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THEORETICAL STUDIES IN LONG-TERM THERMAL ENERGY STORAGE IN AQUIFERS

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1. INTRODUCTION

One of the most promising methods for long-term thermal energy storage is the use of underground aquifers. Aquifers are geological formations which contain and conduct water. They may be found at depths ranging from a few meters to hundreds of meters. For many years some of these aquifers have been used for liquid waste disposal and for storing fresh water, oil products, and natural gas. Their use for hot water storage was first suggested in the early 1970's.

In 1978, the Lawrence Berkeley Laborotory (LBL) of the University of California organized and hosted the First International Workshop on Aquifer Thermal Energy Storage. Active workers from nine countries participated in this workshop and their contributions were published in the Workshop Proceedings [1]. Since the Workshop, a periodic Newsletter [2] has kept researchers abreast of the current status of various projects worldwide. Many of these projects were recently reviewed in two survey papers [3 and 4]. Currently, much experimental and theoretical work is being carried out to study the concept of aquifer thermal energy storage. Furthermore, three large-scale "demonstration" experiments were initiated in the United States.

The present paper will describe the LBL theoretical studies in this field. The implications of our results for the implementation of this concept will also be discussed. Our theoretical studies are carried out in two directions:

(1) basic or generic studies to understand the fundamental thermohydrologic processes and to identify key parameters, and

(2) site-specific modeling studies to understand experimental observations and to simulate or predict field results.

Earlier work at LBL was mainly along the first direction with the emphasis on detailed modeling for proving the feasibility of the concept. Many of the results have been published already [5 - 7]. In the section following, we shall describe our recent basic studies. Then our site-specific studies will be discussed under two headings, Field Simulation and Study of Alternative Field Designs. A brief conclusion will complete the paper.

2. BASIC STUDIES

Our recent basic studies emphasize the understanding of the energy recovery factor (i.e., the ratio of energy recovered to energy stored) as a function of aquifer properties and storage parameters. The goal is to arrive at optimal choices of aquifer and storage arrangements. Dimensionless parameter groups that will be useful in the planning and design of practical projects are being studied and validated.

So far in our studies we have neglected buoyancy flow. This is the case for low permeability aquifers or for storage of low-temperature water. Hellstrom, Tsang, and Claesson [8] recently studied the problem and from their work came a criterion which may be used to verify the applicability of this assumption. On the other hand, the results obtained for the functional dependence of the recovery factor may still be true for cases of significant buoyancy flow.

Since many computations have to be made for a study of functional dependence, a simple numerical model [9] is used. Besides assuming no buoyant flow, this model also assumes a steady-state fluid flow field in a laterally infinite, uniform aquifer. The recovery factor is calculated for a series of values of aquifer thickness, storage volume, aquifer and aquitard thermal conductivity, caprock thickness, cycle time period, velocity-dependent dispersion, and the number of cycles. In all cases, equal volumes of fluid are injected and produced. As illustrations, some of the results are shown in Figures 1-4.

Figure 1 shows the energy recovery factor as a function of thermal radius, R_{th}, and aquifer thickness, H. Each dashed line traces the recovery factor for a given fluid volume. There is an optimal value of R_{th}/H which yields the maximum recovery factor for each volume. Generally, the recovery factor is a much more sensitive function for small values of R_{th} and H than for large values. Figure 2 shows the recovery factor as a function of volume for a series of values of aquifer thickness, H. The recovery factor increases rapidly at first, then levels off. Figure 3 shows the recovery factor as a function of the aspect ratio, R_{th}/H, for a series of aquitard to aquifer thermal conductivity ratios. As this ratio decreases, the aspect ratio which yields the maximum recovery factor increases. Figure 4 shows energy recovery as a function of the time period of a single injection-storage-production cycle for several different injected volumes. The aquifer thickness for each volume is such that the aspect ratio is optimal. Lines "a" show the results for a cycle with no storage period, i.e., production begins as soon as injection ends. In this figure, injection and production periods are equal. We have found that varying the relative injection and production periods for a given storage period has only a minor effect on the recovery factor. Lines labeled "b" show the results for a cycle with equal injection, storage, and production periods. Lines labeled "c" show the results for the hypothetical cycle that is all storage period, the hot water being instantly injected and later instantly produced. This represents the limit of very short injection and production periods.

Detailed results of this work are described in a paper under preparation [9]. Systematic graphs of the recovery factor as a function of key dimensionless parameters will be included and their use for practical field applications demonstrated. Plans for further calculations include the incorporation of gravity effects.

3. FIELD SIMULATION

A series of experiments were carried out during 1978-1979 by the Auburn University [10]. We performed a modeling study of these experiments and succesfully simulated the observations without adjusting any parameters. The experiments include two injection-storage-recovery cycles. The first six month injection-storage-production cycle involved the storage of 55,000 m^3 of water at about 55^oC. The injection took 79.2 days, at the end of which the hot water was stored for 52.5 days. Production was then started at an average rate of 245.6 gpm until the recovered water temperature fell to 32.8^oC. At that point 66% of the injection energy was recovered. The second injection-storage-production cycle was carried out in essentially the same manner, using 58,000 m^3 of water at an average temperature of 55.4 ^oC. When the production temperature had dropped to 33^oC, a recovery of 76% of the injected energy was realized.

