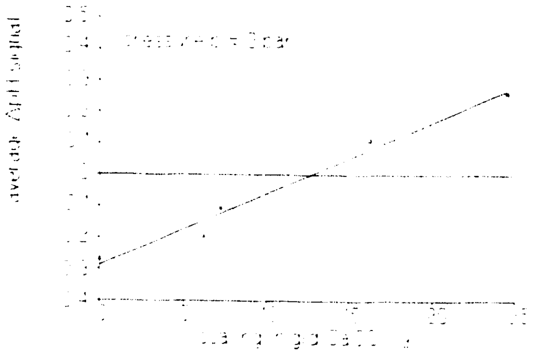

FIG. 7: Average ΔpH-signal of the second measurement device versus the sclaing rate during the field test at SPEOS, Lausanne

Table 1 shows the combinations of pressure and pH_{add} that were investigated.

TABLE 1: Combinations of pressure and additive pH term (pH_{add}), investigated at SPEOS.

Pressure [bar]	Additive pH term pH_{add}	Duration [hours]
0.5	0	12.7
0.5	blind test	58
0.5	0	61.3
2	-0.3	20.6
2	0	76.9
2	+0.25	20.6
2	+0.4	16.6
2	blind test	21.3

After each test period with scale formation the heat exchanger was cleaned and the amount of precipitated $CaCO_3$ was calculated based on the content of Ca^{2+} in the cleaning solution. From the duration of the test period the scaling rate (in g/d) under these special conditions was calculated.

In Fig. 5 these scaling rates are plotted versus the term pH_{add}. The empty boxes represent the values at 2 bar and the full boxes the 0.5 bar values. The water flow at the low pressure was about 1000 l/h, at the high pressure only 550 l/h. These different flows are one reason why the scaling rate at the low pressure is higher. Therefore, for a rough correction, boxes with dotted lines are drawn to illustrate the normalized scaling rates at one flow rate. Another point is that a part of the CO_2 is stripped in the heat exchanger and, therefore, the oversaturation is higher. The figure shows a clear dependence of the scaling rate on the additive term. At $pH_{add} = 0$, scaling still could be observed. This results from the high temperatures at the walls. Temperature of the district heating system water used in the heat exchanger was about 105°C and the groundwater was heated to about 75°C. So the temperature of the walls was nearly 100°C. The pH, however, was calculated only for 75°C.

The average of the ΔpH values resulting from the second measurement device was calculated for each period and are shown in Fig. 6. Again, the empty boxes represent the 2 bar values and the full boxes the 0.5 bar values. A clear dependence can be seen. At $pH_{add} = 0$, the ΔpH signal should also be equal to 0. The fact that it is not might be due to miscalculations of the necessary pH. But this means that the signal of this measurement device can be used for correction of the calculated pH.

In Fig. 7 the good correlation between the ΔpH signal and the scaling rate is shown for the tests with 2 bar. The absolute values shown in this figure, however, are valid only for this system at one specific flow rate and one pressure. But it clearly shows the usefulness of this measurement device.

ENVIRONMENTAL BENEFITS AND RISKS

The main environmental benefit of every ATES system is saving energy. In some cases the hardness of the water causes problems so that a water treatment process is necessary. Conventional treatments use hydrochloric acid, sodium hydroxide or ion exchange (with a consumption of regeneration chemicals in excess). This means either contamination of the underground or raising of the salt load of the surface water. Water treatment with CO_2 offers the possibility to avoid this.

CONSIDERATIONS ABOUT THE GREENHOUSE EFFECT - The emission of CO_2 into the atmosphere is the main cause for the greenhouse effect. ATES systems reduce these emissions by saving energy. The use of carbon dioxide water treatment does not destroy this positive effect. Technically used carbon dioxide comes either from natural sources (springs) or is a byproduct of chemical processes (e.g. synthesis of NH_3). Thus, no CO_2 is produced especially for sale and use in technologies, such as that proposed in this paper.

In addition, the amounts of CO_2 needed are very small. If the water of the ATES system in Lausanne would be treated by the CO_2 method, there would be a consumption of about 54 kg/d of carbon dioxide for a performance of about 870 kW. In comparison, an automobile with a gas consumption of 15 l/100 km (about 16 miles/gallon) produces 37 kg of carbon dioxide per 100 km (62,1 miles). The amount consumed at SPEOS per day is the same as emitted from a car every 146 km (90 miles).

ECONOMICS

Water treatment with CO_2 is very cheep. The injecting system is very easy to build and the operating costs are very low. 100 kg of CO_2 cost about 90 DM (about $ 55). Depending on the heat recovery from the underground, this results in costs of about 0.003 to 0.007 DM/kWh.

POTENTIALLY NECESSARY ADDITIONAL MEASURES

At ATES sites with a very low ground water flow, it is possible that the injection of CO_2 might cause an increase in hardness after a few loading cycles. If this turns out to be a problem, a carbon dioxide stripping unit should be installed to remove the excess CO_2 during the discharging phase.

CONCLUSIONS

The data presented show that the proposed scaling inhibition with carbon dioxide is an economical, effective and environmentally beneficial water treatment method for high temperature ATES systems that experience carbonate scaling problems.

REFERENCES

Axt, G. (1965): Über ein neues Verfahren und Gerät zur kontinuierlichen Messung der Kalkaggressivität. Vom Wasser **31**, 311-327.

Saugy, B. (1990): SPEOS sept ans après. Stockage pilote d'énergie par ouvrage souterrain. Gaz Eaux Eaux Usées **70**, 397- 408.

Wagner, R., Koch, M., and Adinolfi, M. (1988): Chemische und biologische Prozesse in Aquifer-Wärmespeichern. Stuttg. Ber. Siedlungswasserwirtsch. **101**.

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Microbiological and Environmental Effects of Aquifer Thermal Energy Storage

Studies of the Stuttgart Man-Made Aquifer and a Large-Scale Model System

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ABSTRACT

The storage of thermal energy, either heat or chill, in aquifers or impoundments creates local perturbations of the indigenous microflora and the environmental properties. Within an international working group of the International Energy Agency (IEA Annex VI[*]) possible environmental impacts of ATES[**]-systems were recognized and investigated. Investigations of storage systems on natural sites, man-made aquifers and large-scale models of impounded aquifers showed changes in microbial populations, but until now no adverse microbiological processes associated with ATES-systems could be documented (Winters, 1992). However, examinations with a model system indicate an increased risk of environmental impact. Therefore, the operation of ATES-systems should be accompanied by chemical and biological investigations.

ATES-SYSTEMS AND MICROBIOLOGY

Thermal energy storage in an aquifer leads to changes of the geochemical properties, mainly by dissolving and precipitating minerals. These processes lead to environmental changes, especially for autochthonous bacteria and other microorganisms.

The local changes of the subsurface and surface environment have the potential for creating four broad biochemical, geological and microbiological phenomena (Fig. 1).

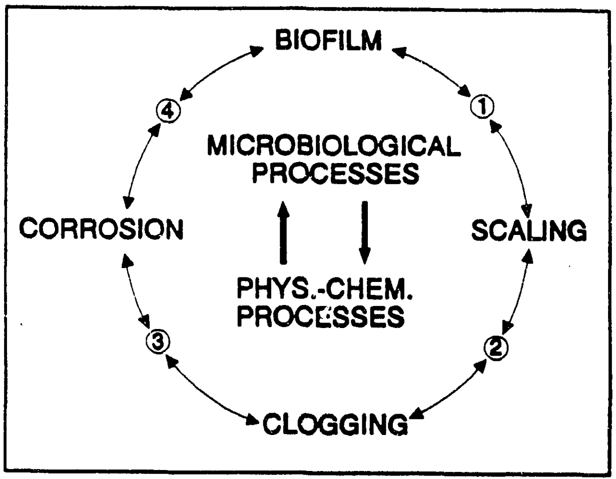

Fig. 1 Biochemical, geochemical, and microbiological interactions in ATES-systems

1. Conditioning of surfaces by microorganisms prior to scaling; biofouling on aquifer material and heat exchangers
2. Clogging by inorganic scales in aquifers, wells and drains
3. Clogging by corrosion products in wells and drains
4. Microbially induced corrosion (MIC)

If an aquifer is used, which is contaminated by pathogens and/or opportunistic pathogens, human exposure to these microorganisms could occur by ingestion of the water or by inhalation of aerosols, i.e. when such aerosols are generated by cooling towers in the vicinity of human activities. Microor-

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[*] 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.

[**] Aquifer Thermal Energy Storage

ganisms within the circulating system of an operational ATES plant live in the water or as biofilms on surfaces. They may lead to biofouling, especially of heat exchangers, or to microbiologically induced corrosion (MIC) (Adinolfi et al., 1990b; Wagner et al., 1988). Another anticipated hazard is the possibility of a mass development of microorganisms in the underground (Ruck et al., 1990). This can be due to temperature increases and lead to clogging and decrease of the groundwater current. Investigations of these potential problems were performed by an international group of researchers in the IEA Annex VI (Winters, 1992). The observations made to date indicate that current ATES system operation is not significantly affected by these problems, and adverse environmental effects caused by microorganisms were not observed in the ATES systems examined.

THE STUTTGART MAN-MADE AQUIFER

In Germany groundwater is the main source of drinking water. Therefore relatively strong legislations and recommendations do not allow any change of the groundwater quality. In special cases, the extraction of the water is allowed, but not the injection or reinjection into the ground. Consequently ATES-systems, using natural aquifers, do not exist.

In 1985 a man-made aquifer was constructed mainly for thermodynamic studies at the University of Stuttgart. This pilot plant (Fig. 2) provided a unique opportunity to examine the effects of the ATES system operation on the microflora of an aquifer.

The store was impounded to prevent ATES system interaction with the surrounding subsurface environment. It consists of a volume of 1,050 m^3 filled with gravel from the River Rhein and water from Lake Constance. The storage volume is impounded with a high density polyethylene (HDPE) liner, which is relatively inert with respect to common aquifer organisms (Winters, 1992). The system permits control of the chemical composition of rock/sediment and water and of the water flow characteristics. The disadvantage of the system was that the storage cycles were controlled by concurrent thermodynamic studies and, therefore, could not be manipulated specifically for microbiological examinations. As a compromise a monitoring program of the current operation was performed.

MICROBIOLOGICAL SAMPLING – The ATES-system was sampled by drawing water from the circulating system (between the store and the heat exchanger) and from a slotted sampling tube which was inserted near the middle of the store. Both sampling points are not optimal for microbiological study purposes. The polypropylene sampling tube within the store may not give representative results in bacterial density. Flow characteristics, surface properties and therefore also the biofilm populations in the sampling tube are different to those in the sediment filled storage volume. The other sampling point, which is situated in the circulating

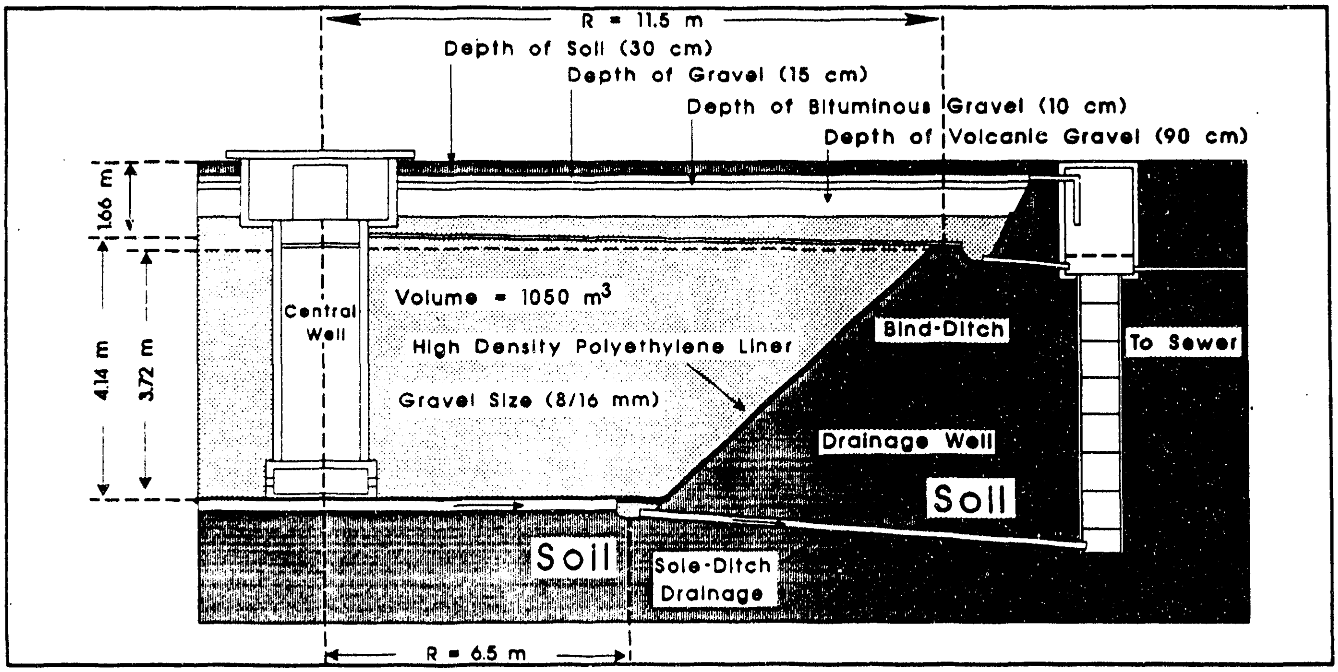

FIG. 2 Impounded ATES-system at the University of Stuttgart

system, is located about 20 m from the store. Depending on the distance to the store, flow rates, materials used and the occurrence of dead legs within the piping system, the microbiological data obtained may not give a completely representative view of the microbiological conditions as they are within the store.

MICROBIOLOGICAL METHODS - Colony forming units (cfu) of heterotrophs in water samples were determined after dilution in sterile sodium chloride on CPS Agar (Collins and Willoughby, 1962; Jones, 1970) using a spread plate technique. The plates were incubated at 20, 30 and 37 °C for 2 weeks. The higher incubation temperatures were used, when samples from zones with higher temperature were investigated. The standard identification methods were used as described by Süßmuth et al. (1987) and in Austin (1988). Further methods for the taxonomic classification were applied as described in Bergey's Manual of Systematic Bacteriology (Krieg and Holt, 1984; Sneath et al, 1986) or in Starr et al. (1981).

For biofilm investigations, gravel samples were taken into sterile bottles with sodiumchloride (NaCl) solution. The samples were treated with ultrasonic vibration in order to detach bacteria from the gravel surface. The ssolutions were then treated like the water samples.

RESULTS OF THE MONITORING – Within the sampling period from 1985 to 1990 sampling was performed monthly, in 1991 quarterly. The storage temperatures varied between 3 and 55 °C and were dependent on seasonal or short term cycles of operation. The temperature difference between the two sampling points (Storage and Circulation) averaged 1.2 °C. Water specimens were analyzed for colony forming units (cfu/ml), which is an estimate of overall microbial growth in water, and examined for the representation of individual taxonomic groups of bacteria.

The water drawn from the store showed consistently higher cfu/ml than the circulating water. Both sampling sites demonstrated the same overall patterns of microbial growth levels (Fig. 3). The difference in cfu may depend on a filter effect of the aquifer. The biggest part of bacterial activity in aquifers and other aqueous environments is situated in biofilms which consist of settling bacteria and extracellular polymeric substances (EPS) which are produced by these organisms (Costerton et al., 1987; Marshall, 1992). Between biofilm and water a permanent interchange of bacteria exists. The cfu/ml are higher in the direct vicinity of the surfaces. Therefore in water samples, drawn from the store with great sediment surface and low flow rates, a higher amount of bacteria is found.

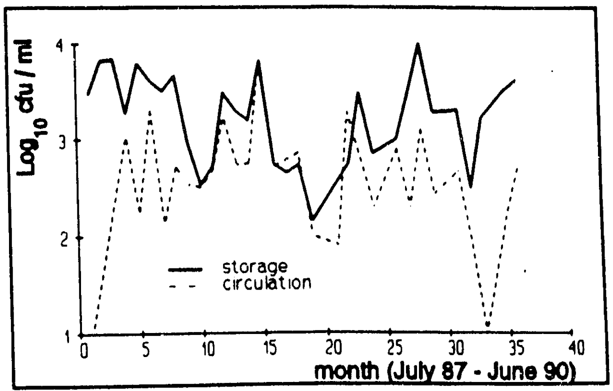

FIG. 3 Colony-forming units (cfu) of heterotrophic bacteria at the Stuttgart man-made aquifer

When the water temperature was increased to 35 °C to 40 °C organisms, which had the ability to form colonies at 37 °C appeared. The taxonomic representation within the microbial population shifted as well. When the temperature of the ATES-system was decreased again, organisms capable of growing at 37 °C disappeared within a few weeks. This is very important, because many pathogenic bacteria or opportunistic pathogens, favor temperatures near 37 °C. The system was checked for enterobacteriaceae, fecal coliforms and other indicator organisms for fecal pollution and additionally for a respiratory tract pathogen, Legionella. During the monitoring period from 1985 to 1991 neither Legionella nor other pathogenic bacteria could be found in the system. Extensive chemical investigations of the water showed constant low nutrient contents (Adinolfi et al., 1990a). In contrast to open or natural aquifers there is no groundwater which may carry additional nutrients into the system.

SIMULATION EXPERIMENTS IN A LARGE-SCALE MODEL SYSTEM

The Stuttgart man-made aquifer showed no adverse microbiological processes. Therefore a large-scale model of the Stuttgart ATES system was constructed to establish a model of the system that could be manipulated by microbiologists for the investigation of undesirable processes (Fig. 4).

The large-scale model consists of a 4.0 m high stoneware column with an inner diameter of 45 cm. The column was filled with the same gravel and water that was used in the impounded aquifer. A heat exchanger was installed in the circulation loop to control the temperature of the water.

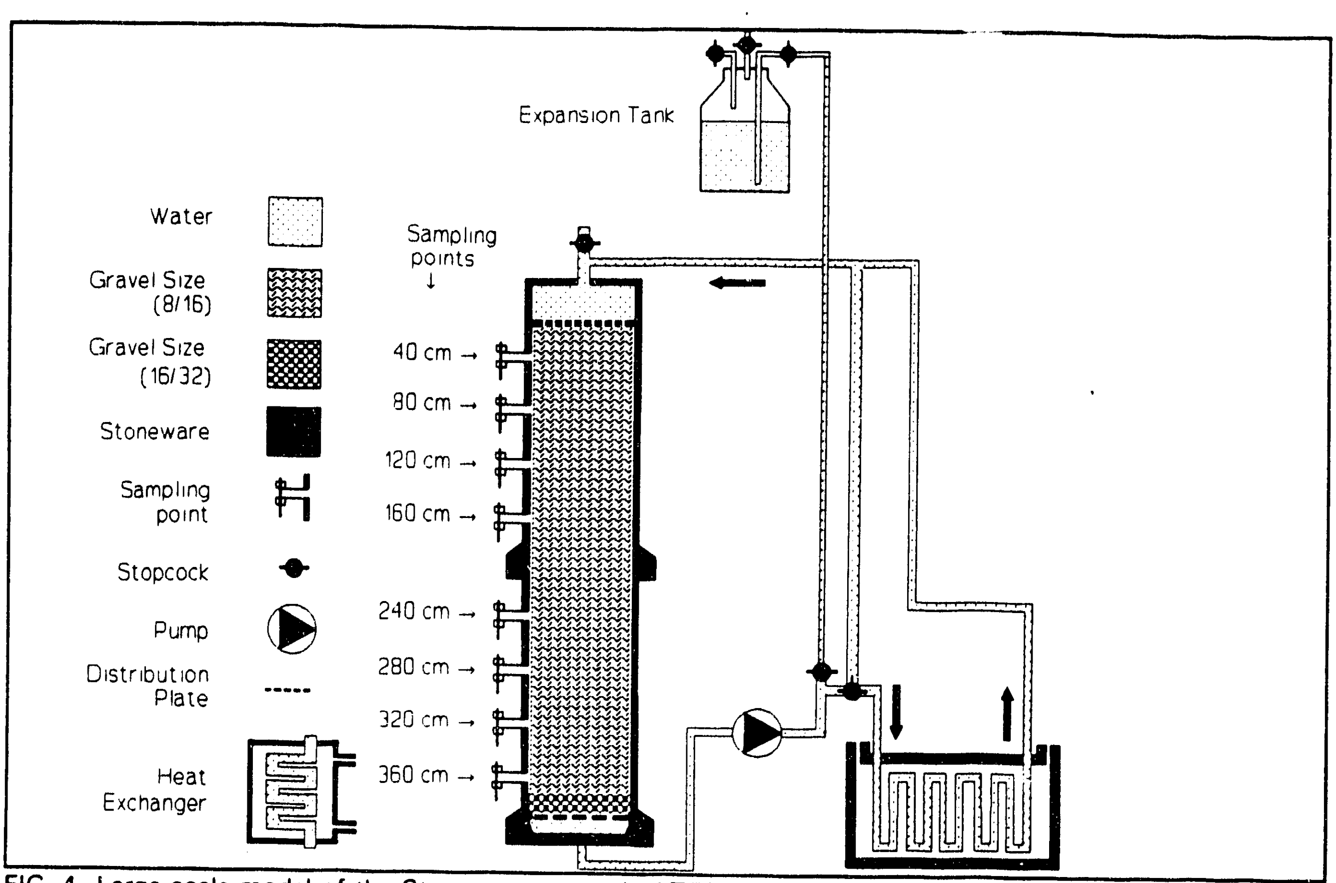

FIG. 4 Large-scale model of the Stuttgart man-made ATES-system

Sampling ports were included over the length of the column to allow gravel specimens to be taken throughout the temperature stratification that builds-up in the column. The column was fully instrumented for temperature measurements within the water and gravel bed at different heights in the column. The flow velocity (5-10 m/d) was designed to approximate the flow rates of the man-made aquifer.

For the investigation of the microbial populations it was very important to avoid material which would attract or favor microbial species that were uncommon for aquifer stores. Therefore stoneware was chosen for the column body. This material is very similar to the gravel used relative to its chemical and surface properties. Organic materials, as well as metals were avoided in the construction of the column system. It consists only of stoneware and glass with joints made of concrete. The only metal contacting the water was galvanized steel in the heat exchanger.

The model was run for a 15-week period with a water temperature of 18 °C to 23 °C to establish an equilibrated microbial flora. The cfu/ml of the water leaving the column during circulation for equilibration (cycle 1) were about ten-fold higher than the cfu of the raw water (Table 1).

TABLE 1 Colony-forming units of water samples at different cycle temperatures

cycle	duration (weeks)	T (°C)	cfu/ml (20 °C)
TW		14	300-2500
1	15	18-23	3200-27500
2	15	20-40	540-11300
3	24	20-55	200-2000
4	12	20-75	100-1200

TW = Water which was used to fill the column
T = temperatures within the column;
high temperature at the entrance of the column (input water), low at the exit.

The taxonomic groups represented in the circulating water were slightly more diverse to those found in the raw water. No unusual taxonomic groups were found and the observed organisms represented in the column closely resembled those of the impounded aquifer. Additionally microorganisms adhering to gravel samples were released from the surface by ultrasonic treatment.

The numbers of microorganisms adhering to the gravel (biofilm) exceeded in all cycles the number in the adjacent water phase by at least 100- to 1,000-fold. The representative taxonomic groups in the biofilms were slightly different when compared to the water populations. Gram negative bacteria were the predominate species in all samples. Coliform bacteria, which are indicator organisms for fecal pollution, were found in all cycles at constant low levels. These enteric bacteria originate from aerosols of sewage treatment test plants that are in the immediate vicinity of the large-scale model.

In a second cycle the temperature of the input water was switched to 40 °C and the microorganisms were allowed to to adapt for approximately 2 weeks. The cfu/ml and the taxonomic groups detected in the water did not change significantly during 15 weeks after the temperature shift. Gram-negative bacteria remained predominant among the heterotrophic microflora in both, water and biofilm populations (Fig.5). At the lower sampling points, associated with lower temperatures, increased representation of gram-positive bacteria was observed.

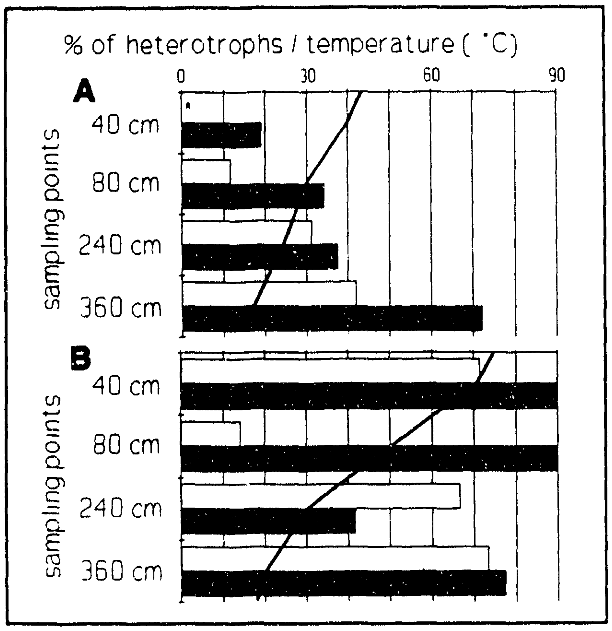

FIG. 5 Combined plot of gram-positive bacteria in % of heterotrophs and temperature at different strata of the model system

A = Cycle 2
B = Cycle 4
☐ = % gram-pos. bacteria in water
■ = % gram-pos. bacteria in biofilm
– = temperature (°C)

In a third cycle with an input water temperature of 50°C to 55°C and an exit temperature of 20°C, only a slight decrease of the cfu/ml was noticed.

After switching the input water temperature up to 65 to 75 °C (cycle 4) and adaptation of the microbial populations, gram-positive bacteria were in the majority, especially in the warmer strata of the column (Fig. 5).

While the predominance of gram-negative bacteria is typical for water samples, gram-positive bacteria are kown to be found in higher percentages in soil (Gottfreund et al., 1983). Many gram-positive bacteria are known to be pathogenic. Pathogenicity of gram-positive bacteria is extremely species-specific. Thus, the increased representation of gram-positive bacteria in the effluent water of the large-scale model may or may not indicate an increased risk for infectious diseases. The fact, that coliform bacteria were always at a low level, demonstrates however, that continued ATES system operation under a variety of temperatures does not increase the levels of enteric bacteria within the ATES system.

All taxonomic groups of heterotrophic bacteria which were found in the model system and the impounded aquifer are listed in Table 2.

TABLE 2 Taxonomic groups of heterotrophic bacteria found in the impounded aquifer and in the model system

groups	gram
pseudomonads Flavobacter/Cytophagales Acinetobacter Alcaligenes Spirillum/Azospirillum Vibrio Hyphomicrobium	–
Arthrobacter Nocardia coryneforms Kurthia Micrococcus Bacillus/sporeformers actinomycetes	+

CONCLUSIONS

Monitoring of an impounded (man-made) aquifer and simulation experiments in large-scale model plants did not show adverse microbiological processes in closed ATES-systems. Neither biofouling or mass development of bacteria nor a significant increase in pathogenic or opportunistic bacteria could be found. Closed storage systems seem not to be susceptible to microbiologically induced hazards, mainly because the nutrients are limited.

For open ATES-systems using natural groundwater the situation may be different, because the groundwater flow may permanently provide the storage area with new nutrients and microorganisms. It is possible, that in cases without nutrient limitations mass development of bacteria leads to an environmental impact. Although no adverse microbiological problems associated with operating ATES-systems were reported to date, because of the manyfold biological and biochemical activities of microorganisms, investigators should continue to be vigilant for potential microbiological problems.

The authors would recommend accompanying chemical and biological investigations for all ATES-systems. It is also very important, that before constructing an ATES system, whether it is man-made or on a natural site, appropriate sampling facilities are designed. In case of doubt, biologists and chemists should cooperate during the planning phase.

REFERENCES

Adinolfi, M., Koch, M., Ruck, W., Stein, M., Weber, W., and Wagner, R. (1990a): Hydrochemische und hydrobiologische Aspekte bei der Wärmespeicherung im Untergrund. In: Wagner, R. (Ed.): Wasser-Kalender 1991, Erich Schmidt Verlag, Berlin, 50-73.

