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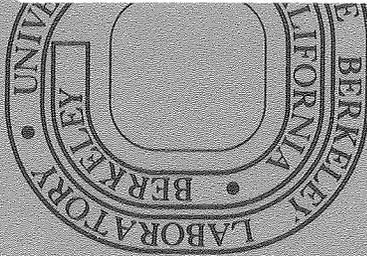
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AQUIFER THERMAL ENERGY STORAGE--A SURVEY

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January 1980

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* Visiting scientist from University of Lund, Sweden

ABSTRACT

The disparity between energy production and demand in many power plants has led to increased research on the long-term, large-scale storage of thermal energy in aquifers. Field experiments have been conducted in Switzerland, France, the United States, Japan, and the People's Republic of China to study various technical aspects of aquifer storage of both hot and cold water. Furthermore, feasibility studies now in progress include technical, economic, and environmental analyses, regional exploration to locate favorable storage sites, and evaluation and design of pilot plants.

Several theoretical and modeling studies are also under way. Among the topics being studied using numerical models are fluid and heat flow, dispersion, land subsidence or uplift, the efficiency of different injection/withdrawal schemes, buoyancy tilting, numerical dispersion, the use of compensation wells to counter regional flow, steam injection, and storage in narrow glacial deposits of high permeability.

Experiments to date illustrate the need for further research and development to ensure successful implementation of an aquifer storage system. Some of the areas identified for further research include shape and location of the hydrodynamic and thermal fronts, choice of appropriate aquifers, thermal dispersion, possibility of land subsidence or uplift, thermal pollution, water chemistry, wellbore plugging and heat exchange efficiency, and control of corrosion.

INTRODUCTION

The need for energy storage arises from the disparity between energy production and demand. The development of viable storage methods will play a significant role in our ability to implement alternative energy technologies and use what is now waste heat. The ability to provide heat at night and during inclement weather is a key factor in the development of solar energy. Conversely, winter cold, in the form of melted snow or water cooled to winter air temperatures, can be used as a coolant or for air conditioning. Practical storage systems would also allow us to capture the heat that occurs as a by-product of industrial processes and power production. Industrial plants and electric utilities generate tremendous amounts of waste heat, which is usually dissipated through an expensive system of cooling towers or ponds to avoid thermal pollution. Because periods of heat demand do not generally coincide with electricity generation or industrial production, a viable storage method is essential if this heat is to be used. Such a method would not only provide for the use of what is now waste heat, but would significantly decrease the necessary investment in cooling and backup heating systems.

In recent years, aquifers have been studied as a very promising means for the long-term, large-scale storage of thermal energy. Aquifers are porous underground formations that contain and conduct water. Confined aquifers are bounded above and below by impermeable clay layers and are saturated by water under pressure. They are physically well suited to thermal energy storage because of their low heat conductivities, large volumetric capacities (on the

order of 10^9 m^3) and ability to contain water under high pressures. Aquifers are also attractive storage sites because of their widespread availability.

Aquifer storage is not a new concept. Since the 1950s aquifers have been used to store fresh water, oil products, natural gas, and liquid wastes. However, their use for thermal energy storage was not suggested until the 1970s. Initial studies were conducted by Rabbimov and others (1971), Meyer and Todd (1972), Kazmann (1971), and Hausz (1974). A good source of information about more recent work is the Proceedings of the Thermal Energy Storage in Aquifers Workshop (Lawrence Berkeley Laboratory, 1978). Current research and development are reviewed in the quarterly ATES Newsletter, also published by Lawrence Berkeley Laboratory. At present, there are several projects throughout the world in which the technical, economic, and environmental aspects of aquifer storage are being studied. We shall survey the status of these projects, which are divided into three broad categories: field experiments, feasibility studies, and theoretical and modeling studies. The paper concludes with a discussion of key problems that warrant further research.

FIELD EXPERIMENTS

Initial field experiments have been described by Werner and Kley (1977), Kley and Nieskens (1975), and Despois and Nougarede (1977 unpub. report). Generally, field projects to date have been performed on a relatively small scale and have used water of moderate temperatures (not greater than 55°C or less than 5°C). Most of these experiments focused on obtaining pressure and temperature data with the objectives of understanding heat and fluid flow in

the aquifer and validating numerical models. There is a need both to extend the temperature range of the investigations and to examine the concept of energy storage on a larger scale. It is also important to look more carefully at other facets of energy storage in aquifers, including the effects of regional flow, land uplift or subsidence, water chemistry and treatment, and economic feasibility.

A number of experiments have been carried out in recent years. Some of the major projects that are either under way or were recently completed are summarized below. First-cycle data for most of these experiments are summarized in Table 1. The energy recovery ratio indicated in this table is defined as the ratio of recovered energy to injected energy with reference to the original groundwater temperature.

Switzerland

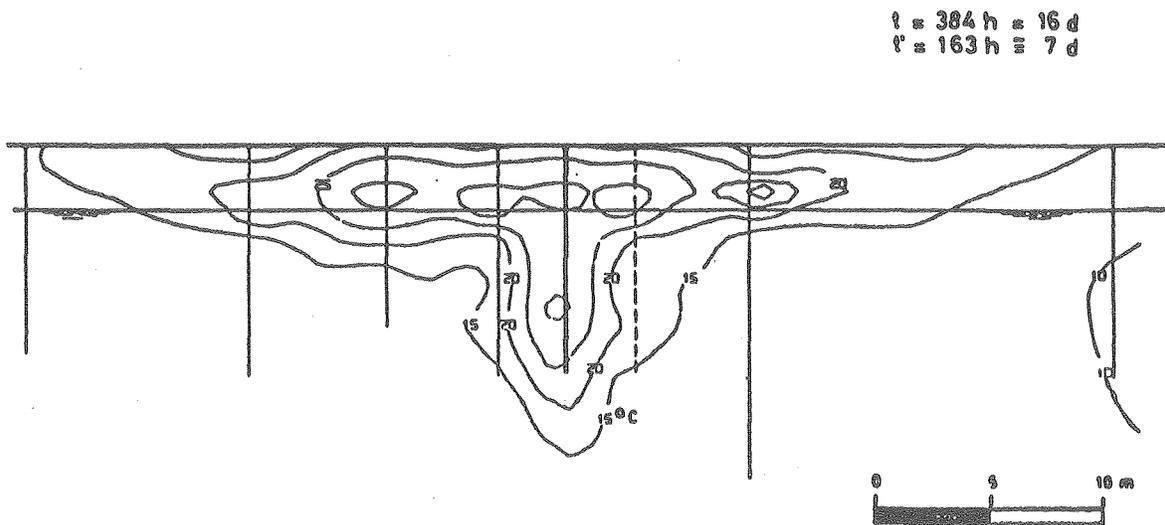
In Switzerland, district heating accounts for 50% of total energy consumption. The amount of yearly consumption that must be stored ranges from 30% for continuous production to as much as 50% for solar production. At present, underground heat storage is being studied as a possible solution to the problem of seasonal storage of thermal energy (Mathey and Menjoz, 1978).

In 1974, the University of Neuchâtel conducted an experiment in which 494 m³ of hot water was injected into a shallow, phreatic aquifer (Mathey, 1975). Details of the experiment are outlined in Table 1. The high permeability of the aquifer caused the lighter hot water to rise. This, together with the small injection volume, resulted in a relatively large heat loss

TABLE 1. FIRST CYCLE DATA FROM AQUIFER THERMAL ENERGY STORAGE FIELD EXPERIMENTS

Site	Groundwater temp. (°C)	Injection temp. (°C)	Amount injected (m ³)	Injection period (days)	Storage period (days)	Amount withdrawn (m ³)	Energy recovery ratio (%)	Comments and references
University of Neuchâtel, Switzerland (1974)	11	51	494	9	~ 122	16,370	~ 40	Shallow phreatic aquifer, large buoyancy convection (Mathey, 1975)
Bonnaud, France (1976-77)	12	40	1,400	20	122	3,000	30	Evidence of strong thermal dispersion (de Marsily, 1978)
Campuget Exp. Gard, France (1977-78)	14	33.5	20,200	88	42 32	17,000	20	Shallow phreatic aquifer (Cormary and others, 1978)
Auburn Univ., Alabama, U.S. (1976)	20	36.4	7,688	17	44	14,260	68	Injection well clogging (Molz and others, 1979)
Auburn Univ., Alabama, U.S. (1978-79)	20	55	54,784	80	51	55,345	65	Evidence of ground sur- face movement (Molz and others, 1979)
Yamagata Basin, Japan (1977-78)	16	23.7	8,843	64	96	9,930	~ 40	Doublet wells too close to each other (Yokoyama and others, 1978)
Texas A & M Univ., College Station, Texas U.S. (1978-79)	21	8.9	31,800	~ 92	~ 60			In progress (Reddell, personal communication)

through the upper unconfined layer (Fig. 1). After pumping 16,370 m³ of water, an amount over 30 times the injection volume, only 40% of the heat was recovered.

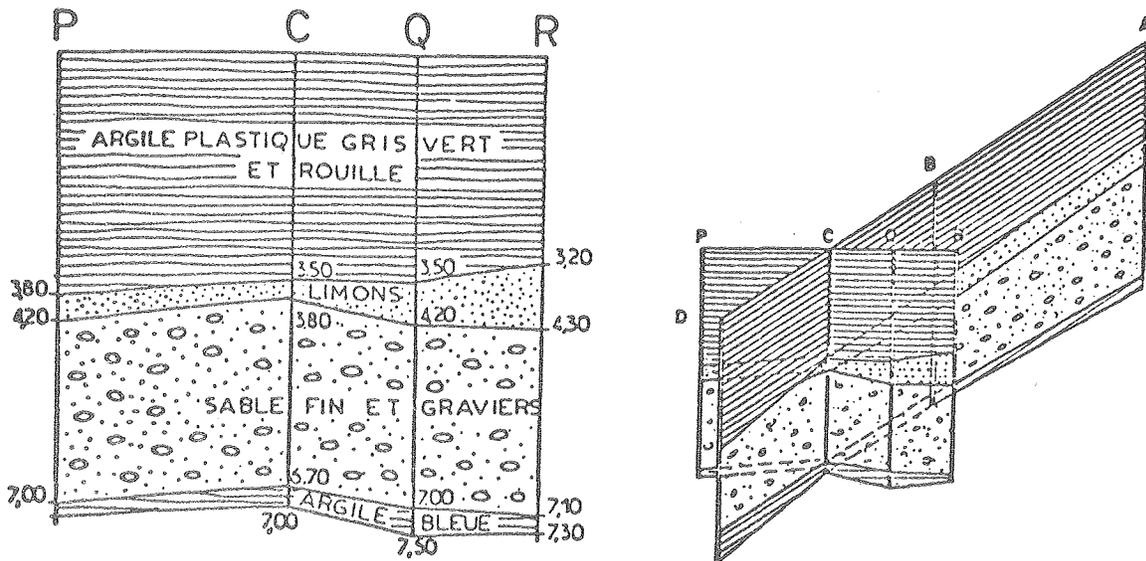
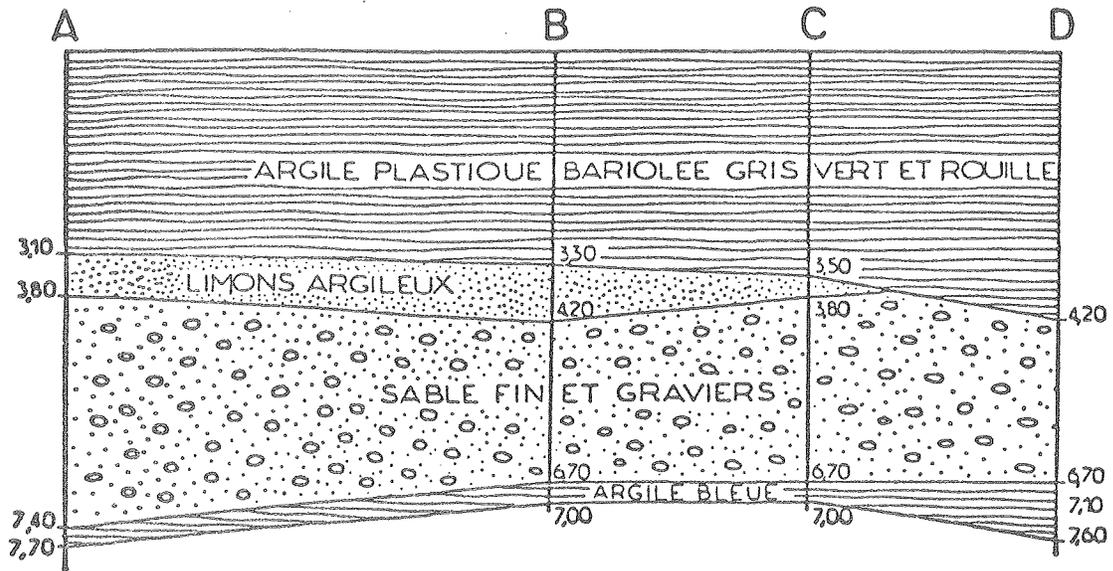


