MASTER

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May 1979

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INTRODUCTION

The concept of storing hot water in aquifers was suggested by several authors (Ref. 1-4) about ten years ago. The corresponding concept of cold water storage was investigated even earlier (Ref. 5-6). However it was not until 1976 that active interest was aroused through a sudden increase in reports of work which was performed to address this important possibility. The projects reported included field experiments and their numerical simulations by the University of Neuchâtel, Switzerland (Ref. 7-9); by Auburn University (Ref. 10) and the United States Geological Survey (Ref. 11); by the Bureau de Recherches Géologiques et Minières (Ref. 12) (France), jointly with the Centre d'Etudes Nucléaires de Grenoble and the Ecole des Mines de Paris. Field experiments of a smaller scale were also done in Switzerland (Ref. 13), Germany (Ref. 14), and France (Ref. 15). Though analytic and simplified modeling calculations were found in the early papers (Ref. 2,3), it was in 1976 that detailed, numerical modeling studies of the aquifer storage concept were done and reported by the Lawrence Berkeley Laboratory (Ref. 16). Furthermore, the role of aquifer storage in future U. S. energy systems was discussed in a General Electric-TEMPO report (Ref. 17). In the same year, a NATO Science Committee Conference (Ref. 18) held at Turnberry, Scotland, also encouraged further research and development of the Aquifer Thermal Energy Storage concept.

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The work by many groups since 1976 led to the first international workshop (Ref. 19) on Aquifer Thermal Energy Storage (ATES) held at Lawrence Berkeley Laboratory in May 1978. This workshop reviewed the status of five U. S. projects and seven projects in Europe and Japan. The participants at the workshop agreed on an international ATES Newsletter (Ref. 20) to be published periodically by the Lawrence Berkeley Laboratory under the sponsorship of the U. S. Department of Energy. This Newsletter summarizes the current status and results of various aquifer thermal energy storage projects around the world, and there was also the establishment of an agreement for a cooperative research and development program on large-scale energy storage under the auspices of the International Energy Authority.

The present paper will review the current projects in their various stages of progress. They are somewhat arbitrarily grouped into three categories: (a) field experiments; (b) theoretical and modeling studies; and (c) feasibility studies. After a description of these projects, we shall discuss what we see as the key problems which need to be solved in the field of ATES. These key problems are proposed as areas where our efforts should be directed in order to make ATES a technically feasible and economically viable means of energy storage.

FIELD EXPERIMENTS

Field experiments on ATES to date, other than the preliminary experiments described in references 13 - 15, are listed in Table 1, which also summarizes the results for the first storage recovery cycle. The first storage-retrieval

experiment done by the University of Neuchâtel (Ref. 7-9) involved a small amount of hot water injected into a shallow phreatic aquifer. Because of the high permeability of the aquifer and the low injection rate, buoyancy movement of the lighter hot water to the top of the ground water was evident, resulting in a large heat loss. Thus only 40% of the heat was recovered after pumping out over 30 times the injection volume. The Campuget Experiment (Ref. 21) by the Ecole des Mines de Paris also involved a shallow phreatic aquifer where influence of rainfall during the experiment was noted. Due to the proximity of the water table to the soil surface, the heat loss was very significant in winter. This suggests that for ATES, a better choice may be a deeper confined aquifer which has a low vertical permeability, in order to cut down possible buoyancy movements.

The Bonnaud experiments were performed in 1976-1977 by the Bureau de Recherches Géologiques et Minières, Orléans, France, jointly with the Centre d'Etudes Nucléaires de Grenoble and the Ecole des Mines de Paris. The aquifer they used was confined, 3 m thick and quite shallow. Detailed data were taken for two series of heat storage experiments from a central well C, surrounded by 11 observation wells. The first series of experiments consisted of three successive injection and production cycles performed in 1976; and the second consisted of four cycles performed in 1977. Results (Ref. 22-23) for only the first cycle are included in Table 1. Large thermal dispersion was observed (Ref. 24) which may be expressed in terms of an exceptionally large apparent thermal conductivity. These results are given in Table 2 along with the results of experiments with ordinary temperature (19° - 20°C) water, listed for comparison.