Adinolfi, M., Thome, L., and Ruck, W. (1990b): Microbial ecology in ATES-systems - experiments in large-scale experimental plants. IEA Annex VI Doc. No. 40-E, Stuttgart (IEA restricted).

Austin, B. (Ed.) (1988): Methods in aquatic bacteriology. John Wiley & Sons, Chichester, New York, Brisbane, Toronto, Singapore.

Collins, V.G., and Willoughby, L.G. (1962): The distribution of bacteria and fungal spores in Blelham Tarn with particular reference to an experimental overturn. Arch. Mikrobiol. **43**, 294-307.

Costerton, J.W., Cheng, K.-J., Geesey, G.G., Ladd, T.I., Nickel, J.C., Dasgupta, M. and Marrie, T.J. (1987): Bacterial biofilms in nature and disease. Ann. Rev. Microbiol. **41**, 435-464.

Gottfreund, E., Gerber, I., und Schweisfurth, R. (1983): Quantitative Verteilung verschiedener physiologischer Bakteriengruppen im Lockergestein zweier Grundwasserleiter bis 90 m Tiefe. Mitt. Dtsch. Bodenkdl. Ges. **38**, 319-324.

Jones, J.G. (1970): Studies on freshwater bacteria: effect of medium composition and method on estimates of bacterial population. J. Appl. Bact. **33**, 679-686.

Krieg, N.R., and Holt, J.G. (Eds.) (1984): Bergey's manual of systematic bacteriology, Vol.1, Williams & Wilkins Co., Baltimore, London.

Marshall, K.C. (1992): Biofilms: an overview of bacterial adhesion, activity, and control at surfaces.

Ruck, W., Adinolfi, M., and Weber, W. (1990): Chemical and environmental aspects of heat storage in the subsurface. Z. angew. Geowiss. **9**, 119-129.

Sneath, P.H.A., Mair, N.S., Sharpe, M.E., and Holt, J.G. (Eds.) (1986): Bergey's manual of systematic bacteriology, Vol.2, Williams & Wilkins Co., Baltimore, London, Los Angeles, Sydney.

Starr, M.P., Stolp, H., Trüper, H.G., Balows, A., and Schlegel, H.G. (Eds.) (1981): The prokaryotes. Springer, Berlin, Heidelberg, New York.

Süßmuth, R., Eberspächer, J., Haag, R., and Springer, W. (1987): Biochemisch-mikrobiologisches Praktikum. Thieme, Stuttgart, New York.

Wagner, R., Koch, M., and Adinolfi, M. (1988): Chemische und biologische Prozesse in Aquifer-Wärmespeichern. Stuttg. Ber. Siedlungswasserwirtsch. **101**.

Winters, A.L. (1992): Summary of research on microbiological processes. IEA Annex VI Subtask D Final Report, PNL-7980, Pacific Northwest Laboratory, Richland, Washington, USA.

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Geohydrologic Characterization for Aquifer Thermal Energy Storage

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ABSTRACT

Successful operation of an aquifer thermal energy storage system depends on three elements: 1) the presence of a suitable aquifer for ground-water supply and energy storage; 2) the availability of a source of free or low-cost thermal energy, such as industrial waste heat or environmental chill; and 3) a temporal mismatch between thermal energy availability and thermal energy use. Using conventional hydrogeologic methods for aquifer characterization, the presence of a suitable aquifer is the most difficult of these three elements to assess quantitatively. By combining conventional methods with drift-and-pumpback and point-dilution single-well tracer tests, however, the rate of ground-water flow, the effective porosity, and the vertical distribution of hydraulic conductivity of the aquifer can be estimated quickly and economically.

Storing thermal energy in ground-water systems (aquifers) is an energy conservation concept designed to partly replace costly or scarce primary energy sources, such as petroleum, with abundant and inexpensive heat or chill. For example, industrial waste heat can be stored in an aquifer for later use in comfort heating. Similarly, the chill of cold winter air can be stored for air conditioning during summer months. An aquifer thermal energy storage (ATES) system in its simplest form is composed of a pair (doublet) of fairly conventional water supply wells drilled into an aquifer. Geologic materials are good thermal insulators, and potentially suitable aquifers are widely available throughout the United States.

During operation of an ATES system, ground water is withdrawn from one well, heated or chilled in a heat exchanger, and then returned for storage to the same aquifer via a second well (Figure 1). For recovery of the stored thermal energy, the second well is pumped, and the hot or cold water is again circulated through a heat exchanger and then returned to the aquifer through the first well. The recovered thermal energy can be used for space or process heating or cooling, thus reducing the need for primary energy. The cycle is repeated on a seasonal or other temporal basis. The ATES system is simple, inexpensive, and relatively efficient.

Successful design and operation of an ATES system depend on three elements: 1) the presence of a suitable aquifer for ground-water supply and energy storage; 2) the availability of a source of free or low-cost thermal energy; and 3) a temporal mismatch between thermal energy availability and thermal energy use.

Element 1 is usually the most difficult component of an ATES system to assess quantitatively. In this paper, we present a practical and economic method for characterizing geohydrologic systems for ATES applications. The method combines conventional hydrologic testing with single-well geochemical tracer tests and is illustrated by a case study of an existing ATES installation in Tuscaloosa, Alabama.

Aquifer characterization is important to the engineering design of an ATES installation; that is, the aquifer must be considered as one important component of the ATES heating or cooling plant. However, unlike the pumps, heat exchangers, and other mechanical components of the system, the aquifer cannot be altered to meet design specifications. Thus, to some degree, the ATES plant must be designed to accommodate the aquifer.

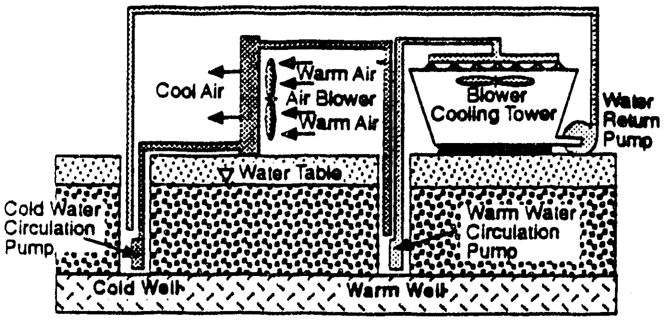

Figure 1. Simplified aquifer thermal energy storage system used for air conditioning. The cooling tower is used to chill water drawn from the warm well during the winter. The chilled water is stored in the aquifer via the cold well, and is recovered during the summer and passed through a heat exchanger to cool warm air. (After Schaetzle and Brett, 1989)

For example, the capacity of the aquifer to accept or yield water limits the flow rate that can be used in an ATES plant. Also, the effective porosity of the aquifer affects the volume of aquifer required to store a given volume of heated or chilled water. This in turn affects the size of an ATES well field. The direction and rate of ground-water flow similarly affects the size, shape, and operation of the well field.

The aquifer's hydraulic conductivity, which is a measure of the ability of the porous geologic media to transmit water, is of first-order importance in design and evaluation of ATES systems, and is dependent on the size and shape of the media pores. Hydraulic conductivity (K) multiplied by aquifer thickness (b) equals aquifer transmissivity, which is a measure of the rate at which water moves through the aquifer under a unit hydraulic gradient. A high hydraulic conductivity (and transmissivity) is desired to produce the largest volume of water from a well with the least drawdown of ground-water level. However, paradoxically, low hydraulic conductivity is desirable for decreased regional ground-water velocity and prevention of excessive tilting of the thermocline from viscosity/buoyancy effects in high-temperature ATES systems. Isotropic aquifer media (having the same hydraulic conductivity in all directions) are desirable to obtain maximum water supply from a well with minimum drawdown. But, conversely, anisotropic conditions (with vertical hydraulic conductivity being much less than horizontal hydraulic conductivity) are desirable for high-temperature ATES systems to resist tilting of the thermocline.

Porosity of geologic media is expressed as the ratio of the pore volume to the total volume of the rock. With regard to the movement of water in a porous medium, only the system of interconnected interstices (effective porosity) is important. The effective porosity of the aquifer matrix is also of first-order importance in ATES systems because it determines the amount of heated or chilled water that can be stored per unit volume of the aquifer. Porosity also is important because it, along with hydraulic conductivity and hydraulic gradient, controls ground-water velocity. Ground-water velocity in a porous medium is proportional to the hydraulic conductivity and gradient (slope of the water table or piezometric surface) and inversely proportional to the porosity.

Areal aquifer boundaries and aquifer thickness, along with effective porosity, determine the volume available for storage of heat or chill. Aquifer volume generally is much greater than the required storage volume, but boundary location may be of interest if the proposed ATES storage site is near zones of recharge or discharge, or on the periphery of a ground-water system.

Thermal characteristics of the aquifer are important in determining the heat capacity of the system and conduction of heat out of the storage volume. Thermal conductivity is the quantity of heat conducted in unit time across an element of surface under a given thermal gradient. Porous geologic materials, saturated with water, do not vary widely in thermal conductivity values. Basically, earth materials are good insulators under ATES conditions, and differences in their thermal conductivities are relatively small. Thus, thermal conductivity is of second-order importance in geohydrologic characterization. Thermal capacity (specific heat) of a material is the quantity of heat required to produce a unit change of temperature in a unit mass of media. Variation in thermal capacity of earth materials, as with thermal conductivity, is small, so characterizing thermal capacity is also of second-order importance.

The following case study is an example of a combined program of conventional and tracer testing. It also illustrates some methods and techniques for conducting the tracer tests. The testing methods presented here can be used to address all of the factors of aquifer characterization noted above except for thermal characteristics.

EXPERIMENTAL

An ATES system has been in operation since 1985 at the University of Alabama Student Recreation Center (UASRC), located on the university campus in Tuscaloosa, Alabama. In this ATES system, ground water is circulated between heat exchangers and the unconfined aquifer via a well field consisting of six production wells. During cool months, the water is chilled and injected into the aquifer. During warm months, the stored water is withdrawn from the aquifer to serve as a heat sink to cool the air in the UASRC building. The production and water-level monitoring wells used for this test are shown in Figure 2.

In November 1991, Pacific Northwest Laboratory (PNL) conducted a series of field tests at the UASRC site to determine aquifer characteristics including the direction and rate of ground-water flow, formation effective porosity, hydraulic conductivity, vertical distribution of flow within the aquifer, and the specific capacity of wells during both injection and withdrawal (Hall and Newcomer, 1992). The purpose of this series of tests was to provide design data for expansion of the well field. All tests were performed at the ambient ground-water temperature of approximately 17°C.

The unconfined aquifer at the UASRC site is within unconsolidated alluvium consisting of sands, gravels, and clays from the nearby Black Warrior River (Schaetzle and Brett, 1989). These deposits are believed to be 10 to 30 thousand years old, formed during the final phases of the Wisconsin Glaciation. The sediments overlie the Pottsville Formation, which consists of well-indurated shales and limestone, is of low permeability, and provides the lower boundary of the unconfined aquifer. In the vicinity of the test site, the sediments are typically 24 to 27 m thick, and the lower 9 to 12 m are saturated with ground water.

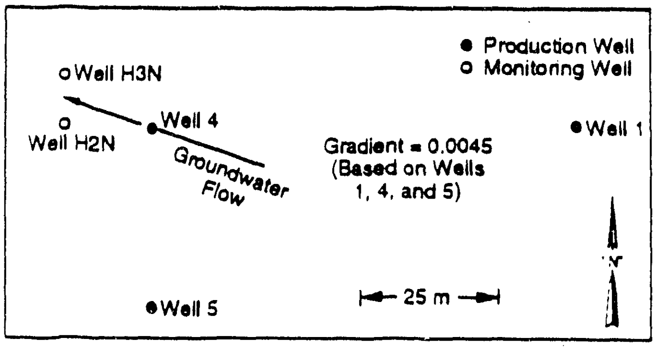

Figure 2. Test wells at the University of Alabama Student Recreation Center (after Hall and Newcomer, 1992).

Production wells 1 through 6 were drilled with a 0.43-m (17-in.) diameter bit and completed through the sediments and slightly into the Pottsville Formation (Schaetzle and Brett, 1989). In each case, 0.25-m (10- in.) diameter PVC screen, with 8.1×10^{-4}-m (0.032-in.) openings, was installed in the lower 15.2 m of the well. The screen was gravel-packed to just above the screen/PVC casing connection, and then grouted with concrete to the surface. Each well was developed by pumping for a period of approximately one day at a rate of 1.3×10^{-2} to 1.6×10^{-2} m^3/s (200 to 250 gpm). The monitoring wells were constructed using 0.051-m (2-in.) PVC casing, and screened and sand-packed near the bottom of the aquifer.

Hydraulic gradient and the direction of flow were determined from water- level measurements taken from well #1, well #4, and well #5, and from survey data provided by the University of Alabama. The water levels were measured from the top of the well casings with a steel tape just before the start of the aquifer tests. The resulting hydraulic gradient was 0.0045. The direction of flow relative to the layout of the well field is shown in Figure 2. A step-injection test was performed at well #1 to determine the injection capacity of a typical production well. Well #4 was used to supply water for injection at well #1, and pumping at well #4 was treated as a concurrent step-drawdown test. Pressure transducers were installed in both wells for monitoring water level change. The discharge end of the supply line leading from well #4 to well #1 was placed below water level in well #1 to prevent frothing and the resulting injection of entrapped air into the aquifer.

The test was started with an initial pumping rate of 5.0×10^{-3} m^3/s (80 gpm), increased in 2.5×10^{-3} m^3/s (40 gpm) increments up to 1.26×10^{-2} m^3/s (200 gpm), and followed by a final increase to 1.77×10^{-2} m^3/s (280 gpm). Each increment was maintained for approximately one-half hour, except for the final pumping rate, which was maintained for approximately one hour. Figure 3 illustrates the changes in water level observed during the test. Note that after approximately 65 min of injection, during the 1.0×10^{-2} m^3/s (160 gpm) flow step, the water level in well #1 rose above the level of the screen.

The specific capacity of each well was determined using the method of Jacob (1946), where change in water level is expressed as a function of flow as follows:

$$S = BQ + CQ^2 \qquad (1)$$

where
S = drawdown in m
Q = flow rate in m^3/s
B = formation loss coefficient
C = well loss coefficient

The graphical method described by Driscoll (1986) was used to determine the values of the coefficients B and C. This method uses a rearranged form of EQ (1), where a best-fit straight line through a plot of S/Q versus Q yields a slope equal to C and an ordinate intercept equal to B. Figure 4 illustrates such plots for the test wells. At well #1, it is seen that, depending on flow rate, ground-water mounding will occur at the rate of approximately 500 to 600 m per m^3/s (~0.1 ft/gpm).

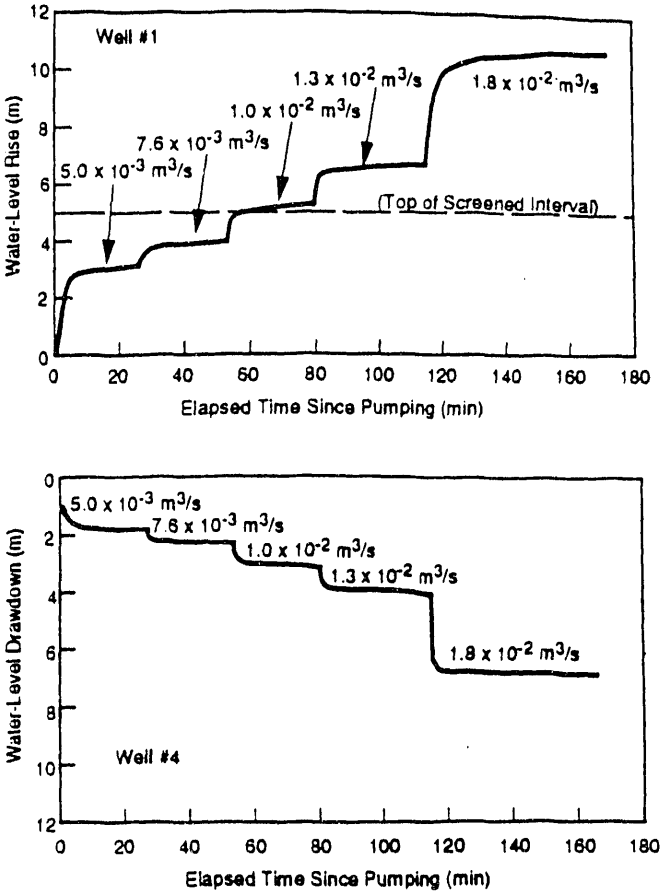

Figure 3. Water-level changes during the step-injection and step-drawdown tests (after Hall and Newcomer, 1992).

A constant discharge pumping test was started at well #4 approximately 18 h after completion of the step-injection test. Based on the results of the step-injection test, a discharge rate of 1.77×10^{-2} m^3/s (280 gpm) was chosen, and that rate was maintained for a duration of 8 h. After pumping was stopped, water level recovery was monitored for 15 h.

Wells H2N and H3N, located 15.2 m and 19.5 m, respectively, from well #4, were used as the principal observation wells. Downhole pressure transducers were used to

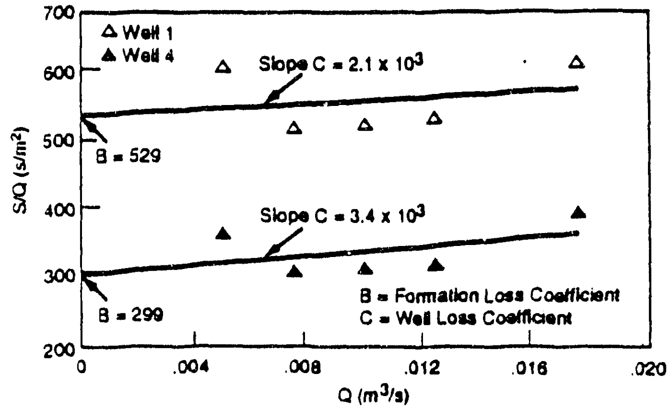

Figure 4. Change in water level normalized to pumping rate *versus* pumping rate for the step-injection and step-drawdown tests (after Hall and Newcomer, 1992).

monitor drawdown and recovery in the pumping and observation wells. Near the end of the 8-h pumping phase of the test, the maximum drawdown observed in the pumping well was 6.94 m. Maximum drawdown in the observation wells was 1.14 m in well H2N, and 0.90 m in well H3N. The test data were corrected for aquifer dewatering prior to analysis using the following equation:

$$H = H' - (H'^2/2b) \qquad (2)$$

where H' = uncorrected drawdown in m
b = aquifer thickness, in m, prior to pumping

A combination of pressure derivatives (Bourdet et al. 1983; Bourdet et al. 1989), straight-line solutions (Jacob, 1946), and type-curve matching techniques (Theis, 1935; Novakowski, 1990) was applied to the corrected data to estimate values of transmissivity, storage coefficient, and specific yield.

Analysis of drawdown data yielded a value of storativity of 0.0002 to 0.0005, specific yield of approximately 0.1, and transmissivity of 280 m^2/day to 320 m^2/day. A similar analysis of recovery data confirmed these results.

Approximately 19 h after pumping ceased during the constant discharge test, a point-dilution test was initiated at well #4 by emplacing a bromide tracer into the well bore. A point-dilution test, as described by Kearl et al. (1988) is used to estimate ground-water velocity. (The rate at which the concentration of a tracer in a well bore decreases over time is a function of ground-water velocity.) For this test, point-dilution was used to estimate the distribution of flow velocities with depth by monitoring bromide concentrations at several depth intervals.

To emplace the tracer, a 1.6×10^{-2}-m (5/8-in.) ID hose, open at both ends, was suspended in the well to the bottom of the aquifer. The hose was weighted with a plastic jug having a radius of approximately 0.18 m. Gravel was added to the jug as ballast. The contained volume of the hose, from water table to the lower end, was 2.2 L, so this volume of distilled water was used to dissolve 125 g of lithium bromide (LiBr). The solution was poured into the top of the hose, displacing well water from the hose. The hose was then withdrawn from the well, leaving the tracer solution in place. The jug used to weight the hose also served to mix the tracer within the well bore as the hose and jug were withdrawn.

Based on the 0.25-m well diameter and the 11.3-m effective aquifer thickness, the predicted bromide concentration immediately after tracer emplacement was 202 mg/L.

Following tracer emplacement, the bromide concentration in the well bore was monitored as a function of time and depth. Downhole measurements were made at 0.9-m (3-ft) intervals over a period of 5 h. The measurements were made using an Ag/AgBr ion-selective electrode and a submersible double-junction reference electrode of the Ag/AgCl type having an inner filling solution of 4 M KCl (saturated with AgCl) and an outer filling solution of 10% KNO_3. The reference electrode is of a new design, which was developed at PNL specifically for deep, in situ electrochemical measurements. The electrodes were connected to a Hach One pH/millivolt meter with 30 m (100 ft) of dual-conductor insulated wire. Figure 5 illustrates the results of measurement.

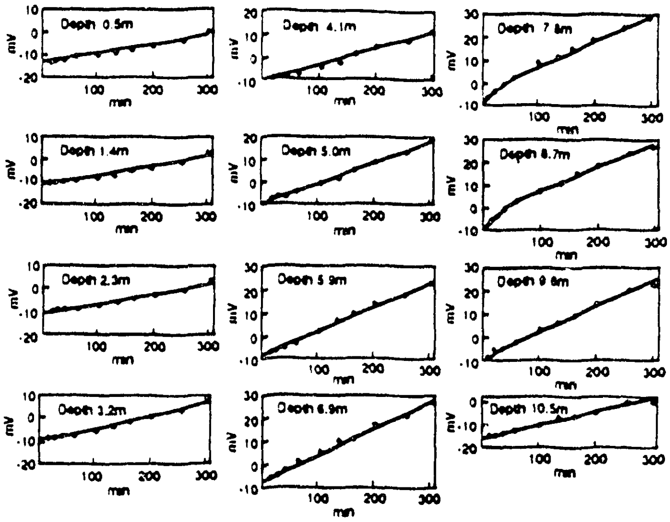

Figure 5. Bromide ion-selective electrode response at 12 depth intervals during the point-dilution test (after Hall and Newcomer, 1992).

The electrodes were calibrated just prior to the point-dilution test using a concentrated solution of lithium bromide and a sample of natural ground water collected from well #4. Well water spiked to a bromide concentration of 10 mg/L yielded a response of 62.1 mv. Based on previous testing, the bromide sensing electrode used in this experiment was known to consistently respond with -56 mv per decade of increasing concentration (i.e., 95% of the theoretical Nernst slope) in the range from 10 to 1000 mg/L. Therefore, millivolt readings for the test may be converted to bromide concentrations using the following equation:

$$A = 10^{(1+(62.1-E)/56)} \qquad (3)$$

where A = bromide concentration in mg/L
E = millivolt reading

Inspection of Figure 5 shows that the bromide tracer was not quite evenly distributed at the time of emplacement. That is, the millivolt responses for each test depth, when extrapolated to zero time, are not all equal. The extrapolated potentials range from -8 to -16 mv. Each of these potentials represents a 0.9-m segment of well bore, except for the deepest test interval, which represents 1.2 m of well bore. Converting the zero-time potentials to bromide concentrations and weighting each according to the length of borehole segment that it represents yields a mean calculated bromide concentration of 206 mg/L. This compares quite favorably to the predicted concentration of 202 mg/L.

To calculate flow velocities, the following equation, modified from Hall et al. (1991a) with EQ (3) above, was used:

$$dE/dt = .0846V^* \qquad (4)$$

where dE/dt = the slope of the plot of mv versus time in minutes
V^* = ground-water flow velocity *through the well bore* in m/day

The theory describing a point-dilution test requires that, in a valid experiment, the slope dE/dt be a straight line (Hall et al., 1991a). Inspection of Figure 5 shows that, at all test depths, the data support a straight-line interpretation. (At some of the test depths, e.g., 8.7 m, there is some curvature in the plot of mv versus time early in the experiment. This curvature may have been caused by initial non-ideal distribution of the bromide tracer between the well bore and the gravel pack, which is effectively part of the well installation. Alternatively, the curvature may be an artifact of vertical mixing within the well bore caused by frequent movement of the sensing electrode assembly early in the experiment.) However, the theory also requires that the tracer be at all times evenly distributed in each test interval within the well bore. That is, mixing within the bore must be fast compared to the rate of ground-water flow through the bore. If this condition is not met, EQ (4) becomes invalid. A plot of mv versus time would then reflect a plug flow component, and the plot would tend toward a step function rather than a straight line.

In conventional practice, a point-dilution test is conducted by isolating a test interval, such as with packers, and by using some mixing device installed in the test interval to keep the composition of the solution homogeneous (Kearl et al., 1988). In this test, and in the test described by Hall et al. (1991a), it was assumed that the natural turbulence in the well bore and gravel pack would provide sufficient mixing. The straight-line slopes seen in Figure 5 support this assumption. Further, the assumption was tested during the conduct of the experiment by moving the sensing electrode to four different positions in the well bore at given depths. At 11 min and at 66 min into the test, at a depth of 0.5 m below the water table, millivolt readings were made adjacent to the well screen on the upgradient side, the downgradient side, and the "left" and "right" sides. This procedure was repeated at the 8.7 m depth at 69 min and 240 min. In no case did the difference between the upgradient and downgradient measurements exceed 0.2 mv, which in the context of this experiment is negligible. Therefore, an assumption of adequate mixing must be taken as correct.

The flow through the well bore, V^*, calculated from EQ (4) is related to seepage velocity within the aquifer as follows:

$$V^* = Vna \tag{5}$$

where V = seepage velocity
n = effective porosity
a = flow distortion factor

The flow distortion factor, a, arises because the hydraulic conductivity of the well is considerably greater than that of the aquifer, thereby causing the flow net (within the horizontal plane) to converge toward the well (Raymond, 1955). For this analysis, the factor will be considered invariant with depth. Because it is difficult to evaluate effective porosity variations at the various test intervals, calculation of meaningful seepage velocities for the intervals is similarly difficult. However, if the flow distortion factor is truly a constant, then V^* is directly proportional to net flux (volume per unit time) for each test interval. Figure 6 illustrates the relative discharge for each test depth in relation to the 6.9-m depth, which showed the highest V^*. The stratigraphy at well #4, determined by particle-size analysis of drill cuttings collected at 1.5-m intervals, is also included in the figure. The correspondence between observed stratigraphy and the results of the point-dilution test is quite good. The greatest ground-water flux is through the relatively clean sand, and the least flux is through the clayey, poorly sorted sediments.

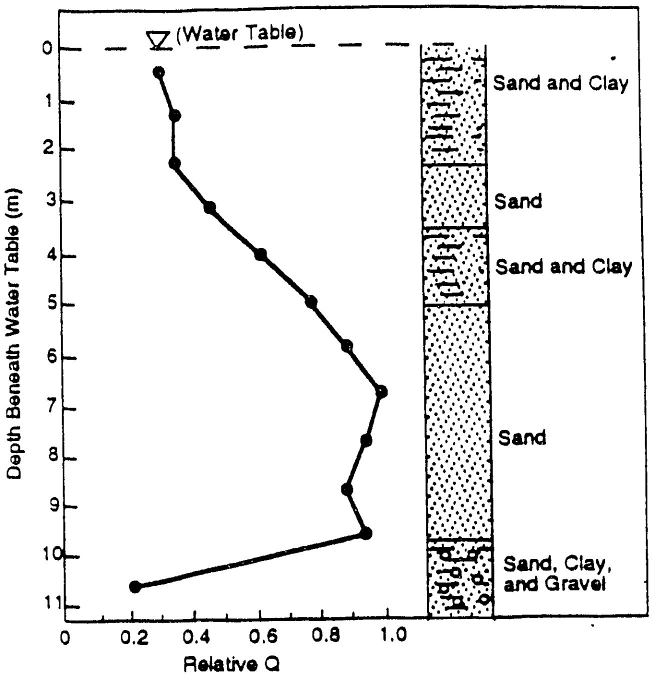

Figure 6. Relative horizontal ground water flux (Q) through the well bore at 12 depth intervals. Aquifer stratigraphy is based on examination of drill cuttings. (After Hall and Newcomer, 1992; and Schaetzle and Brett, 1989)

As noted above, the point-dilution test is conventionally performed in an isolated interval. In this test and in that described by Hall et al. (1991a), there was no attempt to isolate depth intervals. It was assumed that in an aquifer dominated by horizontal advective flow, vertical mixing within the well bore would be negligible compared to horizontal flow vectors. The contrast in calculated relative discharge between the 9.6- and 10.5-m test depths in Figure 6 shows that this assumption is reasonable.