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Figure 1. Experiment by the University of Newchâtel - extension of thermal disturbance in a gravelly aquifer 16 days after a 223-hour injection of 51°C water, at 37 l/min, into the Colombier-Robinson well (Mathey and Menjoz, 1978).

France

In France, several theoretical calculations have indicated that thermal energy storage in aquifers is both economically and technically feasible. Field experiments were designed and carried out during the three-year period from 1976 to 1978. Participating agencies included the Bureau de Recherches Géologiques et Minières, Orléans; Centre d'Etudes Nucléaires de Grenoble; and Ecole des Mines de Paris.



XBL 794-9180

Figure 2. Bonnaud experiment - fence diagram of the experimental well field. (Fabris and Gringarten, 1977)

The Bonnaud experiments (1976 to 1977) involved the injection of hot water into a confined, 3 m thick, shallow aquifer (Fabris and Gringarten, 1977). Eleven observation wells were used to obtain detailed data from two series of heat storage experiments. A fence diagram of the experimental well field is shown in Figure 2. The first series of experiments consisted of three successive injection and production cycles and was followed by the second series (1977) consisting of four cycles. Results of the first cycle are shown in Table 1. More detailed results are shown in Table 2, which also lists results of experiments using lower temperature (19° to 20°C) water for comparison. A temperature log for one of the observation wells is shown in Figure 3. The low thermal recovery of the first cycle is attributed in part to the small scale of the experiment and the substantial thermal dispersion, which was observed throughout the course of the study.

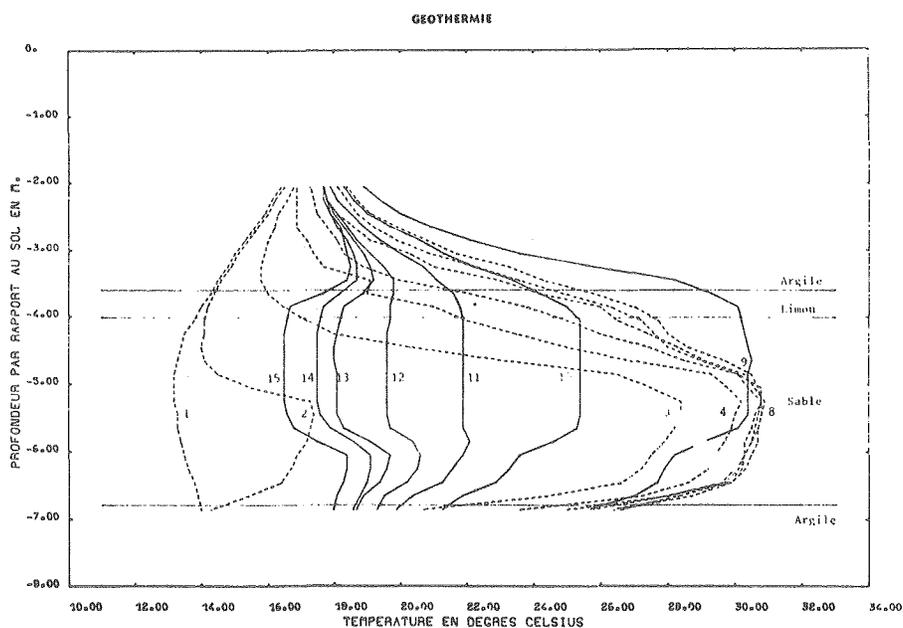


Figure 3. Bonnaud experiment (first cycle) - temperature log in well P2 for the period August 12-14, 1977. (Fabris and Gringarten, 1977)

TABLE 2. APPARENT THERMAL CONDUCTIVITY VALUES* FOR SEVERAL HOT-WATER STORAGE EXPERIMENTS

Research Institute	Aquifer thickness (m)	Injection			Production		Thermal storage radius (m)	Apparent conductivity $\tilde{\lambda}$ (cal/m.s ⁻¹ . °C)	$\tilde{\lambda}/\lambda$
		Temperature (°C)	Q_i (m ³ /hr)	t_i duration (days)	Q_p (m ³ /hr)	t_p duration (days)			
ENSMP BURGEAP at Neuilly, 1974	10	19	15	3	30	3	8	4.5	7.5
ENSMP BURGEAP at Noisy, 1974	30	20	115	3	130	3.7	12	1.8	4
BRGM at Bonnaud, 1977	2.5	34	3.4	6 3 6 6	3.4	6 3 6 6	10 7 10 10	12	20

Source: Sauty and others, 1979, Table 1

* The apparent thermal conductivity, denoted by $\tilde{\lambda}$, is derived from field temperature data. The actual thermal conductivity of the aquifer is denoted by λ .

Ecole Nationale Supérieure des Mines de Paris, Paris, France

Bureau de Géologie Appliquée, Neuilly, France

Bureau de Recherches Géologiques et Minières, Orléans, France

The Campuget experiment (1977 to 1978) was a full-scale storage project with the goal of storing enough heat to meet the needs of 100 housing units (Cormary and others, 1978). Research included careful monitoring of a phreatic aquifer used for large-scale interseasonal storage, measuring the efficiency of heat recovery, performing a numerical simulation, and studying applications to space heating using existing greenhouses. Over a three-month injection period, 20,200 m³ of water, heated by simple solar collectors and heat pumps, was injected into a shallow, unconfined aquifer (Table 1). The experiment consisted of two waiting and withdrawal periods. The change in temperature during each period is shown in Table 3.

Table 3. TEMPERATURE MEASURED AFTER EACH PHASE OF THE CAMPUGET EXPERIMENT

Phase	Length of period (d)	Temperature at end of period* (°C)
Continuous injection of 20,200 m ³ of hot water	88	33.5
First waiting period	42	30.0
Withdrawal of 5,000 m ³ of water	43	21.0
Second waiting period	32	19.0
Withdrawal of 12,000 m ³ of water	55	14.0

* Initial aquifer temperature was 14°C. Source: Cormary and others, 1978

During pumping, a significant decrease in efficiency was observed between the first and second withdrawal periods, from 54% to 10%. As in the case of the Swiss experiment, the water was stored in a shallow, phreatic aquifer, resulting in a large heat loss through the unsaturated zone (Fig. 4). Contributing to the loss of efficiency was a decrease in air temperature from 16°C in October 1977 to 6°C in January 1978 and an accumulation of 700 mm of rainfall

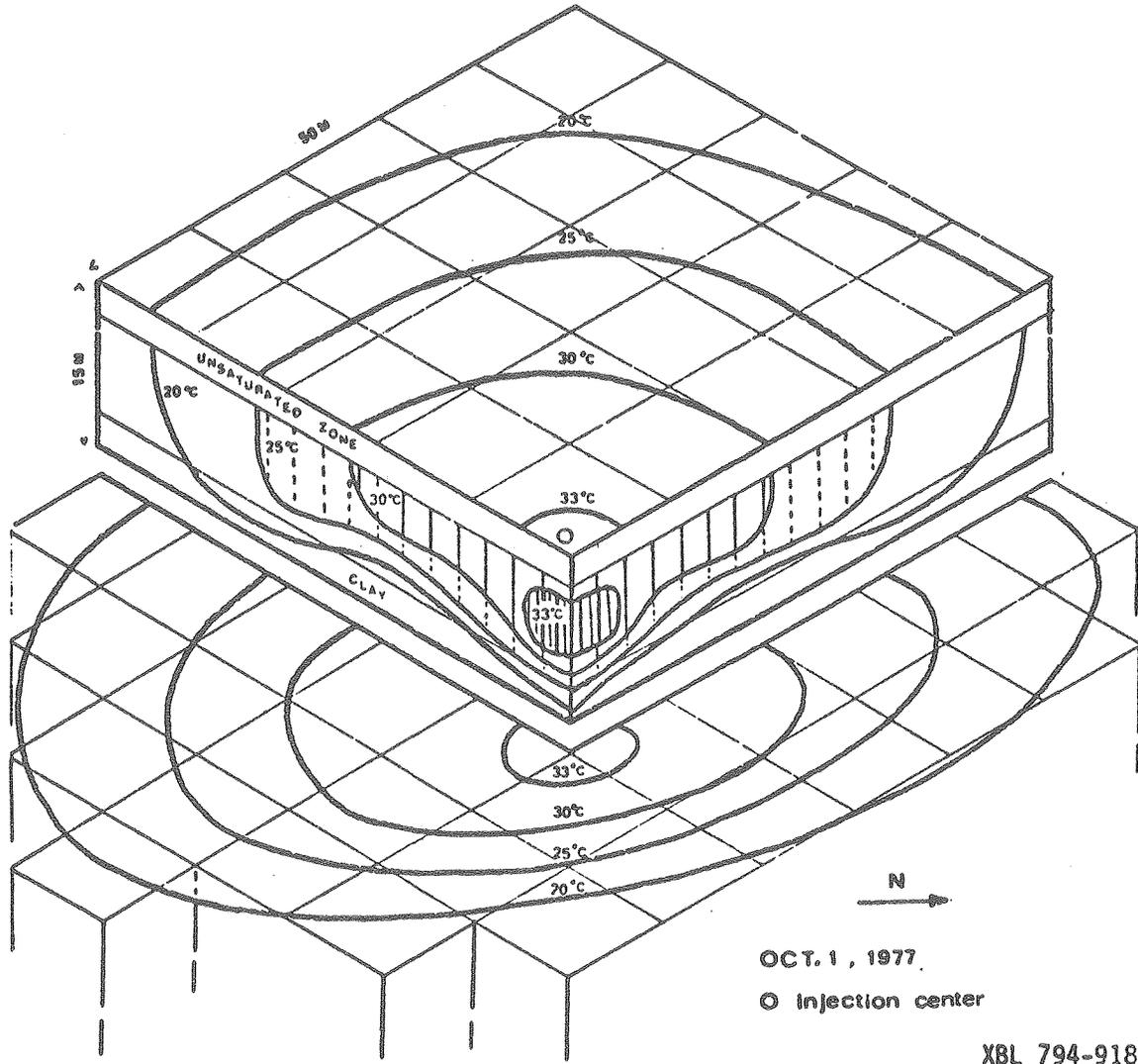


Figure 4. Campuget experiment - temperature distribution in the aquifer at the end of the storage period, October 2, 1977. (Cormary and others, 1978)

between October and March, which caused a decrease in the thickness of the unsaturated zone from 3 to 1 m from October 1977 to January 1978 (Table 4).

