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ENERGY STORAGE IN AQUIFERS--A SURVEY OF RECENT THEORETICAL STUDIES

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ENGLISH ABSTRACT

The disparity between energy production and demand has led to increased research into the use of aquifers for the long-term, large-scale storage of thermal energy. Currently, there are several field experiments and feasibility studies under way in which the technical, economic, and environmental aspects of aquifer storage are being researched. The present paper surveys the recent theoretical efforts in aquifer storage research and the impact their results may have on these field projects. Major work is highlighted according to three categories: (1) semianalytic studies, (2) numerical modeling studies, and (3) site-specific studies.

FRENCH ABSTRACT

La disparité entre la production et le besoin de l'énergie a eu pour résultat d'augmenter la recherche concernant l'emploi des aquifères pour l'emmagasinement à long terme et à grande échelle de l'énergie thermique. A present, il y a de nombreuses expériences in-situ et d'études qui ont pour but les aspects techniques, économiques et naturels dans l'environement de l'emmagasinement des aquifères. Cette présentation fait le relevé de récents efforts théoriques concernant la recherche du stockage des aquifères et l'effet que leurs résultats pourraient avoir sur ces projets in situ. Les travaux principaux sont illustrés en trois groupes: (1) les études semi-analytiques, (2) les études de modèle numérique, et (3) les études sur des emplacements spécifiques.

KEY WORDS

Mathematical modeling; thermal energy storage; aquifers; storage; hydrothermal flows; seasonal storage; type curves; thermal stratification.

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 network 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 which 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 their 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. Over the last few decades aquifers have been used to store fresh water, oil products, natural gas, and liquid wastes. However, it has only been in recent years that their use for thermal energy has been suggested. Initial studies were conducted by Rabbimov, Umarov, and Zakhidov (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 (Berkeley, 1978). Current research and development activities are reviewed in the quarterly ATES Newsletter prepared by Lawrence Berkeley Laboratory.

Recent work includes field experiments at Mobile, Alabama (USA), Gaud (Fance), Bonnaud (France), College Station (USA), Yamagata (Japan) and other locations (see review paper, Tsang and others, 1980). Generally, these field projects have been relatively small-scale and have used water of moderate temperatures (not greater than 55°C nor less than 5°C). Most of these experiments have focused on obtaining pressure and temperature data with the objectives of understanding heat and fluid flow in the aquifer, and validating numerical models. However, plans are currently being made both in the USA and Europe for large scale demonstration projects.

SURVEY OF THEORETICAL STUDIES

The present paper summarizes recent theoretical efforts, the results of which will be useful in the planning and execution of field projects and may even be crucial to their success.

Current theoretical and modeling studies are summarized in Table 1. As can be seen from the table, a number of numerical models are under development, although their details are yet to be reported. Summarized below are descriptions of several of these efforts classified somewhat arbitrarily into three categories: (1) Semianalytic studies, (2) numerical studies, and (3) site-specific studies.

TABLE 1. Theoretical and Modeling Studies in Aquifer Thermal Energy Storage

Research Institute	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
University of Neuchâtel, Switzerland (Mathey, 1977; Mathey and Menjoz, 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 and others, 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 and others, 1978)	Finite difference method using a complex potential function
United States Geological Survey, U.S.A. (Papadopulos and Larson, 1978)	Intercomp model (finite difference scheme) used to model the Auburn (1976) experiment (Molz and others, 1978)
Lawrence Berkeley Laboratory, U.S.A. (Tsang and others, 1978b)	Three-dimensional integrated finite difference model for conduction, convection, and consolidation Extensive generic studies Modeling of the Auburn (1978) experiment (Molz and others, 1980)
University of Houston, U.S.A. (Collins and others, 1978)	Model to study steam injection into permeable earth strata (two-phase program)

Semi-analytic studies. A number of groups have been working on the understanding of specific thermohydraulic processes that may be critical to the success of aquifer thermal energy storage. Attempts are also being made to derive lumped parameters that may relate different field conditions.