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Auburn University (Ref. 25-26) carried out two series of experiments, one
in 1976 and the other in 1978-79, at the Mobile site in Alabama. One injec-
tion well and 14 observation wells were used. The first series of experiments
involved the storage of 36.4°C waste hot water from a nearby power plant.
Clogging of the injection well was experienced, probably due to fine particu-
lates that went through their filter system. The second series of experiments
involved storage of water pumped from a more shallow aquifer and heated to
55°C. With periodic backwashing, no significant injection well clogging was
experienced. Detailed data were collected to validate numerical models. A
storage-recovery factor of 65% was found. The second series of experiments
are still in progress.

The Japanese field experiment (Ref. 27), conducted by the University of
Yamagata, consisted of two dual-purpose wells and one observation well. In
summer, cooling water was withdrawn. After direct cooling, waste water was
sprinkled on the roof for heat collection by conduction and radiation. The
water was then filtered and further heated by a heat exchanger and recharged
through the second well. The process was reversed in winter. A storage-
recovery factor of about 40% was found.

The objective of the Texas A & M University experiment (Ref. 28) is
(a) to study the use of a cooling pond in winter to chill the water from
70°F to less than 50°F and (b) to study the storage of the chilled water in an
aquifer for several months and then to use it for air-conditioning in summer.
The injection phase of the experiment has just been completed, and pumping has
not yet begun.

All the current field projects are relatively small-scale, with storage temperatures not more than 55°C, and not lower than 8°C. Most of these were aimed at pressure and temperature data for the general understanding of heat and fluid flow in the aquifer and for the validation of numerical models. There is a need both to extend the storage temperature range and to look more carefully at other facets of the ATES concept, such as effects of regional flow, land uplift or subsidence, water treatment and the economics of the operation.

Many of these will probably be addressed in two new field demonstration projects being proposed in the United States. The first is at the J. F. Kennedy Airport, New York (Ref. 29), where it is proposed to store winter-chilled water in an aquifer to be used for summer air-conditioning of the airport buildings. Four test wells have been drilled and evaluated so far, and the data are being studied. The second proposed project considers the feasibility of storing in an aquifer the waste heat from an aluminum plant in Bellingham, Washington, for subsequent use in the district heating of residential and commercial buildings. An initial feasibility study indicates that the 4.6×10^8 BTU/hr of waste heat (200°F hot water) from the aluminum plant could be used to heat 12,000 homes by means of an ATES system.

Recently it has been learned that substantial large-scale aquifer thermal storage has been done in the People's Republic of China over the last 10-20 years. This involves a number of industrial-scale projects mainly on cold water storage (Ref. 6).

THEORETICAL AND MODELING STUDIES

The current projects in theoretical and modeling studies are summarized in Table 3. From this table it can be seen that a number of numerical models are under development although their details are yet to be reported. We shall here comment on three of these projects: (a) Lund University, Sweden, (b) BRGM, France, and (c) Lawrence Berkeley Laboratory, U.S.A.

At Lund (Ref. 30-31), a two-dimensional finite difference model was specifically developed to study the storage of hot water in eskers, which are long and narrow glacial deposits of high permeability. Besides the esker project, a number of theoretical studies were made using semianalytic methods to examine several related topics in thermal storage, such as buoyancy tilting of a vertical thermal front, entropy analysis of numerical dispersion, effects of temperature-dependent viscosity in a two-well extraction-injection system, and other basic problems.

A number of numerical models were developed at BRGM, France (Ref. 32-33), for the study of fluid and heat flow, including a two-dimensional steady-flow semianalytical model, a layered two-dimensional finite difference model, and a program to calculate dispersion effects. Some of these techniques were used to model the Bonnaud experiment which was described in the last section.