Throughout the experiments, precipitation of carbonates was neither observed nor detected through chemical analysis. Local bacterial growth did develop but was successfully treated with chlorine injections and did not result in clogging.

Table 4. COMPUTER-ESTIMATED ENERGY BALANCE FOR THE WATER
(17,000 m³) PRODUCED DURING THE CAMPUGET EXPERIMENT

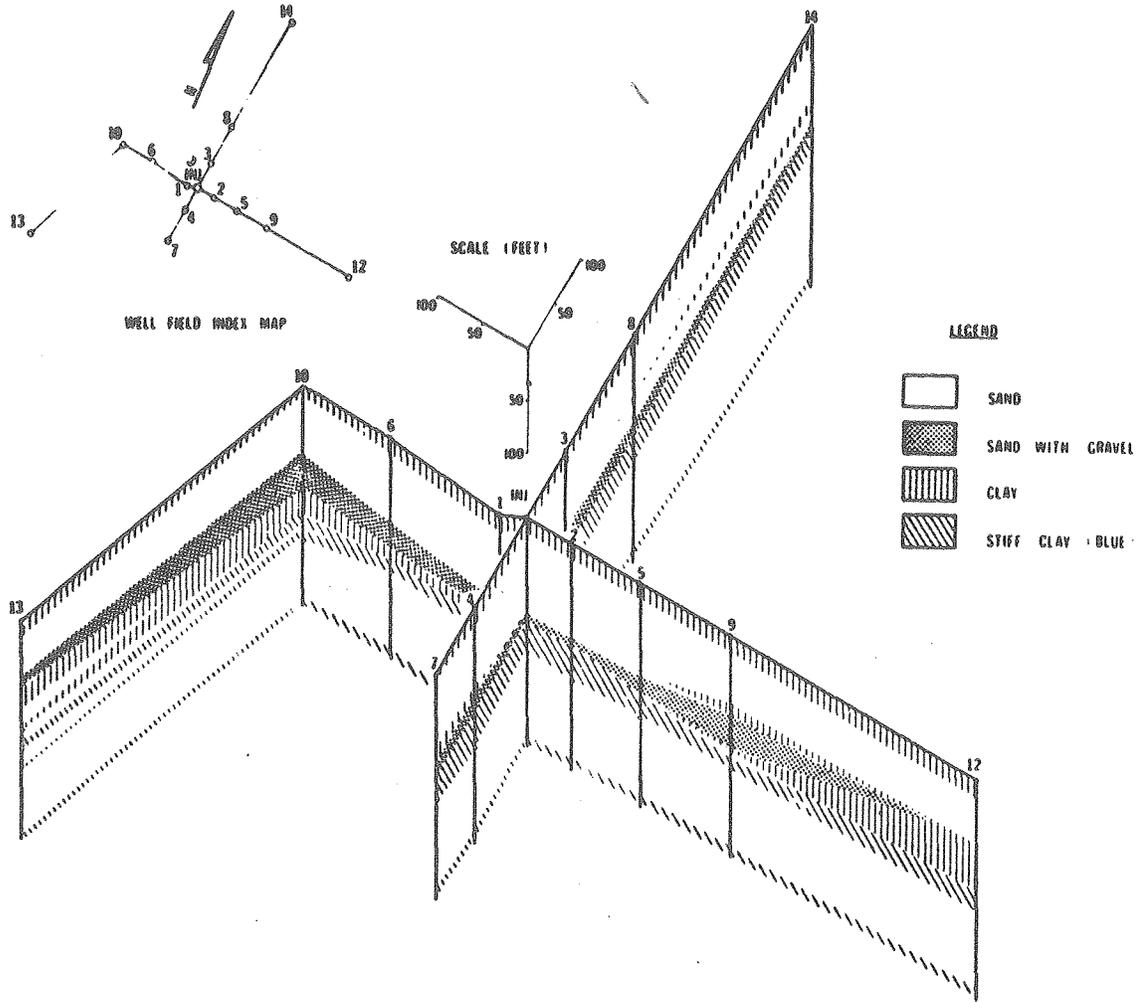
	Energy (Joules)	% of initial heat content
Initial energy content (17,000 m ³ of hot water at 33.2°C; ambient water at 14.5°C)	1.329 x 10 ¹²	100.0
Energy losses due to:		
dispersion in aquifer	0.481 x 10 ¹²	36.2
conduction through unsaturated zone	0.460 x 10 ¹²	34.6
conduction to lower confining layers	0.046 x 10 ¹²	3.5
regional flow (local gradient 1%)	0.092 x 10 ¹²	6.9
infiltration of rainwater	0.033 x 10 ¹²	20.5
Energy recovered	0.217 x 10 ¹²	16.3

Source: Iris, personal communication (1979).

United States

Auburn University.

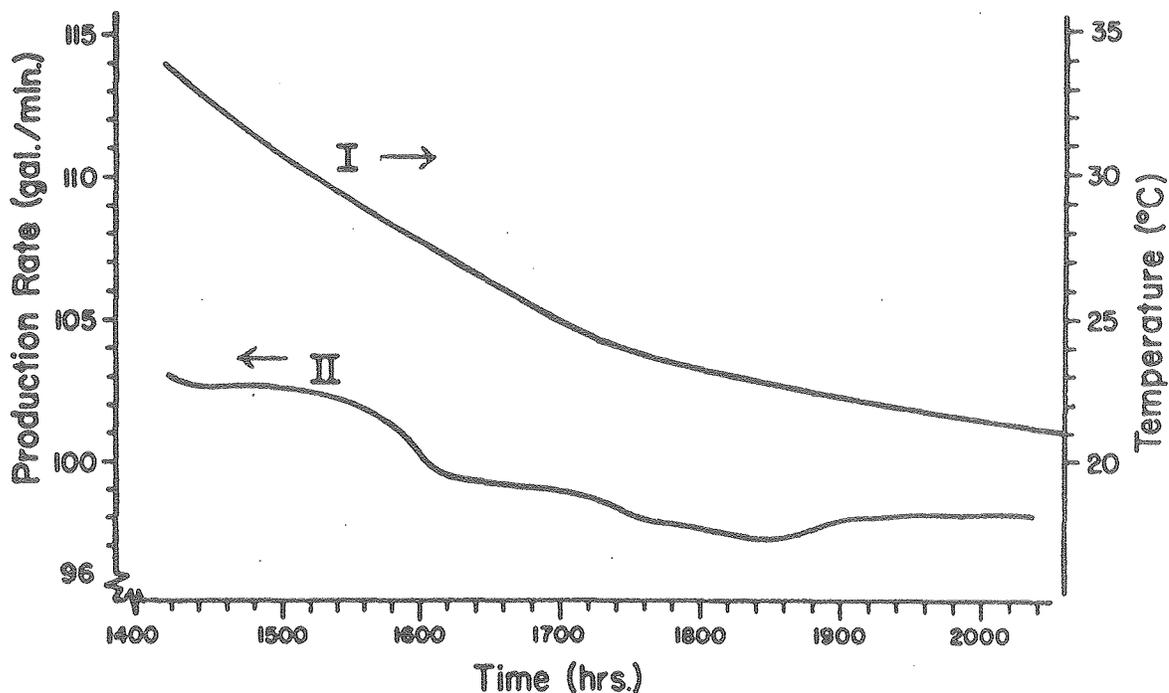
A series of field experiments is being conducted by the Water Resources Research Institute of Auburn University to test the concept of storing large quantities of hot water in confined aquifers and to provide data for calibrating mathematical models. For a preliminary experiment initiated in June 1975 (Molz and others, 1978), a well field was constructed near Mobile, Alabama consisting of a central injection-production well surrounded by 10 observation and 3 boundary wells (Fig. 5). An additional observation well was placed just above the upper confining layer. Warm water (averaging 36°C) was obtained from the effluent discharge canal of a power plant and injected into a confined aquifer where the temperature of the formation water was about 20°C (Table 1). Clogging, thought to be primarily due to a high level of suspended solids in



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Figure 5. Experiment by Auburn University - fence diagram of the experimental well field; the injection well is labeled INJ. (Molz and Warman, 1978)

the injected water, was a serious problem throughout the injection period. Following a storage period of approximately 41 days, 14,260 m³ of water was produced from the aquifer. Figure 6 shows production rate and temperature as functions of time. In view of the relatively small volume of injected water and a partially penetrating injection well, an energy recovery ratio of 68% was encouraging.



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Figure 6. Experiment by Auburn University - temperature curve (curve I) and production flow rate (curve II) as functions of time during the recovery portion of the experiment (Warren, Molz, and Jones, 1977)