The tracer emplacement for this test also served as the beginning of a drift-and-pumpback test, as described by Hall et al. (1991b). In a drift-and-pumpback test, the tracer is allowed to drift away from the well under natural gradient for a period of days. Then, the well is pumped to recover the tracer. The time required to recover the center of mass of the tracer is then used to calculate net seepage velocity and effective porosity of the aquifer using the following equations:

$$n = \pi b K^2 I^2 T^2 / Qt \tag{6}$$

where n = effective porosity
b = aquifer thickness (11.3 m)
K = hydraulic conductivity (24.6 m/day to 28.0 m/day)
I = hydraulic gradient (0.0045)
t = pumping time to recover center of mass of tracer in days
T = drift time plus t in days
Q = pumping rate in m^3/day

and
$$V = Qt/\pi b T^2 K I \tag{7}$$

where V = seepage velocity in m/day

The drift time for this test was 2.039 days. Pumping rate during recovery of the tracer was 327 m^3/day. Bromide concentration during pumping was monitored using a conventional bromide ion-selective electrode and a double-junction reference electrode. Figure 7 illustrates the results of bromide measurements. The concentration curve in the figure was integrated, and it was calculated that the center of mass of the bromide tracer was recovered after 50.6 min, or 0.0351 days. Applying EQ (6) and EQ (7) resulted in a calculated net effective porosity of 16% to 21% and net seepage velocity of 0.6 to 0.7 m/day at well #4.

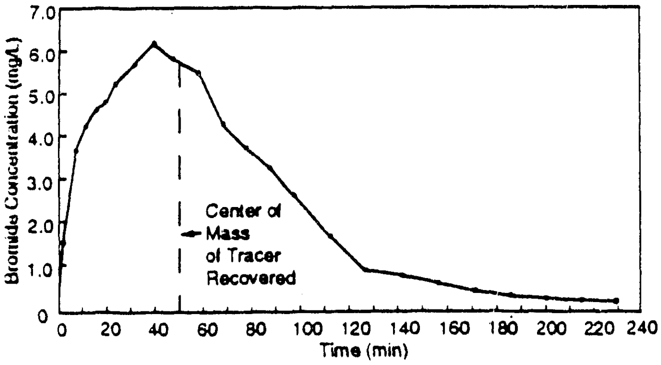

Figure 7. Bromide concentration *versus* time during the pumpback stage of the drift-and-pumpback test (after Hall and Newcomer, 1992).

DISCUSSION

The flow determined through this series of tests, 0.6 to 0.7 m/day, is greater than the apparent flow rate observed by monitoring the migration of "chill" in the aquifer during actual use of the ATES installation, which is approximately 0.45 m/day. Some difference was expected because the chill is effectively retarded by heat exchange between the injected cool water and the sediments and entrapped water of the aquifer. (The volume of entrapped water in the sediments is reflected by the difference between effective porosity and total porosity.) Thus, in designing future ATES installations in similar sediments, or in designing the expansion to the UASRC well field, assuming a retardation coefficient of approximately 1.3 to 1.5 would be reasonable.

The effective porosity of 16% to 21% is greater than the 6% to 12% values measured for other sites in this aquifer (Cronin et al., 1989; Hall et al., 1991a). However, the higher porosity is reasonable because the hydraulic conductivity at the UASRC site is also greater. Finally, the results of the point-dilution test warrant additional comment. In EQ (5) it was shown that the mean flow velocity through the well bore, V^*, is proportional to seepage velocity, V, effective porosity, n, and a flow distortion factor, a. In conventional practice, the flow distortion factor is determined by laboratory calibration of some given combination of screen and gravel pack by comparing measured V^* against a known velocity, V, for a "well" established in a laboratory-scale "aquifer" (Kearl et al., 1988). Then, a velocity, V, for a real aquifer is obtained from field measurement of V^* and by estimating porosity, n. That is, the flow distortion factor is considered to be strictly a function of well construction, and to be independent of the nature of the aquifer.

In this test, laboratory calibration was obviously not necessary. Velocity and porosity are known from the results of the companion tests, and the mean V^* (0.91 m/day) is easily calculated from the experimental data. Therefore, from EQ (5), the flow distortion factor must be equal to approximately 7 to 8. If the flow distortion factor is truly independent of variation within the aquifer, then Figure 6 accurately depicts the relative flux, and also the relative hydraulic conductivity, for each test depth.

However, laboratory tests as well as computer simulations have shown that the flow distortion factor should be approximately 2.0 (Raymond, 1955). In this test, the value for that factor was approximately four times the expected value. Further, even higher values have been reported in the literature (Kearl et al., 1988). We interpret the disparity between laboratory experiments and field measurements as follows.

Laboratory experiments with porous media are of small scale, both in time and space, compared to real aquifers, and the media used in such experiments to simulate aquifers are often uniform and well sorted. Within the conduct of an experiment, the laboratory-scale well will not undergo significant development. (Certainly this is also true for computer simulations, where aquifer characteristics are fixed.) However, a real well is developed over time, every time it is pumped, and progressively more fine-grained material is withdrawn from the aquifer near the well bore. That is, in the vicinity of the well, the aquifer is more conductive than the rest of the aquifer, and the sediments are better sorted.

Thus, in the laboratory tests and computer simulations, *but not at a real well installation*, the assumption of a uniform aquifer immediately adjacent to, and extending from, the well is a valid assumption. Therefore, the pattern of flow distortion at a real well is probably not accurately represented by the results of laboratory-scale or computer experiments.

For the present test, there is an important consequence. It is unlikely that the relative development of poorly sorted sediments, such as the material near the bottom of the aquifer, will be the same as that of the overlying sand stratum. That is, the hydraulic conductivity of well-sorted sand will be less affected by well development than the poorly sorted material, so the flow distortion factors of the two strata will probably be different. It seems intuitively likely that the relative rates of flow (i.e., the relative hydraulic conductivities) shown in Figure 6 for the poorly sorted sediments are too high compared to the sand layer. The figure must be taken as a semi-quantitative representation of the vertical distribution of flow.

ACKNOWLEDGEMENT

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REFERENCES

Bourdet, D., J. A. Ayoub, and Y. M. Pirard (1989). "Use of pressure derivative in well-test interpretation." Paper SPE 12777, SPE Formation Evaluation, June:293-302.

Bourdet, D., T. M. Whittle, A. A. Douglas, and Y. M. Pirard (1983). "A new set of type curves simplifies well test analysis." World Oil, May:95-106.

Cronin, W. E., S. P. Luttrell, and S. H. Hall (1989). Aquifer Characterization of the Veterans Administration Hospital, Tuscaloosa, Alabama. PNL-7139, Pacific Northwest Laboratory, Richland, Washington.

Driscoll, F. G. (1986). Ground Water and Wells, 2nd Edition, Johnson Division, UOP Inc., St. Paul, Minnesota.

Hall, S. H., and D. R. Newcomer (1992). Hydrologic Characterization of the Unconfined Aquifer at the University of Alabama Student Recreation Center, Tuscaloosa, Alabama. PNL-8004, Pacific Northwest Laboratory, Richland, Washington.

Hall, S. H., D. R. Newcomer, and S. P. Luttrell (1991a). Hydrologic Characterization of the Unconfined Aquifer at the General Motors Harrison Division Plant, Tuscaloosa, Alabama. PNL-7641, Pacific Northwest Laboratory, Richland, Washington

Hall, S. H., S. P. Luttrell, and W. E. Cronin (1991b). A Method for Estimating Effective Porosity and Ground-Water Velocity, Journal of Ground Water, 29(2):171-174.

Jacob, C. E. (1946). "Drawdown Test to Determine Effective Radius of Artesian Wells." Trans. Am. Soc. Civ. Eng., 112:1047-1070.

Kearl, P. M., 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.

Novakowski, K. S. (1990). "Analysis of aquifer tests conducted in fractured rock: a review of the physical background and the design of a computer program for generating type curves." Ground Water, 28(1):99-105.

Raymond, J. R. (1955). An Electrical Technique for Ground Water Velocity Measurement. HW-36217, General Electric Company, Richland, Washington.

Schaetzle, W. J., and C. E. Brett (1989). The Aquifer Chill Storage Project at the University of Alabama, Tuscaloosa: Progress Report for 1985 and 1986. PNL-6797, Pacific Northwest Laboratory, Richland, Washington.

Theis, C. V. (1935). "The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage." Trans. Am. Geophys. Un., 2:519-524.

Prediction of Long-Term Operational Conditions for Single-Well Groundwater Heat Pump Plants

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ABSTRACT

When using groundwater as a primary energy source in combination with heat pumps, the groundwater is pumped from the groundwater zone, cooled in the heat exchanger of the heat pump, and then reinjected into the groundwater zone.

The design of traditional groundwater heat pump plants is based on the use of a separate pumping and reinjection well. An alternative design is to use a single-well for both pumping and reinjection. However a minimum distance between well screens is required in order to prevent break-through, caused by short-circuiting of the cooled groundwater.

The present paper describes a simplified mathematical model to be used to analyze steady-state operational temperature conditions for a single-well groundwater heat pump plant. The model is based on a finite element solution of the temperature distribution in the pumping and reinjection zones of the groundwater reservoir.

Furthermore, a model for the calculation of the ratio of the vertical to the horizontal permeability is presented in the paper. This ratio is one of the important parameters in the design of a single-well groundwater heat pump plant.

Both models have been tested against data from a full-scale experimental plant on the campus of the Technical University, where the hydrogeological conditions are familiar. The results of a comparison between model predictions and experimental field data are included in the paper.

INTRODUCTION

The use of groundwater and aquifers in connection with improved energy utilization has aroused increased interest over the last decade. The groundwater aquifers have been used both for energy storage [1] and as a natural energy resource in combination with heat pumps.

Groundwater aquifers located at greater depths have thus been used for the storage of hot water at approximately 100°C [2], [3]. Higher-located aquifers have been used extensively for the storage of warm water as well as chilled water, utilizing the same basic principles of energy exchange between the water and the porous matrix. [4], [5].

When groundwater is used as a natural energy resource, it is supplied from a reservoir and cooled in the heat exchanger of a heat pump. The groundwater is then reinjected into the ground. In such systems, the long-term steady-state operational conditions require, that energy is supplied to the aquifer from which the groundwater is pumped at the same rate as that which energy is produced. This supply of energy to the groundwater zone is mainly obtained through the energy inflow from the surface. To obtain steady-state operational conditions at acceptable operational temperatures, requires a large area to volume ratio of the groundwater zone affected by this operation.

Because of the requirement that drinking water reservoirs should not be affected, it is necessary that a mass and energy balance is maintained locally. Such an operational constraint is usually met by using a double-well configuration, where two wells are sufficiently separated, so as not to create an interference. Water is then pumped from one well, returned from the heat pump and reinjected through the other well. Furthermore, it is normally required that a minimum distance to drinking water supply wells is kept in order to avoid thermal pollution [7].

An alternative design may be to use the same well for both pumping and reinjection, but with a depth interval to separate injection and production zones [8].

This single-well configuration has many advantages over the double-well solution; primarily the potential for a lower implementation cost and, in addition, the fact that the plant will be thermally neutral within a smaller area. The single-well concept however requires a much more careful design so as to minimize the risk of operational problems, such as short-circuiting between the production and injection zones. In the present paper, design criteria for such a single-well plant is discussed and design tools in the form of models and parameter curves are presented.

THE SINGLE-WELL MODEL AQUIFER.

The model aquifer shown in figure 1 is used as a basis for the derivation of the mathematical models described in the following chapters. In the model aquifer, 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.

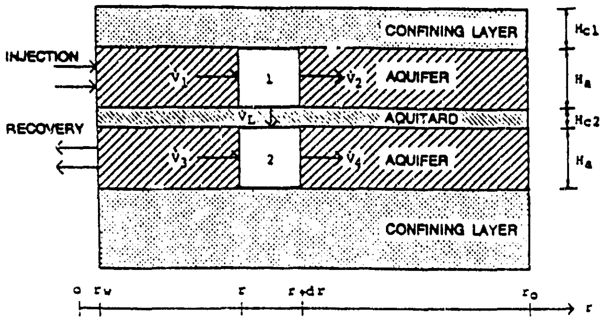

Figure 1. Model Aquifer for a Single Well Heat Pump Plant.

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 and sent 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 from the lower layer by both heat conduction and convection. Energy inflow as geothermal heat is disregarded and thus the model will give a conservative estimate of the injection temperature. The flow in both the upper and lower aquifer is assumed to be horizontal without a vertical flow 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 best conditions for the reheating of the water 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.

MATHEMATICAL MODELLING.

GOVERNING DIFFERENTIAL EQUATIONS -

To predict the operational conditions for the plant, mathematical models for the flow and energy transport in the aquifer were developed.
The models are based on a combination of an analytical and a numerical solution of the conservation equations for mass and energy.
The solution domain for the equation is defined in chapter 2 and illustrated in figure (1).

Dimensionless radius, piezometric head and flow rate are defined as follows:

$$r=\frac{\hat{r}}{\hat{H}_a};\quad h=\frac{\hat{h}}{\hat{H}_a};\quad u_D=\frac{\hat{u}_D}{\hat{K}_a};\tag{1}$$

Dimensionless injection temperature is defined as:

$$T=\frac{\hat{T}_0-\hat{T}}{\Delta\hat{T}_P}\tag{2}$$

where T_0 is initial groundwater temperature. Since only steady-state conditions are considered, time does not enter into the problem. Dimensionless groups arising from these dimensionless variables are defined at the end of this chapter.

It is assumed that the temperature variations in the aquifer are so small that the influence on the groundwater density can be disregarded.
Based on this assumption, the mass conservation equation in dimensionless form can be written:

$$\frac{1}{r}\frac{d(ru_D(r))}{dr}+u_L(r)=0\tag{3}$$

In this equation, u_D represents the Darcy velocity and u_L leakage from the aquifer. These velocities are expressed by equation (4).

$$u_D=-\frac{dh}{dr};\quad u_L=2\frac{\hat{K}_{c2}\hat{H}_a}{\hat{K}_a\hat{H}_{c2}}h=N_L^2h\tag{4}$$

N_L is a dimensionless leakage factor. Combining equation (3) and equations (4) gives the following equation for the piezometric head in the aquifer:

$$r^2\frac{d^2h}{dr^2}+r\frac{dh}{dr}-N_L^2r^2h=0\tag{5}$$

Equation (5) is the modified Bessel differential equation of order zero. The general solution to this equation is given by equation (6) [8]:

$$h=C_1I_0(N_Lr)+C_2K_0(N_Lr)\tag{6}$$

The coefficients in equation (6) are determined from the boundary conditions for the problem. The boundary condition used for the flow problem is a Neumann condition specified at the well, i.e. $dh/dr_{r=rw}$ = N_Q is specified. N_Q is a dimensionless injection number defined by equation (9) with other dimensionless groups. At the outer radius, a Dirichlet condition specifying that

$h = 0$ at $r \to \infty$ is used. It is further assumed that the leakage from the upper aquifer to the lower aquifer is proportional to the difference between the piezometric heads in the two aquifers. Because of symmetry the relationship between the piezometric head in the two aquifers is: $h_1(r) = - h_2(r)$, where h_2 is the piezometric head in the lower aquifer.

The energy equations for the upper and lower aquifers have the following form:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T_1}{\partial r})-N_p\mu_D\frac{\partial T_1}{\partial r}-(N_{u1}+N_{ul})T_1+N_{u2}T_2=0 \qquad (7)$$

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T_2}{\partial r})+N_p\mu_D\frac{\partial T_2}{\partial r}\\ &-(N_{u2}+N_pu_L)T_2+(N_{u2}+N_p\mu_L)T_1=0\end{aligned} \qquad (8)$$

The additional dimensionless coefficients used in equations (7) and (8) are defined by equations 9 and 10.

$$N_Q=\frac{\dot{O}_{inj}}{2\pi\hat{r}_w\hat{H}_a\hat{K}_a}; \quad N_p=\frac{(\hat{\rho}\hat{C})_w\hat{H}_a\hat{K}_a}{\hat{\lambda}_a}; \qquad (9)$$

$$N_{ul}=\frac{\hat{\lambda}_{cl}}{\hat{\lambda}_a}\frac{\hat{H}_a}{\hat{H}_{cl}}; \quad N_{u2}=\frac{\hat{\lambda}_{c2}\hat{H}_a}{\hat{\lambda}_a\hat{H}_{c2}} \qquad (10)$$

N_P is a modified Peclet number describing the convective heat transport in the aquifer. N_{u1} and N_{u2} are modified Nusselt numbers for the confining layers and the separating layer between the two perforations.

The boundary conditions used for the upper aquifer were specified temperature at the well and a no-flux boundary condition at the outer radius . The boundary conditions used for the lower aquifer were natural groundwater temperature at the outer radius and a zero heat flux at the well.

SOLUTION PROCEDURE - The governing equations described in section 3.1 were solved by using an analytical solution technique for the flow equation and a numerical technique for the temperature equations.

The mass conservation equation as expressed by equation (5) was solved analytically. The solution to this equation may by found in [8] and is given by:

$$h(r)=\frac{N_Q}{N_L}\frac{K_0(N_Lr)}{K_1(N_Lr_w)} \qquad (11)$$

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_Q denotes a dimensionless injection number defined by equation (9). Differentiation of equation (11) gives the following expression for the dimensionless Darcy velocity:

$$u_D(r)=N_Q\frac{K_1(N_Lr)}{K_1(N_Lr_w)} \qquad (12)$$

By inserting the expression for the Darcy velocity given by equation (12) into equations (7) and (8), the N_P and N_Q dimensional 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:

$$P_e=N_QN_p=\frac{(\hat{\rho}C)_wQ}{2\pi\hat{\lambda}_a\hat{r}_w} \qquad (13)$$

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 discreticized 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.

DESIGN PROCEDURE FOR SINGLE WELL GROUNDWATER HEAT PUMPS.

HYDRAULIC DESIGN PARAMETERS. - The criteria used in the design of a single-well heat pump plant are 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 in section 3. From equation (11), 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:

$$N_P = \frac{h}{N_Q\, r_w} = \frac{1}{N_A} \frac{K_0(N_A)}{K_1(N_A)} \tag{14}$$

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

From equation (14), 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 2.

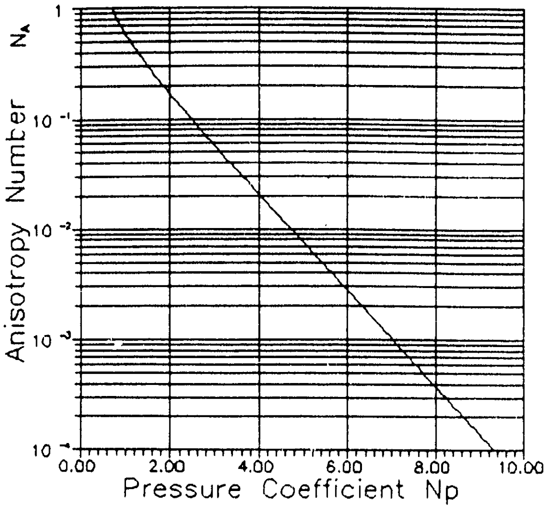

Figure 2. Anisotropy number N_A as a function of the pressure coefficient N_P.

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.

OPERATIONAL CONDITIONS FOR THE SINGLE-WELL PLANT - The energy equations describing the temperature distribution in the upper and lower aquifers were solved numerically using the finite element method and for different values of the dimensionless parameters. Some of the results of this parameter study are shown in figure 3.

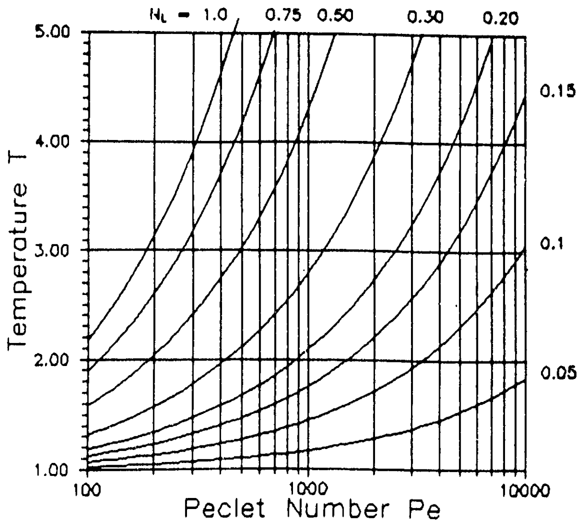

Figure 3. Dimensionless injection temperature as a function of P_e and the leakage factor N_L for N_{u1} = 0.1 and N_{u2} = 0.2

The data represented in the figure is the dimensionless injection temperature T, as a function of the dimensionless injection number P_e, for 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.

EXPERIMENTAL RESULTS AND COMPARISON AGAINST MODEL RESULTS.

EXPERIMENTAL TEST FACILITY - In order to allow thermal break-through phenomena to be studied, a full-scale test stand for single-well groundwater heat pumps has been set up on the campus of the Technical University of Denmark.

The reservoir contains 3 instrumentation wells, which were established for temperature and pressure measurements.

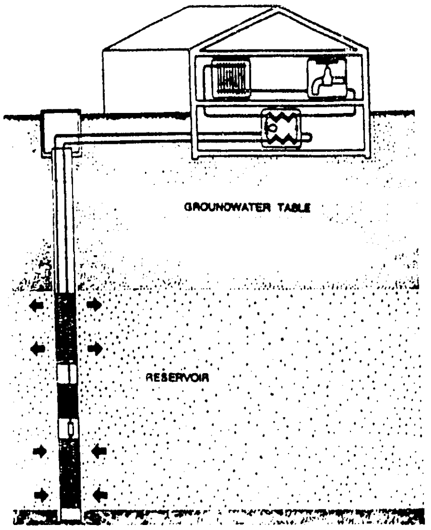

Figure 4. Illustration of single-well design used at the University test facility.

The design of the well is illustrated in figure 4. Groundwater was produced from the aquifer through a screen at a depth of 38-43 metres below surface and injected through a screen at a depth of 29-34 metres below surface. The two screens are separated by a packer.

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

The groundwater was produced and circulated with the help of a submerged pump placed 2 metres above the well-screens. The flow-rate was 1.5 to 3.0 m^3/hour. In the heat pump installation, the groundwater was cooled 2-3°C before reinjecting into the reservoir. The initial groundwater temperature was 8.8 °C. The heat capacity of the heat pump was 10 kW. 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 device. In total, 4976 m^3 of groundwater was cooled and 5156 m^3 of groundwater was reheated, which corresponds to an extraction of 62514 GJ of heat from the reservoir and a reheating amount of 27403 GJ into the aquifer.

COMPARISON BETWEEN MODEL PREDICTIONS AND EXPERIMENTAL DATA - The mathematical models described in the previous chapters were used to predict the operational behavior of the well. The relevant data for the test stand is shown in table 1.

In order to estimate the vertical to horizontal permeability ratio, the pressure required to inject water and produce water in the well dipole at a specified rate was recorded. Based on this data, the factor of anisotropy N_A could be read from figure 2, and the dimensionless leakage number N_L could be calculated.

Data for single-well installation

Aquifer height Ha	5	m
Distance between well screens H_{C2}	4	m
Aquifer horizontal permeability Ka	10^{-4}	m/s
Heat conductivity	3	W/mK
Average groundwater temperature	8.8	C°
Specified temperature difference in heat pump evaporator	2.2	C°
Effective well radius r_w	0,25±0,05	m
Injection rate Q	4.63 10^{-4}	m^3/s

Values of parameters used at anisotropy test.

Injection pressure	0.031	bar
Injection rate Q	2.78 10^{-4}	m^3/s

Table 1. Key data for the single-well test stand.

Based on the data listed in table 1, the limits for N_L were calculated to 0.47 and 0.70 and for P_e to 511 and 341. The values of N_{u1} and N_{u2} were 0.15 and 1.25.

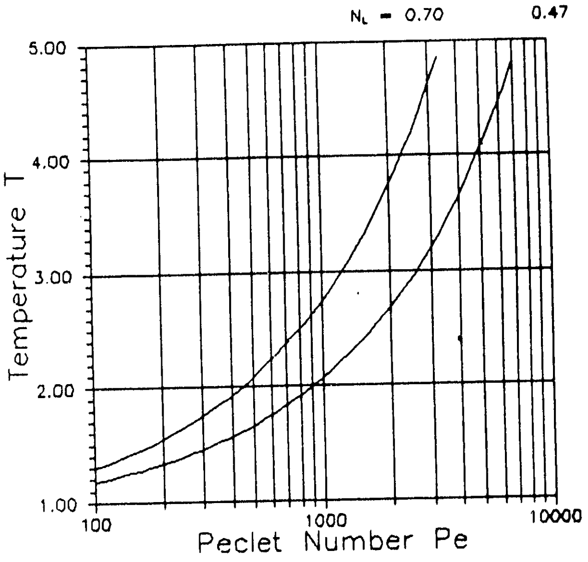

Figure 5. Dimensionless injection temperature as a function of the injection number P_e for the two limiting values of the leakage number N_L and Nu_1 = 0.15, Nu_2 = 1.25.

The relationship between these parameters is illustrated in figure 5, which shows dimensionless temperature as a function of injection number P_e.

The the measured temperature of produced groundwater as a function of time is shown in figure 6 which also shows the calculated steady-state temperature level. As can be seen from the figure, the measured temperature is within the estimated upper and lower limit of the steady-state operational temperature.

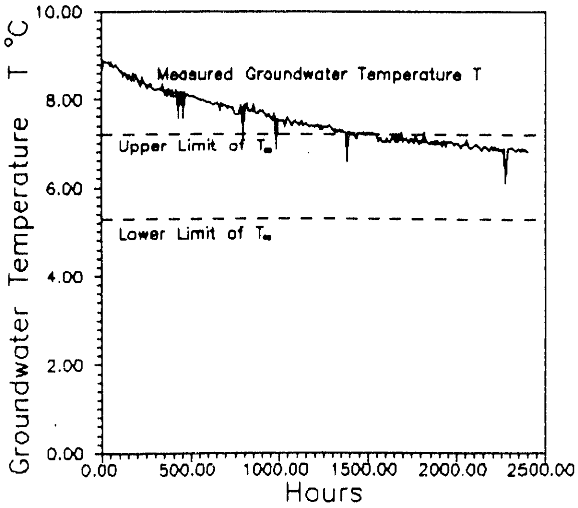

Figure 6. The figure shows the measured temperature of produced groundwater as a function of time and the calculated upper and lower limit of the steady-state groundwater temperature T_∞.

CONCLUSION.

The use of groundwater as an energy resource has aroused increasing interest. Natural groundwater is today used in combination with heat pumps for private home heating. Normally such heat pump installations consist of a production and a reinjection well. By drilling only one well for both the pumping and the reinjection of the groundwater, however, the installation cost can be considerably reduced. It has been demonstrated that the long term operational conditions of a single-well groundwater heat pump plant can be predicted by the models presented in the paper and these can therefore be used as tools in the design procedure. An estimation of vertical to horizontal permeability is particularly essential in the design procedure. A comparison between model prediction and data from a long term operation of a single well at the Technical University of Denmark has demonstrated good agreement between predicted and measured performance.

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: "The Danish Aquifer Energy Storage Project. Operational Experience". JIGASTOCK 88, Versailles, France, 1988.

[3] M. C. Hoyer, M. Walton, R. Kanivetsky, T. R. Holm: "Short-term Aquifer Thermal Energy Storage Test Cycles, St. Paul, Minnesota, U.S.A.". ENERSTOCK 85, Toronto, Canada, 1985.

