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Author

Tsang, C.F.

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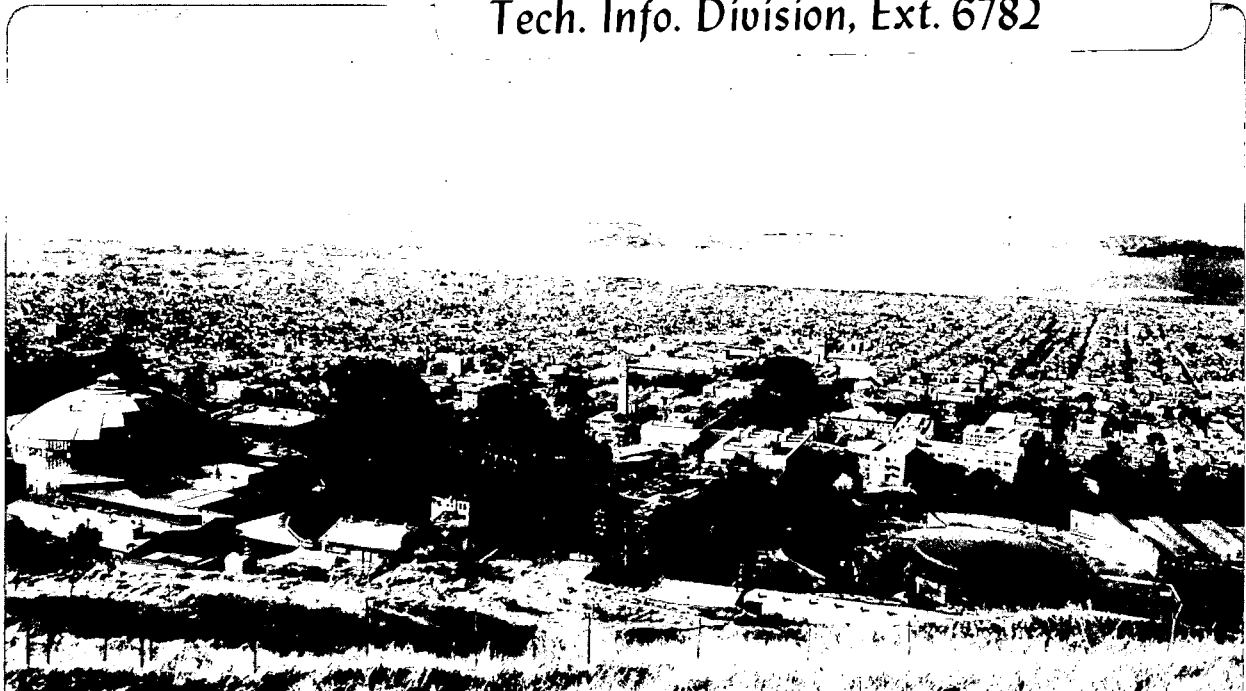
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July 1981

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A SURVEY OF RECENT INTERNATIONAL ACTIVITIES
IN AQUIFER THERMAL ENERGY STORAGE

C. F. Tsang
Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1981

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A SURVEY OF RECENT INTERNATIONAL ACTIVITIES
IN AQUIFER THERMAL ENERGY STORAGE

Chin Fu Tsang

1. INTRODUCTION

Many new projects have been initiated in the field of aquifer thermal energy storage (ATES) since the last Lawrence Berkeley Laboratory survey (1) in 1979. Some of the resulting advances are reported in the quarterly ATES Newsletter, later renamed STES (Seasonal Thermal Energy Storage) Newsletter (2). The present paper attempts to summarize these recent activities and may be considered an update of the previous survey paper (1).

This paper will begin by giving the general background for ATES with a brief discussion of its technical and economic feasibility. This will be followed by a review of recent project advances in various countries. Finally, a discussion of research needs and key problems related to ATES implementation will conclude the paper.

2. BACKGROUND

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 (usually 10^5 m^3 or more) and ability to contain water under high pressures. Aquifers are also attractive storage sites because of their widespread availability.