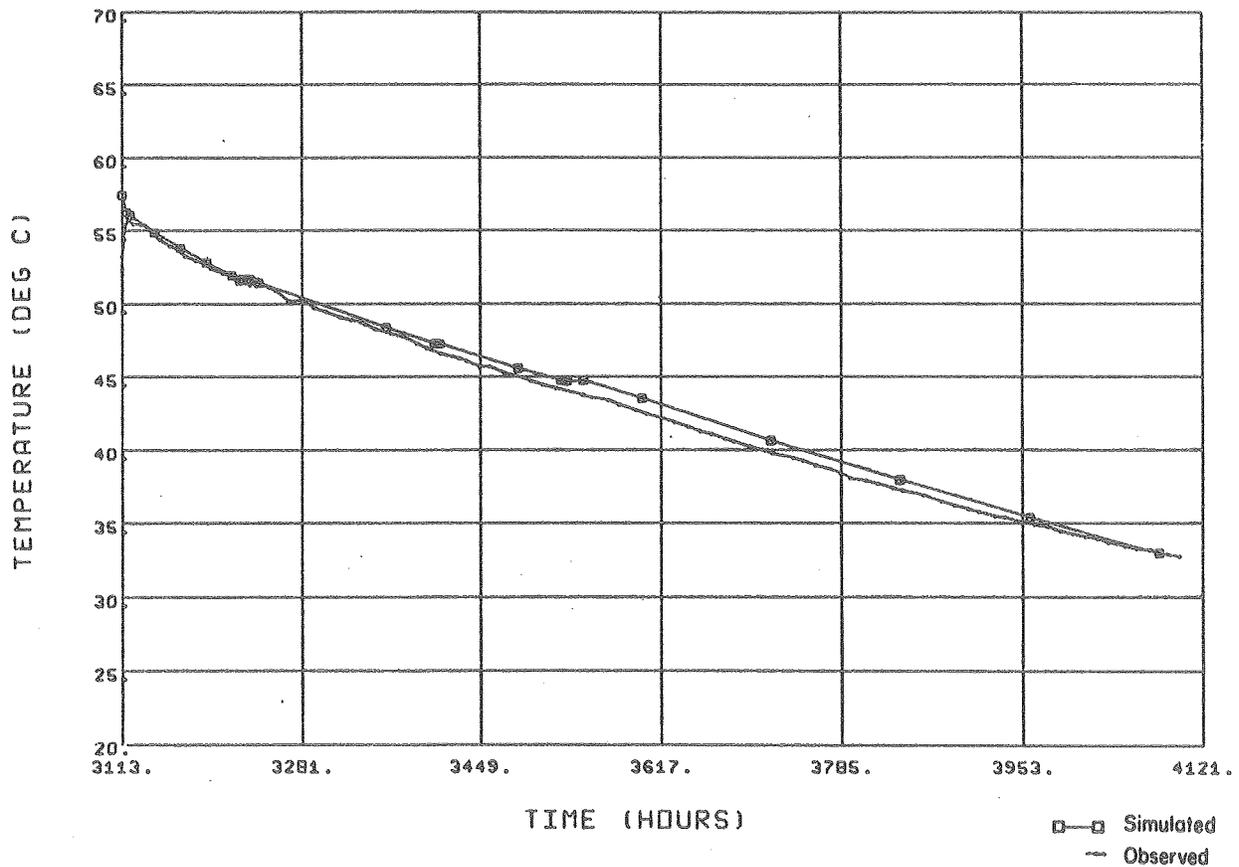
For a second set of experiments begun in March 1978 (Molz and others, 1979), water obtained from a shallow semiconfined aquifer at the experimental site was heated by means of an oil-fired heater and injected into the deeper confined aquifer (Table 1). After a period of storage, the water was produced until its temperature fell to 33°C, which was 13°C above the original water temperature in the aquifer. During this first 6-month cycle, clogging problems were encountered but were much less severe than in the preliminary experiment. The improvement is attributed to the use of ground water rather than surface water and to some backwashing of the injection well. The loss of permeability is probably due to clay particle swelling, dispersion, and migration in the

storage formation. A second problem encountered was convection in the observation wells, which caused erroneous temperature readings. The problem was corrected early in the experiment by backfilling the wells with coarse sand.

A second 6-month cycle was completed during March 1979 (Molz and Parr, 1979). Injection volume and temperature were similar to that in the first cycle. The aquifer was still "warm" from the previous cycle where production had stopped 13°C above ambient groundwater temperature. For the injection period, the average specific capacity of the injection well was found to be significantly greater than in the previous experiment. This indicates that the degree of clogging may stabilize at an acceptable level when water that is low in suspended solids is used and suitable backwashing procedures are implemented during injection. Water samples taken during the production phase show that approximately 3500 kg of clay were pumped out from the storage formation. Measurement of ground surface elevation changes indicated a rise of 4 mm near the injection well during injection. The ground subsided to its original elevation during production. An energy recovery ratio of 73% was obtained, which is significantly better than that obtained for the first cycle (65%).

These experiments have been simulated at Lawrence Berkeley Laboratory using a numerical model of the aquifer system. The aquifer parameters used were determined based on well test analyses, laboratory measurements, and a preliminary parameter variation study. The simulated production temperatures and energy recovery ratio agree well with field data. Larger discrepancies between calculations and experimental data are observed in detailed temperature

distribution comparisons. There appears to be a smoothing and "compensation" effect by which some discrepancies are averaged out and some cancel during the injection-and-production process, so that the final production temperatures are simulated very well (Fig. 7). For the first cycle, the simulated recovery of 66% agrees well with the observed value of 65%. The corresponding figures for the second cycle are 76% (simulated) and 74% (observed).



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Figure 7. Simulation of experiment by Auburn University (first cycle) - calculated and observed production temperatures during the recovery period. (Tsang and others, 1980)

Texas A & M University

The objective of the experiment at Texas A & M University is to demonstrate the economic and technical feasibility of cold water storage in aquifers. In particular, Reddell and others (1978) are developing a prototype system in which water is chilled by winter cold and stored in an aquifer for use in summer for air conditioning. Chilled-water storage is of special interest in Texas, where air conditioning accounts for one-third of the residential energy load. Aquifer storage is considered technically feasible based on several years' experience with injection, storage, and recovery of surface water, and is especially attractive in that 80% of the land in Texas is underlain by aquifers.

The storage site is located in the alluvial floodplain of the Brazos River, Texas. Groundwater quality is poor, having high concentrations of sodium, chloride, and iron. The site consists of 2 wells that can be used for either injection or production and 12 observation wells, which are used to monitor water levels and temperature profiles.

In the winter of 1978 to 1979, water was pumped from a shallow aquifer into a 5000 ft² (464.5 m²) cooling pond. When wet-bulb temperatures dropped below 50°F (10°C), water was pumped through a spray system and cooled to the air temperature. The chilled water was reinjected into the aquifer and stored until summer. Currently, cold water is being withdrawn and used in a heat-exchange process for air conditioning while warm waste water is being reinjected into the aquifer. Initial data are shown in Table 1.

Preliminary calculations indicate that the efficiency of heat recovery should improve with each injection-pumping cycle, up to three to five cycles. This could be verified by a long-term study over a period of more than 3 years. A long-term study would also allow for statistical variation in weather and would thus permit some evaluation of long-term efficiency.

Japan

In the temperate zone, Japan has a climate characterized by warm summers and cold winters and is well suited to the development of a total energy system. The average temperature in August at Yamagata, Japan is 24.5°C compared with an average temperature in January of -1.2°C. Average yearly precipitation is 1,200 mm, of which 300 mm is snow. In 1977, a field project was initiated to study seasonal storage of thermal energy: winter storage of cold water for summer use and summer storage of warm water for winter use (Yokoyama and others, 1978). Applications to air conditioning, fish breeding, and agriculture are being studied.

The test site, consisting of two dual-purpose wells and one observation well, is located in Yamagata Basin, which is underlain by alluvial deposits. Experiments are being conducted using a confined, sand-and-gravel aquifer, 19 m thick. During summer, cold water is withdrawn and used to air condition a commercial building while warm waste water is sprinkled on the 300-m² roof for heat collection. After passing through a filtration tower, the water is further heated by a heat exchanger and recharged through a second well. The process is reversed during winter when warm water is withdrawn and used to melt snow.

For the first experiment, warm water was injected between July 16 and September 18, 1977 (Table 1). Researchers were able to maintain a constant water level throughout the experiment, even with daily discharging. There was no evidence of clogging and permeability appeared to remain constant.

Between January and March 1978, some 9,430 m³ of water from melted snow with an average temperature of 5.3°C was injected into the aquifer. The water was withdrawn 4 months later at an average temperature of 14°C. Failure to get cooler water may be attributed to the small volume of injected water and the short distance between injection and production wells, which resulted in the mixing of warm and cold water.

At present, a second cold-water storage experiment is underway. Cold water stored during winter 1979 will be withdrawn during summer and used to cool a commercial building.

In addition to field experiments, numerical methods have been used to simulate aquifer storage. A three-dimensional model that takes thermal convection into account has been developed.

China

In China, the use of aquifers for thermal energy storage was developed from reinjection experiments designed to reduce subsidence and raise groundwater levels (City of Shanghai Hydrogeological Team, 1977). During the 1950s, in the city of Shanghai, widespread use of groundwater by a number of factories led to subsidence and a significant drop in the groundwater level. In an attempt to remedy these problems, several factories began experimenting with

reinjection of cold water from air conditioning systems. Experiments over the next few years were generally successful in restoring groundwater levels and increasing output from production wells. In addition, reinjection and well construction methods were continually improved through experiments with different techniques, volumes, and injection periods.

During the spring and summer of 1965, the Shanghai Cotton Mill Factory initiated a large-scale artificial recharge experiment using four water sources: deep well water, industrial waste water, filtered industrial waste water, and tap water. Researchers also experimented with continuous versus intermittent withdrawal and different reinjection/shut-in cycles. Temperature changes and water quality were monitored both before and after injection. Results indicated that there was little water flow in the aquifer and that there were only small changes in water temperature. These experiments became the basis for later projects, which used winter injection of cold water for summer use and summer injection of hot water for winter use.

During the same period, the Shanghai Water Company conducted extensive experiments using a variety of reinjection methods and three specially designed reinjection wells, 95 m deep, to study changes in groundwater level, water quality, and temperature. Their experiments yielded relatively complete quantitative records, which confirmed the effectiveness of using gravity recharge methods to raise groundwater levels.

Based on these large-scale experiments and their own studies, the City of Shanghai Hydrogeological Team concluded that by using reinjection, they could

effectively control subsidence and groundwater levels and that it was possible to store cold water in winter for summer use in air conditioning. These conclusions led to a city-wide reinjection program in which 70 factories used 134 deep wells for simultaneous recharge. As a result of the program, the groundwater level rose by more than 10 m.

Groundwater produced during summer had a very low temperature and thus became a new source of chilled water for industrial use. At the conclusion of summer pumping there was a net average increase in the land level of 6 cm—the first time in several decades of continuous subsidence that any surface uplift had been observed.

The program grew in subsequent years so that now there are several hundred wells in use. Production and injection methods have been greatly improved and the program has been expanded to include summer injection of hot water for use in winter. Because of the success at Shanghai, many industrial cities and large villages have adopted similar reinjection and thermal energy storage programs.

FEASIBILITY STUDIES

Current feasibility studies of energy storage in aquifers range from general economic and systems analyses to evaluation and design of pilot plants. The technical work being done entails field and laboratory investigations of the hydrogeological, chemical, and biological aspects of aquifer storage. Several programs call for regional geologic surveys to locate possible storage

sites and many studies are aimed at specific applications. Feasibility studies in progress are summarized in Table 5. The following are brief descriptions of several of these projects.

United States

Desert Reclamation Industries/Port Authority of New York

The objective of a study being conducted by the New York State Energy Research and Development Administration is to assess the feasibility of converting the air-conditioning system at the John F. Kennedy Airport in New York City from a conventional refrigeration machine to a system using cold water stored in an aquifer under the airport (Hibshman, 1978). The project would be equivalent in magnitude to providing central air conditioning to every home in a city of 25,000.

Water would either be drawn directly from near-freezing Jamaica Bay, or be chilled by winter air. Three ways of capturing cold from winter air have been considered: cooling towers, dry coolers, and cooling ponds. Use of cooling ponds has been rejected because of space limitations and the dangers of attracting birds and creating fog near the airport.