[4] Sun Yong-fu, Li Qin-fen, Wu Ji-hong: "The Experiment of Storing Cold and Warm Water in Aquifer in Shanghai P.R. China and its Effect". THERMASTOCK 91, Scheveningen, The Netherlands, 1991.

[5] A. Eriksson, S. Johansson: "Experience from the Aquifer Thermal Energy Storage System at SAS Frösnavik Office, Sweden". THERMASTOCK 91, Scheveningen, The Netherlands, 1991.

[6] S. N. Sørensen, J. Reffstrup, B. Qvale: "The Development of Danish Legislative Guidelines and Design Rules for Utilisation of Groundwater in Heat Pumps." Association of Hydrogeologists, Memoires of the 18th Congress: Hydrogeology in the Service of Man. Cambridge, UK, 1985.

[7] S. N. Sørensen: "The Establishment and Operation of Groundwater-Based Heat Pump Systems". Laboratory for Energetics, The Technical University of Denmark. Ph.D.-Report RE 91-2, 1991.

[8] G.E. Myers: "Analytical Methods in Conducting Heat Transfer", McGraw-Hill, 1971.

LIST OF SYMBOLS

$\hat{C}$	Specific heat capacity.
$\hat{H}$	Height of geological layers.
h	Piezometric head.
N_A	Anisotropy number.
N_L	Leakage number.
N_P	Pressure coefficient.
N_Q	Injection number.
Nu	Modified Nusselt numbers.
P_e	Peclet number.
Q	Injection-production rate.
r_w	Well radius.
r	Radius.
T	Temperature.
ΔT_f	Temperature difference over heat pump evaporator.
u_D	Darcy velocity.
u_L	Leakage velocity.
Subscripts:	
a	Aquifer.
d	Darcy.
C	Confining layer.
L	Leakage.
w	Well.
ˆ	Variables with dimension.

PHREEQM-2D: A Computer Model to Calculate Geochemical Reactions During Transport of Groundwater; Model Description and Application to the Utrecht University ATES

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ABSTRACT

When hot water is injected into an aquifer, the water will react with the minerals present in the aquifer. The most important processes are cation exchange, precipitation/dissolution of carbonates, and dissolution/precipitation of silicates. If the redox condition of the water is changed during the process (e.g., because of contact with oxygen in the air or because of mixing of water with a different redox status) redox reactions will be important as well.

In many cases, the water will have to be treated to prevent carbonate scaling during heating. This treatment will influence the reactions in the aquifer. Because the water is (at least partly) reused each cycle, the reactions in the aquifer may cause an increase or a decrease in necessary treatment in subsequent cycles. Also, the treatment and the reactions in the aquifer may have an influence on the environmental impact of the store because the quality of the water lost from the store is changed.

To be able to assess the relevance of these processes, a model has been developed that calculates the chemical reactions during transport of groundwater. An example of use of the model is given for the Utrecht University ATES system. At this site, a split treatment of Ca-Na softening is used to prevent carbonate sealing. The calculations have helped to make decisions on how to proceed with water treatment.

INTRODUCTION

For ATES, groundwater is withdrawn (from the 'cold well(s)') in periods of heat surplus, heated, and injected back into the aquifer (using the 'hot well(s)'). In periods of heat demand, the heated water will be withdrawn again, cooled, and injected back into the 'cold well(s)'. When the water is heated and cooled, chemical reactions might occur because the water contains dissolved solids and the relevant equilibrium constants (complex association constants and mineral solubility products) are generally temperature dependent. During heating in the heat exchanger, these reaction may cause severe scaling problems. Calcium carbonate scaling during heating is a very common problem, encountered in many cases where (hard) water is heated. Silica scaling is encountered where groundwater is cooled down from high temperatures, especially in geothermal operations. During ATES, calcium carbonate scaling can be a severe problem. It has been encountered at many projects, for instance at St. Paul (Holm et al., 1987) and at SPEOS (Saugy et al., 1988). Further information on geochemical problems encountered at existing projects can be found in Jenne et al. (1992).

Formation of calcium carbonate scale can be prevented by different water treatment techniques. Previous analyses (Willemsen et al., 1988a; Willemsen, 1990) of water treatment methods to prevent calcium carbonate scaling for ATES have shown that the treatment techniques that remove solutes, like Na exchange and precipitation with lime, decrease in intensity with each cycle. Ca-Na exchange is the treatment technique that is used most frequently for ATES. It has a relatively low impact on the groundwater quality; it has a decreasing intensity with cycles; it is commercially available and it can operate fully automatically. Drawbacks of Ca-Na exchange are the discharge of salt to the sewage and the potential for clay swelling in the aquifer. Clay swelling, followed by migration of the clay particles and subsequent clogging of the pores is a phenomena that is among others encountered when fresh water is injected into aquifers containing brackish/salt water (Olsthoorn, 1982). The potential for clay swelling is generally calculated with the Sodium Adsorption Ration (SAR; Appelo and Postma, 1992).

Ca-Na exchange significantly influences the SAR. Because future development of the SAR at the Utrecht University ATES also depends on the reactions in the aquifer, PHREEQM-2D is used to predict the future behaviour of the SAR.

PHREEQM-2D

The model PHREEQM-2D (Willemsen, 1992) is a coupled chemical transport model that couples a groundwater transport model (HST2D, Hagoort, 1989, derived from HST3D, Kipp, 1987) to a geochemical reaction model (PHREEQE, Parkhurst et al., 1980). HST2D calculates the solution to the flow equations using finite differences and writes information on temperatures and flow velocities across boundaries into a file.

This file is later read by PHREEQM-2D. In PHREEQM-2D, up to 30 solutes can be transported and diffused, also using finite differences. Reactions among these solutes and with solids and a gas phase can be calculated with PHREEQE. Reactions that can be calculated are equilibrium dissolution/precipitation for up to 20 minerals simultaneously, kinetic calculations for 1 mineral, cation exchange, redox reactions, aqueous complexation and calculation of the gas composition of a bubble formed by the water.

PHREEQM-2D uses an established procedure to correct numerical dispersion. Other coupled chemical transport models do not correct at all (e.g., Appelo and Willemsen, 1987; Liu and Narasimham, 1989;). Some use iteration between transport and chemisty to improve the accuracy (Sequential Iteration Approach, e.g., Förster, 1986; Cederberg et al., 1985). Others solve the total system of coupled equations directly (e.g., Lichtner, 1985). The direct solution to the complete set of equation is very time consuming. In general, the Sequential Iteration Approach is considerably faster (Yeh and Tripathi, 1989). However, iteration between tranport and chemistry may result in severe problems with respect to convergence. The method of fractional steps (with correction for numerical dispersion) that is employed by PHREEQM-2D is unconditionally stable and second order correct within certain limits. The models that do not iterate and do not correct for numerical dispersion like the PHREEQM/CHARM1 model (Appelo and Willemsen, 1987 Nienhuis et al., 1988; Willemsen et al., 1988b) suffer from numerical dispersion when the grid size/time step is to large.

Table 1. Fractional steps in PHREEQM-2D for each time-step

step	calculation of
1	transport in x-direction
2	reactions (PHREEQE)
3	diffuse in x-direction
4	reactions (PHREEQE)
5	transport in y-direction
6	reactions (PHREEQE)
7	diffuse in y-direction
8	reactions (PHREEQE)

PHREEQM-2D uses eight fractional steps per time step These steps are shown in Table 1. This table shows that fo all cells, PHREEQE is called 4 times per time step. If ther are 100 cells and 100 time steps, there are 40,000 calls to PHREEQE. On a 16 MHz 386 SX-machine with 387 coprocessor, a call to PHREEQE takes approximately 1 second (this will depend on the chemistry of the problem), which would mean that this simulation would take about 11 CPU-hours to run. This calculation time can be reduced by calling PHREEQE only if a solute concentration has changed significantly.

PHREEQM-2D is a second order correct transpor model by correcting for numerical dispersion caused by the backwards in space (BIS), forward in time (FIT) approximation to the transport and by the backwards in time (BIT) approximation to the reactions. The numerical dispersion caused by the BIS, FIT approximation to the advection is related to the grid size and time step (Abbott and Basco, 1989).

$$D_{num,advection,x} = \frac{v_x}{2}(\Delta x - v_x \Delta t) \qquad (1)$$

(See Notation section for definition of terms).

The numerical dispersion caused by the BIT approximation to reactions is equal to

$$D_{num,reactions,x} = \frac{v_x}{2}\frac{R_x - 1}{R_x} v_x \Delta t \qquad (2)$$

(Willemsen, 1992; Herzer and Kinzelbach, 1989).

Combining these two gives

$$D_{num,total,x} = \frac{v_x}{2}(\Delta x - \frac{v_x \Delta t}{R_x} \qquad (3)$$

Diffusion is now calculated using a corrected D_{model}:

$$D_{model\,x} = D_{physical\,x} - D_{numerical\,x} \qquad (4)$$

For the y-direction the calculation is similar.

The retardation factor R_x will be different for different processes that can be active in any cell in the finite difference grid at any time. This means that there can be several different R's simultaneously.

To prevent errors in the electrical neutrality (which is used to calculate pH in PHREEQE) only one value for D_{model} is used for all solutes. Therefore, the R_x used in equations (2) and (3) is constant. The R_x used is the R_x for the solute with the largest change in concentration with time. This implies that PHREEQM-2D is second order correct if there is only one reaction front or, if there are more fronts, if fronts are fully separated. The limits for grid and time step for PHREEQM-2D are as follows:

$$Cr_x = \frac{v_x \Delta t}{\Delta x} < 1 \qquad (5)$$

$$Pe_x = \frac{v_x \Delta x}{D_x} < 2 \qquad (6)$$

and similar for the y-direction. Above Cr=1, the model will be unstable; above Pe=2, there can be numerical dispersion. For a more complete description of PHREEQM-2D, including model verification and a comparison to other coupled models, the reader is referred to Willemsen (1992).

UTRECHT UNIVERSITY ATES

At the Utrecht University, an ATES system has recently been implemented. This system can store about 6000 MWh of thermal energy per year. For a description of the system and the general performance during the first year, the reader is referred to Van Loon and Van der Heide (1992) and to Van Loon and Paul (1991). The most significant data are given in Table 2.

Table 2. Some data on the Utrecht University ATES

$T_{injection}$ loading	90°C
$T_{injection}$ unloading	45°C
m^3 water loaded	ca 100,000
m^3 water unloaded	ca 100,000
$T_{minimum}$ usable	50°C
distance hot 'cold' well	60 m

To prevent calcium carbonate scaling during loading of the store, a conventional Ca-Na ion exchanger has been installed for water treatment. It was recognized that this type of water treatment creates a risk of clogging of the aquifer by clay swelling (Willemsen and Van der Weiden, 1991). This risk is minimized by keeping the SAR below 11 by split treatment: 60% of the water is treated and 40% is not treated.

RESULTS OF FIRST CYCLE - During the first storage cycle, no clogging has been observed, in either the wells the or the heat exchanger. Analyses of water samples taken from the injection and production cycles are shown in Table 3.

From other samples (Heidemij, 1992; Willemsen and Van der Weiden, 1991) it is known that a fresh/brackish water quality boundary is located in the aquifer used for storage. This explains why during charging, the water quality of the recovered water changes. From the measurements it can be concluded that gradually more water is produced from the deeper, higher layers.

The amount of Ca and Mg removed during charging is approximately 60%, coïnciding with the split of the treatment (see Tabel 3). The injected Ca, Mg, Na and K concentrations are fairly constant. There is one analysis of K that shows an anomalously high value.

The most striking feature is the drop in pH combined with an increase in alkalinity during discharging. This implies an increase in Total Inorganic Carbon content (TIC). This could be explained by acidification of the water followed by carbonate dissolution. The acidification could conceivably be caused by CO_2-production as a result of decomposition of organic matter (Brons et al., 1991) and/or by proton buffering. The only other realistic explanation seems to be that the incoming water from below has a higher CO_2 content. This is not considered likely because the chloride-content hardly changes from 30/9/91 to 5/12/91. However, the presence of different water qualities in the aquifer makes a proper distinction between the reactions difficult, if not impossible. Maybe

Table 3 Water composition during first cycle (in mg/l)

function	·	charging	charging	charging	charging	charging	charging	discharging	discharging	discharging
sample date	25/5/89	13/6/91	13/6/91	29/7/91	29/7/91	30/9/91	30/9/91	5/12/91	28/1/92	31/3/92
location (well)	cold	cold	warm	cold	warm	cold	warm	warm	warm	warm
pH (at 20°C)	8.1	8.0	8.1	8.0	8.0	8.06	8.13	7.44	7.68	7.95
Ca	42	48	17	50	20	51	21	25	30	32
Mg	15	20	11	28	11	25	11	11	11	12
Na	140	210	280	210	280	210	280	300	285	290
K	16	24	10	25	11	29	41(?)	21	29	28
HCO_3	211	196	196	190	191	218	220	284	285	260
Cl	240	275	n.d.	390	n.d.	380	n.d.	390	410	415
SAR	4.7	6.4	13.0	5.9	12.5	6.0	12.3	12.6	11.3	11.1

n.d. not determined SAR = Na $(Ca + Mg)^{-0.5}$; value in mmol/l

future cycles will provide more information, when the water quality in the aquifer is more homogeneous.

During production, the Ca, Na and K concentrations increase. The calculated SAR of injected and produced water is between 11 and 13, which is too high. It is also higher than expected. The increase is caused by the inflow of other water. From these data, and from previous work on water treatment for the Utrecht University ATES system (Willemsen and Van der Weiden, 1991), the following concerns arise.

During discharge the cooled water is injected without treatment. In the next cycle, the water is treated again. This will cause an increasing SAR. At present no well clogging has been observed, although the SAR has increased to 13. At the Plaisir Project (Pfiffer et al., 1991) wells became clogged after Ca/Na exchange. The water withdrawn from the clogged wells had a very high clay content. Although Pfiffer et al. (1991) did not attribute the clogging to clay swelling, all facts point towards this cause. It is, therefore, of importance to predict the future behaviour of the SAR in the storage aquifer at the Utrecht University.

The water is injected with a positive saturation index with respect to calcite (Willemsen and Van der Weiden, 1991). In the aquifer, this supersaturated calcite might precipitate. The amount precipitated might be enhanced by back-exchange of Ca for Na from the cation exchange complex (cec) in the aquifer (this was calculated by Willemsen et al., 1988a). This precipitate may eventually clog the aquifer around the well. It is, therefore, important to know the amounts of precipitate.

If the water becomes undersaturated with respect to calcite during cooling, calcite dissolution might occur around the cold well. If the amount dissolved per cycle is more than the amount precipitated (because Ca is removed by the treatment each cycle), this could cause a continuing increase in pH and alkalinity. Apart from the SAR-problem mentioned above, such an increase in pH and alkalinity would not constitute a problem because calcite dissolution would soo decrease due to this increasing pH. The process is self-stabilizing. However, an increasing pH could increase the risk o clay swelling. Adding hydroxide is a technique that is used i the laboratory to peptize clay.

Calculations have been performed with PHREEQM-2 to get answers to the concerns mentioned above.

CALCULATIONS PERFORMED - The most significant data on the store are shown in Table 2. Other data use in the calculations are shown in Table 4.

Table 4. Data used during Calculations

Initial temperature	15 °C
Effective thickness aquifer	20 m
Longitudinal dispersivity	5 m
Transversal dispersivity	0.5 m
Porosity	35 %
Water composition	Table 3 cold well 29/7/91
CEC (estimated)	100 meq/l water
Original amount calcite	1000 meq/l water

During charging of the store, the water is taken fro the cold well. The water is changed in composition (60% Ca Mg, Fe to Na exchange on equivalent basis) and injected int the warm well at a temperature of 90°C. During discharg the water is taken from the warm well and injected into th cold well at a temperature of 45°C, without treatment. Th amounts of water are given in Table 2.

For the first cycle, the amount of water injected and th temperature of the water are different. To be able to compar the calculated data with the measurements, an approximatio of amounts of water and temperatures has been used: 10 days charging 65°C, total 64,000 m³; 50 days chargin

90°C, total 14,000 m^3. We have assumed that during the first cycle, 50,000 m^3 will be withdrawn from the store.

REACTIONS - The following reactions have been assumed to be operative in the store:

- cation exchange
- calcite equilibrium dissolution/precipitation.

For cation exchange, the Gaines-Thomas convention for description of the activity of the adsorbed solutes is used (Appelo and Postma, 1992; Willemsen, 1992). The exchange constants used are given in Table 5.

Table 5. Cation exchange constants

reaction	K_{ex}	ΔH° (Kcal/mol)
$2\ NaX + Ca^{++} \rightarrow CaX_2 + 2\ Na^+$	6.3	1.0
$2\ NaX + Mg^{++} \rightarrow MgX_2 + 2\ Na^+$	4.0	1.0
$NaX + K^+ \rightarrow KX + Na^+$	5.0	0.0

For the calcite solubility product and for relevant aqueous complexes the database from Smith (1988) has been used.

In the calculations the pH of the original water is assumed to be 7.7 instead of 8. At this pH, the water is at equilibrium with calcite at 15°C.

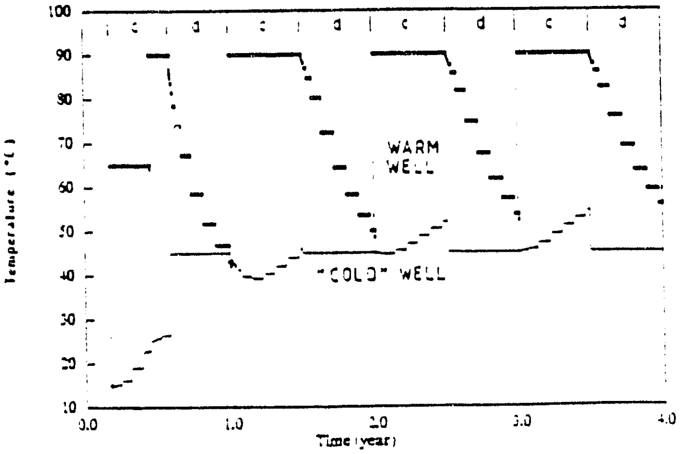

Figure 1. Calculated temperatures in the warm and cold well. c: charging, d: discharging of store

It is clear that other processes will also occur in the aquifer. The most significant are:

- Silica dissolution (and to a minor extent: precipitation)
- Precipitation/dissolution of other carbonates, notably $FeCO_3$, also in the form of solid solutions
- Decomposition of organic matter, which increases the amount of TIC
- Proton buffering
- Reactions with other minerals, e.g., oxides, sulfides.

These processes have been neglected, because the possible extent of these reactions cannot be quantified without site specific empirical data. On the other hand, experiments on material from other sites have shown that, in general, carbonate precipitation/dissolution and cation exchange are the most significant processes (Appelo et al., 1990a).

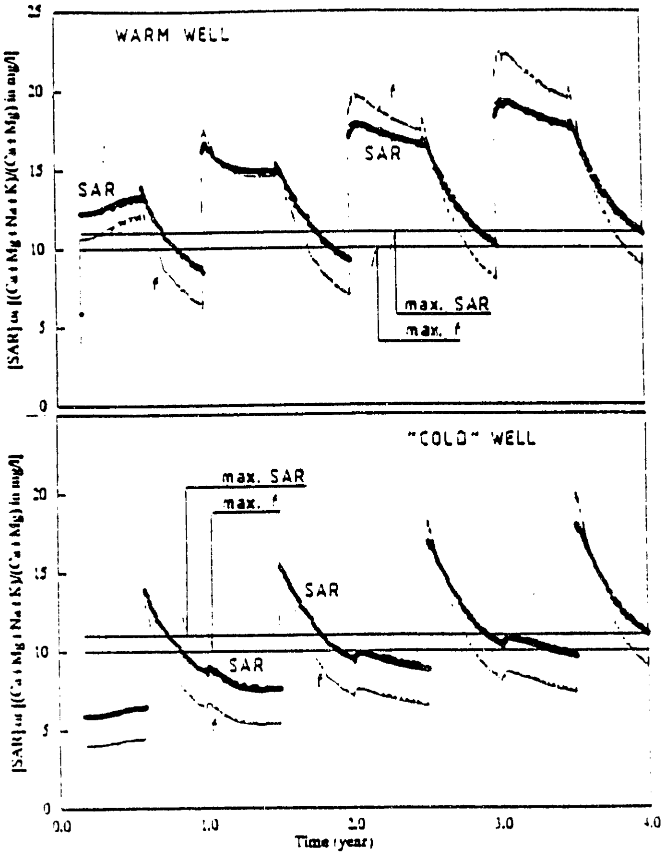

Figure 2. Calculated SAR in the warm (above) and cold well (below). Also shown is the fraction f, this is Ca+Mg+Na+K divided by Ca+Mg (in mg/l). Above the lines shown as limits, there is a clay swelling potential.

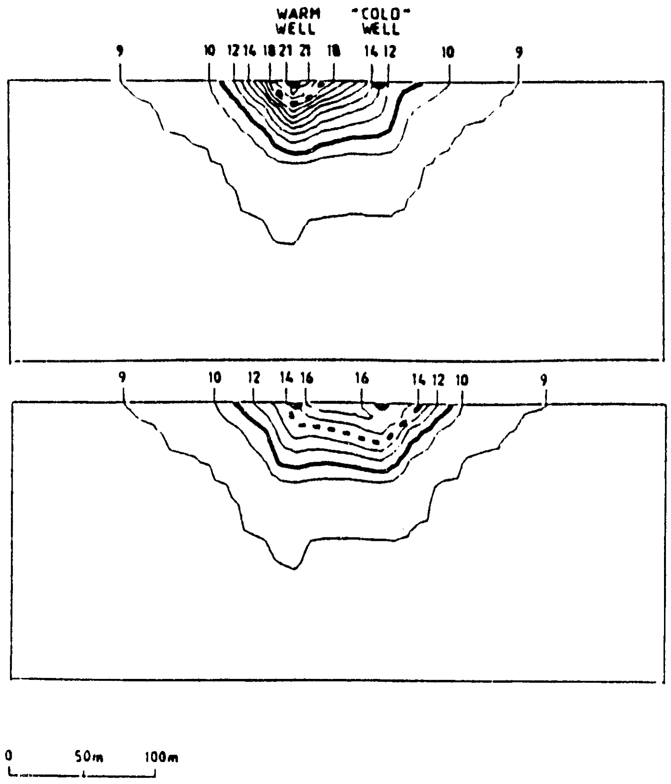

Figure 3. Contours of the calculated NaX - concentration (in meq/l porosity) after the 4th charging cycle (above) and the 4th discharging cycle (below). Above 15 meq/l (= 15% CEC occupation) there is a risk of clay swelling.

RESULTS AND DISCUSSION

Figure 1 shows the calculated temperatures in the warm and cold well, where as Figures 2 and 3 show the calculated SAR and the contours of the calculated SAR after the 4th cycle.

Figures 4 and 5 show the calculated amount of calcite precipitated around the warm and cold well and the contours of the calculated amount of precipitated calcite in the aquifer after the 4th cycle.

Figure 6 shows the calculated TIC and alkalinity in the cold well, and Figure 7 the calculated pH in the warm and cold well.

These figures show the following. The SAR increases with cycles to approximately 25 during the 4th cycle in the warm well (figure 2). The SAR is highest during charging around the warm well, but during discharging, the SAR initially peaks to an even higher value. If we compare this to the measured data, we find that the measurements also show initially a higher SAR during production from the warm well.

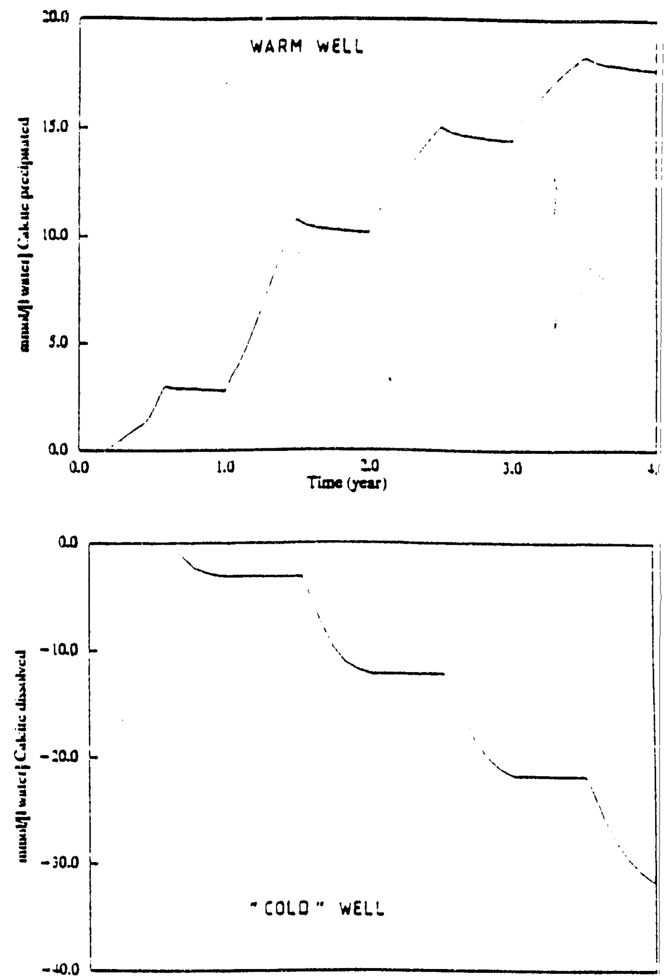

Figure 4. Calculated cumulative amounts of calcite precipi tated in the warm well (above) and cumulativ amount dissolved in the cold well (below). Dat in mmol / [l porosity]

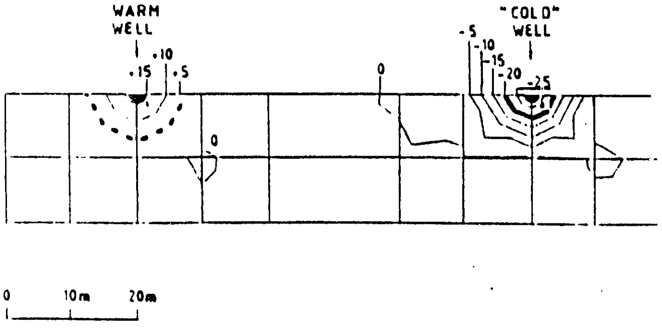

Figure 5. Contours of the calculated amount of calcite the aquifer after the 4th cycle. Data in mmol / porosity

Figure 2 also shows the fraction f. This is (Ca+Mg+Na+K)/(Ca+Mg) in mg/l. According to Jones (1964) this value should be kept below 10 for injection of water into oil fields if clay swelling is to be prevented. It is clear that the rule according to Jones (1964), agrees very well to the SAR-rule.

The jig-saw nature of the lines in figures 1, 2, 7 and 8 is because PHREEQM-2D has more time-steps between HST2D-time steps, and is also caused by the tolerance on changes in composition before PHREEQE is called. The amount of calcite that precipitates during each cycle decreases with cycles, because gradually all the Ca in the groundwater is removed by the treatment (figures 2 and 4). The total amount precipitated around the warm well is about 17 mmol/l after the 4th cycle. This would mean that the porosity could have been reduced from 0.35 to 0.3498 and clogging due to calcite precipitation is not likely.

Dissolution of calcite is calculated for the area around the cold well. The total amount dissolved is larger than the amount precipitated. Precipitation and dissolution are only calculated near the wells. At nodes some distance from the wells, dissolution/precipitation is not significant. This could be different if kinetics were included in the calculations.

The alkalinity and TIC content of the water in the store hardly change as a result of the reactions with calcite. This shows that reactions with calcite are relatively insignificant for the composition of the water and that it might be possible to decrease the treatment intensity with successive cycles. If the alkalinity would increase with cycles and if this would compensate the decrease in Ca, the treatment could not be decreased. A decreasing treatment will reduce the risk of clay swelling.