3. TECHNICAL AND ECONOMIC FEASIBILITY

A large number of feasibility studies for ATEs systems have been made, many of which are described and cited in Reference 1. More recent studies are also described in the proceedings of the recent International Energy Agency Conference in Berlin (3), as well as the STES Quarterly Newsletter (2). In general, the results of these generic studies have been favorable. Of particular note among the many recent papers are the results of hydrothermal studies at the Lawrence Berkeley Laboratory and the economic feasibility studies by General Electric TEMPO.

The Berkeley studies (4,5,6) employ semi-analytic and detailed numerical modeling techniques to study the energy recovery factors over a large range of

parameter values for different storage temperatures and periods, aquifer properties, and boundary conditions. Dimensionless parameter groups were developed and "type" graphs were produced. The results have been verified to some extent by field experiments. These studies indicate that for a wide range of reasonable parameter values, the energy recovery factor (defined as energy recovered divided by energy injected for storage) ranges from 50% to 80% or more. Here energy is evaluated with reference to energy at room temperature.

Earlier economic studies (7) showed aquifer storage to be the least expensive long-term, large-volume sensible heat storage method. However, specific estimates are very site- and scenario-dependent. Meyer (8) of General Electric TEMPO carried out a detailed evaluation of ATES for a cogeneration-district heating system for the Minneapolis-St. Paul Twin-City area in Minnesota, U.S.A. His conclusion was that potential benefits of incorporating ATES were substantial. Among several possible scenarios evaluated, the best case resulted in a net annual energy savings of 36.9×10^{12} Btu, which is about 32% of the total energy required without ATES. This translates into an annual fuel cost savings of \$31 million. Numerous other benefits were quoted, including reduction of the amount of cogeneration capacity required, reduction of the size and cost of transmission pipelines, and avoidance of air-pollution problems of dispersed boilers.

4. REVIEW OF CURRENT PROJECTS

Current international projects are summarized below. Some of the details may be found in various issues of the STES Newsletter (2) and a number of recent conference proceedings (3, 9, 10).

4.1 Switzerland

Efforts in Switzerland have been continued consistently since the early hot water injection experiments in 1974. Recent work involves a major project

named SPEOS, with participation from the Centre of Hydrogeology of the University of Neuchatel, Laboratory of Geology and Institute of Economics and Energy Management of the Swiss Federal Institute of Technology, and Dr. Bernard Mathey.

The general concept is to store hot water (70-80°C) from solar collectors or waste heat producers in an aquifer, and to withdraw the warm water for space heating. In this way the use of heat pumps can be limited or avoided.

The aquifer storage concept adopted for this project is based on a vertical water movement (vertical piston) induced by two horizontal levels of radial drains drilled from a deep vertical central well. This system allows control of the thermal front, which is horizontal in this case. Thus, natural convection effects in the main storage zone and vertical leakage effect of the warm water in the disturbed soil around wells are limited. Both of these effects could be important in either the single well or doublet systems. Moreover, a high maximum flow rate can be maintained during the production period without excessive velocities near the drains, thus limiting clogging effects and transport of solid particles.

A preliminary search for suitable sites (producer-storage-consumer) in Switzerland led the project team to choose the Dorigny site near Lausanne for a demonstration project. The pilot plant will be a shallow accumulator (from a depth of 6 m to 25 m) in alluvial deposits, of a 30,000 m³ volume. Chemical effects will be reduced by using a closed circuit in the storage system.

Numerical simulations showed that for the hydrogeological conditions of the Dorigny aquifers, an average temperature of 32°C during the first 5-month production period could be expected, if the injection temperature is 70°C and a natural regional flow of 1‰ gradient is assumed. On the other hand, the average temperature would be 37°C if the natural flow can be by-passed.

The project SPEOS was selected in November 1980 as a pilot International Energy Agency project by the countries that have signed the implementing agreement for energy conservation through energy storage.

4.2 France

Major groups involved in ATES studies include the Bureau de Recherches Geologiques et Minieres, Orleans; Institut de Mecanique de Grenoble; and Ecole des Mines de Paris.