General Electric--Tempo

The GE Tempo Center for Advanced Studies is conducting a study to estimate the value of annual-cycle thermal energy storage for a proposed hot-water district heating system in the St. Paul/Minneapolis urban area of Minnesota (Meyer, 1980). The proposed system, based on cogeneration of power and heat by the Northern States Power Company, would use coal-fired cogeneration for

Table 5. SUMMARY OF CURRENT FEASIBILITY STUDIES IN AQUIFER THERMAL ENERGY STORAGE

Research institute	Program objectives	Scope of study
General Electric-TEMPO Center for Advanced Studies, Santa Barbara, California, United States (Meyer, 1980)	Assess the feasibility of installing a new district heating system in the Minneapolis/St. Paul metropolitan area based on cogeneration of power and heat and use of aquifers for storage	System design analysis; environmental analysis; economic analysis including estimates of a reasonable time scale, capital requirements, and fuel savings achievable
University of Texas, Austin, Texas, United States (Collins and others, 1978)	Assess the feasibility of deep aquifer storage of high-pressure hot water and deep cavern storage of hot oil	Mathematical modeling and computer simulation to study thermal losses, pumping requirements, solution and transport of minerals, and thermo-mechanical stresses
Tennessee Valley Authority (TVA), Jackson, Tennessee, United States (Eissenberg, 1979)	Survey the potential of thermal energy storage in aquifers in the TVA service area	Parametric modeling of aquifers and aquifer storage; development of criteria for determining the suitability of an aquifer for thermal energy storage
Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States (Eissenberg, 1979)	Perform an environmental impact analysis of aquifer thermal energy storage	Survey environmental and economic effects of aquifer storage; economic analysis of chilled water storage at JFK airport
New York State Energy Research and Development Administration, Desert Reclamation Industries, Plainfield, New Jersey, and the Port Authority of New York and New Jersey, United States (Hibshman, 1978)	Assess the feasibility of converting the air-conditioning system at the John F. Kennedy Airport in New York City from a conventional refrigeration machine system to a system using cold water stored in an aquifer under the airport	Economic and technical analyses; study of cooling towers, dry coolers, and cooling ponds as methods of capturing winter cold
Rocket Research Company, Redmond, Washington, United States (Eissenberg, 1979)	Assess the feasibility of using waste heat from an industrial plant in a planned district heating system in Bellingham, Washington	Market and technical analyses; review of alternative heat source options; provision of a conceptual design and cost estimate; large-scale demonstration project

Table 5. SUMMARY OF CURRENT FEASIBILITY STUDIES IN AQUIFER THERMAL ENERGY STORAGE (continued)

Research institute	Program objectives	Scope of study
Hooper and Angus Associates Ltd. and Hydrology Consultants Ltd., Toronto, Canada (1979)	Provide a preliminary assessment of using aquifers for chilled water storage or as a source of chilled water	Technical and economic analyses; analysis of using heat pumps in conjunction with aquifers for heating and cooling applications
Weizmann Institute of Science, Rehovot, Israel (Nir and Schwarz, 1978)	Study the concept of a total energy system that would utilize aquifer storage to provide cold water for cooling a power plant and warm water for agricultural uses	Environmental, economic, and technical analyses; review of possible pilot operations
Faculte Polytechnique de Mons, Belgium (Brych, 1979)	Evaluate the feasibility of several methods of underground thermal energy storage	Technical and economic evaluation; testing of promising methods; site selection and implementation of a full-scale storage system
RISØ National Laboratory, Roskilde, Technical University of Denmark, Lyngby, and the Danish Geological Survey, Denmark (Qvale, 1978)	Locate favorable sites for warm water storage and implement a test facility	Nationwide geological and hydrological survey to locate favorable sites; development of mathematical models; design, construction, and operation of a demonstration plant
Kernforschungsanlage Julich, Messerschmitt-Bolkow-Blohm, Munchen, Bundesanstalt fur Geowissenschaften und Rohstoffe, Berlin, Kraftanlagen, Heidelberg, and Univ. of Stuttgart (Jank, 1978)	Conduct a comprehensive review of existing information on energy storage systems and provide an advanced systems analysis of operating a storage system within a regional and national system of energy supply	Analysis of potential savings from incorporating thermal energy storage into district heating systems; analysis of using artificial lakes, aquifers, and aquifers filled with artificial bulk material for energy storage; experimental investigation of chemical transport, corrosion and biological processes in an aquifer; design and construction of a small-scale pilot system

Table 5. SUMMARY OF CURRENT FEASIBILITY STUDIES IN AQUIFER THERMAL ENERGY STORAGE (continued)

Research institute	Program objectives	Scope of study
Swedish Board for Energy Source Development, Stockholm, Sweden (Mathey, personal commun.)	Determine necessary technical, economic, environmental, and institutional conditions for storage of heat from various sources	Investigation of several types of accumulators including oil tanks and ground water basins
University of Neuchatel and the Institute de Production d'Energie de l'Ecole Polytechnique Federale, Lausanne, Switzerland (Mathey, personal commun.)	Study various aspects of aquifer storage of hot water with temperatures as near as possible to 100°C.	Research of biochemical, thermal, and hydraulic aspects of hot water storage including field and lab tests and numerical modeling; determination of optimal sites and management schemes
Ecole des Mines de Paris, Fontainebleau, France (Iris and de Marsily, 1979)	Study the technical and economic feasibility of a space heating system for the Paris area using aquifers for heat storage, solar captors for heat production, and heat pumps for energy transformation	Determination of in situ parameters necessary to predict the efficiency of a storage system; definition of optimal conditions for a storage site; optimization of a global system; environmental analysis including a study of bacteriological pollution

baseload power and oil-fired boilers for peak and standby needs. Unlike most large district-heating systems in the United States, which produce steam, this system would send out hot water, which is the common practice in Europe.

Economic and environmental benefits of a system incorporating thermal energy storage have been assessed and compared with a cogeneration system that does not use energy storage. The study shows that the oil-fired boilers used in the conventional system as a backup, and to meet peak loads, can be replaced by heat storage wells. Even though some of the heat is lost during storage, use of heat storage wells yields a net energy savings of 2 to 22% by making it possible to operate the cogeneration equipment at greater capacity. It is estimated that energy storage would reduce capital cost requirements for boilers, cogeneration equipment, and pipelines by \$66 to \$258 million. The breakeven capital cost of thermal energy storage is estimated to range from \$43 to \$76 per kilowatt. An important factor in evaluating the breakeven operating cost is the yearly savings in expenditures for fuel estimated at \$14 to \$31 million. Reduction of air and thermal pollution are additional benefits of using heat storage wells.

University of Texas

The University of Texas, with Subsurface Disposal Corporation and Bovay Engineers, Inc., is in the second year of a study assessing the feasibility of deep aquifer storage of high-pressure hot water, 343°C, 18.6 MPa (2,700 psi) and deep cavern storage of hot oil (Collins and others, 1978; Collins, 1979). A study already completed has indicated that underground storage of high-

temperature, high-pressure fluid is geologically feasible in approximately 80% of the continental United States.

To study aquifer storage, mathematical modeling and computer simulation are being used to evaluate thermal losses, pumping requirements, and solution transport of minerals. Additional studies of drilling procedures, well design, and cavern leaching have been performed and will be used to make cost estimates. On the basis of preliminary results, it appears that aquifer storage of hot water at temperatures above 149°C may not be feasible because of down-hole pumping requirements and problems associated with silica dissolution and reprecipitation.

A mathematical model has also been developed to study heat storage in solution caverns in massive salt deposits. Salt formations are promising storage sites because of their low porosity and permeability and their semi-plastic properties, which allow small fractures and openings to close. At present, the most serious problem facing salt-cavern storage appears to be possible deformation of the cavern due to creep or plastic flow. A possible solution is to fill the cavern with gravel or coarse sand.

Results just completed for a 10-MWe power plant indicate that a hot-oil, gravel-filled, two-well thermocline system, providing 80 MWe of storage capacity, could be built for about \$3.4 million. Operating costs would amount to about 10% of the energy transferred (during pumping), with thermal losses of less than 1% when the system is operated on a 24-hour storage-recovery cycle

at a temperature of 343°C. These figures indicate that such storage systems would be very cost effective for power generating systems.

Bellingham, Washington

Rocket Research Company directed a study of the feasibility of using industrial waste heat in a planned district heating system in Bellingham, Washington. The source of energy is the Intalco Aluminum Company, which generates 93.3°C waste heat at a rate of 4.85×10^8 KJ/h (4.6×10^8 Btu/h). An initial study has demonstrated the feasibility of using this waste heat for space heating in 12,000 homes in Bellingham. The average return of investment is estimated at 63%.

Research plans call for market and technical analysis, a review of alternative heat-source options, and provision of a conceptual design and cost estimate. A large-scale demonstration project is also planned.

Canada

At present, approximately 3% of Canada's annual energy expenditure is for mechanical refrigeration for air conditioning. It is believed that an annual storage cycle of chilled water in aquifers can reduce this expenditure. Hooper and Angus Associates Ltd., in association with Hydrology Consultants Ltd. (1979) is working under a contract with the Ministry of Energy, Mines and Resources, Canada, to provide a preliminary technical and economic assessment of using aquifers for chilled-water storage or as a source of chilled water. Specific objectives of the study are to identify the most promising applications and systems and to determine areas for further research and development.

In addition to studies of chilled-water extraction and storage, the study will include an examination of using heat pumps in conjunction with aquifer storage for heating and cooling applications.

Israel

In Israel, aquifer storage is being studied as part of a total energy system that would provide water for both heating and cooling purposes (Nir and Schwarz, 1978). In semi-arid zones, inland location of power plants is difficult because of limited water resources for direct or wet tower cooling. Finding year-round users of waste heat is also a problem in this region. The only potential use identified thus far is for winter agriculture where heat would be used in greenhouses and soil heating. A total energy system using aquifers for storage offers a possible solution to the problems associated with seasonal demand for heat and the large amounts of cooling water required by power plants.

A preliminary study of using aquifer storage in conjunction with power production has been undertaken in southern Israel. The project under study calls for the power plant to withdraw cold water from the aquifer and return warm water, in a closed cycle, to a warm region of the aquifer. During the cold season there would be an additional cycle in which warm water would be withdrawn and delivered to users.

The following topics have been identified for further study: crop selection to make maximum use of the available heat; heat dissipation in excess of agricultural demand; plant response to heat input in surrounding soil, water,

and air; heat dissipation from soils; and materials and configurations for efficient heat transfer from water to soil. Pilot operations under consideration include: recharge into specified geological formations; aquifer operation with controlled storage and recovery; control of greenhouse and uncovered soil temperatures using warm water and heat sources; and a power plant condenser operation with high temperatures and variable water quality.

Switzerland

In Switzerland, a feasibility study of a demonstration project using aquifer heat storage has been initiated (Mathey, personal communication). One of the basic problems is the selection of a suitable site, which requires the presence of a producer and consumer of heat and an aquifer. The most promising site emerging from preliminary investigations is a new building at the Polytechnical School at Lausanne. Waste heat from the computer building and solar energy could be used as sources of heat for the low-temperature (25 to 40°C) space heating system. A well-studied phreatic aquifer is located near the school. Another interesting site is the Geneva airport where waste heat from the accelerator at CERN could be stored in a 20 m thick aquifer under the runway and used to melt snow on the runway.