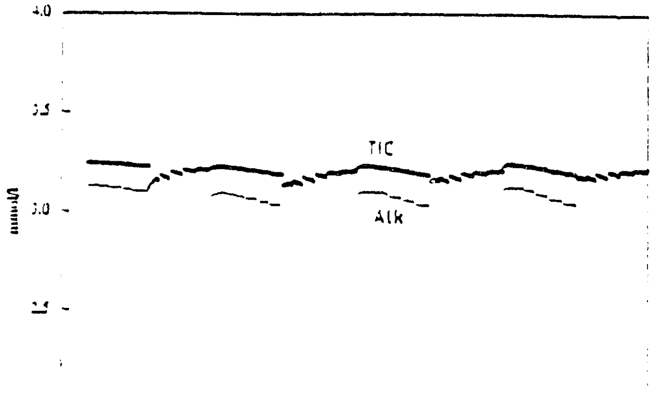

Figure 6. Calculated alkalinity and TIC in the cold well. Data in mmol [l water]

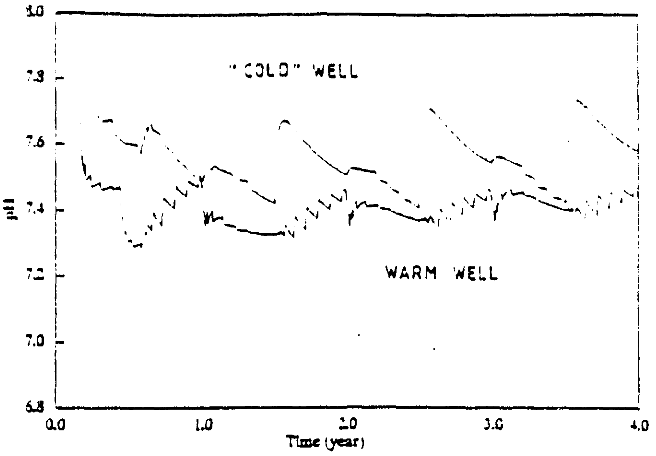

Figure 7. Calculated pH around warm and cold well.

The pH increases slightly with cycles due to the dissolution of calcite. The initial drop in pH, and the difference in pH between the warm and cold well, is caused by the dependence of pH on temperature. The increase in pH with cycles does not seem very significant.

EVALUATION AND CONCLUSIONS

PHREEQM-2D can be a valuable tool for designing water treatment systems for ATES. The model can accurately predict the time and space-dependent behaviour of reactive solutes during transport in aquifers, provided the data are accurate. As all models, PHREEQM-2D needs input data. It needs hydrological data on permeabilities, heat conductivities and porosities. There is of course an uncertainty in these data. In general, for field problems this uncertainty in hydrological data is significant. The uncertainty in geochemical data might be even larger.

Geochemical data like solubilities have been gathered for ideal systems. Natural systems may behave differently as a result of processes like inhibition, solid solutions and unexpected complexion with organic components (Appelo et al., 1990a). For many dissolution/precipitation reactions, kinetics are important but kinetic rate constants and reaction surface area are seldom known.

PHREEQM-2D has been verified on analytical solutions (Willemsen, 1992) and validated on column-experiments. Cation exchange and calcite dissolution kinetics have been modelled accurately (Appelo et al., 1990b). For cation exchange the constants can be estimated from literature. As long as minerals can be assumed to be in equilibrium with the water composition, the data can be based on literature (if solid solutions formation is neglectible). For calcite dissolution kinetics, however, the parameters are site dependent and had have to be determined empirically.

In the computations above, we have assumed calcite equilibrium to be valid. The residence time of the water in the cell where the well is located is more than 7 hours. If the reaction is not inhibited, this residence time will be sufficient for equilibrium with calcite. In all other cells, the residence times are even larger, so the assumption of calcite equilibrium seems correct. Reseach performed by Griffioen (1992) and Banck (1989) (see also Appelo et al., 1990a) has shown that the presence of ortho-phosphate (o-PO_4) and Dissolved Organic Carbon (DOC) in the water can inhibit calcite precipitation to a large extent. Griffioen (1992) found in coleumn experiments that even after 44 hours reaction time, the Ion Activity Product over the solubility constant (IAP/K) for calcite was higher than 10. At Utrecht University the Dissolved Organic Carbon (DOC) and o-PO_4 levels are significantly lower than at Delft (Griffioen, 1992) and at Lomma (Banck, 1989). (Lomma: 3 to 4 mg/l DOC and 0.3 to 0.6 mg/l o-PO_4; Delft: 25 to 35 mg/l DOC (including CH_4) and 10 to 15 mg/l o-PO_4; Utrecht: 0.5 to 2 mg/l DOC and 0.1 to 0.3 mg/l o-PO_4). The kinetics of the precipitation reaction will influence the location of the precipitation. If the reaction is fast (faster than assumed) the precipitate may be found directly around the well. In that case clogging is not impossible. It is therefore of importance to quantity this reaction rate. However, considering the empirical results described above, a significantly faster reaction (faster than equilibrium in 7 hours) is not considered likely.

If the model predictions are not correct, this might be caused by:

- mixing of different water compositions
- influence of reactions not included in the model, like silica dissolution and organic matter decomposition.

From this discussion we conclude that the model needs to be validated on data from existing ATES projects, preferably from projects where water and sediment composition are (approximately) homogeneous.

The calculations on the Utrecht University ATES system may not give an accurate prediction of future water compositions; however, it does give an insight into the possible development of the chemistry of the store. The following conclusions may be drawn regarding future water treatment.

If the split of 60% treatment, 40% bypass is not changed, there is a significant risk that clay swelling will clog the aquifer in the future.

The percentage treated should be changed such that the SAR of the injected water stays below 11. If this means that the saturation index for calcite after heating would increase to an unacceptable level, experiments should be performed. These experiments should assess the maximum calcite saturation index at 90°C at which no scaling occurs and the maximum SAR that can be injected without risk of clay swelling. (It is not impossible that this would show that water treatment is not necessary because carbonate precipitation is inhibited sufficiently.)

At present, work is underway to install a system that will regulate the water treatment split according to the Ca concentration in the water. The split will be regulated such that the injected Ca concentration is constant. The Na and Mg concentration will be analyzed regularly so the split can be set in such a way that the SAR will stay below 11.

ACKNOWLEDGEMENTS

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NOTATION

Cr = Courant number ($v\Delta t/\Delta x$)
D = Dispersion coëfficient (m^2/s)
D_{num} = Numerical dispersion coëfficient (m^2/s)
Pe = Cell Peclet number ($v\Delta x/D$)
R = Retardation factor
T = Temperature (°C)
v = Groundwater flow velocity (m/s)
Δt = Time step (s)
Δx, Δy = Distance between nodes in x- resp. y-direction (m)

REFERENCES

Abbot, M.B. and D.R. Basco, (1989). Computational fluid dynamics: an introduction for engineers. Longman Scientific and Technical. Harlow, England. 425 pp.

Appelo, C.A.J. and A. Willemsen. (1987). Geochemical calculations and observations on salt water intrusions, I. A combined geochemical/mixing cell model. J. Hydrol. 94: 313-330.

Appelo, C.A.J., J. Griffioen and M.J.J. v.d. Weiden. (1990a). Environmental and chemical aspects of thermal energy storage in aquifers and research and development of water treatment methods. Subtask B (Bio) geochemical reactions. Heidemij Adviesbureau, Arnhem, The Netherlands. 91 pp.

Appelo, C.A.J. and D. Postma (1992). Groundwater, geochemistry and pollution. Balkema, The Netherlands.

Appelo, C.A.J., A. Willemsen, H.E. Beekman, and J. Griffioen, (1990b). Geochemical calculations and observations on salt water intrusions II. Validation of a geochemical model with laboratory experiments J. Hydrol. 120 : 225-250.

Banck, A. (1989). Lomma Pilot ATES Plant: experiences and results. Lund University of Technology, Lund, Sweden IEA Annex VI report 29-E. 81 pp.

Brons, H.J., J. Griffioen, C.A.J. Appelo and A.J.B. Zehnder (1991). (Bio)geochemical reactions in aquifer material from a thermal energy storage site. Water Res., (25), 729-736.

Cederberg, G.A., R.L. Street and J.O. Leckie (1985). A groundwater mass transport and equilibrium chemistry model for multicomponent systems. Water Resour. Res., 21 (8): 1095-1104.

Griffioen, J. (1992). Cation exchange and carbonate chemistry in aquifers following groundwater flow. Ph.D. Thesis. Free University, Amsterdam, 182 pp.

Förster, R. (1986). A multicomponent transport model. Geoderma 38: 261-278.

Hagoort (1989). HST2D-PC. Heat and solute transport simulation for personal computers. Hagoort, Delft, The Netherlands.

Heidemij (1992). 2^e voortgangs rapportage meetprogramma warmte-opslag Rijksuniversiteit Utrecht (ondergrondse deel). report 638/45617-45619W.

Herzer, J. and W. Kinzelbach (1989). Coupling of transport and chemical processes in numerical transport models. Geoderma 44: 115-127.

Jenne, E.A., O. Anderson, A. Willemsen and L.W. Vail (1992). Well, hydrology and geochemistry problems encountered in ATES systems and their solutions. This Issue.

Jones, F.O. (1964). Influence of chemical composition on clay blocking of permeability. J. Petr. Techn. April, 1964, p 441-446.

Kipp, K.L. (1987). HST3D: A computer code for simulation of heat and solute transport in three-dimensional groundwater flow systems. US Geological Survey - Water Resources Inv. Rep. 86-4095.

Lichtner, P.C. (1985). Continuum model for simultaneous chemical reactions and mass transport in hydrothermal systems. Geoch. Cosmoch. Acta 49 (3) 779-800.

Liu, C.W. and T.N. Narasimhan (1989). Redox-controlled multiple species chemical transport. 1. model development, and 2. Verification and application. Water Resour. Res. 25 (5): 869-882 and 883-910.

Loon, L.J.M. van and A. Paul (1991). Aquifer thermal energy storage at the state University of Utercht, The Netherlands. Proceedings Thermastock '91; Int. conf. Scheveningen The Netherlands; NOVEM, Utrecht, The Netherlands.

Loon, L.J.M. van and K. van der Heide (1992). High temperature ATES at the University of Utrecht, The Netherlands. This Issue.

Nienhuis, P.R., C.A.J. Apello and A. Willemsen (1988). PHREEQM - PHREEQE in a moving cell flow tube. Institute for Earth Sciences, Free University, Amsterdam, The Netherlands.

Olsthoorn, T.N. (1982). Verstopping van persputten (clogging of recharge wells; in Dutch). KIWA mededeling nr. 71. KIWA, Rijswijk, The Netherlands.

Parkhurst, D.L., D.C. Thorstenson and L.N. Plummer, (1980). PHREEQE - A computer program for geochemical calculations. US Geological Survey, Water Resources Inv.: 80-96.

Pfiffer, M., M. Durin, J. Despois and B. Fritz (1991). The heat storage at Plaisir Thiverval Grignon (France). Thermastock '91, Proceedings Int. Conference Scheveningen. NOVEM, Utrecht, The Netherlands.

Smith, R.W. (1988). Calculation of equilibrium at etevated temperatures using the MINTEQ geochemical code. PNL-6700, Pacific Northwest Laboratory, Richland, Washington.

Willemsen, A. (1990). Environmental and chemical aspects of thermal energy storage in aquifers and research and development of water treatment methods; Subtask A: coupled geochemical tranport model. IF Technology, Arnhem, The Netherlands.

Willemsen, A. (1992). PHREEQM-2D, PHREEQE in a multicomponent mass transport model, coupled to HST2D. Manual and user guide. IF Technology, Arnhem, The Netherlands.

Willemsen, A., J. Buitenkamp, M.J.J. v.d. Weiden, P.R. Nienhuis and C.A.J. Appelo, (1988a). Chemical reactions and effects of water treatment during ATES: experiments and coupled chemical transport modelling. Proc. Jigastock. Versailles. October 1988 Volume II p. 591-597. AFME. Paris, France.

Willemsen, A. and M.J.J. van der Weiden (1991). Heat losses and groundwater chemistry of the Utrecht University ATES. Thermastock '91. Int. Conference Scheveningen. NOVEM. Utrecht. The Netherlands.

Willemsen, A., P.R. Nienhuis and C.A.J. Appelo. (1988b). CHARM1. CHemical Aquifer Reaction Model with 1-dimensional transport. Heidemij Adviesbureau. Arnhem. The Netherlands.

Conformal Flow Models for Warm and Cold Storage in Aquifers

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ABSTRACT

The paper presents the thermohydraulic models for aquifer thermal energy storage developed by the Lund Group for Ground Heat. The basic assumption is 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 the 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

Heat (or cold) storage 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 analyses 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 hot 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 time 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 1987). 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:

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T - T C_w \vec{q}) \qquad (2)$$

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 λ. 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 1988a). 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:

$$t_0 = \frac{HC}{\kappa k C_w} \, \frac{\pi^2(\mu_0 + \mu_1)}{32G(\rho_0 - \rho_1)g} \qquad (4)$$

Nomenclature:

C	volumetric heat capacity of aquifer, J/m^{3}K.
C_w	volumetric heat capacity of water, J/m^{3}K.
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.
κ	anisotropy factor, equal to $\sqrt{k'/k}$.
μ_0	dynamic viscosity in region 0, kg/ms.
μ_1	dynamic viscosity in region 1, kg/ms.
ρ_0	density in region 0, kg/m^3.
ρ_1	density in region 1, kg/m^3.

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 (Hellström et al 1988b).

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, analysis of breakthrough, and so on).

An illustrative example is taken from a project with both heat and cold storage in an aquifer beneath the Sheraton Hotel in Malmö, Sweden. Figure 1 shows a horizontal, rectangular area in the aquifer where the four injection wells and the four extraction wells are indicated by circles. The stagnation points are located at the intersections of the stagnation lines, which are drawn in black. The stream lines between the wells are given by the gray lines. Figure 2 shows the stagnation lines and the extent of the heated region in the aquifer after a certain period of time. The shaded area represents the region heated by water injected during the first half of the period, while the white area close to the wells shows the warm region due to water injected during the second half of the period.

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 (1971) and Claesson (1978).

The heat balance programs listed below use an entropy conservation technique that eliminates the numerical dispersion (Hellström et al 1986). 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 1986; Hellström and Bennet 1989). They have been used extensively for design studies and parameter sensitivity studies (Doughty et al 1982).

REFERENCES

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

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

Doughty C, Hellström G, Tsang CF, Claesson J. 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.

Hellström G, Bennet J. 1989. Model of Aquifer Storage System, Doublet Well. Manual for Computer Code. Mathematical Physics, Lund.

Hellström G, Bennet J, Claesson J. 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.

Hellström G, Tsang CF, Claesson J. 1988a. Buoyancy Flow at a Two-Fluid Interface in a Porous Medium: Analytical Studies. Water Resources Research, Vol. 24, No. 4, pp.493-506.

Hellström G, Tsang CF, Claesson J. 1988b. 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.

Lantz RB. 1971. Quantitative Evaluations of Numerical Diffusion. Soc. of Petroleum Eng. J., p. 315, Sept. 1971.

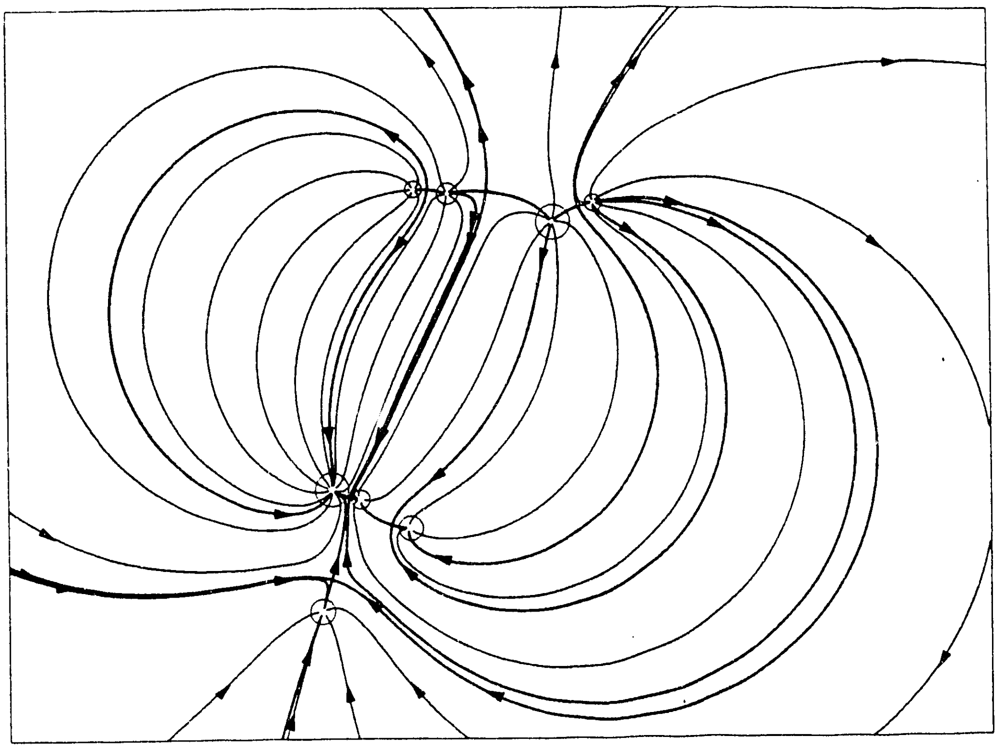


Figure 1. Stagnation lines and streamlines for an aquifer thermal energy storage system involving four injection wells and four extraction wells in Malmö, Sweden.

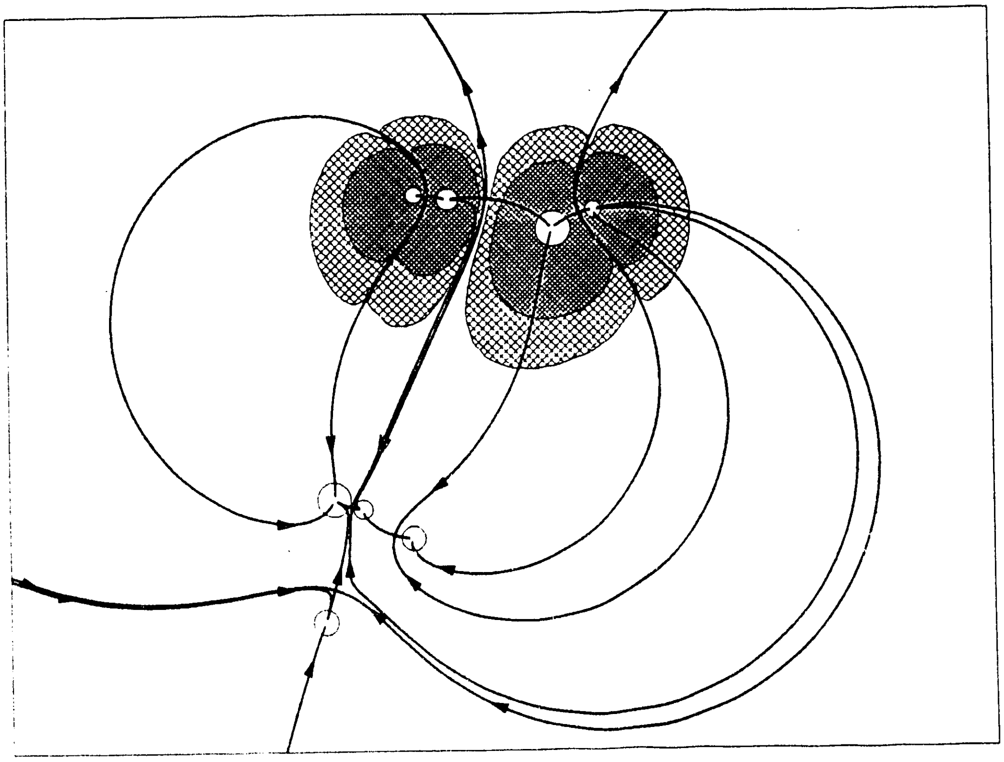


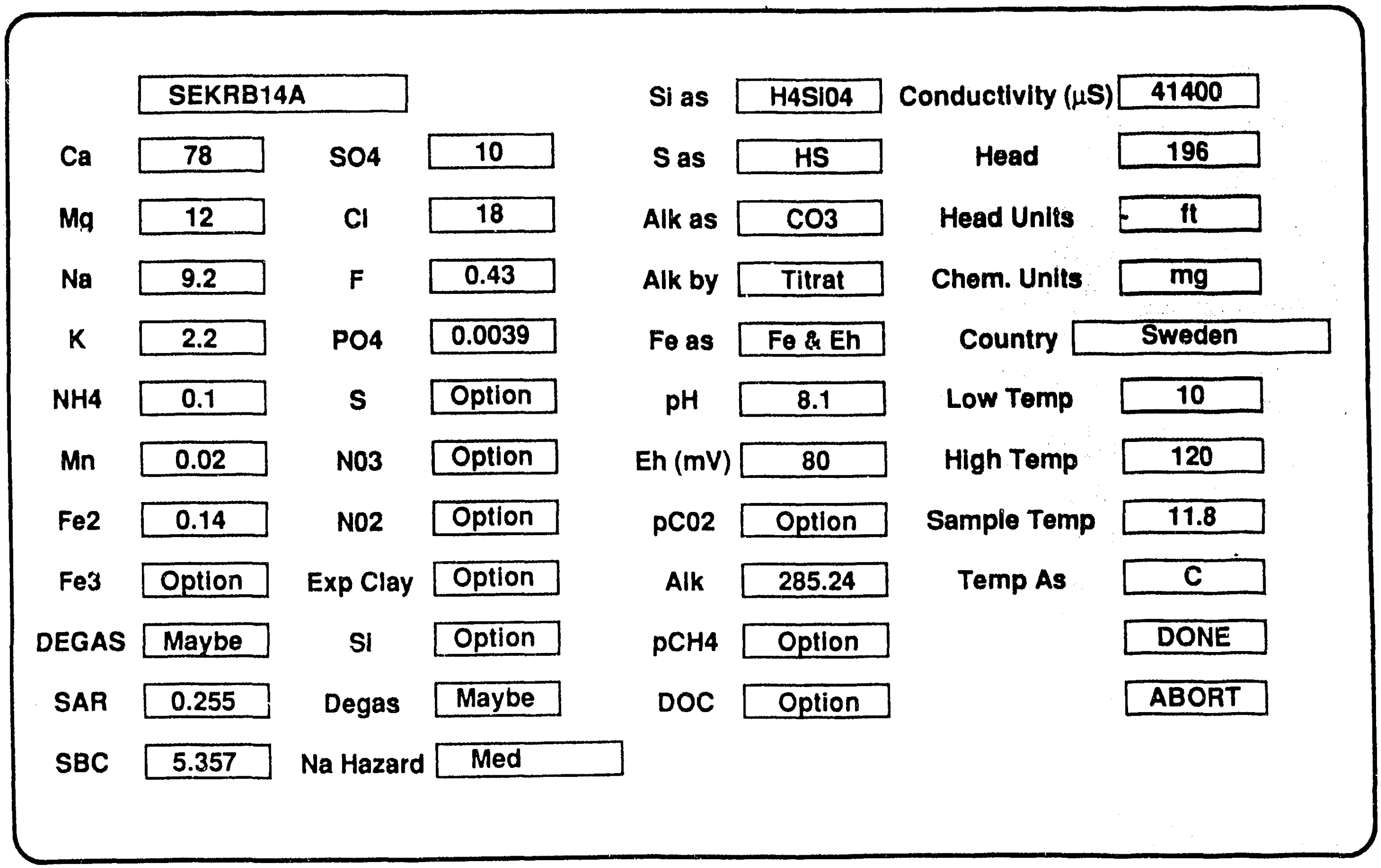
Figure 2. Stagnation lines and extent of heated region after a certain time period. The shaded area represents the region heated by water injected during the first half of the period, while the white area close to the wells shows the warm region due to water injected during the second half of the period.

saturation with respect to calcite in the reactor by injecting and rapidly mixing alkali with the water. In the fluidized bed reactor where high pumping rates cause fine sand to be fluidized, calcite precipitation is enhanced by the high surface area of the fine sand (van Dijk and Wilms 1990). If an $SI_{calcite}$ in excess of 2.5 occurs, very fine grained precipitates may form that may pass the rapid sand filter and clog the aquifer.

In a low-nitrate environment, the *in situ* oxidation of reduced Fe and Mn may be accomplished with nitrate injected upgradient from a source well. High nitrate concentrations stimulate microbial growth, which results in Fe^{II} and Mn^{II} oxidation (Vanek 1990). A cascade treatment can be used when the aquifer is relatively shallow and unconfined. The ground water is aerated by cascading from a trough onto a surface covered with small rocks that promote oxidation and further aeration. The precipitated oxides are removed by passing the water through a slow sand filter. The treated water infiltrates to the aquifer and creates a local body of treated water that is used as the source water for heating and storage at a different location in the aquifer. In the VYREDOX treatment (Hallberg and Martinel 1976), ground water is extracted, aerated and reinjected in an outer circle of 4-6 wells. The water flows towards the source well, and although there is some mixing with local ground water, the water reaching the source well is sufficiently low in Fe. In the case of eskers-type aquifers, the air-saturated water can be injected upgradient of the source well, as in the nitrate method.

Acidification is generally the least desirable means of avoiding carbonate scaling because acidification of the water 1) causes increased corrosion during heating as a result of both increased Cl and H concentrations and injection, and 2) it must be added each cycle before heating of water resulting in an increased Cl concentration with each cycle. However, acidification may be the method of choice if an aquifer contains only traces of carbonate minerals and degassing can be facilitated. Similarly, where siderite ($FeCO_3$) clogging may occur, acidification and degassing may decrease the concentration of CO_3 enough to bring the $SI_{siderite}$ to zero with little increase in dissolved iron concentration.

There are three means of reducing the required cation exchange treatment capacity for a given water and specified megawatts of energy storage. One means is to condition the water by withdrawing water from the source well, passing it through the exchanger and injecting it into the source well. The second is to increase the storage temperature in one or more storage-recovery cycles until the design temperature is reached (van Loon and Holde 1992). The third is to reduce the storage temperature and increase the stored volume.



	SEKRB14A			Si as	H4SI04	Conductivity (µS)	41400
Ca	78	SO4	10	S as	HS	Head	196
Mg	12	Cl	18	Alk as	CO3	Head Units	ft
Na	9.2	F	0.43	Alk by	Titrat	Chem. Units	mg
K	2.2	PO4	0.0039	Fe as	Fe & Eh	Country	Sweden
NH4	0.1	S	Option	pH	8.1	Low Temp	10
Mn	0.02	N03	Option	Eh (mV)	80	High Temp	120
Fe2	0.14	N02	Option	pC02	Option	Sample Temp	11.8
Fe3	Option	Exp Clay	Option	Alk	285.24	Temp As	C
DEGAS	Maybe	SI	Option	pCH4	Option		DONE
SAR	0.255	Degas	Maybe	DOC	Option		ABORT
SBC	5.357	Na Hazard	Med				

S9204056.1

H2O*TREAT*

H2O*TREAT* allows a user to perform the complex geochemical calculations that are required to design ATES water treatment systems using a general-purpose geochemical model, MINTEQ, without mastering the somewhat complex input and output data structures of the geochemical code. A point and click screen menu is available for H2O*TREAT* on DOS machines. An example of an input data screen is shown in Figure 1. For non-DOS machines the FORTRAN source codes, the geochemical database files, and a UNIX control script are available.

Because the quantity of available water chemistry data varies widely, data input requirements have been divided into "Required" and "Optional" (Table 1). "Required" data are considered essential for a meaningful analysis to be performed. Inclusion of certain "Optional" data may result in a significant improvement in the reliability of the analysis.

Table 1. H_2O*TREAT* Input Data

Required	Optional
[Ca]	[K]
[Mg]	[NH_4]
[Na]	[Mn]
[SO_4]	[Fe^{II}]
[Cl]	[Fe^{III}]
pH	[F]
Conductivity	[PO_4]
Head	[NO_2]
Sample Temperature	[NO_3]
Low Temperature	[Si]
High Temperature	Eh
Alkalinity	pCO_2
	pCH_4
	DOC

H2O*TREAT* estimates the fraction of water that must be treated by Na-exchange and by H-exchange to prevent carbonate scale formation in the heat exchanger. To perform this calculation, H2O*TREAT* successively increases the fraction of the total relevant cations (Ca, Mg, Fe, and Mn) until the saturation index for one of the significant carbonate solids exceeds 0.3. The fraction immediately greater than the fraction resulting in a saturation index that exceeds 0.3 is the estimated treatment fraction required. These calculations are repeated for the range of high to low temperatures specified by the user. Figure 2 illustrates the change in treatment requirements as a function of temperature for a water chemistry controlled by calcite saturation. 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^+. H2O*TREAT* does not consider the change in treatment requirements that will occur after several cycles of treatment because of the change in water chemistry caused by the treatment process or by the change in aquifer temperature.