Of particular interest is a recent project by the Ecole des Mines, which is named "heliogeothermal doublet" for interseasonal recharge, currently being implemented at Aulnay-Sous-Bois, near Paris. In winter, 150,000 m³ of water from a 15-meter aquifer 60 m below the surface will be produced at aquifer temperature (10-15°C) and used to heat 220 housing units by means of a heat pump. The water is cooled by the heat pump to 5°C and is reinjected into the aquifer. In the summer, the "cold bubble" is pumped back out, heated by solar collectors working at a very low temperature, and injected through the production well at aquifer temperature.

This method has many advantages:

- conservation of both the water resource and the energy resource of the aquifer
- minimum distance between the two wells, compatible with urban property boundaries
- collection of solar heat at a very low temperature using simple collectors (without glass covers) with a high level of efficiency.

Presently, the doublet wells have been drilled and characterization of the aquifer, testing of the solar collectors, and detailed system design are being carried out.

4.3 Sweden

Sweden has been very active in studying many alternative ways of underground heat storage, including employment of vertical and horizontal closed pipes, peat bogs, caverns, and eskers as well as aquifers.

Feasibility studies for aquifer storage at a number of sites have been carried out. Two examples may be mentioned.

The first was performed by the Royal Institute of Technology at Stockholm, involving field and modeling investigations of low temperature storage in shallow glaciofluvial deposits (eskers) in Stidvig.

Field tests involved artificial recharge of warm water in an infiltration basin and measurement of groundwater levels and temperatures at a network of points in the aquifer. These tests provided hydraulic characterization of the system (5 m thickness, permeability approximately $3.0 \times 10^{-10} \text{ m}^2$, effective porosity approximately 10%), and of its leaky contact with a nearby stream. The tests also provided estimates of transport characteristics of the esker deposit on the scale of a storage system (approximate dispersivity 2-7 m on a 50 m reach). The field information allowed calibration of a finite element model which was then employed to evaluate various cyclic storage geometries and design characteristics of the operation of an aquifer energy storage system over a ten year period.

The second example is work performed by Kjessler and Mannerstrale AM and Lund Institute of Technology, who carried out a field experiment with heat storage in a fissured limestone aquifer in Landskrona in southern Sweden. The objective of the experiment was to assess the feasibility of using the aquifer for the seasonal storage of warm water. The water in the aquifer will be used as a source for heat pumps, which will supply heat to nine one-family houses. A glass-covered common yard will provide solar heat source.

During the experiment, which lasted for 40 days, 1,700 m³ of warm water (25°C) was injected. Injection and extraction of water took place in two wells, 40 m apart, at a depth of 30 to 80 m. After injection and storage periods of 10 days each, warm water was produced for 20 days. The pumping rate was the same during injection and extraction. About 29% of the heat was recovered when the extracted volume was equal to the injected volume.

A numerical model was used to simulate the storage process. The results indicate that flow in the aquifer is highly variable. A large fraction of the flow seems to take place in the fissured zones where increased water flow was detected during a preliminary pump test. Further studies will be devoted to the thermal processes and modeling of these strongly heterogeneous aquifers.

4.4 West Germany

The main emphasis of the German work in ATEs has been the development of an artificial aquifer storage system. Extensive feasibility studies have been made by Messerschmitt-Bolkow-Blohm GmbH. Such a system conceptually consists of a gravel layer with processed material which is separated from the surrounding groundwater by walls and then saturated with water. Heat storage is accomplished by feeding hot water through a drainage system into the upper part of the aquifer. At the same time, an equal quantity of cold water is produced from the lower part through a second drainage system. The water level in the gravel layer remains unchanged. Provided the permeability within the gravel and the difference in temperature between hot and cold water are properly chosen, the device behaves similarly to a hot water tank, in which the hot and cold water remain stratified.

Other studies in West Germany include the theoretical and modeling work at Rheinisch-Westfälische Technische Hochschule Aachen and field injection studies at the University of Tübingen.