THEORETICAL AND MODELING STUDIES

Table 6 summarizes current theoretical and modeling studies of energy storage in aquifers. As the table shows, a number of numerical models are under development although their details are yet to be reported. We shall comment on only four of these projects, conducted by Lund University, Sweden,

Table 6. Theoretical and modeling studies in aquifer thermal energy storage

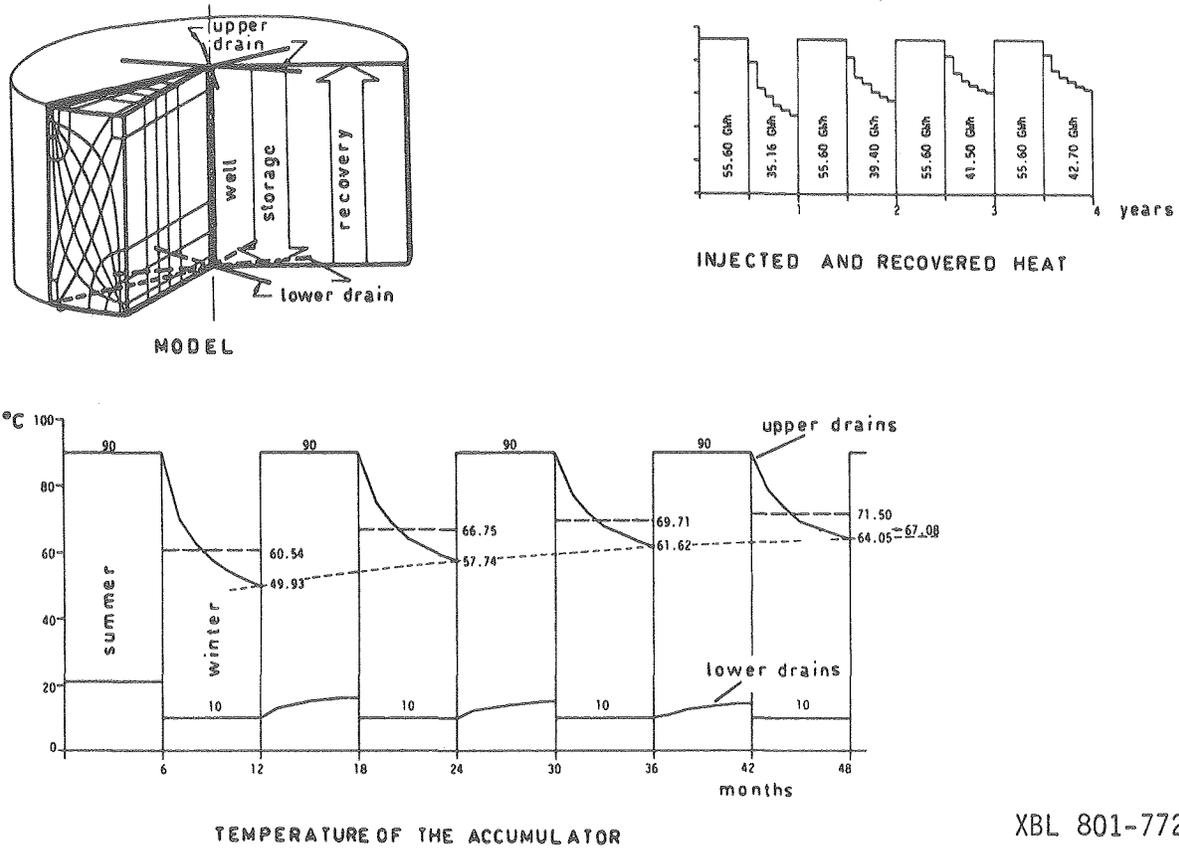
Research Institute (reference)	Project
Technical University of Denmark, Denmark (Qvale, 1978)	One- and two-dimensional finite element models Study of using compensation wells for countering regional flow
Lund University, Sweden (Hellstrom, 1978; Claesson and others, 1978)	Two-dimensional, doublet, semianalytic model Two-dimensional finite difference program developed to study storage in eskers
Ecole Polytechnique Fédérale, Lausanne, and University of Neuchâtel, Switzerland (Mathey, 1977; Mathey and Menjós, 1978)	Two- and three-dimensional finite element models
Institut de Production d'Energie de l'Ecole Polytechnique Fédérale de Lausanne, Switzerland (Joos, 1978)	Three-dimensional finite element model. Laboratory experiments on free convection in porous media.
Ecole des Mines de Paris, France (de Marsily, 1978)	Two-dimensional, radial, finite difference model Two- and three-dimensional finite element models
Bureau des Recherches Géologiques et Minières (BRGM), France (Gringarten et al., 1977; Sauty, Gringarten and Landel, 1978)	Layered two-dimensional finite difference model Modeling of the Bonnaud experiment Dispersion modeling studies
University of Yamagata, Japan (Yokoyama et al., 1978)	Finite difference method using a complex potential function
United States Geological Survey, United States of America (Papadopoulos and Larson, 1978)	Intercomp model (finite difference scheme) used to model the Auburn (1976) experiment
Lawrence Berkeley Laboratory, United States of America (Tsang et al., 1978b)	Three-dimensional integrated finite difference model for conduction, convection, and consolidation Extensive generic studies Modeling of the Auburn (1978) experiment
University of Houston, United States of America (Collins et al., 1978)	Model to study steam injection into permeable earth strata (two-phase program)

Institut de Production d'Energie de l'Ecole Polytechnique Fédérale de Lausanne, Switzerland, Bureau de Recherches Géologiques et Minières (BRGM), France, and Lawrence Berkeley Laboratory, U.S.A.

At Lund, a two-dimensional finite-difference model was specifically developed to study the storage of hot water in eskers (long and narrow glacial deposits of high permeability). In addition to the esker project, a number of theoretical studies were made using semi-analytic methods to examine several related topics in thermal storage including buoyancy tilting of a vertical thermal front, entropy analysis of numerical dispersion, and effects of temperature-dependent viscosity in a two-well extraction-injection system (Hellstrom, 1978; Claesson and others, 1978; Hellstrom and others, 1980).

A three-dimensional finite element model for diffusion and convection has been developed at the Institut de Production d'Energie de l'Ecole Polytechnique Fédérale de Lausanne, Switzerland (Joos, 1978). This model has been used to simulate an aquifer heat storage system where the flow is vertical between two horizontal networks of drain pipes (Pacot, 1978). The storage volume has the shape of a standing cylinder (see Fig. 8). Bench-scale experiments and mathematical modeling of free convection in porous media have been performed (Joos, 1978).

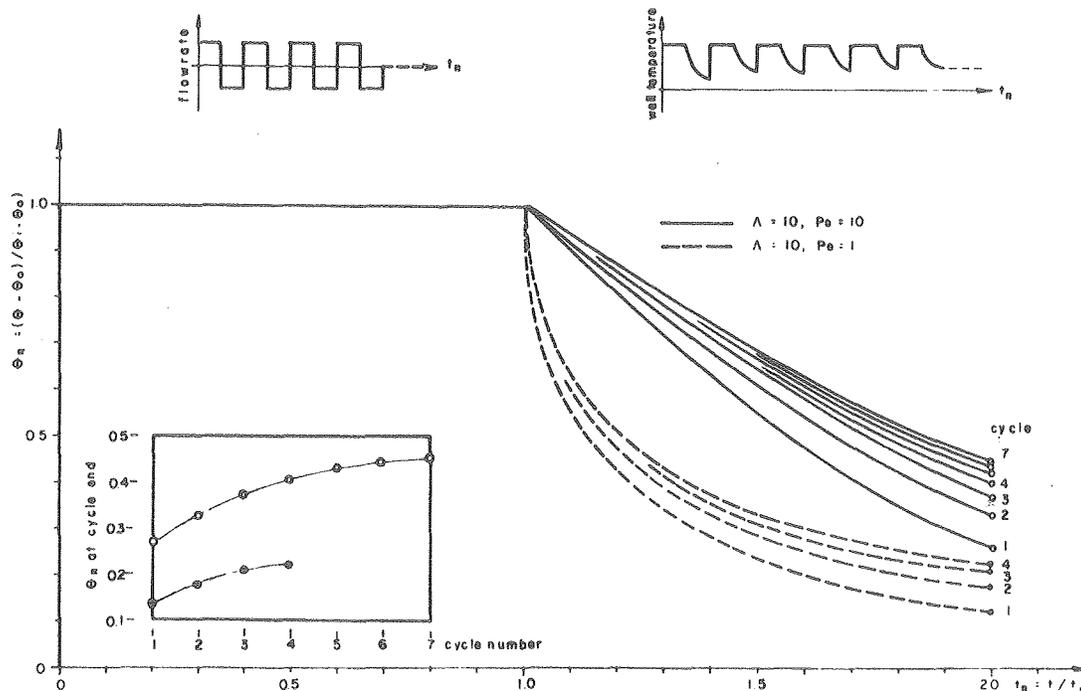
A number of numerical models were developed at BRGM, France, for the study of fluid and heat flow, including a two-dimensional, steady-flow semi-analytical model; a layered, two-dimensional, finite-difference model; and a program to calculate dispersion effects (Gringarten and others, 1977). Some



XBL 801-7724

Figure 8. Aquifer heat storage system showing vertical flow between two horizontal networks of drain pipes. (Mathey, 1978)

of these techniques were used to model the Bonnaud experiment, which was described in the first section. For a single-well system, the effects of various physical parameters and operating conditions on the temperature of the produced water have been studied (Fabris and others, 1977). The behavior of the system is described by dimensionless parameters. Type curves have been drawn and recovery factors evaluated for various combinations of these parameters (see Fig. 9).



Temperatures evolution at central well during successive cycles of hot water injection and production. Consequences of $\tilde{\lambda} = 10 \cdot \lambda$ ($Pe = 1$ instead of 10).

XBL 801-7725

Figure 9. The effects of various physical parameters and operating conditions on the temperature of the produced water after a storage period in a single-well system. (Fabris and others, 1977)

A number of numerical models have been developed over the last 6 years at Lawrence Berkeley Laboratory to study single- and two-phase fluid and heat flow in porous media (Tsang and others, 1979). Among these models is the program CCC (conduction, convection and compaction), which was chosen for the aquifer thermal energy storage (ATES) studies. CCC employs the integrated finite-difference method and is a fully three-dimensional model incorporating the effects of complex geometry, temperature-dependent fluid properties, gravity, and land subsidence or uplift. This code has been validated against a number of semi-analytic solutions and is currently used to model the Auburn

field data (Molz and others, 1978). Extensive generic studies of the ATEs concept have been made using CCC. Some of the results are illustrated in Figures 10, 11, and 12 which show the thermal front diffusion during hot-water storage for an inhomogeneous aquifer (Fig. 10), for a well partially penetrating the aquifer (Fig. 11), and for a two-well extraction-and-injection system (Fig. 12). For the particular case of a low-permeability aquifer with a 10^6 kg/d flow rate, calculated energy balances for successive production-storage cycles are listed in Table 7.