The MINTEQ code (Felmy et al. 1984) is included in H2O*TREAT*. The MINTEQ code is a thermodynamic model used to calculate solution equilibria for geochemical applications. Version 3.00 contains formulations for correcting equilibrium constants for the effect of temperature from 0° to 300°C and pressure. The MINTEQ User's Manual (Peterson et al. 1987) describes the input files, input options, database files, and methodology for using the MINTEQ code. However, this information is not necessary for the operation of H2O*TREAT*.

CONCLUSION

H2O*TREAT* is a public-domain software package to aid engineers in the design of water treatment systems for aquifer thermal energy storage. H2O*TREAT* was developed for use by engineers with limited or no experience in geochemistry.

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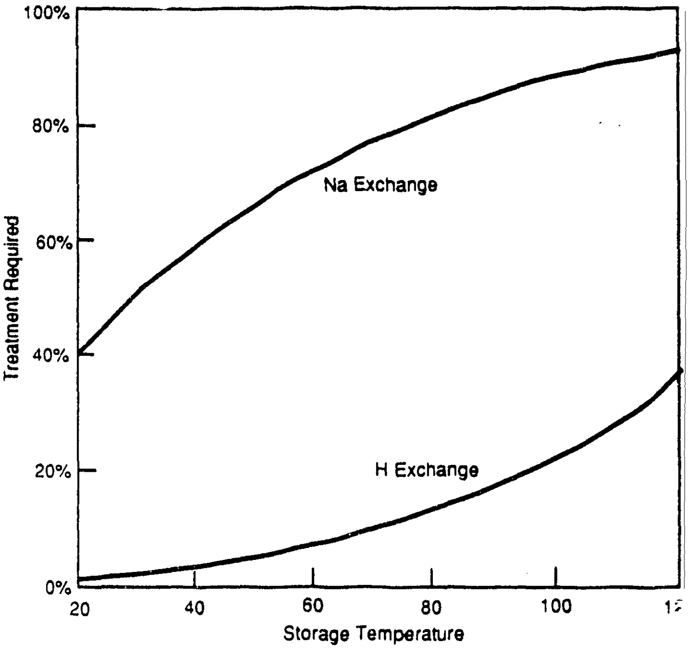

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H2OTREAT: An Aid for Evaluating Water Treatment Requirements for Aquifer Thermal Energy Storage

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ABSTRACT

A public-domain software package is available to aid engineers in the design of water treatment systems for Aquifer Thermal Energy Storage (ATES). Geochemical phenomena that cause problems in ATES systems include formation of scale in heat exchangers, clogging of wells, corrosion in piping and heat exchangers, and degradation of aquifer materials. Preventing such problems frequently requires employing water treatment systems. Individual water treatment methods vary in cost, effectiveness, environmental impact, corrosion potential, and acceptability to regulatory bodies. Evaluating these water treatment options is generally required to determine the feasibility of ATES systems. The H2O*TREAT* software was developed by Pacific Northwest Laboratory for use by engineers with limited or no experience in geochemistry. At the feasibility analysis and design stages, the software utilizes a recently revised geochemical model, MINTEQ, 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 specific mineral defines whether that mineral is oversaturated, hence may precipitate at the specified temperature. The saturation indices of key calcium, iron, silica, and manganese carbonates, oxides, and hydroxides (calcite, rhodochrosite, siderite, $Fe(OH)_3$[a], birnessite, chalcedony, and SiO_2) are calculated. User input is separated into "required" and "optional" data (Table 1). Currently, H2O*TREAT* does not perform cost calculations; however, treatment capacity requirements are provided. Treatments considered include 1) Na and H ion exchangers and pellet reactors to avoid calcite precipitation, and 2) *in situ* nitrate addition and cascade precipitators to prevent Fe and Mn oxide precipitation. The H2O*TREAT* software also provides the user with guidance on other geochemical problems that must be considered, such as SiO_2 precipitation, corrosion, and environmental considerations. The sodium adsorption ratio and sodium hazard are calculated to evaluate the likelihood of clay swelling and dispersion caused by high Na concentrations (e.g., as a result of Na ion exchange water treatment used to prevent calcite precipitation). H2O*TREAT* is available for DOS and UNIX computers.

INTRODUCTION

The chemistry of aquifers often represents a significant problem in the design of Aquifer Thermal Energy Storage (ATES) systems. The precipitation of minerals in heat exchangers can result in significant scale formation that can make the heat exchanger less efficient or inoperable. Many ground waters are naturally corrosive to many common materials used in heat exchangers, pumps, and pipes. Changes in temperature may make these waters even more corrosive. In addition, precipitation of minerals within the aquifer or precipitates transported into the aquifer can clog the aquifer.

Water treatment technologies are available that can mitigate these problems. The cost, effectiveness, and environmental consequences of these treatment technologies vary considerably. The selection and sizing of the appropriate treatment technology for a specific situation (aquifer chemistry and design temperature) require significantly more background in geochemistry than most design engineers who are making a feasibility assessment for ATES are likely to possess.

A public-domain software package is now available to aid engineers in the design of water treatment systems for ATES. The H2O*TREAT* software was developed for use by engineers with limited or no experience in geochemistry at the feasibility analysis and design stages. The software was developed by Pacific Northwest Laboratory for the U. S. Department of Energy as part of the United States' contribution to Annex VI of the International Energy Agency.

GEOCHEMICAL PROBLEMS

The most general geochemical problem encountered in ATES systems is that of precipitation of carbonate on heat exchangers and clogging of the injection well and/or storage aquifer by Fe and Mn oxides or by carbonates. The deposition of a significant amount of scale on heat exchangers greatly reduces their thermal transfer efficiency and deposition on the well screen, gravel pack, or in the aquifer markedly decreases the injection rate at a fixed pressure.

The major geochemical reactions of concern in ATES are:

- precipitation (scale formation, aquifer clogging),
- dissolution,
- redox transformations (oxidation of reduced Fe and Mn),
- cation exchange,
- swelling of expandable clays,
- dispersion of fine-grained sediments, and
- degassing (formation of gas phase).

The solubility of carbonate minerals decreases with increasing temperature. Although calcite is the predominate carbonate mineral formed, ferrous carbonate (siderite) is suspected as the cause of reduced permeability in 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 (IAP). The logarithm of the ratio of the IAP to the solubility value (K_{sp}) is known as the saturation index (SI); i.e., IAP = $A_{Ca}\ A_{CO3}$ and $SI_{calcite} = \log_{10}(IAP/K_{sp})$, where A_{Ca} = activity of Ca and A_{CO3} = activity of CO3. At $SI_{calcite}$ values of less than 0.3, calcite precipitation appears to be too slow to pose a problem (van Dijk and Wilms 1990; Banck 1989; Griffioen 1992; Willemsen and Appelo 1985) because of the interference of components such as dissolved organic carbon (DOC), Mg, and PO_4 with the precipitation process (Jenne 1990; Griffioen 1992). Other factors that affect precipitation and calculation of SI's include the formation of solid solution of $CaCO_3$ with Mg, Fe, and Mn. If $SI_{calcite}$, correctly estimated at the temperature to which the water is to be heated, is at or below zero no water treatment is required. For SI ≥ 0.3, water treatment is indicated. Because storage at a lower temperature than originally contemplated might remove the necessity for water treatment, it is important to estimate the temperature at which $SI_{calcite}$ is ≤ 0.3. It is also important to note that errors in calculated SIs for carbonate minerals may result from the loss of CO_2, with resultant rise in pH, during pumping, sampling, and while awaiting analysis.

The hydroxides and oxides of Fe and Mn, respectively, hereafter referred to as oxides, precipitate upon reaction with atmospheric O_2 as a consequence of oxidation of the reduced metal. Ferrous iron, Fe^{II}, and Mn^{II} are commonly the dominant forms of dissolved Fe and Mn in aquifers that are depleted of O_2. This is primarily a result of microbial processes that deplete the oxygen as surface water infiltrates and moves down gradient from a recharge area. When O_2 is depleted, then NO_3, NO_2, Mn^{IV}, Fe^{II}, and then SO_4 serve in turn as electron receptors. Because every oxygen molecule that comes into contact with reduced ground water can oxidize 4 Fe^{II} to Fe^{III} or 2 Mn^{II} to Mn^{IV} atoms, the entry of even small amounts of air may cause considerable oxide precipitation. ATES systems should preclude air entry if 1) the source water concentration of Fe or Mn is >0.1 mg/L because O_2 entry may cause oxide precipitation with resultant scaling and clogging and may also increase corrosion rate, or 2) if pCO_2 is greater than the value in equilibrium with the atmosphere, then a partially open system may allow degassing and a pH increase with resultant precipitation of Ca, Fe, and Mn carbonates.

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 (Molz et al. 1981), but more generally from increased Na saturation of expandable clays caused by use of Na-exchange water treatment or a significant reduction in ionic strength as when a foreign, lower ionic strength water is introduced into a saline aquifer (Jones 1964). The likelihood of clay dispersion, swelling, and reduced permeability is characterized by a high, medium, or low Na hazard (Richards 1954, p. 80; Jackson 1958, p. 258).

Gases are often present in ground water in amounts greater than would be in equilibrium with atmospheric pressure. If during injection, the 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 phase that can block aquifer pores, greatly decreasing permeability and causing a system to fail.

TREATMENT METHODS

Sodium exchange, hydrogen exchange, and the pellet reactor treatment methods are considered here to avoid carbonate precipitation whereas nitrate injection, cascading, and air-saturated water or peroxide injection treatments are included to avoid iron and manganese oxide precipitation.

Either NaCl or HCl are used to recharge the cation exchanger. Use of the H-saturated exchanger results in lower pH and additional carbonate mineral dissolution during heated water storage. Therefore, Na exchange is to be preferred to H exchange. Additionally, the fraction of storage water that must be treated is expected to decrease with each cycle when Na exchange is used, but is expected to increase if H exchange is used. The pellet reactor has been used to soften domestic water supplies since the mid-seventies in The Netherlands (van Dijk and Wilms 1990), achieving very rapid but not excessive over

REFERENCES

Banck, A. 1989. Lomma Pilot ATES Plant: Experiences and Results. International Energy Agency, Annex VI, Report 29-E.

Dijk, J.C. van and D. Wilms. 1990. "Water Treatment Without Waste Material: The Dutch Experiences with Pellet Reactors. " Ontharding van drinkwater, in Proceedings of a Studieday in Antwerpen, Belgium, December 11, 1990. Technologish Institute KVIV Genootschap Milieutechnologie, Antwerpen, Belgium.

Felmy, A. R., D. C. Girvin, and E. A. Jenne. 1984. MINTEQ: A Computer Program for Calculating Aqueous Geochemical Equilibria. EPA-600/3-84-032 (NTIS PB84-157148), National Technical Information Service, Springfield, Virginia.

Griffioen, J. 1992. Cation-Exchange and Carbonate Chemistry in Aquifers Following Groundwater Flow. Jasper Griffioen, Amsterdam.

Hallberg, R.O. and R. Martinel. 1976. "VYREDOX-*In situ* Purification of Ground Water." Ground Water 14:88-93.

Jackson, M.L. 1958. Soil Chemical Analysis. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Jenne, E.A. 1990. "Aquifer Thermal Energy Storage: The Importance of Geochemical Reactions." Hydrochemistry and Energy Storage in aquifers, Proceedings and Information No. 43, eds. J.C. Hooghart & C.W.S. Posthumus, pp. 19-36.

Jones, F.O. 1964. "Influence of Chemical Composition of Water on Clay Blocking of Permeability." J. Petroleum Technology 16:441-446.

Loon, L.J.M. van and K. van der Holde. 1992. "High Temperature ATES at the State University of Utrecht, The Netherlands" (this proceedings).

Molz, F.J., A.D. Parr, and P.F. Angersen. 1981. "Thermal Energy Storage in Confined Aquifer: Second Cycle." Water Resours. Res. 17:641-645.

Peterson, S. R., C. J. Hostetler, W. J. Deutsch, and C. E. Cowan. 1987. MINTEQ User's Manual. NUREG/CR-4808, PNL-6106, prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D. C.

Richards, L.A. (ed). 1954. Diagnosis and Improvement of Saline and Alkali Soils. U.S. Department Agriculture, Handbook no. 60, U.S. Government Printing Office, Washington, D. C.

Vanek, V. 1990. "*In situ* Treatment of Iron-Rich Groundwater by the Addition of Nitrate," Department of Ecology, Univ. Lund., ISSN 1100-6366, 33 pp.

Willemsen, A. 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 Hydrology, pt. 4:68-78.

Exergy Analysis of Aquifer Thermal Energy Storages

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ABSTRACT

The application of exergy analysis (Second-Law analysis) to aquifer thermal energy storage (ATES) systems is investigated in order to facilitate proper assessments of overall system performances. The investigation involves the creation of an elementary ATES model, and the development of the corresponding expressions for efficiencies and for the quantities of energy and exergy that are injected and recovered. It is demonstrated that ATES performance measures based on exergy often are more useful and meaningful than those based on energy. Exergy efficiencies account for the temperatures associated with energy transfers to and from an ATES, as well as the quantities of energy transferred, and consequently provide a measure of how nearly ATES systems approach ideal thermodynamic performance. Energy efficiencies only account for energy transfer quantities, and thus do not provide a measure of approach to ideal performance. In fact, energy efficiencies are often misleadingly high because some of the energy recovered can be at too low a temperature to be available for a useful purpose. However, it is shown that the use of an appropriate threshold recovery temperature can partially eliminate the inherent misleadingness in ATES energy efficiencies.

INTRODUCTION

In use, aquifer thermal energy storage (ATES) systems must be integrated with other components into larger thermal systems, and hence their characteristics must be accurately expressed if proper analytical assessments of overall system performances are to be made. At present, however, in spite of the fact that much ATES research has been performed [1-3], no valid and generally accepted standards have been established for the evaluation and comparison of the performance of different ATES systems. In fact, conventional performance measures, which are normally based on energy quantities, are often misleading.

The present work is part of a research program directed towards investigating the need for considering exergy analysis in the design and evaluation of thermal energy storage (TES) systems. Other results of the program have been reported elsewhere [4-7]. Here, the application of exergy analysis to ATES systems is investigated. Exergy is defined as the maximum amount of work which can be produced by a quantity of matter or energy in a reference environment, and is discussed elsewhere [4-7].

In the remainder of this paper, an elementary ATES model is developed; expressions are developed and examined for the quantities of energy and exergy that are injected and recovered for an ATES, and for energy and exergy efficiencies; the effect of introducing a threshold temperature is considered, below which residual heat remaining in the aquifer water is not considered worth recovering; and an illustrative example using realistic ATES parameter values is presented.

ATES MODEL

A general ATES is considered. Charging occurs over a finite time period, t_c, and after a holding interval discharging occurs over another finite time period, t_d, which can differ from t_c. The working fluid is water, having a constant specific heat c, and assumed incompressible. The temperature of the aquifer and its surroundings prior to heat injection is denoted T_o and is referred to as the reference-environment temperature. Only heat stored at temperatures above T_o is considered, and pump work is neglected.

During charging, heated water at a constant temperature T_c is injected at a constant mass flow rate $\dot{m}_c$ into the ATES. Then, after a storing period, discharging occurs, during which water is extracted from the ATES at a constant mass flow rate $\dot{m}_d$. The fluid discharge temperature is taken to be a function of time, i.e., $T_d = T_d(t)$. The discharge temperature after an infinite time is taken to be the temperature of the reference-environment, i.e., $T_d(\infty) = T_o$, and the initial discharge temperature is taken to be between the charging and reference-environment temperatures, i.e., $T_o \le T_d(0) \le T_c$. Here, for simplicity, the discharge temperature is taken to decrease linearly with time from an initial value $T_d(0)$ to a final value T_o. The final temperature is achieved at a time t_f, and remains fixed at T_o for all times after t_f. That is,

$$T_d(t) = \begin{cases} T_d(0) - (T_d(0) - T_o)\dfrac{t}{t_f} & , \; 0 \le t \le t_f \\ T_o & , \; t_f \le t \le \infty \end{cases} \tag{1}$$

Other discharge temperature-time profiles are possible, but most others would be inconveniently complex mathematically for the present discussions. The linear profile above is sufficiently realistic and simple to illustrate the importance of using exergy analysis in ATES evaluation and comparison, without obscuring the central ideas of the paper. The temperature-time profiles considered in the present model for the fluid flows during the charging and discharging periods are summarized in Fig. 1.

The two main types of thermodynamic losses that occur in ATES systems are accounted for in the model. These losses occur between the beginning of charging and the end of discharging, and are as follows:

- Energy losses. Energy injected into an ATES that is not recovered is considered lost. Thus, energy losses include energy remaining in the ATES at a point where it could still be recovered if pumping were continued, and energy injected into the ATES that is convected in a water flow or is transferred by conduction far enough from the discharge point that it is unrecoverable, regardless of how much or how long water is pumped out of the ATES. The effect of energy losses is that less than 100% of the injected energy is recoverable after storage.

- Mixing losses. As heated water is pumped into an ATES, it mixes with the water already present (which is usually cooler), resulting in the recovered water being at a lower temperature than the injected water. In the present model, this loss results in the discharge temperature T_d being at all times less than or equal to the charging temperature T_c, but not below the reference-environment temperature T_o (i.e., $T_o \le T_d(t) \le T_c$ for $0 \le t \le \infty$).

ENERGY AND EXERGY ANALYSES

To perform energy and exergy analyses of the performance of ATES systems, the quantities of energy and exergy injected into the ATES during charging and those recovered during discharging must be evaluated.

The energy flow E associated with a flow of water at a constant mass flow rate $\dot{m}$, for an arbitrary period of time, where temperature T is a function of time t, is

$$E = \int_t \dot{E}(t)\, dt \tag{2}$$

where the integration is performed over the time period, and the energy flow rate at time t is

$$\dot{E}(t) = \dot{m}\, c\, (T(t) - T_o) \tag{3}$$

Combining the above two equations, and noting that $\dot{m}$, c and T_o are assumed constant,

$$E = \dot{m}\, c \int_t (T(t) - T_o)\, dt \tag{4}$$

The corresponding exergy flow ε is

$$\varepsilon = \int_t \dot{\varepsilon}(t)\, dt \tag{5}$$

where the exergy flow rate at time t is

$$\dot{\varepsilon}(t) = \dot{m}\, c[(T(t) - T_o) - T_o \ln (T(t)/T_o)] \tag{6}$$

Combining Eqs. 5 and 6,

$$\varepsilon = \dot{m}\, c \int_t [(T(t) - T_o) - T_o \ln (T(t)/T_o)]\, dt \tag{7}$$

or, in terms of E (see EQ (4)),

$$\varepsilon = E - \dot{m}\, c\, T_o \int_t \ln (T(t)/T_o)\, dt \tag{8}$$

CHARGING - The energy input to the ATES during charging, for a constant water injection rate $\dot{m}_c$ and over a time period beginning at zero and ending at t_c, is expressed by EQ (4) with $T(t) = T_c$. That is,

$$E_c = \dot{m}_c\, c \int_{t=0}^{t_c} (T_c - T_o)\, dt = \dot{m}_c\, c\, t_c (T_c - T_o) \tag{9}$$

The corresponding exergy input is expressed by EQ (7), with the same conditions as for E_c. Thus, after integration,

$$\varepsilon_c = \dot{m}_c\, c\, t_c\, [(T_c - T_o) - T_o \ln (T_c/T_o)] \tag{10}$$

Alternatively, with EQ (8),

$$\varepsilon_c = E_c - \dot{m}_c\, c\, t_c\, T_o \ln (T_c/T_o) \tag{11}$$

DISCHARGING - The energy recovered from the ATES during discharging, for a constant water recovery rate $\dot{m}_d$, for a time period starting at zero and ending at t_d, is expressed by EQ (4) with $T(t)$ as in EQ (1). Thus,

$$\begin{aligned} E_d &= \dot{m}_d\, c \int_{t=0}^{t_d} (T_d(t) - T_o)\, dt \\ &= \dot{m}_d\, c\, (T_d(0) - T_o)\, \frac{\tau(2t_f - \tau)}{2t_f} \end{aligned} \tag{12}$$

where

$$\tau = \begin{cases} t_d & , \quad 0 \le t_d \le t_f \\ t_f & , \quad t_f \le t_d \le \infty \end{cases} \qquad (13)$$

The corresponding exergy recovered is expressed by EQ (7), with the same conditions as for E_d. Thus,

$$\varepsilon_d = \dot{m}_d c \int_{t=0}^{t_d} [(T_d(t) - T_o) - T_o \ln(T_d(t)/T_o)]\, dt \quad (14)$$

or, with EQ (8),

$$\varepsilon_d = E_d - \dot{m}_d\, c\, T_o \int_{t=0}^{t_d} \ln\,(T_d(t)/T_o)\; dt \quad (15)$$

Here,

$$\int_{t=0}^{t_d} \ln\,(T_d(t)/T_o)\; dt = \int_{t=0}^{t_d} \ln\,(at + b)\; dt$$
$$= \frac{a\tau + b}{a} \ln\,(a\tau + b) - \tau - \frac{b}{a} \ln b \quad (16)$$

where

$$a = \frac{T_o - T_d(0)}{T_o\, t_f} \quad (17)$$

$$b = \frac{T_d(0)}{T_o} \quad (18)$$

Note that when $t_d \ge t_f$, the expression for the integral in EQ (16) reduces to

$$t_f \left[\frac{T_d(0)}{T_d(0) - T_o} \ln \frac{T_d(0)}{T_o} - 1 \right]$$

ENERGY AND EXERGY BALANCES - An energy balance on any ATES taken over a complete charging-discharging cycle states that

Energy injected = Energy recovered + Energy lost (19)

A corresponding exergy balance states that

Exergy injected = Exergy recovered + Exergy lost (20)

If f is defined as that fraction of the injected energy E_c that can be recovered if the length of the discharge period approaches infinity (i.e., water is extracted until all recoverable energy has been recovered), then

$$E_d(t_d \rightarrow \infty) = f\, E_c \quad (21)$$

From the above energy balance, $(1 - f)E_c$ is the energy irreversibly lost from the ATES. Clearly, f varies between zero for a thermodynamically worthless ATES to unity for an ATES having no energy losses during an infinite discharge period. (Note that even if $f = 1$, the ATES can still have mixing losses that reduce the temperature of the recovered water and consequently cause exergy losses). Since E_c is given by EQ (9) and $E_d(t_d \rightarrow \infty)$ is given by EQ (12) with $\tau = t_f$, EQ (21) can be rewritten as:

$$\dot{m}_d\, c\, (T_d(0) - T_o)\, t_f / 2 = f \dot{m}_c\, c\, (T_c - T_o)\, t_c \quad (22)$$

or, after rearranging,

$$f = \frac{t_f\, \dot{m}_d\; (T_d(0) - T_o)}{2\, t_c\, \dot{m}_c\; (T_c - T_o)} \quad (23)$$

Since $T_d(0)$ can vary from T_o to T_c, the temperature-related term $(T_d(0) - T_o)/(T_c - T_o)$, like f, varies between zero and unity. The time ratio t_f/t_c and mass-flow-rate ratio $\dot{m}_d/\dot{m}_c$ can both take on any positive values (subject to the above equality).

EFFICIENCIES AND LOSSES - For either energy or exergy, efficiency is defined as the fraction, taken over a complete cycle, of the quantity input during charging that is recovered during discharging, while loss is the difference between input and recovered amounts of the quantity. Hence, the energy loss as a function of the discharge time period is given by $[E_c - E_d(t_d)]$, while the corresponding exergy loss is given by $[\varepsilon_c - \varepsilon_d(t_d)]$. It is emphasized that energy losses do not reflect the temperature degradation associated with mixing, while exergy losses do.

The energy efficiency η for an ATES, as a function of the discharge time period, is

$$\eta(t_d) = \frac{E_d(t_d)}{E_c} = \frac{\dot{m}_d(T_d(0) - T_o)}{\dot{m}_c(T_c - T_o)}\; \frac{\tau\,(2t_f - \tau)}{2\, t_f\, t_c} \quad (24)$$

and the corresponding expression for the exergy efficiency ψ is

$$\psi(t_d) = \frac{\varepsilon_d(t_d)}{\varepsilon_c} \quad (25)$$

Note that the energy efficiency in EQ (24) simplifies, when the discharge period t_d exceeds t_f, i.e., $\eta(t_d \ge t_f) = f$. Thus, for an ATES in which all injected energy is recoverable during an infinite discharge period, i.e., $f = 1$, the energy efficiency can reach 100% if the discharge period t_d is made long enough. The corresponding exergy efficiency, however, remains less than 100% because, due to mixing losses, much of the heat is recovered at near-environmental temperatures. Only a thermodynamically reversible storage would permit the achievement of an exergy efficiency of 100%.

EFFECT OF A THRESHOLD TEMPERATURE

In practice, it is not economically feasible to continue the discharge period until as much recoverable heat as possible is recovered. As the discharge period increases, water is recovered from an ATES at ever decreasing temperatures (ultimately approaching the reference-environment temperature T_o), and the energy in the recovered water is of decreasing usefulness.

To determine the appropriate discharge period, a threshold temperature T_t is often introduced, below which the residual energy in the aquifer water is not considered worth recovering from an ATES. For the linear temperature-time relation used here (see EQ (1)), it is clear that no heat could be recovered over a cycle if the threshold temperature exceeds the initial discharge temperature, while the appropriate discharge period can be evaluated using EQ (1) with T_t replacing $T_d(t)$ for the case where $T_o \leq T_t \leq T_d(0)$. Thus,

$$t_d = \begin{cases} \dfrac{T_d(0) - T_t}{T_d(0) - T_o}\, t_f \quad , & T_o \leq T_t \leq T_d(0) \\ \\ 0 \quad , & T_d(0) \leq T_t \end{cases} \tag{26}$$

Thus, the effect of a threshold temperature in practice is to place an upper limit on the allowable discharge time period.

ILLUSTRATIVE EXAMPLE

In this example, experimental data are used from the first of four short-term ATES test cycles, using the Upper Cambrian Franconia-Ironton-Galesville confined aquifer, and performed at the University of Minnesota's St. Paul campus from November 1982 to December 1983 [8]. During the test, water was pumped from the source well, heated in a heat exchanger and returned to the aquifer through the storage well. After storage, energy was recovered by pumping the stored water through a heat exchanger and returning it to the supply well.

For the test cycle considered here, the water temperature and volumetric flow rate are shown as a function of time during the injection and recovery processes in Fig. 2. The storage period duration (13 days) is also shown. Charging occurred during 5.24 days over a 17 day period. The water temperature and volumetric flow rate were approximately constant during charging, and had mean values of 89.4°C and 18.4 l/s respectively. Discharging also occurred over 5.24 days, approximately with a constant volumetric flow rate of water and linearly decreasing temperature with time. The mean volumetric flow rate during discharging was 18.1 l/s, and the initial discharge temperature was 77°C, while the temperature after 5.24 days was 38°C. The ambient temperature was reported to be 11°C.

In the subsequent calculations, mean values for volumetric flow rates and charging temperature are used. Also, the specific heat and density of water are both taken to be fixed, at 4.2 kJ/kg-K and 1000 kg/m^3, respectively. Since the volumetric flow rate (in litres/second) is equal to the mass flow rate (in kilograms/second) when the density is 1000 kg/m^3, $\dot{m}_c = 18.4$ kg/s and $\dot{m}_d = 18.1$ kg/s. Also, the reference-environment temperature is fixed at the ambient temperature, i.e., $T_o = 11°\text{C} = 284$ K.