When considering underground storage of hot water, the recovery factor is of major concern in determining the economic feasibility of a project. It is especially convenient to have at hand general type-curves by which an engineer can quickly decide whether or not a particular project should be carried out. In this light, a general study using mathematical models has been made by Bureau de

Recerches Géologiques et Minières (Sauty and others, 1978) to determine the effect of various physical parameters and operating conditions on the temperature of water produced after a storage period in a one-well system (alternative injection and production through the same borehole). For each case the overall heat return has been evaluated.

A dimensional analysis has determined the dimensionless parameters governing the behavior of the system in terms of physical factors (reservoir thickness, thermal conductivities, heat capacities, etc.), and operating conditions (flow rate, duration of injection, storage, and production periods). Type curves have been drawn and heat recovery factors evaluated for various combinations of these factors.

This study concerns single-phase, thermal energy storage in relatively deep aquifers (regional velocity neglected and the confining layers regarded as practically infinite in thickness). For the study, Sauty and coworkers define the dimensionless parameters P_e and Λ as follows: $P_e = (\rho_F C_F)/\lambda A \cdot Q/(2\pi h)$, $\Lambda = [(\rho_A C_A)^2 h^2]/(\lambda_R \rho_R C_R) \cdot 1/t_i$, where h is the aquifer thickness, $\rho_F C_F$, $\rho_R C_R$, and $\rho_A C_A$ the heat capacities of the fluid, the confining rocks and the aquifer, respectively, and λ_R and λ_A the respective thermal conductivities of the rock and aquifer. The Peclet number P_e represents heat loss at the thermal front, and the Λ coefficient the heat loss through the confining rocks.

It has been shown that for these numbers higher than 10, the recovery of a stabilized cycle is greater than 75% (still higher, if the reference temperature at the surface is lower than the natural aquifer temperature, meaning less heat loss). However, it should be considered that overall energy eficiency must take into account various losses in the well and at the surface as well as energy consumption (pumping water in and out of the wells).

Another factor that may strongly affect the energy recovery ratio is the existence of heat dispersion effects in the aquifer. Analyses of several French field experiments indicate that this effect may be approximately represented by an apparent thermal conductivity value an order of magnitude higher than the normal value. For apparent conductivity ten times the normal value, the Peclet number is reduced by a factor of 10. In Fig. 1, the temperature of the water during the production half cycle is shown for successive cycles of hot water injections for $\Lambda = 10$ and $P_e = 10$ or 1 (Fabris and others , 1977).

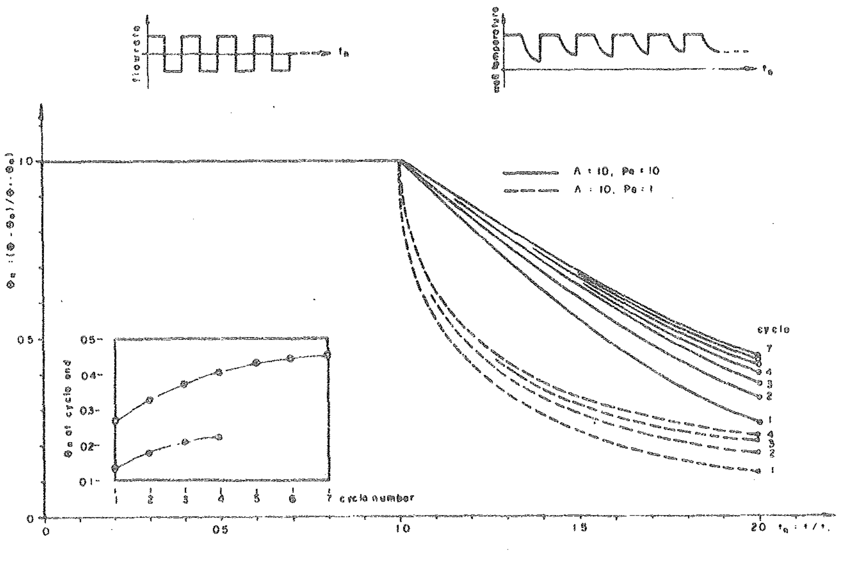

Fig. 1. Temperatures evolution at central well during successive cycles of hot water injection and production. Consequences of $\tilde{\lambda} = 10\lambda$ (Pe = 1 instead of 10). (XBL 801-7725)