Table 7. COMPUTED ENERGY BALANCE FOR A LOW-PERMEABILITY AQUIFER *

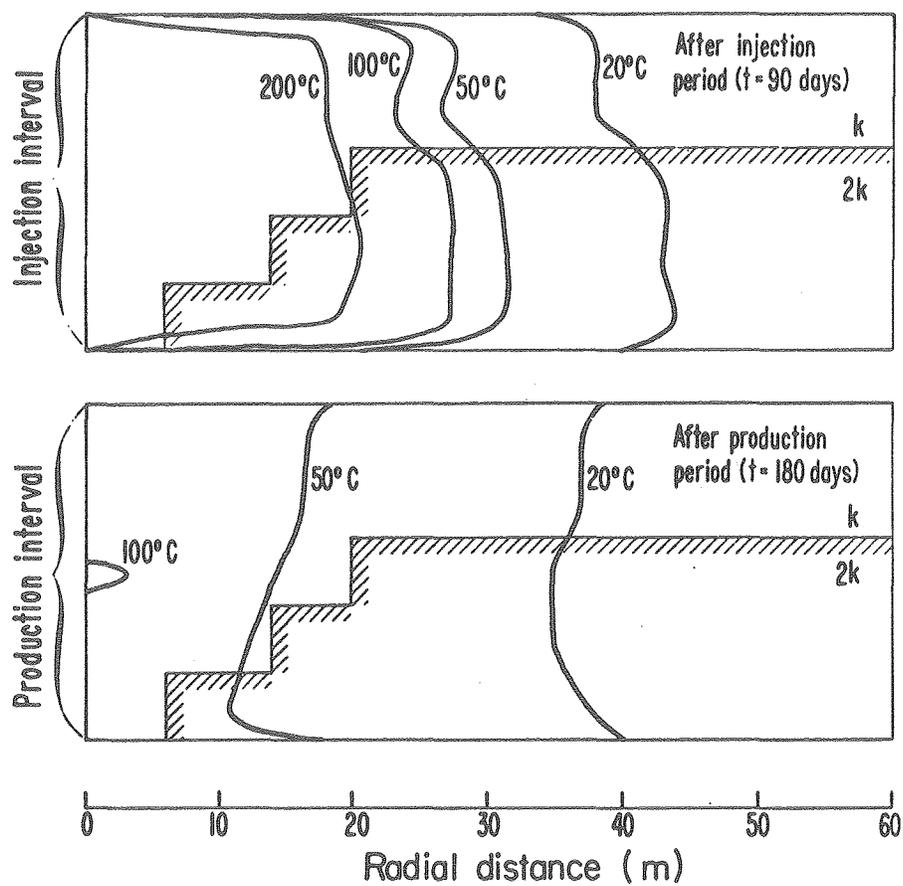
Cycle	Energy injected ($J \times 10^{13}$)	Energy recovered ($J \times 10^{13}$)	Energy loss from aquifer ($J \times 10^{13}$)	Energy diffused to heat aquifer ($J \times 10^{13}$)	Energy recovered (%)	Prod. temp. at end of cycle (°C)
1	5.71	4.96	0.053	0.71	86.8	124
2	5.71	5.09	0.068	0.55	89.2	139
3	5.71	5.14	0.077	0.49	90.0	147
4	5.71	5.18	0.084	0.45	90.7	151
5	5.71	5.20	0.091	0.42	91.1	155

* Calculations are for the first five cycles for the case of 90-d injection (flow rate of 10^6 kg/d) and 90-d production periods. Injection and ambient temperatures are 220 and 20°C, respectively; the aquifer is 100 m thick.

Source: Tsang and others, 1978, Table 2

On the whole, a substantial amount of modeling work is being done. However, there is a great need to have these models properly validated and then carefully applied to help us understand the processes underlying the ATEs concept.

Effect of reservoir inhomogeneity - cycle 1

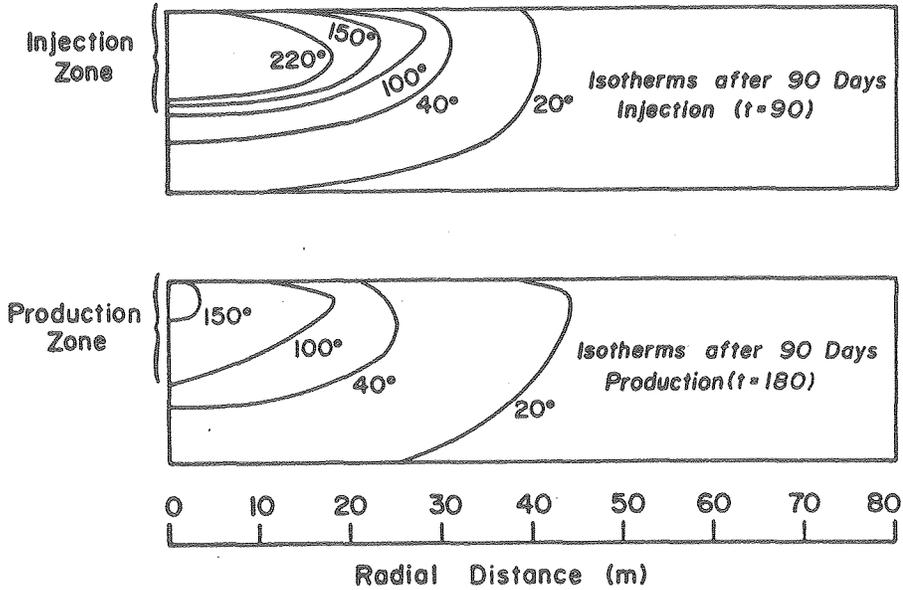
 $T_{inj} = 220^{\circ}\text{C}$ $H = 50\text{m (5 layers)}$ $\Delta r = 2\text{m}$


XBL 785-2517

Figure 10. Effects of reservoir inhomogeneity after 90-day injection and production periods (Tsang et al., 1978).

CYCLE 1: Partial Penetration

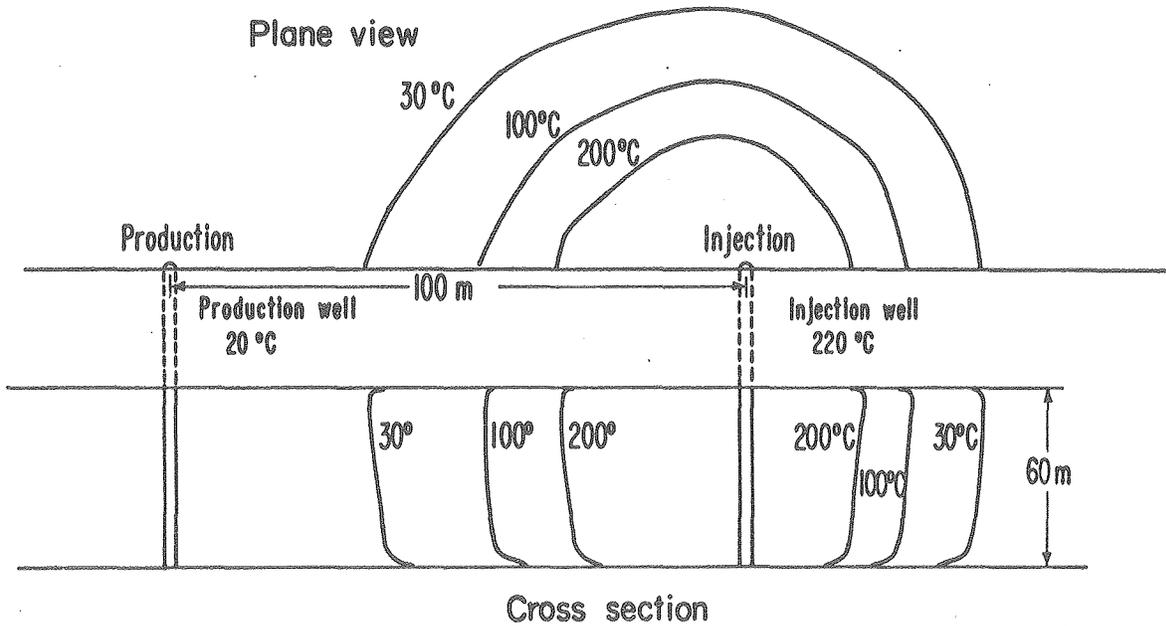
$T_{inj} = 220^{\circ}\text{C}$; $\Delta R = 2\text{ m}$; $H = 100\text{ m}$



XBL 7712-11224

Figure 11. Calculated isotherms for partial penetration after 90-day injection and production periods in the first cycle. (Tsang et al., 1978)

Cycle 1 (after 90 days' injection)



XBL 785-2508

Figure 12. Calculated isotherms for a two-well system after 90 days of injection; plane and cross section views. (Tsang et al., 1978)

FUTURE RESEARCH

In this section we put forth what we consider to be the key technical problems that need to be addressed in current or future ATES projects. On the one hand, based on experiences in petroleum engineering, hydrology, and geothermal energy development, the ATES concept is expected to be technically feasible. On the other hand, significant research and development are needed to ensure successful implementation of the ATES system. These areas of needed research include the following.

Shape and Location of the Hydrodynamic and Thermal Fronts.

The hydrodynamic front may be tracked by chemical tracers. It is expected to arrive at any observation point before the thermal front. Thus, proper monitoring may yield information about the stored thermal bubble before its arrival at any observation well. The thermal front may be tracked by temperature measurements made in observation wells or by surface geophysics. The latter is a new method proposed by LBL, which may provide an economical way to monitor the hot-water bubble during injection, storage, and production stages. Because most of the heat loss is through the hot-cold water interface, a knowledge of the shape and location of the thermal front is quite important for implementation of the ATES concept.

Buoyancy Flow and Formation Permeability.

The Neuchâtel and Campuget experiments indicated that if the vertical formation permeability is high, buoyancy convection of the lighter hot water will be significant, leading to high heat losses and low energy recovery.

The effects of the buoyancy flow are enhanced by the forced convection during the injection period. Studies are needed to set design guidelines concerning the choice of aquifers with optimal permeability values for a given storage rate. Such guidelines may help to increase energy recovery and make a given ATES system economically feasible.

Thermal Dispersion

Due to the nonhomogeneity of the aquifer porous media, fingering or extra dispersion will occur at the thermal front. This was observed in the Bonnaud experiment and it tends to significantly decrease the energy recovery. Hence, theoretical and experimental studies are required to estimate its effects and, if possible, to design a way to minimize them.

Natural Regional Flow

A substantial regional flow will move the hot water bubble away from the storage site. Studies on countering such flow by means of compensation wells were done in Denmark and in the United States at Louisiana State University. Further work is needed in this area.

Land Subsidence or Uplift

Highly accurate land-level surveys should be made on the surface, and vertically within wells, in order to detect land movements during an ATES operation and to evaluate the accuracy of subsidence models. These surveys will yield information necessary for environmental impact statements and developing guidelines for injection and production operations.

Thermal Pollution

Proper accounting of the heat left in the aquifer at each storage-recovery cycle should be made. The rate of dissipation of the heat into the surroundings has to be investigated to ensure minimal effects on the environment.

Water Chemistry

Experience should be gained in the careful analysis of the compatibility of the aquifer water and the hot/cold storage water. The interaction between the injected water and the porous rock medium should also be investigated. Both laboratory experiments and in-situ studies are much needed to evaluate any adverse effects.

Wellbore Plugging and Heat Exchange Efficiency

Scaling and biological growth result in reduced efficiency in the heat exchangers above ground and in well plugging below ground. Specific studies should be made to determine general factors responsible for these adverse effects.

Corrosion

An area of general concern is corrosion. Advanced techniques should be used to measure corrosion rates throughout the system. Corrosion control techniques need to be developed for general application over a wide range of conditions.

In any pilot or demonstration project, it is crucial to both adequately address the key problems listed above and demonstrate the economic feasibility of the ATEs concept. In this way we will obtain a proper understanding, a

data base, and the necessary working experience that will allow the general commercial implementation of aquifer thermal energy storage systems.