During charging, it can be shown using Eqs. 9 and 11, with $t_c = 5.24\ \text{d} = 453{,}000$ s and $T_c = 89.4°\text{C} = 362.4$ K, that

$$E_c = (18.4\ \text{kg/s})(4.2\ \text{kJ/kg-K})(453{,}000\ \text{s}) \times (89.4°\text{C} - 11°\text{C}) = 2.74 \times 10^9\ \text{kJ}$$

and

$$\varepsilon_c = 2.74 \times 10^9\ \text{kJ} - (18.4\ \text{kg/s})(4.2\ \text{kJ/kg-K})(453{,}000\ \text{s}) \times (284\ \text{K}) \ln (362.4\ \text{K}/284\ \text{K}) = 0.32 \times 10^9\ \text{kJ}$$

During discharging, the value of the time t_f is evaluated using the linear temperature-time relation of the present model and the observations that $T_d(t = 5.24\ \text{d}) = 38°\text{C}$ and $T_d(0) = 77°\text{C} = 350$ K. Then, using EQ (1) with $t = 5.24$ d,

$$38°\text{C} = 77°\text{C} - (77°\text{C} - 11°\text{C})\,(5.24\ \text{d} / t_f)$$

which can be solved to show that $t_f = 8.87$ d. Thus, with the present linear model, the discharge water temperature would reach T_o if the discharge period was lengthened to almost 9 days. In reality, the rate of temperature decline would likely decrease, and the discharge temperature would asymptotically approach T_o. Also the value of the fraction f can be evaluated with EQ (23) as

$$f = \frac{(8.87\ \text{d})(18.1\ \text{kg/s})(77°\text{C} - 11°\text{C})}{2(5.24\ \text{d})(18.4\ \text{kg/s})(89.4°\text{C} - 11°\text{C})} = 0.701$$

Thus, the maximum energy efficiency achievable is approximately 70%. With these values and Eqs. 17 and 18, it can be shown that

$$a = (11°\text{C} - 77°\text{C})/(284\ \text{K} \times 8.87\ \text{d}) = -0.0262\ \text{d}^{-1}$$

$$b = (350\ \text{K})/(284\ \text{K}) = 1.232$$

Consequently, expressions dependent on discharge time period, t_d, can be written for E_d, ε_d, η and ψ using Eqs. 12 to 18, 24 and 25. Also t_d-dependent expressions for energy loss ($E_c - E_d$) and exergy loss ($\varepsilon_c - \varepsilon_d$) can be written. These quantities are plotted as a function of t_d in Fig. 3.

Several points in Fig. 3 are worth noting. First, for the conditions specified, all parameters level off as t_d approaches t_f, and remain constant for $t_d \geq t_f$. Second, as t_d increases towards t_f, the energy recovered increases from zero to a maximum value, while the energy loss decreases from a maximum of all the input energy to a minimum (but non-zero) value. The exergy recovery and exergy loss functions behave similarly qualitatively, but exhibit much lower magnitudes. Third, both efficiencies increase from zero to maximum values as t_d increases, with the energy efficiency always exceeding the exergy efficiency. Further, the difference between the two efficiencies increases with increasing t_d. This latter point demonstrates that the exergy efficiency gives less weight than the energy efficiency to the energy recovered at higher t_d values since it is recovered at temperatures nearer to the reference-environment temperature.

If a threshold temperature is introduced and arbitrarily set at 38°C (the actual temperature at the end of the experimental discharge period of 5.24 d), then the data in Fig. 3 for $t_d = 5.24$ d apply and one can see that

- the exergy recovered (0.127×10^9 kJ) is almost all (91%) of the exergy recoverable in infinite time (0.139×10^9 kJ), while the energy recovered (1.60×10^9 kJ) is not as great a portion (83%) of the ultimate energy recoverable (1.92×10^9 kJ).
- the exergy loss (0.19×10^9 kJ) exceeds the exergy loss in infinite time (0.18×10^9 kJ) slightly (by 5.5%), while the energy loss (1.14×10^9 kJ) exceeds the energy loss in infinite time (0.82×10^9 kJ) substantially (by 39%).
- the exergy efficiency (40%) has almost attained the exergy efficiency attainable in infinite time (43.5%), while the energy efficiency (58%) is still substantially below the ultimate energy efficiency attainable (70%).

To gain confidence in the model and the results, some of the quantities calculated using the linear model can be compared with the same quantities as reported in the experimental paper [8]:

- The previously calculated value for the energy injection during charging of 2.74×10^9 kJ is 1.1% less than the reported value of 2.77×10^9 kJ.
- The energy recovered at the end of the experimental discharge period of $t_d = 5.24$ days can be evaluated with EQ (12) as

$$E_d(5.24\text{ d}) = (18.1)(4.2)(77 - 11) \times \frac{5.24(2 \times 8.87 - 5.24)}{2 \times 8.87}\, 86{,}400\, \frac{\text{s}}{\text{d}} = 1.60 \times 10^9\ \text{kJ}$$

which is 1.8% less than the reported value of 1.63×10^9 kJ.

- The energy efficiency at $t_d = 5.24$ d can be evaluated with EQ (24) as

$$\eta(5.24\text{ d}) = \frac{1.60 \times 10^9\ \text{kJ}}{2.74 \times 10^9\ \text{kJ}} = 0.584$$

which is 1.0% less than the reported value of 0.59 (referred to as the "energy recovery factor").

CONCLUSIONS

Although energy-based performance measures are normally used in ATES assessments, it is demonstrated using an elementary ATES model that ATES performance measures based on exergy often are more useful and meaningful than those based on energy. Exergy efficiencies account for the temperatures associated with energy transfers to and from an ATES, as well as the quantities of energy transferred, and consequently provide a measure of how nearly ATES systems approach ideal performance. Energy efficiencies can only account for quantities of energy transferred, and can often be misleadingly high, such as in cases where heat is recovered at temperatures too low to be useful. The use of an appropriate threshold recovery temperature can partially avoid the most misleading characteristics of ATES energy efficiencies. Although the analysis presented is for a particular storage cycle, analogous results would be expected for other ATES cycles, and the methodology should be adaptable to a wide range of ATES designs.

NOMENCLATURE

a	parameter in ε_d expression
b	parameter in ε_d expression
c	specific heat
E	energy
f	fraction
m	mass
t	time
T	temperature
ε	exergy
η	energy efficiency
ψ	exergy efficiency

Subscripts

c	charging period
d	discharging period
f	final
o	reference environment
t	threshold

Superscripts

$\cdot$	rate

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REFERENCES

1. *Proc. 5th Int. Conf. on Thermal Energy Storage (Thermastock 91)*, Scheveningen, The Netherlands, 13-16 May 1991.
2. *Proc. Bienniel Congr. Int. Solar Energy Soc.*, Denver, 17-24 Aug. 1991.
3. *Proc. 3rd Int. Conf. on Energy Storage for Building Heating and Cooling (Enerstock 85)*, Toronto, 22-26 Sept. 1985.
4. Rosen, M.A., Appropriate Thermodynamic Performance Measures for Closed Systems for Thermal Energy Storage, *Trans. ASME J. Solar Energy*

Engineering, 1992 (accepted for publication).

5. Rosen, M.A., Hooper, F.C. and Barbaris, L.N., Exergy Analysis for the Evaluation of the Performance of Closed Thermal Energy Storage Systems, *Trans. ASME J. Solar Energy Engineering*, Vol. 110, pp. 255-261, 1988.
6. Rosen, M.A., Nguyen, S. and Hooper, F.C., Evaluating the Energy and Exergy Contents of Vertically Stratified Thermal Storages. In [1], pp. 7.4.1-7.4.6.
7. Rosen, M.A., On the Importance of Temperature in Performance Evaluations for Sensible Thermal Energy Storage Systems. In [2], pp. 1931-1936.
8. Hoyer, M.C. et al., Short-term Aquifer Thermal Energy Storage (ATES) Test Cycles, St. Paul, Minnesota, U.S.A. In [3], pp. 75-79.

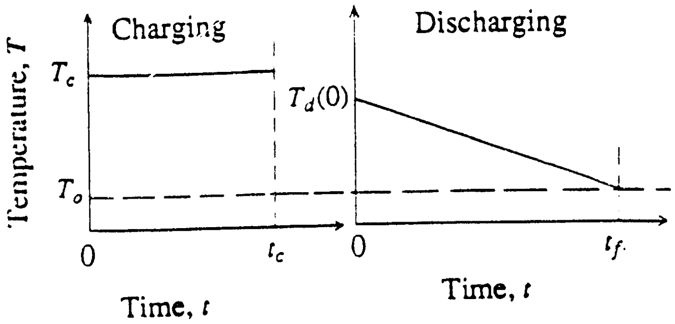

Fig. 1 Temperature-time profiles assumed for the charging and discharging periods in the ATES model considered.

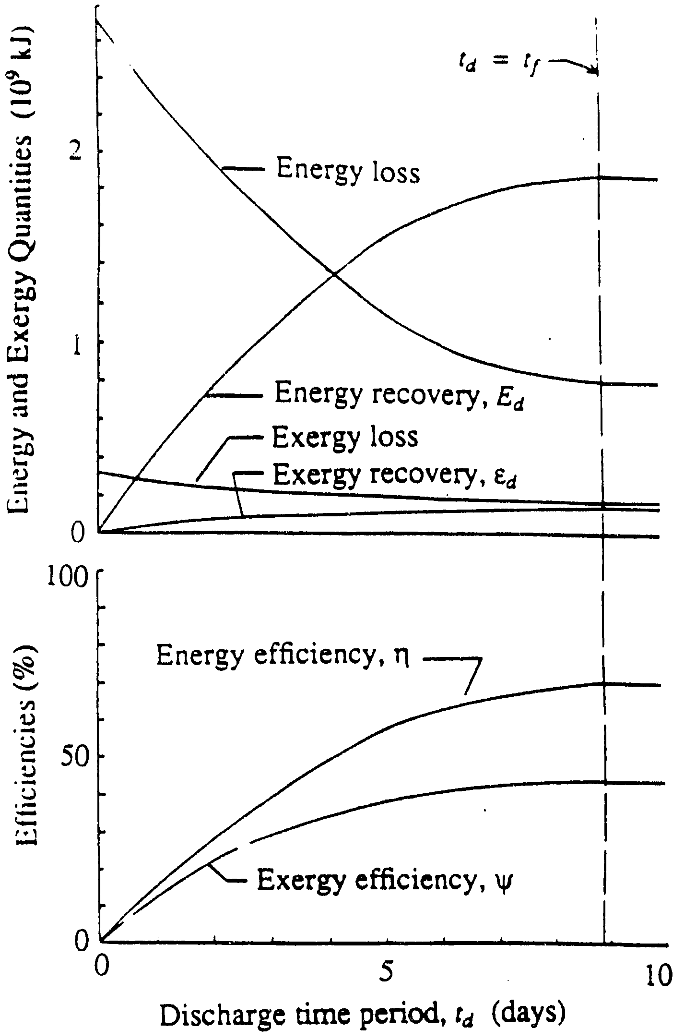

Fig. 3 Variation of several calculated energy and exergy quantities and efficiencies, as a function of discharge time period, for the illustrative example.

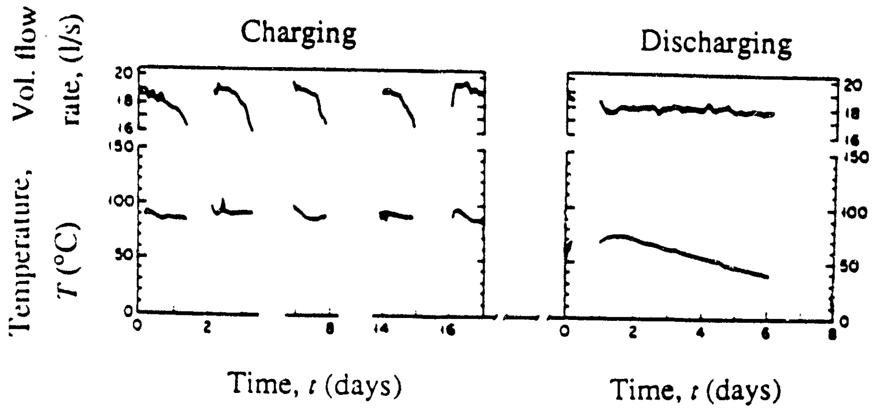

Fig. 2 Observed values for the temperature and volumetric flow rate of water, as a function of time during the charging and discharging periods, for the experimental test cycle used in the illustrative example.

Review of the Aquifer Seasonal Thermal Energy Storage Building HVAC System at the Melville, New York, Mid-Island Mail Facility

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ABSTRACT

The successful widespread commercialization of aquifer thermal energy storage (ATES) in the United States will depend on the effectiveness with which the experiences gained from early full-scale systems are used as guides in the design, installation and operation of future projects. One such early system from which both anecdotal and quantitative information is available is the Mid-Island Postal Facility in Melville, New York. At this facility, built in the mid-1980s, an ATES system has been integrated with the building's central heating and cooling plant. "Cold" wells are charged with water that is cooled during the winter by heat pump and closed circuit cooler operation. Water from these cold wells is then used to meet the facility's cooling load during the summer, before being pumped back into the ground at "Warm" wells. Dehumidification during summer operation is accomplished by a liquid desiccant system that uses propane boilers to provide a heat source for desiccant regeneration. This system will also add water to the air during periods of low humidity. This paper provides an overview of the project, and describes the analysis being performed to assess energy and economic merits of this innovative system.

INTRODUCTION

The U.S. Postal Service's (USPS) Mid-Island Mail Processing Facility (MPF) is located in Melville New York. The facility (23875 m^2) services a population of 2.5 million with sophisticated, computerized mail sorting equipment. Approximately 1200 employees work over the course of a 24-hour day, 7 days a week. The peak period is between 6 p.m. and 3 a.m. Monday through Friday. Various types of mail processing equipment at the facility processes approximately 5 million pieces of mail each day.

The facility was designed and built with systems to use minimum off-site energy, and a building envelope designed to achieve maximum energy savings. The facility incorporates state-of-the-art features that are designed to be energy efficient, aesthetically pleasing, and economically feasible. Lighting for the workroom area is provided by variable high pressure sodium fixtures, each controlled by a central computer generated radio signal. The luminaire wattage is governed by USPS work program needs, and is reduced as allowable by the natural light level achieved through skylighting, which encompasses 4% of the roof. The building envelope includes white hypalon membrane roofing, mechanically fastened over R-30 insulation, and exterior walls made of insulated precast concrete.

Heating, ventilation, and air conditioning (HVAC) of the building (Figure 1) is provided by a unique combination of ground water heating/cooling with a liquid-desiccant system for humidity control. A seasonal aquifer thermal energy storage (ATES) system was designed to provide "cold" water to handle the cooling load during summer and "warm" water as a heat source for a heat pump in winter. Backup up cooling is provided by the heat pump; backup heating is accomplished through modular boilers. Triethylene glycol is used as the liquid-desiccant for moisture removal from workroom supply air. The desiccant system can also add water to the air during periods of low humidity.

Conceptually, the HVAC system at the Melville MPF offers significant operational advantages over more conventional systems. Mechanical refrigeration for cooling was downsized from peak cooling load levels, and its operation schedule can be reduced. Thus, a sizable reduction in summer electric peak loading is expected relative to conventional systems, along with a decrease in total summer electrical usage. Downsizing of the HVAC equipment because of desiccant dehumidification also reduces the amount of ozone-depleting compounds such as CFCs that are required. Because the desiccant system provides dehumidification, a higher temperature (and thus higher efficiency) well cooling system can be used than in other ATES designs. Finally, the glycol liquid-desiccant system provides a much more precise control of building humidity than conventional commercial HVAC systems. Such glycol systems also are purportedly (Amsterdam 1988) highly effective at eliminating bacteriological pollutants, and can help in the removal of airborne particulates.

Because of these perceived advantages and the unique opportunity for study this innovative existing application affords, the U.S. Department of Energy's (DOE) Pacific Northwest Laboratory (PNL) has entered into agreements with the USPS, the U.S. Geological Survey (USGS), and the New York State Energy Research and Development Authority (NYS ERDA) to evaluate the project. PNL is operated for the U.S. DOE by Battelle Memorial Institute.

A technical assessment of the ATES/desiccant HVAC system at Mid-Island Mail Facility has been initiated, with emphasis on predicting the operating performance and cost-effectiveness of the thermal system. This paper first describes the ATES/desiccant HVAC system installed at the USPS MPF at Melville, and then discusses the approach to be taken for the technical assessment.

DESIGN SUMMARY

- Ground Water System: Three wells supply cold water to the building during the summer, and are recharged in the winter through heat pump and closed-circuit cooler operation. Three other wells supply warm water during the winter as a heat source for the heat pumps, and are recharged in the summer by the water that has been circulated through the building (and thus warmed).
- Heat Pump: Two 352 kW chillers are operated in series to reduce supply cold water temperature from the wells as required to meet the summer cooling load. Condenser water is used for winter heating. During the winter heating season, the heat pumps also produce cold water to recharge the cold water wells.
- Closed-Circuit Cooler: A roof-top closed-circuit cooler is used to reduce warmer well water temperatures in the winter (in conjunction with the heat pumps, or alone) prior to injection into cold wells.
- Radiant Gas Heaters: Perimeter mail platforms are heated during cold periods with overhead propane gas radiant heaters.
- Modular Boilers: Back-up heating and regeneration of liquid-desiccant is accomplished through the use of modular propane boilers.
- Liquid Desiccant System: Air conditioning of workspace supply air is accomplished using "conditioners" supplied by the desiccant system manufacturer (Figure 2). Heating and cooling coils are located in each conditioner to control supply air dry bulb temperature. For dehumidification, triethylene glycol is sprayed over unit cooling coils in summer, absorbing water from the supply air stream. Water absorbed by the glycol is removed at a central liquid desiccant concentrator serviced by the modular boilers. In winter the cycle is reversed, and the liquid-desiccant system is used to add water to the supply air stream as necessary to increase relative humidity.

WELL DESCRIPTION

The ATES system consists of six wells, each 55 m in depth, and made up of a 0.305-m diameter (I.D.) steel busing fitted with a 15.2 m long screen, of 0.2 m diameter. The screen is surrounded by an 0.46 m diameter fine gravel envelope that extends 6.1 m above the screen for a total height of 21.3 m. The casing above the gravel pack is enclosed in cement grout. The well pump is located within the casing above the screen and within the water table at a sufficient distance to allow for drawdown. Clearance of 25 mm around the pump on all sides allows for recharge. The pump drive motor is located above the well. The subsurface in which the wells are located is comprised of glacial outwash sand and gravel sediments known as manetto gravel. The ground water table is 12.2 m below surface grade. At the level of the well screen the aquifer is classified as the upper glacial aquifer.

Wells 1A, 2A, and 3A are located on the eastern boundary of the USPS property (Figure 3). The temperature of water from these wells prior to ATES system operation has been recorded at 17.5 °C. This relatively high temperature is considered to be a result of warm water discharge into the ground from off-site wells located to the north that service air conditioners of large office complexes. Through regional flow of ground water, this discharge impacts the aquifer below the USPS/MPF. As a consequence, the warmest wells of the ATES system, (the east wells) are used as the winter supply for the heat pumps. Therefore, in summer, warm water return from the USPS/MPF is injected into the ground at these wells.

Wells 4, 5, and 6 are located on the western side of the USPS property (Figure 3). The temperature of water from these wells prior to ATES system operation was recorded at 13.3 °C. These wells are not in line with the regional flow of discharge water from the off-site wells to the north. These wells are for summer supply of cool water to the heat pumps and are reinjected with cool water during winter.

WELL SYSTEM OPERATING CONCEPT

The well system is designed to supply the USPS/MPF with cool water to meet the building cooling load during summer and warm water for heating during winter. The basic concept employed is that of seasonally storing masses of warm and cool water in separate locations in the aquifer. As it is warmed in summer, the water is injected into east (warm) wells 1A, 2A, and 3A; as it is cooled in winter, the water is injected into west (cold) wells 4, 5, and 6.

Because the building envelope is well insulated and internal heat gains caused by equipment is high, design calculations indicated that more cooling energy is required on a seasonal basis than heating. To meet the additional cool water requirements beyond what can be produced during winter heat pump operation, water drawn from the east wells may also be passed through the roof-top closed-circuit cooler and redeposited into the west wells. The roof-top closed-circuit cooler is designed to reduce water temperatures in the winter prior to injection into cold water wells. This additional cooling capacity is required to help offset the heat loading generated by the mail processing operation to balance annual heating and cooling ground water thermal storage. Following seasonal changeover, a cool water mass should be available from the west wells for summer cooling, and a warm water mass should be available from the east wells for winter heating. The heat losses caused by (horizontal) regional water flow and vertical conduction, along with other geologic factors, limit the amount of stored heat or chill that can be recovered from the wells. As a result of the regional flow, the southernmost west (cool) and east (heat) wells have the coolest and warmest water, respectively.

The summer cooling process was designed to use 9.4 °C water during periods of highest temperature. When cool water well recovery temperatures are above 9.4 °C, the heat pumps are designed to operate as water chillers to further chill the water as required. The design goal is to be able to obtain direct cooling with well water without electric chillers at all, but this will be dependent on whether the amount of cold water stored in the previous season (less recovery losses) is adequate to meet the annual cooling load and whether recovery flow rates can be maintained at design levels. The wells were designed to supply water at 26 L/s. Maximum design system operation is for two wells (a total of 52 L/s) to be operated simultaneously. Reinjection is assumed to be to two wells when a single 26 L/s supply well is being employed by the system, and three wells for a 52 L/s two well supply to system. The design assumes wells will be pumped only as required to meet the heating or cooling needs of the building on a daily basis. Single-well operation occurs during moderate cooling and heating periods. Two-well supply operation occurs during periods of high cooling needs.

ASSESSMENT

The goal of the assessment is to develop models to predict the annual energy costs and performance of the existing HVAC system if it is operated "per design", and compare the system's economics to a "baseline" HVAC system model. Because the HVAC system at the USPS/MPF has a central chilled water loop, a conventional central system will be used for the base line model. This base line model will include a water chiller, a boiler, a cooling tower, and standard air handling units with heating coils (for supply air heating) and cooling coils (to provide both cooling and dehumidification of supply air).

For mathematical modelling, mechanical system schematics, equipment specifications, and shop drawings will be referred to, and necessary data needed to define the building envelope, equipment operating schedules, occupancy schedules, and control modes of HVAC system will be obtained from the USPS. A limited amount of monitored electrical data, fuel cost records, and anecdotal information is also available. To the extent possible, this data will be used to support model development and validation. In addition, algorithms will be developed to model the performance of the glycol liquid-desiccant system using information provided by the manufacturer.

In the analysis of ATES systems, the coupling of the aquifer's performance with the dynamic "load" it is serving is often overly simplistic. Total annual heating and cooling load estimates typically have been used to estimate the "average" recovery flow rates from the aquifer for the entire heating/cooling season and the total "charge" of water that must be recovered over the season. Following a survey of the site, a hydrogeologic model is then developed to predict how well a seasonal ATES system can meet these requirements. The aquifer models numerically solve for the thermal response of the subsurface environment (Vail 1989), accounting for horizontal transport and vertical conduction within the aquifer. However, even if the aquifer model is highly accurate, this simplified approach to coupling the aquifer with the building can result in significant errors in predicting of system performance because it does not capture the dynamic impact of changing building loads (i.e., hourly, daily, monthly). Also, if average flow rates are used, the analysis might falsely predict that an ATES system is adequate when actually it might fail to produce sufficient flows at cold enough temperatures late in the summer, the time when peak cooling loads generally occur. An equally unsophisticated approach, and one that is often used to estimate chiller annual energy consumption for buildings with conventional HVAC systems, is the "equivalent full load hours" (EFLH) method. Results of EFLH analyses are overly conservative if cooling loads vary much from the peak. Using peak recovery flow rates to estimate ATES seasonal performance might lead to overly conservative well designs.

On the other end of the spectrum, the most sophisticated method for modeling the USPS/MPF would link an ATES computational model created to predict aquifer performance (i.e., flow rates, and heat/chill recovery efficiency) directly with a sophisticated transient simulation model of the actual building, so that the HVAC dynamic effects can be captured. Such an approach is beyond the scope of the assessment described here. Instead, PNL will precalculate hourly building loads using a building thermal model, and convert these loads to required aquifer recovery flow rates. The loads will be averaged over larger time increments (e.g., days) if desired, to match the computational time step of PNL's aquifer analysis program (Vail 1985). Leaving water temperatures from the building will be calculated by an energy balance based on predicted recovery flow rate. Using this approach, the aquifer capability at the USPS/MPF can be compared with actual required cooling and heating water flow rates. Whenever the aquifer is inadequate to meet cooling or heating needs, the balance will be assumed to come either from increased reliance on mechanical refrigeration (cooling) or the back-up modular boiler (heating).

The building cooling and heating load information can also be used to determine operation requirements for the closed-circuit cooler. Finally, predicted latent heat loads will also provide a prediction of the annual desiccant system operation. From this, an estimate of annual energy usage for the desiccant system will then be obtained, including the propane used by modular boilers for regeneration of desiccant in the concentrator.

The economic assessment will be conducted using an analysis methodology developed by PNL for thermal storage evaluations (Brown 1987). Levelized energy costs of the ATES/desiccant HVAC system at the USPS/MPF will be compared to those for the base-line system. Operating and maintenance costs for the existing system and economic parameters used in the analysis will be provided by the USPS. Standard estimating procedures will be used to develop comparative costs for the base-line system.

An additional, supporting, investigation is being conducted by the USGS to better understand the geotechnical performance of the ATES wells at the MPF. The objectives of this investigation will include defining the local geohydrologic setting, evaluating the potential causes of well clogging, and providing general recommendations for improving overall system operation. This data will help in the development of a more accurate computational model of the aquifer, which will be used for the technical assessment.

Finally, a desiccant system operation assessment will be performed. The primary objective of this evaluation will be to identify any performance anomalies and provide recommendations (where possible) for improving and maintaining the performance of the desiccant system. This task will include on-site monitoring and analysis of existing operational data (both logs and anecdotal data) of the liquid-desiccant system. This work will also help support validation of the desiccant system performance model being created for the technical assessment.

CONCLUDING REMARKS

The ATES/desiccant HVAC system at the USPS/MPF in Melville provides a unique opportunity for an in-depth study of an innovative system that in theory offers both energy and environmental advantages over more conventional systems. The technical/economic assessment described in this paper should provide a means of evaluating the cost effectiveness of this system. Supporting studies, operational logs, and anecdotal data will also provide insights on actual performance. It is hoped that this study and the experience gained from maintaining and operating the system will help guide the evaluation of designs of similar systems in the future, both at USPS facilities and at other locations.

ACKNOWLEDGEMENT

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REFERENCES

Amsterdam, D. 1988. The Antibacterial Effects of Glycol Compounds Used in No-Frost Refrigeration and Hygrol Dehumidification Systems. Research Bulletin, Niagara Blower Company, Buffalo, New York.

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

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

Brown, D. R., J. A. Dirks, M. K. Drost, G. E. Spanner, and T. A. Williams. 1987. "An Assessment Methodology for Thermal Energy Storage Evaluations". PNL-6372, Pacific Northwest Laboratory, Richland, Washington.