Another interesting study, performed by Lund University, focused on thermal buoyancy flow (Hellstrom and others, 1979). In the injection of hot water into a cold water aquifer, the hot water tends to flow to the top of the cold due to the difference in density and viscosity of waters with different temperatures. This induces a mixing of hot and cold water, resulting in heat dissipation that decreases the energy recovery ratio. When hot water is injected into an aquifer, the interface between hot and cold water is primarily vertical. This vertical interface is unstable and will tend to tilt outward from the injection well. The rate at which the system tends to equilibrate, i.e., with the hot water on top of the cold water, is a decisive factor in determining the feasibility of a system with vertical injection and production wells. A strong disturbance of the temperature field will lead to higher heat loss (larger surface area of the hot region, increased heat dispersion). It will also require a more complicated extraction system in order to avoid excessive mixing of hot and cold water in the well.

The aim of the Lund study was to find an explicit order-of-magnitude expression for the influence of the buoyancy flow, making it possible to estimate the rate at which the thermal front "tilts" without resorting to numerical models. The analysis was based on a number of analytical solutions for a vertical thermal front in cylidrical and two-dimensional Cartesian coordinates. The diffusiveness of the thermal front was also taken into account. Several assumptions about the behavior of the thermal front were made in order to modify the analytical solutions for nonvertical situations. Finally, the tilting rate for a given system was quantified by a characteristic tilting time-constant which equals the time it takes for an initially vertical front to tilt 45°. Major conclusions include:

(1) Buoyancy flow is found to be proportional to the density difference between stored and native waters, and to the square root of the product of vertical and horizontal permeabilities of the aquifers, and inversely proportional to aquifer thickness and average viscosity of the injected and native waters. The dependence on aquifer thickness and permeabilities will suggest a criterion for the selection of potential storage aquifers. The density and viscosity dependence will introduce a guideline for optimal storage temperatures.

(2) Two key lumped parameters are derived which would make it possible to relate results of different cases by means of a similarity transformation.

Figure 2 shows the results for the following example. Consider a 20 m thick alluvial aquifer with a vertical permeability that is 1/10th of the horizontal one. The heat capacity of the aquifer is 2.7 MJ/m^{3}K. The temperature of the injected water is 85°C, and the ambient water is 15°C. The figure shows the tilting angle (assuming a straight front) as a function of permeability (m^2) and storage time (days). Let us require that the thermal front should not tilt more than 60° during a storage period of 90 days. The corresponding maximum allowable permeability is then about 3x10^{-11} m^2. This example does not include the effects of a superimposed forced convection, which will cause a further increase in the tilting angle.

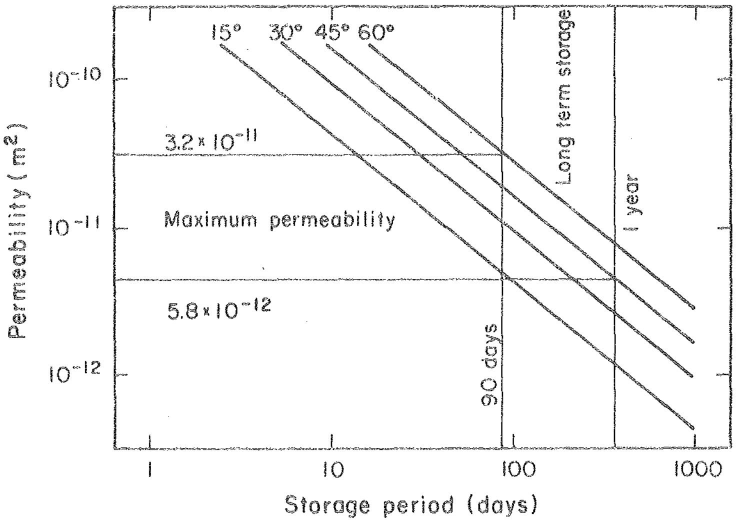

Fig. 2. Thermal front tilting angle as a function of permeability and storage period. (XBL 7910-13050)

Numerical modeling studies. Several groups, including Lund in Sweden and BRGM in France, are involved in numerical modeling work. We shall consider here only studies by Ecole Polytechnique Fédérale de Lausanne (EPF-L), Switzerland, and Lawrence Berkeley Laboratory, U.S.A.