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REFERENCES CITED

- ATES Newsletter: Berkeley, Earth Sciences Division, Lawrence Berkeley Laboratory, PUB-294.
- Brych, J., 1979, Aquifer storage efforts in Belgium, in ATES newsletter: Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 2.
- Bureau de Recherches Geologiques et Minières and others, 1976, Etude experimentale d'un doublet hydrothermique, in Rapport scientifique annual: Orleans, France, Service, Geologique National, 9 p.
- City of Shanghai Hydrogeological Team, 1977, Artificial recharge into groundwater systems (in Chinese, Summary translated by C. F. Tsang), in ATES newsletter; Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 3.
- Claesson, J., Efring, B., Hellstrom, G., and Olanders, P., 1978, Theoretical analysis and computer simulation of solid-fluid heat storage systems in the ground; extractions of earth heat, in Interim report, part I and II: Lund, Sweden, Lund Institute of Technology, Departments of Mathematical Physics and Building Science, 190 p.
- Collins, R. E., Fanchi, J. R., Morrell, G. O., Davis, K. E., Huha, J. K., and Henderson, R. L., 1978, High temperature underground thermal energy storage, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 62-66.

- Collins, R. E., 1979, High temperature underground thermal energy storage, in ATES newsletter: Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 2.
- Cormary, Y., Iris, P., Marie, J. P., de Marsily, G., Michel, H., and Zaguine, M. F., 1978, Heat storage in a phreatic aquifer, Campuget experiment (Gard, France), in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 88-93.
- de Marsily, G., 1978, Peut-on stocker de l'énergie dans le sol? Annales des Mines, v. 1978, no. 4, p. 11-24.
- Eissenberg, D. M., 1979, A summary, in ATES newsletter: Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 2.
- Fabris, H., Gringarten, A. C., Landel, P. A., Noyer, M. L., and Sauty, J. P., 1977, Etude des possibilités du stockage d'eau chaude en aquifère profond, ler rapport d'avancement: Orléans, France Bureau de Recherches Géologiques et Minières, Rapport 77 SGN 658 HVD.
- Fabris, H., and Gringarten, A. C., 1977, Etude experimental de stockage et de transfert de chaleur en aquifère, paper RS 598 in Résumé des principaux resultats scientifiques et techniques du Service Géologique National pour 1977: Orléans, France, Service Géologique National, Supplement to the Bulletin of the Bureau du Recherches Géologiques et Minières.
- Gringarten, A. C., Landreau, A., Lienhardt, M. J., and Peaudecerf, P., 1976, Etude des possibilités de stockage d'eau chaude en provenance de centrales thermiques: Rapport 76, Societé Géologique National 389, AME-BRGM.
- Gringarten, A. C., Landel, P. A., Noyer, M. L., and Sauty, J. P., 1977, Etude théorique du stockage d'eau chaude par puits unique aquifère en l'absence d'écoulement regional (programme Esther), paper RS-576, in Résumé des principaux resultats scientifiques et techniques du Service géologique national pour 1977: Orléans, France, Service Géologique National, Supplement to the Bulletin of the Bureau de Recherches Géologiques et Minières.
- Hausz, W., 1974, Heat storage wells, Presented at Symposium on efficient use of fuels in process and manufacturing industries: Santa Barbara, Institute of Gas Technology (GE Tempo paper P-655).
- Hellstrom, G., 1978, Aquifer storage projects in Sweden, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 67-70.

- Hellstrom, G., Tsang, C. F., and Claesson, J., 1979, Heat storage in aquifers; buoyancy flow and thermal stratification problems: Lund Institute of Technology, Lund, Sweden, 70 p.
- Hibshman, H. J., 1978, Air conditioning Kennedy Airport with winter cold, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 56-61.
- Hooper and Angus Assoc. Ltd. and Hydrology Consultants Ltd., 1979, Study to examine the technical and economic feasibility of using aquifers as a chilled water source or storage medium for building air conditioning systems: Toronto, Energy Mines and Resources Canada, 2 vols.
- Iris, P., and de Marsily, G., 1979, Campuget experiment, interpretation by models--development of the research, in ATEs newsletter: Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 3.
- Jank, R., 1978, Aquifer storage efforts in Germany, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 71-74.
- Joos, B., 1978, Tests de sensibilité du programme diffusion-transport, in Rapports Scientifiques et Techniques sur le Comportement des Nappes Souterraines, V. 6: Lausanne Switzerland Institute de Production d'Energie, Centre d'Hydrogéologie de l'Université de Neuchâtel.
- _____, 1978, Convection naturelle dans les aquifères; simulation du comportement du milieu par modèles numériques in Rapport scientifiques et techniques sur le comportement des nappes souterraines, V. 6: Lausanne, Switzerland, Institut de Production d'Energie, Centre d'Hydrogéologie de l'Université de Neuchâtel.
- Katter, L. B., and Hoskins, R. L., 1979, Applications of thermal energy storage to process heat and waste heat recovery in the primary aluminum industry: Redmond, Washington, Rocket Research Company, CONS-5080-1, 114p.
- Kazmann, R. G., 1971, Exotic uses of aquifers: Journal of Irrigation Drainage Division, American Society Civil Engineers, v. 97, IR3, p. 515-522.
- Kley, W., and Nieskens, H. G., 1975, Möglichkeiten der warmespeicherung in einem Porengrundwasserleiter und technische probleme bei einer Ruckgewinnung der Energie (Practical ways of heat storage in a porous aquifer and technical problems of energy recovery): Zeitschrift der Deutschen Geologischen Gesellschaft, v. 126, no. 2, p. 397-409.

- Larson, S. P., Papadopoulos, S. S., and Mercer, J. W., 1976, Transport of water and heat in an aquifer used for hot water storage; digital simulation of field results, (abstract), in Program, Symposium on Uses of Aquifer Systems for Cyclic Storage of Water, Fall Annual Meeting of the American Geophysical Union, San Francisco: Tulsa, American Geophysical Union.
- Mathey, B., 1975, Le stockage de chaleur dans les nappes souterraines (application a l'énergie solaire): 2me Symposium de la Societé Suisse, Lausanne EPFL.
- Mathey, B., 1977, Development and resorption of a thermal disturbance in a phreatic aquifer with natural convection: Journal of Hydrology, v. 34, p. 315-333.
- Mathey, B., and Menjos, A., 1978, Underground heat storage: choice of a geometry and efficiency, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 80-87.
- Meyer, C. F., 1978, Large-scale thermal energy storage for cogeneration and solar systems, in Proceedings, 5th Energy Technology Conference and Exposition, Washington, D.C.: Government Institute, Inc.
- Meyer, C. F., 1980, Potential benefits of thermal energy storage in the proposed Twin City district heating cogeneration system, in Proceedings, International Assembly on Energy Storage, Dubrovnik, Yugoslavia: National Academy of Science (USA) and Council of Academies (Yugoslavia).
- Meyer, C. F., and Hausz, W., 1978, Energy management objectives and economics of heat storage wells, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 17-28.
- Meyer, C. F., Todd, D. K., and Hare, R. C., 1972, Thermal storage for eco-energy utilities: GE-Tempo Report GE72TMP-56.
- Meyer, C. F., and Todd, D. K., 1973, Heat storage wells: Water Well Journal, v. 27, no. 10, p. 35-41.
- Molz, F. J., and Parr, A. D., 1979, Confined aquifer experiment--heat storage, in ATEs newsletter: Berkeley, Lawrence Berkeley Laboratory, PUB-294, v. 1, no. 3.
- Molz, F. J., Parr, A. D., Andersen, P. F., Lucido, V. D., and Warman, J. C., 1979, Thermal energy storage in confined aquifers: Auburn, Alabama, Auburn University, Water Resources Research Institute, (preprint), 29 p.

- Molz, F. J., and Warman, J. C., 1978, Confined aquifer experiment--heat storage, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 46-50.
- Molz, F. J., Warman, J. C., and Jones, T. E., 1978, Aquifer storage of heated water, part I, a field experiment: Ground Water, v. 16, no. 4, p. 234-241.
- Nir, A., and Schwarz, J., 1978, Survey of thermal energy storage in aquifers coupled with agricultural use of heat under semi-arid conditions, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 77-79.
- Noyer, M. L., 1977, Simulation des transferts thermique dans les aquifères; conditions de validité des solution analytiques: Orléans, France, Department Géothermie, Bureau de Recherches Géologiques et Minières.
- Pacot, P., 1978, Simulation des transferts de chaleur en aquifère, pour le developpement des stockage souterrains en énergie, in Rapports scientifiques et techniques sur le compartement des nappes souterraines, v. 6: Lausanne, Switzerland, Institut de Production d'Energie, Centre d'Hydrogéologie de l'Université de Neuchâtel.
- Papadopoulos, S. S., and Larson, S. P., 1978, Aquifer storage of heated water, part II, Numerical simulation of field results: Ground Water, v. 16, no. 4, p. 242-248.
- Proceedings, 1978, Thermal Energy Storage in Aquifers Workshop: 1978, Berkeley, Lawrence Berkeley Laboratory, LBL-8431.
- Qvale, E. B., 1978, The Danish seasonal aquifer warm-water storage program, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 75-76.
- Rabbimov, R. T., Umarov, G. Y., and Zakhidov, R. A., 1971, Storage of solar energy in a sandy-gravel ground: Geliotekhnika, v. 7, no. 5, p. 57-64.
- Reddell, D. L., Davison, R. R., and Harris, W. B., 1978, Thermal storage of cold water in ground water aquifers for cooling purposes, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 51-55.
- Sauty, J. P., Gringarten, A. C., and Landel, P. A., 1979, The effect of thermal dispersion on injection of hot water in aquifers, in Proceedings, Second Invitational Well Test Symposium: Berkeley, Lawrence Berkeley Laboratory, LBL-8883, p. 122-131.

- Tsang, C. F., Lippmann, M. J., Goranson, C. B., and Witherspoon, P. A., 1977, Numerical modeling of cyclic storage of hot water in aquifers; EOS, Transaction of the American Geophysical Union, v. 57, no. 12, p. 918.
- Tsang, C. F., Buscheck, T., Mangold, D., and Lippmann, M., 1978, Mathematical modeling of thermal energy storage in aquifers, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 37-45.
- Tsang, C. F., Lippmann, M. J., and Witherspoon, P. A., 1979, Underground aquifer storage of hot water from solar energy collectors, in de Winter, F., and Cox, M., eds., Sun, mankind's future source of energy, proceedings, International Solar Energy Society Congress, New Delhi, India: New York, Pergamon Press, v. 1, p. 490-493.
- Tsang, C. F., Buscheck, T., and Doughty, C., 1980, Aquifer Thermal Energy Storage, a Numerical Simulation of Auburn University Field Experiments, submitted to Water Resources Research.
- Warman, J. C., Molz, F. J., and Jones, T. E., 1977, Subsurface waste heat storage; experimental study: Auburn, Alabama, Auburn University, Water Resources Research Institute (preprint).
- Werner, D., and Kley, W., 1977, Problems of heat storage in aquifers: Journal of Hydrology, v. 34, p. 35-43.
- Yokoyama, T., Umemiya, H., Teraoka, T., Watanabe, H., Katsuragi, K., and Kasamaru, K., 1978, Seasonal regeneration through underground strata, in Proceedings, Thermal Energy Storage in Aquifers Workshop: Berkeley, Lawrence Berkeley Laboratory, LBL-8431, p. 94-106.