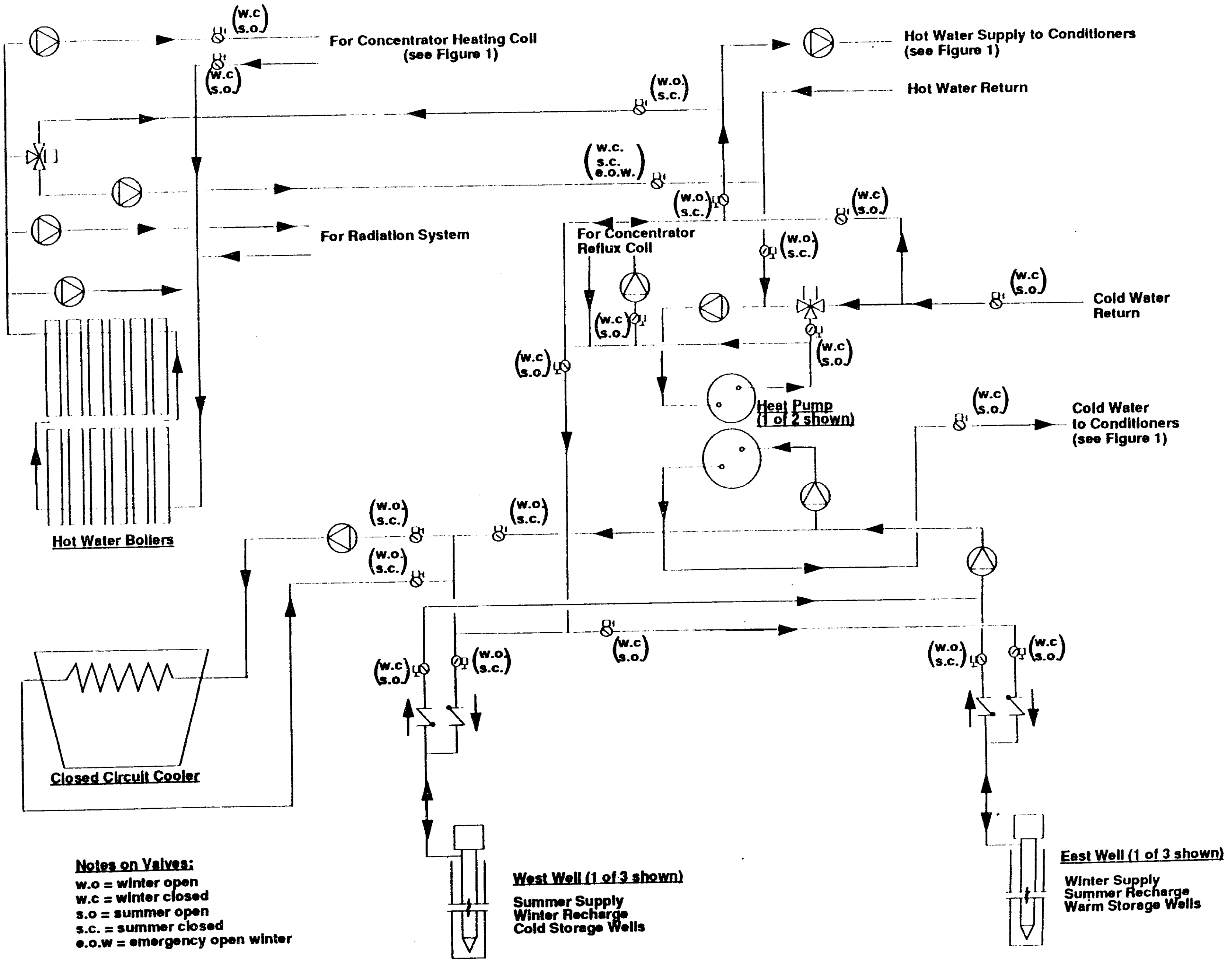

Figure 1. HVAC System Schematic

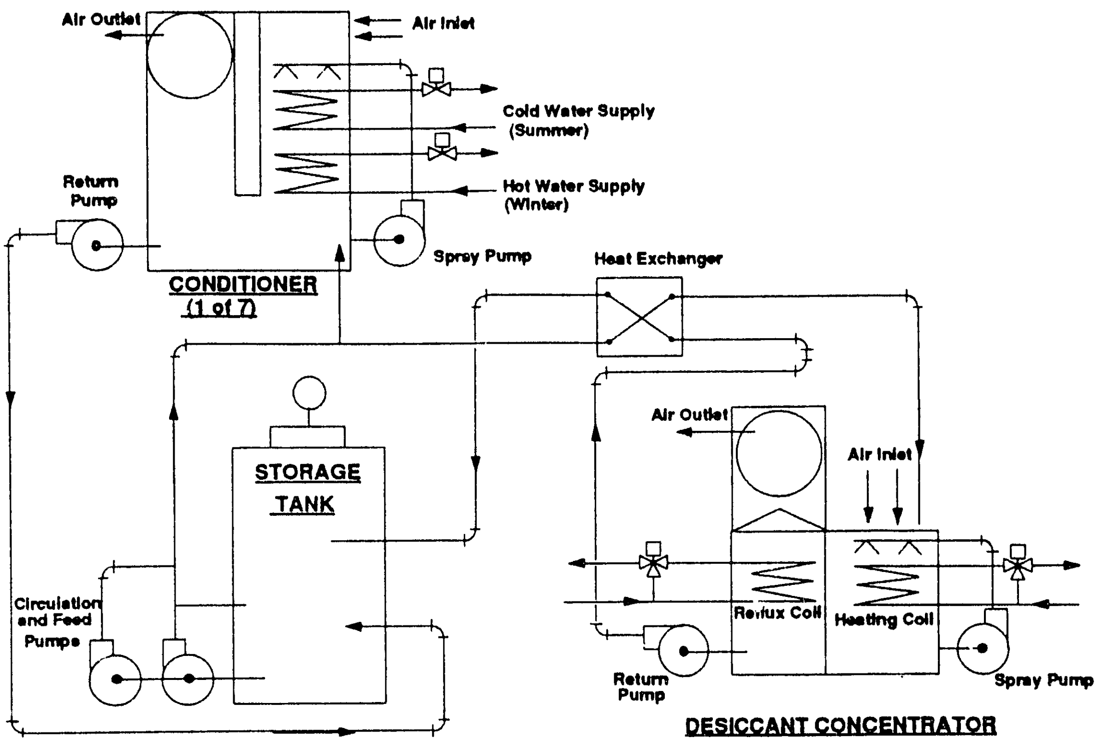

Figure 2. Liquid Desiccant System Schematic

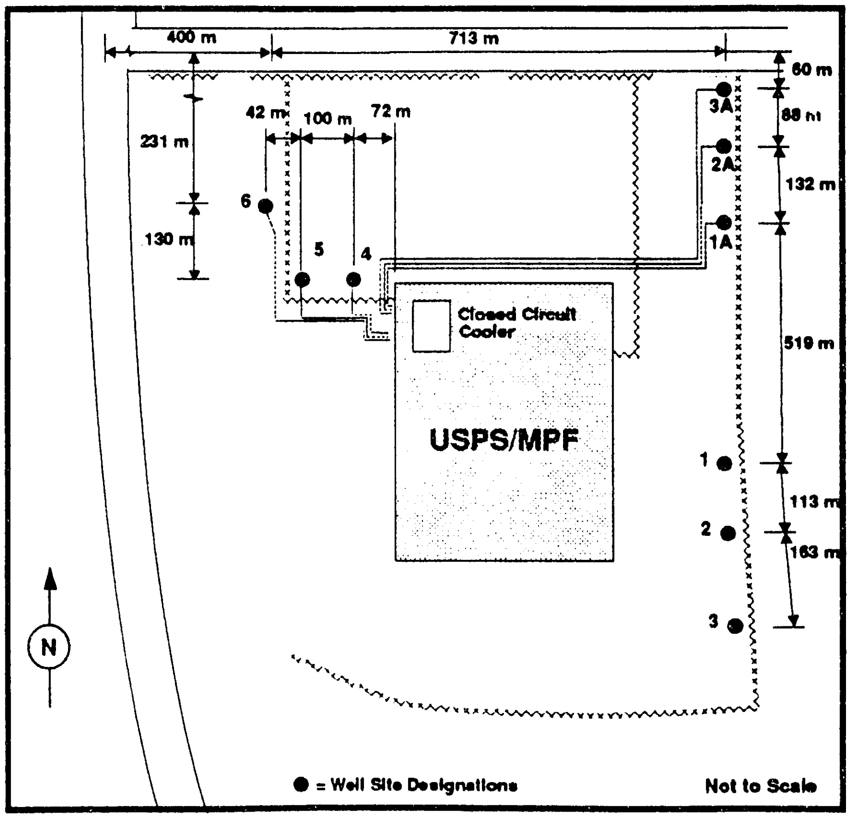

Figure 3. Well Site Details

Monitoring Energy Consumption at the Canada Centre ATES Site

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ABSTRACT

The Canada Centre Building was designed to accommodate 1,900 workers on 12 floors in a 30,000 m^2 office structure in Scarborough, Canada. Its unique energy conserving features include 700 m^2 of roof mounted solar energy collectors, chillers modified to operate as heat pumps, and an aquifer thermal energy storage (ATES) system operating on four 60 m deep wells producing flows of 10 to 30 L/s from a 10 m thick fine to medium sand aquifer. The ATES and solar domestic hot water heating systems have been used since 1985.

Instrumentation for ATES performance monitoring was installed during construction of the building, for research and verification of geothermal models. Energy monitoring, however, was implemented in 1991, to evaluate the energy consumed in operating various energy conserving systems. Initial data show coefficients of performance (COP) of about 4 to 5 for the ATES and heat pump systems respectively.

INTRODUCTION

The Canada Centre Building in the City of Scarborough within Metropolitan Toronto in Ontario, Canada, was designed for Public Works Canada as an energy efficient office building accommodating 1,900 workers on 12 floors, with two levels of parking below grade.

After completion of initial energy modelling and design of a conventional HVAC system based on model results, the possibility of incorporating an aquifer thermal energy storage (ATES) system was investigated. Two aquifers were identified below the building site. After hydrogeological testing in 1981-82, it was decided to use the lower of the two aquifers for the ATES system. In 1982, the HVAC system configuration was expanded to include potential year-round cooling of the building using the groundwater from the lower aquifer. Construction of the building and aquifer groundwater wells was started in 1982 and completed in late 1984. The ATES system was put into operation in 1985.

Due to uncertainties associated with the incorporation of a relatively new technology into the overall energy management of the building, a comprehensive field research program was initiated, to verify geothermal and hydrogeological modelling predictions, and to allow for modification of energy management systems to optimize the utilization of the ATES system. Fifteen observation wells were drilled within the property limits (2.2 hectare area), each equipped with seven resistance temperature device (RTD) sensors and one pressure transducer. Five RTD's are located within the aquifer at equal spacing, and one each in the aquitard and aquiclude above and below the aquifer respectively.

All mechanical systems, including pumps and valves, are operated from a central computer console. The building's HVAC system is operated in a pre-programmed energy conserving sequence, with provisions for operator over-ride. The heating and cooling demands of the building are satisfied using one or more of the following energy conserving and HVAC components:

- Two steel forced draft cooling towers with a total capacity of 2708 kW.
- Two hermetically sealed centrifugal chillers of 1354 kW capacity each.
- Four short term concrete storage tanks of 197,500 L capacity each.
- A fine to medium sand aquifer located 60 m below basement level, supplying 10 to 30 L/s groundwater from each of four production/injection wells.
- Seven plate type heat exchangers, two of which are dedicated to the ATES system.
- Two 635 kW electric resistance boilers, and one standby 210 kW electric resistance boiler for domestic hot water (DHW).
- Evacuated tube type solar energy collectors occupying 700 m^2 of the south facing portion of an A frame type roof topping.

The solar system uses a 50-50 propylene glycol water mixture. All DHW is provided by the solar collectors, even during the coldest of winter days, provided some sunshine is available.

AQUIFER AND WELL FEATURES

The ATES system and the hydrogeological features of the aquifer have been described in detail by Morofsky (1983) and Mirza et al. (1985). The aquifer consists of a fine to medium sand, known geologically in Toronto as the Scarborough formation. It is located at a depth of approximately 60 m below ground level, and averages about 10 m in thickness. A geological profile is shown in Figure 1. The transmissivity of the aquifer ranges between 150 and 200 m^2/day, with a storativity of about 10^{-4}. Hence, the aquifer is fully confined. No leakages or interfering boundaries were apparent during the aquifer pumping tests.

The locations of four production wells (PW) and all observation wells (OW) used in the operation and research of the ATES system are shown in Figure 2. The production wells are full formation penetrating gravel packed wells.

The geophysical logs and construction details of one production well are shown in Figure 3. All production wells were constructed using stainless steel and welding for the casings and wire wound screens. The 100 mm thick gravel pack was placed several metres above the screen level to allow for possible losses and settlement during well development.

During grout sealing of the external casing, problems were encountered with migration of methane from the aquifer. The methane is generated by peat lenses within the aquifer. During investigations, the shut-in pressure of the methane was found to be over 300 kPa. It is believed that the heat of hydration of the grouting cement expanded the casing initially, which upon pumping of groundwater, shrank, allowing methane to escape between the casing and the grout. In future installations, the casing will be cooled during grout sealing.

The specific capacities of the four wells, measured in 1985, ranged between 115 and 142 m^3/day/m. Recent pumping tests (Strata Engineering Corp., 1992) show the well efficiencies have declined between 28% to 72% from those measured in 1985. The decline in well specific capacity is being investigated. Scaling is suspected. Calcite scale was found on low level alarm probe tips located in standpipes within the gravel pack surrounding the well screens (Figure 3).

ATES SYSTEM OPERATION

1985-1989: - The ATES energy management system was initially designed and intended solely to provide cooling, based on a building occupancy of 1,900 work places. The system design called for groundwater to be pumped up from the "warm wells", PW3 and PW4, at an ambient temperature of about 9-10°C, and cooled down to about 7-8°C in the cooling towers. Cooling tower freezing problems were encountered when attempts were made to cool the groundwater much below 6°C. The cooling towers were also incapable of cooling the groundwater much below ambient during "warm" winter days.

During summer, the groundwater, at an average stored temperature of between 8-9°C, was pumped up from the cold wells to cool the building. The warm return water, at an average temperature of about 13°C, was then injected into the warm wells. No problems were encountered with re-injection, since all well heads are equipped with a vortex degassing unit.

1989-Present: - In 1989, the two chiller units were modified to operate as heat pumps, at a conversion cost of about $80,000. Since 1990, the chillers have been used to cool the groundwater to about 3°C for injection in the cold wells. The reject heat from the condenser side of the heat pumps has been found to satisfy most of the winter space heating requirements of the building. The electrical resistance boilers have been used, but for never more than 5 to 7 days during the severest of winter days in 1991 and 1992.

ENERGY MONITORING

The total electricity purchase for the building has been fairly steady, at between 7,500 and 8,000 MWh per annum, irrespective of the heating and cooling degree days (18°C), which are on average, about 3,750 and 300, respectively, for this site. The building floor area is 30,470 m^2. The occupied floor area is 25,300 m^2. A review of the purchased electricity records (Hickling Corp., 1990) showed total energy consumption values of about 300 kWh/m^2 of the occupied floor space, until about 1989. After conversion of the two chillers to heat pump mode, the purchased energy consumption of the occupied floor space has dropped to about 250 kWh/m^2. The energy consumed per work place has also declined, from over 8,400 kWh in 1985 (900 work places), to less than 5,000 kWh during 1989 (1,500 work places).

Although energy reductions may appear to be dramatic, the efficiencies and cost savings achieved as a result of investment in ATES and heat pumps are not yet determined. The capital costs are known. The operating costs of the four aquifer pumps and the heat pumps, however, are not known. Hence, an energy monitoring system was installed in 1991, primarily to monitor the energy demands of the chiller heat pumps and the aquifer pumps. Because a central computing facility was added to the building load in 1986-87, it was felt that the same monitoring system should also capture the energy demand of this facility.

The energy monitoring system is a modular data acquisition unit with a proprietary monitoring and analysis software package. Transducers isolate power levels before connection to the data acquisition system.

Each power transducer consists of two current transformers and three voltage readouts. Calculations for the power factor are accounted for electrically. A conditioned signal is sent to the data acquisition system. In all, seven power transformers are used to read the seven energy points (a central computing facility which is cooled by the aquifer, the two chiller heat pump units and the four aquifer well pumps).

The software for the system has built-in processing and analysis capabilities, and is set up to scan each monitoring point once every 10 seconds. The electrical power consumption values are averaged over 5 minute intervals and logged. They are then internally integrated into daily values of energy consumption.

Daily energy profiles and totals are saved on disk. The system has been designed with a modem interface, such that a personal computer (PC) located elsewhere in Toronto or in a remote city such as Ottawa can tap into the data base for information on current consumption, or previous consumption if it has not been off loaded on disks.

INITIAL RESULTS AND DISCUSSION

Logs of energy consumption show that the average daily (24 hour day) energy consumption, between mid-November 1991 and mid-February 1992 is as follows:

Chiller Heat Pumps	4,500 kWh
Aquifer Pumps PW1 and PW2	732 kWh
Aquifer Pumps PW3 and PW4	1,161 kWh
Computing Facility	6,170 kWh

The central computing facility is cooled at nights and weekends with cold water from the cold wells, PW1 and PW2. Assuming the night and weekend cooling load of the central computing facility to be 50 % of its average daily load, it can be seen that the aquifer is providing a COP equivalency of just over 4.

During the reported monitoring period, almost all of the building heating load has been met with the heat pumps (condenser heat), and the extraction of 7-8°C temperature change (delta T) from about 12 L/s of groundwater flow from the warm wells, PW3 and PW4.

The estimated COP of this type of operation is likely between 5 and 6, when the potential for "free" cooling during the summer of 1992 is taken into consideration. The current (May, 1992) groundwater temperature is 4.5°C in PW1 and PW2 and about 5.5°C in the nearby observation wells. The groundwater temperature is expected to rise to about 6.5°C by mid-June, 1992, after storage during May and part of June, 1992. This rise in temperature will occur due to conductive and convective losses and mixing with the 9°C ambient temperature groundwater, when pumping commences to meet the cooling demand in summer.

The energy monitoring system has helped to quantify net benefits, defined as the energy savings accruing from the use of ATES and heat pumps, less the energy required to operate them. The monitoring program is also yielding a more rational explanation of how the total purchased electricity is being used within the building.

Additional monitoring points need to be added, as and when funds become available, to more precisely account for the energy balance within the building. A better accounting and rationalization of the energy and cost savings achieved is necessary to justify future requests for earth energy and ATES related R&D funding.

CONCLUSIONS

Initial data from the newly installed energy monitoring system has shown promising and interesting results, the full impact of which can be determined after about one year of operation and observation. Initial results show the COP equivalency of the aquifer based cooling system for a central computing facility to be about 4.

The COP of the heat pumps and ATES system together is expected to be between 5 and 6, when the summer 1992 cooling potential, with the colder stored water, is taken into account.

The investment in the energy monitoring system (about $30,000) is felt to be justified, in light of the knowledge being gained about the energy demands and costs of energy conserving systems and components. It is hoped that better information and rationalization of costs and savings will lead to not only better energy management within the Canada Centre Building, but also justify future funding requests to research operating problems and to further experiment with similar energy conservation technologies.

REFERENCES CITED

Hickling Corporation. 1990. Canada Centre Building, Scarborough - Five Year Energy Systems Performance Summary. Hickling Ref. 2720. Prepared for IEA ECES Annex 7 Working Group. April.

Mirza, C., Lau, K. C., Nadon, R. L. and Crawford, A. M. 1985. Aquifer thermal energy storage - a new technology. Proceedings, Seventh Canadian Hydrotechnical Conference, Saskatoon, Sask. May, vol. 1A, pp: 389-409.

Morofsky, E. L. 1983. Overview of Canadian aquifer thermal energy storage field trials. Proceedings, International Conference on Heat Storage in Theory and Practice, Stockholm, Sweden. Swedish Council for Building Research, pp:221-231

Strata Engineering Corp. 1992. Well Efficiency Testing, Aquifer Thermal Energy Storage System, Canada Centre Building, Scarborough. Report S-92-331 submitted to Public Works Canada, Ontario Region. April.

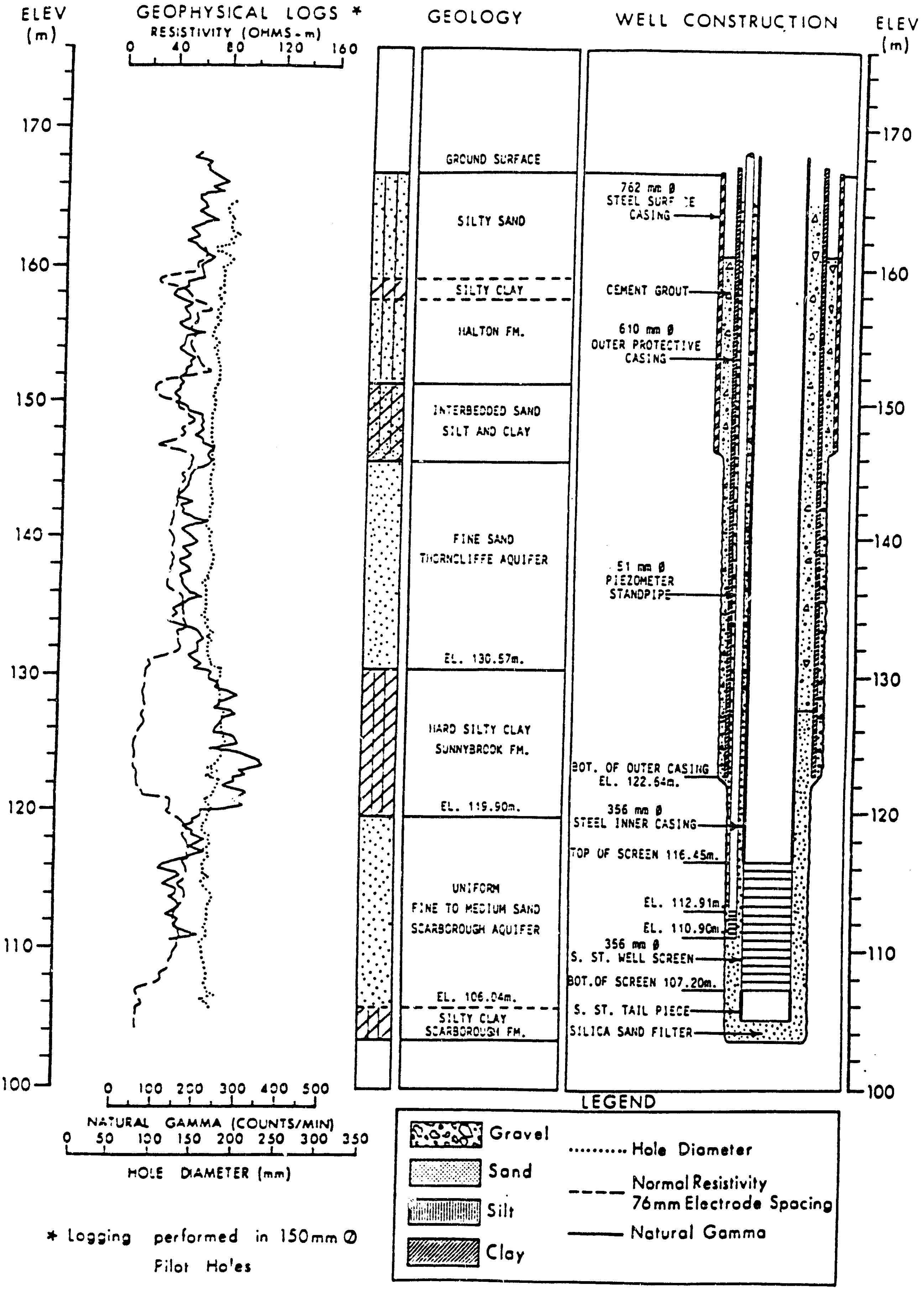

Figure 3. Geophysical logs and well construction details, PW1.

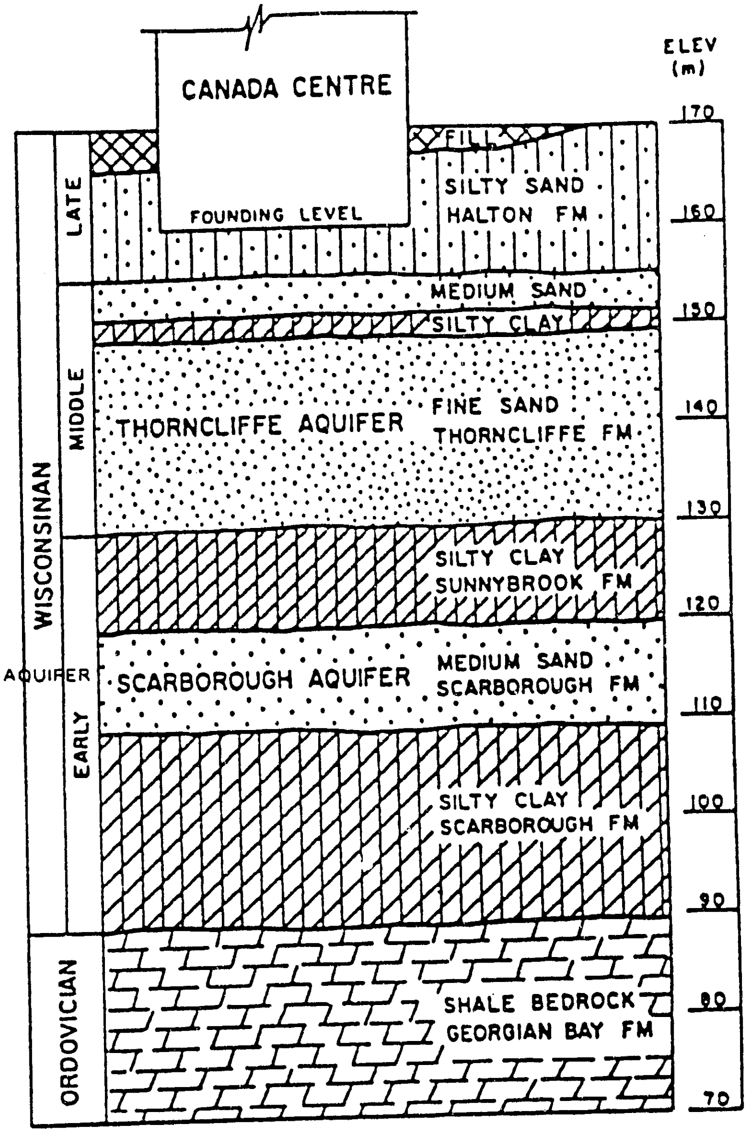

Figure 1. Geological profile, Canada Centre ATES site.

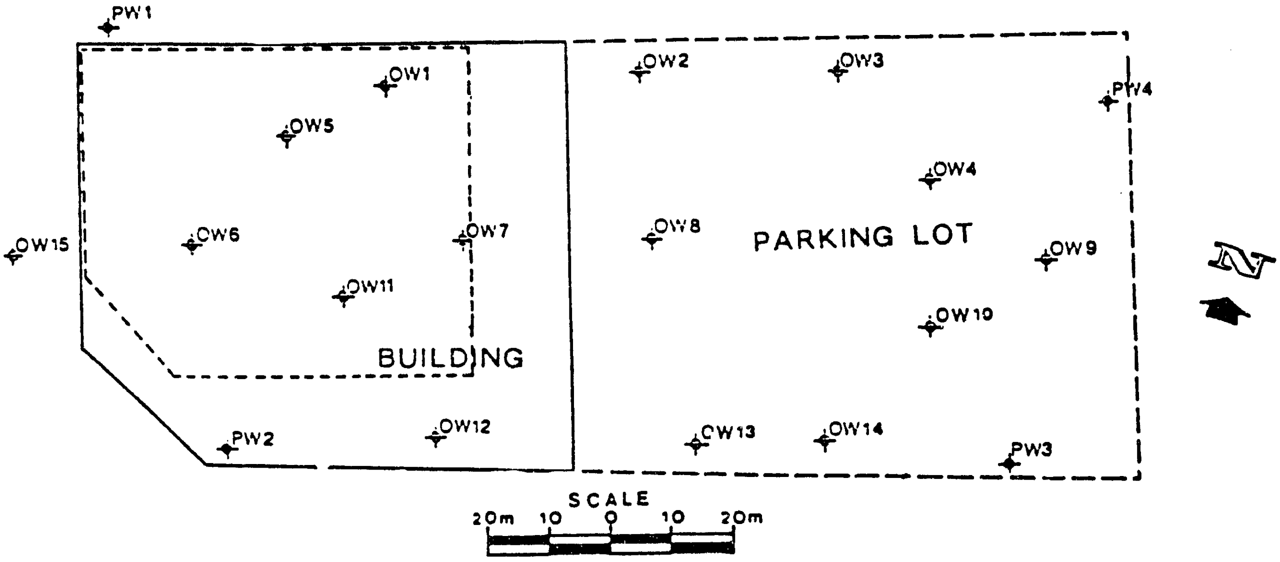

Figure 2. Plan of production and observation wells.

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