The Swiss theoretical studies emphasize the need to account for natural convection which greatly decreases storage efficiency. The studies by Menjos and Joos (1977) Pacot (1978) and Joos (1978) use a storage arrangement as shown in the upper part of Fig. 3. Their accumulator consists of a large diameter central well provided with horizontal radial drainage systems 50 m apart. Hot water is injected at the top while cold water is withdrawn from the bottom for storage. The reverse process is used for recovery. A finite element model is used to calculate temperature and pressure distribution during semiannual cycles of injection and production.

The results are shown in the middle and lower portions of Fig. 3. The heat recovery increases with each annual cycle. The mean storage temperature and the minimum storage temperature steadily increase. For these calculations, constant rock and water properties are assumed. A later series of simulations, performed by Pacot, uses an improved computer model from Joos which includes variability in the kinematic viscosity of water with temperature. The resulting change in hydraulic conductivity has a considerable effect on some of the pressures and temperatures, but the energy recovery factor is similar to the previous case.

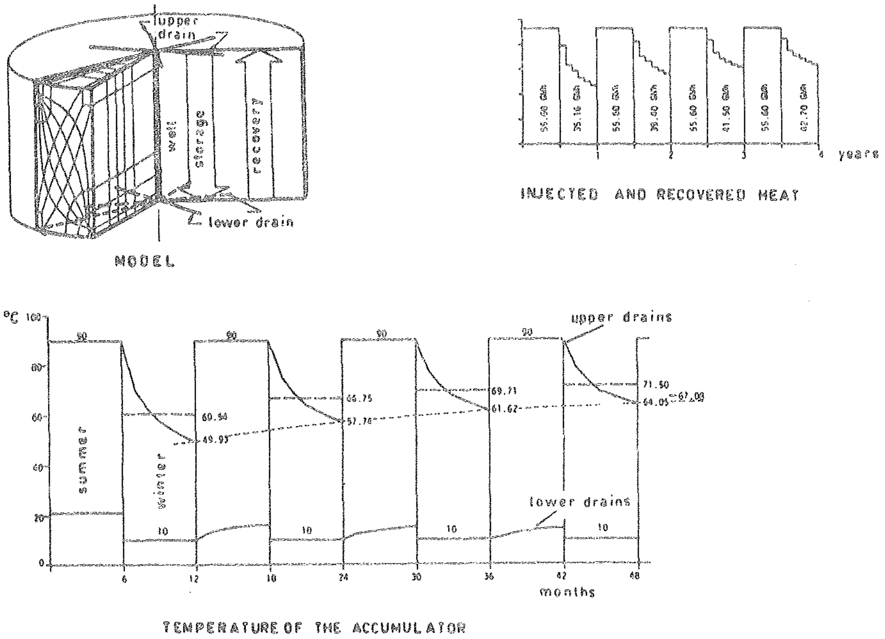

Fig. 3. Aquifer heat storage system showing vertical flow between two horizontal networks of drain pipes (Pacot, 1978) (XBL 801-7724)

A number of numerical models have been developed over the last six years at Lawrence Berkeley Laboratory to study single- and two-phase fluid and heat flow in porous media (Tsang and others, 1978). 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 semi-analytic solutions and is currently used to model the Auburn (1978) field data. Extensive generic studies of the ATES concept have been made using CCC. Some of the results are illustrated in Figs. 4 through 5 which show diffusion of the thermal front during hot water storage for an inhomogeneous aquifer (Fig. 4) and for a two-well extraction and injection system (Fig. 5).

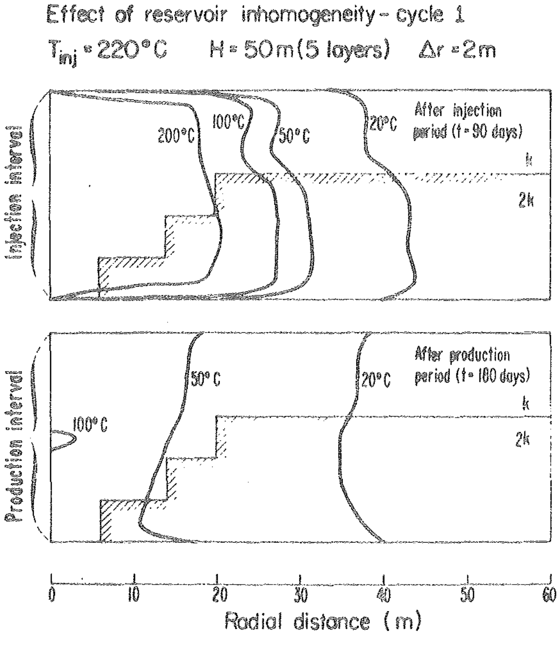

Fig. 4. Effects of reservoir inhomogeneity after 90-day injection and production periods (XBL 785-2517)