4.5 Canada

Public Works Canada, through its Energy Secretariat, initiated an ATEs Demonstration Program in 1980. The current project represents a preliminary investigation of the Demonstration Program. The joint consulting team of Hooper and Angus Associates Ltd., and Hydrology Consultants Ltd. was asked to select, from a number of federal buildings in Ontario, a suitable building for such a demonstration project. After consideration, the Atmospheric Environment Service (AES) building at North York was selected as the appropriate site.

The project is now in the beginning phase to (a) verify the existence of an aquifer formation near the site and to establish some of its important characteristics; (b) assess the impact of the proposed ATEs system on the building loads and physical plant; (c) prepare recommendations for further phases of work, such as well field development, aquifer modeling, aquifer testing, and design and construction of building modifications, monitoring, etc.

4.6 China

In China, the excessive extraction of groundwater in industrial cities, over a period of many years, has caused land subsidence and an annual lowering of the water table. In an effort to solve this problem, an experiment was begun in 1958 in Shanghai to recharge aquifers through injection wells.

By 1965 it was realized that injection was beneficial not only for controlling land subsidence and raising the water table, but for improving the groundwater temperature and quality for later use. At that time, based on the experience in injection and aquifer storage gained from several years of experimentation, large-scale chilled water storage was begun in Shanghai for application in the cotton mill industry. Summer injection for winter temperature and humidity control was also initiated. At present, approximately 10 cities store chilled water in winter for use in summer cooling.

Thus the more than ten years of work by the Chinese represents substantial practical experience in chilled water storage. New field tests and theoretical research are recently initiated to better understand both hot and chilled water storage systems.

4.7 Israel

Recent Israeli work includes that of Weizmann Institute of Science and the Tahal Engineers. One area of note is their study of soil heat storage.

Soil warming as a medium for heat supply to winter crops was studied widely during the last decade both experimentally and theoretically. However, it is found that if heat is continually applied at relatively shallow depths (30-40 cm) by day under local winter conditions it may cause overheating of the root zone with attendant water losses and increase in salinity, whereas application of heat at night only would require costly storage capacity, heat transfer and control systems.

Nir et al. of the Weizmann Institute suggested the use of greenhouse soil as a heat storage medium and a self-controlling mechanism for the supply of heat to the root zone of flower beds and subsequently to the greenhouse air. Heat is stored initially at different depths in the soil to allow for the delay in delivery by conduction. Low cost, pool-heating solar collectors are used to supply warm water which is circulated through plastic irrigation pipes buried in the ground. The depth of storage depends on local soil thermal properties, on the irrigation method and the season. With 2-3 layers of heat input pipes placed at the optimal depths, a stratified storage of heat is created, which is then utilized according to seasonal and weather conditions.

This study is expected to provide input data for technological and economic evaluation of an autonomous solar greenhouse.

4.8 United Kingdom

In the latter part of 1980, the Hydrogeological Unit of the Institute of Geological Sciences of Great Britain completed a literature study into Aquifer Thermal Energy Storage. This literature survey was coupled with a paper study into aquifers suitable for preliminary experiments in ATEs within the United Kingdom. The study is funded by the Department of Energy. It was concluded that the Lower Greensand aquifer in the Cambridge area and the Sherwood Sandstone of the Midlands are apparently suitable for ATEs experimental studies. Differences in aquifer thickness and the potential availability of hot injection water in these areas suggested that the scale of experiments in the two aquifers would be somewhat different. An experiment in the former site was initiated.

By the end of Spring 1981, an injection/production borehole and three observation boreholes have been completed in the Lower Greensand aquifer and it is hoped that injection of water at about 60°C and a rate of 30 m³/day over 50 days will commence this summer. Storage and extraction periods of similar duration will follow.

4.9 United States

During the last two years, an ambitious program was managed by Pacific Northwest Laboratory for the U. S. Department of Energy. This multi-faceted program is well summarized in Reference 11.

The program is divided into an Aquifer Thermal Energy Storage Demonstration Task and a parallel Seasonal Storage Technology Task. The purpose of the ATEs Demonstration Task is to demonstrate the commercialization potential of aquifer thermal energy storage technology using an integrated system approach to

multiple demonstration projects. The parallel Storage Technology Task is designed to provide support to the overall STES Program. The initial activities of this task are primarily directed toward support of the ATES Demonstration Task.