A number of numerical models (Ref. 34) have been developed over the last 5 or 6 years at Lawrence Berkeley Laboratory to study single- or two-phase fluid and heat flow in porous media. Among these models is the program "CCC" (conduction, convection, and compaction), which was chosen for the ATES

studies. This program 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 semianalytic solutions and is currently used to model the Auburn (1978) field data. Extensive generic studies (Ref. 35-36) of the ATES concept have been made using "CCC," including studies of hot water storage for an inhomogeneous aquifer, for the case of a storage well partially penetrating an aquifer, and for a two-well extraction and injection system. In a particular case of a low-permeability aquifer with 10^6 kg/day flow rate, calculated energy balances for successive production-storage cycles are tabulated in Table 4.

On the whole, a substantial amount of modeling work is being done or has been initiated. However, there is much need to have these models properly validated and then carefully applied to understand the processes underlying the ATES concept, thus leading to an optimal field arrangement.

FEASIBILITY STUDIES

Current feasibility studies are listed in Table 5, where the objectives and the scope of each study are also outlined. These range from general economic and systems analyses, and comparison with other storage systems, to site evaluation and design of pilot plants. Several regional geological surveys are also being carried out to suggest possible sites for ATES. In several projects, considerations are also given to specific applications of the storage system and how to couple ATES to a national energy supply network. Technical

work proposed includes field and laboratory investigations into thermal, hydrodynamical, chemical, and biological aspects of this problem. Most of these projects are in their initial phases and detailed results are expected in the near future.

KEY PROBLEMS

In this section we put forth what we consider to be the key technical problems that need to be addressed in current or future projects. On the one hand, based on the 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. Already the current field experiments suggest several problems that have to be solved or avoided. The key problems include:

Shape and Location of the Hydrodynamic and Thermal Fronts

The hydrodynamic front may be tracked by chemical tracers. It is expected to arrive at an 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 tracking of the thermal front may be accomplished by temperature measurements in observation wells or by surface geophysics. The latter is a new method proposed by LBL which, if proven, may provide an economical technique to monitor the hot water bubble during injection, storage, and production stages. Since a substantial part 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.

Optimal Flow Rate and Formation Permeability

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

Evaluation of Thermal Dispersion

Due to the nonhomogeneity of the aquifer porous media, fingering or extra dispersion will occur at the thermal front. This was noted 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 also in Louisiana State University in the United States. Further work is needed in this area.

Prediction of 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 predictability by subsidence models. This will

yield information necessary for environmental impact statements and develop guidelines for injection and production operations.

Prediction of 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 the plugging of the well below ground. Specific studies should be made to determine general factors responsible for these adverse effects, and control techniques need to be developed.

Corrosion Studies

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 adequately address the key problems listed above, besides demonstrating the economic feasibility of the ATES concept. In this way a proper understanding, a data base, and the necessary working experience will be built up for the general commercial implementation of aquifer thermal energy storage systems.

ACKNOWLEDGEMENTS

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TABLE 1 First cycle data from aquifer thermal energy storage field experiments.

Site	Ambient temp. (°C)	Injection temp. (°C)	Amount injected (m³)	Injection period (days)	Storage period (days)	Amount withdrawn (m³)	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 (Ref. 5)
Bonnaud, France (1976-77)	12	40	1,400	20	122	3,000	30	Evidence of strong thermal dispersion (Ref. 23 and 24)
Campuget Exp. Gard, France (1977-78)	14	33.5	20,200	88	42 / 32	17,000	20	Shallow phreatic aquifer (Ref. 21)
Auburn Univ. U.S.A. (1976)	20	36.4	7,688	17	44	14,260	68	Injection well clogging (Ref. 25)
Auburn Univ. U.S. (1978-79)	20	55	57,784	80	51	55,345	65	(Molz, private communication)
Yamagata Basin, Japan (1977-78)	16	23.7	8,843	64	96	9,930	40	Doublet wells too close to each other (Ref. 27)
Texas A & M Univ., U.S. (1978-79)	21	8.9	31,800	92	60			In progress (Reddell, personal communication)