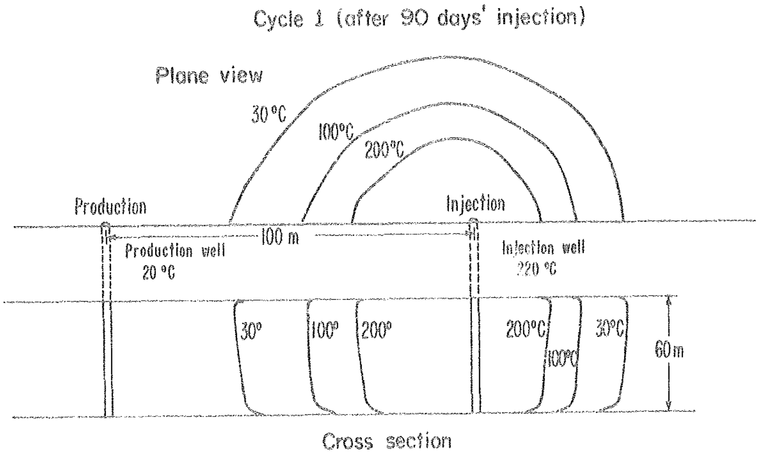

Fig. 5. Calculated isotherms for a two-well system after 90 days of injection; plane and cross section views (Tsang and others, 1978) (XBL 785-2508)

Site-specific modeling studies. Numerical model calculations are made to understand data from specific field experiments. On one hand, practical field situations are studied and associated physical and chemical processes understood. On the other hand, the numerical models are validated by the data to ensure that all major processes are incorporated. Thus they can be used as a predictive tool for future experiments.

Simulations of Bonnaud and Campuget experiments have been performed by French scientists. Similar work has also been done by the Swiss. Below, however, we shall describe the modeling of the Auburn field experiments (Molz and others, 1980) by Lawrence Berkeley Laboratory as representative of work done in this category.

In their work, LBL first carried out a well-test analysis of the field pressure data to determine the aquifer transmissivity, storativity, and the distance and direction of the nearest hydraulic barrier. With the aquifer characteristics thus obtained, a series of simulations were made, given the varying injection flow rates and temperatures, and the subsequent rest and production flow rates. Results of the simulation include the recovery factor and plots of production temperature versus time, as well as temperature contour plots and temperature profiles taken at various times during the simulations.

Experimentally, two storage-retrieval cycles were done. For the first cycle, the simulated recovery factor of 0.66 agrees well with the observed value of 0.65. For the second cycle, the simulated value is 0.76 and the observed value is 0.74. Details of the comparison between simulated and observed energy recovery can be studied in production temperature versus time plots (Fig. 6 and 7). For both cycles, the initial simulated and observed temperatures agree (55°C). During the early part of the production period, the observed temperature decreases slightly faster than the simulated temperature. During the latter part, the simulated temperature decreases faster than the observed temperature so that by the end of the production period, the simulated and observed temperatures again agree (33°C). The discrepancy over the whole range is at most 1 to 2 degrees.