Under the ATES Demonstration Task, three demonstration projects were initiated. These are summarized in Table 1.

Under the Seasonal Storage Technology Program, work includes legal and institutional assessment, economic assessment, environmental assessment, field test facilities, compendia of existing technology, physiochemical analysis, and numerical simulation. Of particular interest is the field test facility work at Mobile, Alabama, performed by Auburn University. During the period 1979-1980, two injection-storage-production cycles were made involving storage of 55,000 m³ of water at about 55°C. The cycle period is approximately six months with approximately equal injection, storage, and production periods. The energy recovery ratio was found to be 66% and 76% for the first and second cycle, respectively. The experimental data have been successfully simulated by the Lawrence Berkeley Laboratory.

Currently, Auburn University is carrying out a new series of experiments involving storage of 60°C and 90°C water. Simultaneous modeling and prediction calculations are being made by Lawrence Berkeley Laboratory.

TABLE 1

Site	Prime Performing Organization	Energy Source	Storage Temp.	User Application	Aquifer	Comments
Bethel, Alaska	TRW, Inc.	Diesel-Electric Utility	<105°C	District Heating	Uncertain: Perhaps 30-61 m thick, somewhere between 122 to 244 m below surface	Special technical problem due to the presence of about 122 m of permafrost.
State Univ. of New York, Stonybrook Campus	Dames and Moore	Winter Chill	4°C	District Cooling	Magothy aquifer, ~200 m thick	Two chilling methods are being considered: (1) existing cooling towers; (2) outside air building fan systems
University of Minnesota, St. Paul Campus	University of Minnesota	University Heating Plant	150°C	District Heating	Franconia-Ironton-Galesville aquifer ~ 70 m thick	The high storage temperature introduces major uncertainties in anticipating aquifer behavior

4.10 Denmark

The Risø National Laboratory, the Denmark Technical University and the Geological Survey of Denmark have been very active in both fundamental and field studies in ATEs.

Recently, a Danish ATEs demonstration plant has been planned for a site about 30 km north of Copenhagen. The storage aquifer will be connected to an incineration plant capable of charging the storage facility with surplus heat in summer, and the stored heat will then be delivered to a district heating network in the neighborhood during autumn.

The aquifer underlying the site has been subjected to thorough geological tests. It is confined by layers of clay, and is about 15 m thick, with a depth to the top of it of about 10 m. The system is designed with one central well surrounded by 4 wells placed in a circle with a radius of 40 m. During heat injection, cold ground water is pumped from the 4 peripheral wells to heat exchangers at the incineration plant, and the heated water is injected into the aquifer through the central well. During the delivery phase, the stored warm water is produced and sent to the district heating system, and the cooled water is reinjected through the peripheral wells.

The system is expected to be ready for preliminary tests in the autumn of 1981 and the first operation cycle is expected to start in the summer of 1982.

4.11 Activities in other countries

ATEs activities are going on in other countries, conducted by a number of researchers including Professor J. Brych of Belgium, Professor Yokoyama of Japan, and Professor Hoogendoorn of The Netherlands. Details may be found in recent issues of the STES Newsletter.

5. GENERAL REMARKS ON ATES IMPLEMENTATION

From the above overview, one can see that very many exciting activities are going on in many countries. This reflects the general realization of the potential of ATES.

In general, we do not foresee any major, unsurmountable technical hinderances to the implementation of ATES. However, further research is needed for a better understanding of the physical and chemical processes, and for more confident prediction of storage performance and hence system economics. This will be discussed in the next section. Furthermore, as is usual practice in hydrological or reservoir engineering projects, great care should be exercised for any ATES application that a proper evaluation of aquifer properties and a complete modeling and system analysis be made.

6. 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 recent ATES studies, 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.

Thermal dispersion: Due to the nonhomogeneity of the aquifer porous media, fingering or thermal dispersion will occur at the thermal front. This was observed in a number of experiments and it tends to significantly decrease the energy recovery. Hence, theoretical and experimental studies are required to estimate its effects.

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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