TABLE 2 Apparent thermal conductivity values[*] for several hot water storage experiments

| Research Institute | Aquifer thickness (m) | temperature (°C) | Injection | | Production | | Thermal storage radius (m) | Apparent conductivity $\tilde{\lambda}$ (cal/m/s/°C) | $\tilde{\lambda}/\lambda$ |
			Q_i (m³/hr)	t_i duration (days)	Q_p (m3/hr)	t_p duration (days)			
ENSMP BURGEAP at Neuilly 1974	10	19	14	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

[*] 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 Minìeres, Orléans, France

Source: Ref. 24, Table 1

TABLE 3 Numerical modeling studies in aquifer thermal energy storage

Research Institute (reference)	Project
Technical University of Denmark, Denmark (Ref. 19)	One- and two-dimensional finite element models Study of using compensation wells for countering regional flow
Lund University, Sweden (Ref. 30 and 31)	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 (Ref. 8 and 9)	Two- and three-dimensional finite element models
Ecole des Mines de Paris, France (Ref. 21)	Two-dimensional, radial, finite difference model Two- and three-dimensional finite element models
Bureau des Recherches Géologiques et Minières (BRGM), France (Ref. 22, 23, and 24)	Layered two-dimensional finite difference model Modeling of the Bonnaud experiment Dispersion modeling studies
University of Yamagata, Japan (Ref. 27)	Finite difference method using a complex potential function
United States Geological Survey, United States of America (Ref. 26)	Intercomp model (finite difference scheme) used to model the Auburn (1976) experiment
Lawrence Berkeley Laboratory, United States of America (Ref. 36)	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 (Ref. 19)	Model to study steam injection into permeable earth strata (two-phase program)

TABLE 4 Computed energy balance for a low-permeability aquifer. Calculations are for the first five cycles for the case of 90-day injection (flow rate of 10^6 kg/day) and 90-day production periods. Injection and ambient temperatures are 220 and 20°C, respectively; the aquifer is 100 m thick.

Cycle	Energy injected (J x 10^{13})	Energy recovered (J x 10^{13})	Energy loss from aquifer (J x 10^{13})	Energy diffused to heat the aquifer (J x 10^{13})	Energy recovered (%)	Prod. temp. at end of cycle (°C)
1	5.71	4.96	.053	.71	86.8	124
2	5.71	5.09	.068	.55	89.2	139
3	5.71	5.14	.077	.49	90.0	147
4	5.71	5.18	.084	.45	90.7	151
5	5.71	5.20	.091	.42	91.1	155

Source: Ref. 35, Table 2

TABLE 5 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	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 utilizing 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 Houston, Texas, United States	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	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	Perform an environmental impact analysis of aquifer thermal energy storage	Survey environmental and economic effects of aquifer storage. Conduct an 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	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.

TABLE 5 Current feasibility studies in aquifer thermal energy storage (continued)

Research Institute	Program objectives	Scope of study
Rocket Research Company, Redmond, Washington, United States	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 alternative heat source options Provision of a conceptual design and cost estimate Large-scale demonstration project
Hooper and Angus Associates Ltd., and Hydrology Consultants Ltd., Toronto, Canada	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 Rehovat, Israel	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
Faculté Polytechnique de Mons, Belgium	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	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

Research Institute	Program objectives	Scope of study
Kernforschungsanlage Jülich, Messerschmitt-Bölkow-Blohm, München, Bundesanstalt für Geowissenschaften und Rohstoffe, Berlin, Kraftanlangen Heidelberg, and Univ. of Stuttgart	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
Swedish Board for Energy Source Development, Stockholm, Sweden	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 Neuchâtel and the Institute de Production d'Energie de l'Ecole Polytechnique Fédérale, Lausanne, Switzerland	Study various aspects of aquifer storage of hot water with temperature 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	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