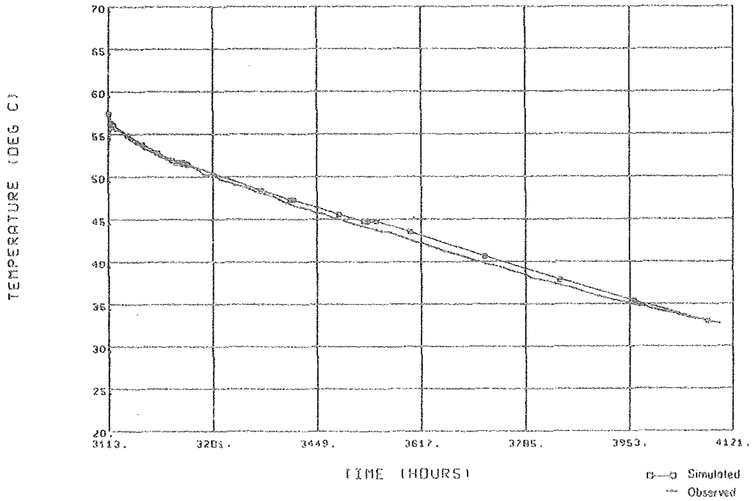

Fig. 6. Simulation of experiment by Auburn University (first cycle) - calculated and observed production temperature during the recovery period (Tsang and others, 1980) (XBL 798-11428)

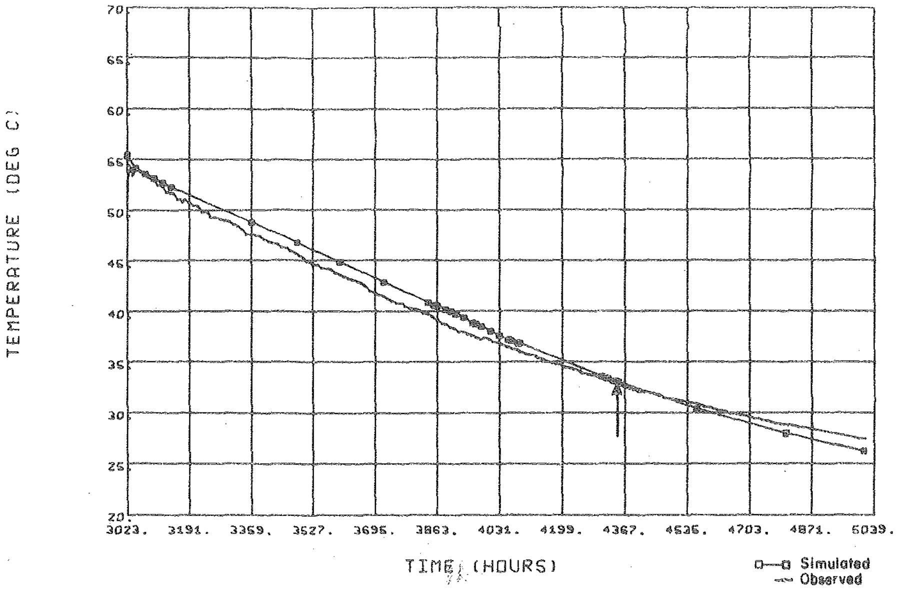

Fig. 7. Simulation of experiment by Auburn University (second cycle) - calculated and observed production temperatures during the recovery period (Tsang and others, 1980) (XBL 798-11426)

A parameter sensitivity study was also carried out by LBL. In simulating the Auburn University field experiment the vertical/horizontal permeability ratio (K_v/K_h) in the aquifer and the permeability and storativity values in the aquitards could not be determined directly and had to be estimated. The parameter study indicates that the estimated recovery factor is very sensitive to permeability and the K_v/K_h ratio. In the Auburn simulation, using a value of K_v/K_h equal to 0.1 is critical to obtaining good agreement with the field data. Increasing aquitard permeability by a factor of 10 had only a slight effect on energy recovery. The effect on energy recovery was also slight when thermal conductivity was increased by a factor of 2, but significant changes were observed when thermal conductivity was increased by a factor of 20.

To study the effect of partial well penetration on the results of the Auburn field experiments, a simulation was run assuming full penetration of the well. Energy recovery was estimated to be 0.69, differing only slightly from the value 0.68 obtained for the partial penetration case.

CONCLUDING REMARKS

The recent work in theoretical studies of aquifers for the storage of hot water has been highlighted above. Further information may be found in the reference list. Current activities coupled with planned field experiments will help us to make the aquifer thermal energy storage concept a practical reality. Much theoretical work is yet to be done to give us a better understanding of buoyancy flow, thermal dispersion, the effects of land subsidence or uplift, natural regional flow, as well as providing the basis for optimizing storage-recovery schedules and volumes.

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