The first stage of our simulation calculations involved the determination of the hydraulic parameters of the aquifer (the transmissivity and storativity), and the location of a linear hydrologic barrier through well test analysis. Conventional well test type curve analysis techniques require a constant or carefully controlled flow rate. To get around this limitation, LBL has developed a computer-assisted analysis method, program ANALYZE [11, 12] that can handle a system of several production and injection wells, each flowing at an arbitrarily varying flow rate. This program was applied to the Auburn case, treating the injection period also as a part of the well test data [13].

With parameters thus obtained, the LBL three-dimensional, complex geometry, single-phase model, CCC, was used to make detailed modeling studies. A radially symmetric mesh was assumed. There is one major hydrologic parameter that was not determined by well test analysis. This parameter, the ratio of vertical to horizontal permeability, has to be inferred from field experience and parameter studies. After making a preliminary parameter study, we decided to use a value of 0.10 for this ratio. The same ratio was suggested by the USGS [14].

Results of the simulation include the recovery factor, plots of production temperatures versus time, as well as temperature contour plots and temperature profiles at various times during the injection, storage, and production periods. Both the first and second cycles have been successfully simulated. For the first cycle, the simulated recovery factor of 0.68 agrees well with the observed value of 0.66. For the second cycle the simulated value is 0.78, and the observed value is 0.76. The details of the comparison between simulated and observed energy recovery can be studied in production temperature versus time plots (Figures 5 and 6). For both cycles, the initial simulated and observed temperatures agree (55^{o}C). During the early part of the production period, the observed temperatures decreased slightly faster than the simulated temperatures. During the latter part, the simulated temperatures decreased faster than the observed temperatures so that by the end of the production period the simulated and observed temperatures again agree (33^{o}C). The discrepancy over the whole range is, at most, 1-2 degrees.

Temperature contour maps of vertical cross-sections of the aquifer at given times (e.g., Figure 7) show the details of buoyancy flow, heat loss through the upper and lower confining layers, and the radial extent of the hot water in the aquifer. Buoyancy flow is important in this rather permeable system. Comparison with temperatures recorded in observation wells throughout the aquifer show that the simulated temperature distribution agrees generally with observed temperatures. However, these discrepancies are much larger than the difference between calculated and observed production temperatures. Apparently there are local variations in the aquifer which tend to average out. Temperatures versus radial distance at given depths and times are also plotted (e.g. Figure 8) and, from these profiles, the effects of thermal conductivity and dispersion on the shape of the thermal front can be studied.

In order to prove the mesh-independence of these results, the first cycle has been modeled again, using first a coarser mesh (doubling the radial step) and then a finer mesh (half the radial step). The coarse mesh recovery factor is 0.65, to be compared with a value of 0.66 using our first mesh. Interestingly, the coarse mesh simulation yields a recovery factor slightly closer to the observed value than does the original simulation, so the increased numerical dispersion may be more closely simulating thermal dispersion due to local heterogeneities in the aquifer. Temperature as a function of radial distance and the production temperature as a function of time also confirm the insensitivity of the results to the mesh chosen.

Based on these results [15], one may conclude that (a) we understand the physical processes involved in the ATES system at the Auburn field site, thus giving us confidence in dealing with confined aquifers of a similar type, and (b) the LBL numerical model "CCC" is a satisfactory code that may be useful for further applications.

4. STUDY OF ALTERNATIVE FIELD DESIGNS

Besides simulation of experimental results, we also perform parameter sensitivity studies as well as modeling to support experimental planning and design. In the case of the Auburn experiments, several parameter variation calculations were made to study results to be expected for different arrangements.

Figure 9 shows the effect of partial penetration of the storage well into the aquifer. With the Auburn field parameters, if the storage and retrieval well penetrates the full thickness of the aquifer, the production temperature (solid line) drops steadily with time from the storage temperature of 55°C and the recovery factor, ε, is 69%. However, if during production the well is withdrawing water from only the upper half of the aquifer, the decrease of production temperature (broken line) during the initial production period is much slower. This may be of significant interest since in most applications production temperature decrease should be minimized over the main part of the production period.

In anticipation of the next series of planned Auburn experiments where water at 90°C will be stored, we performed a series of calculations for this temperature. Figure 10 shows the production temperatures for one such case. As one might expect, the recovery factor is much lower because of the higher buoyancy flow associated with the higher temperature.

Table 1 summarizes the recovery factors using the model "CCC" for four storage temperatures and three values of aquifer permeability. In all the cases, storage volume is assumed to be 55,000 m^3, thickness of the aquifer is 21 m, and permeability of the aquitard is 10^{-5} of that of the aquifer. The Auburn experiment corresponds to the 52 d permeability case. This table represents a substantial amount of computation, including different cycle periods and different penetration arrangements. The variations of the recovery factor are clearly seen. Details of these studies are presented and discussed in a paper under preparation.

5. CONCLUSIONS

Substantial work has been done at LBL and elsewhere in both basic and site-specific studies. The phenomenology of the thermohydraulic flow associated with aquifer thermal energy storage is reasonably well understood. A few questions which are not mentioned in the present paper still remain, such as dispersive phenomena, aquifer regional flow control, well injectivity, and total system efficiency analysis. With the provision that an aquifer is properly selected and carefully characterized, we believe that an aquifer energy storage system can be successfully designed.

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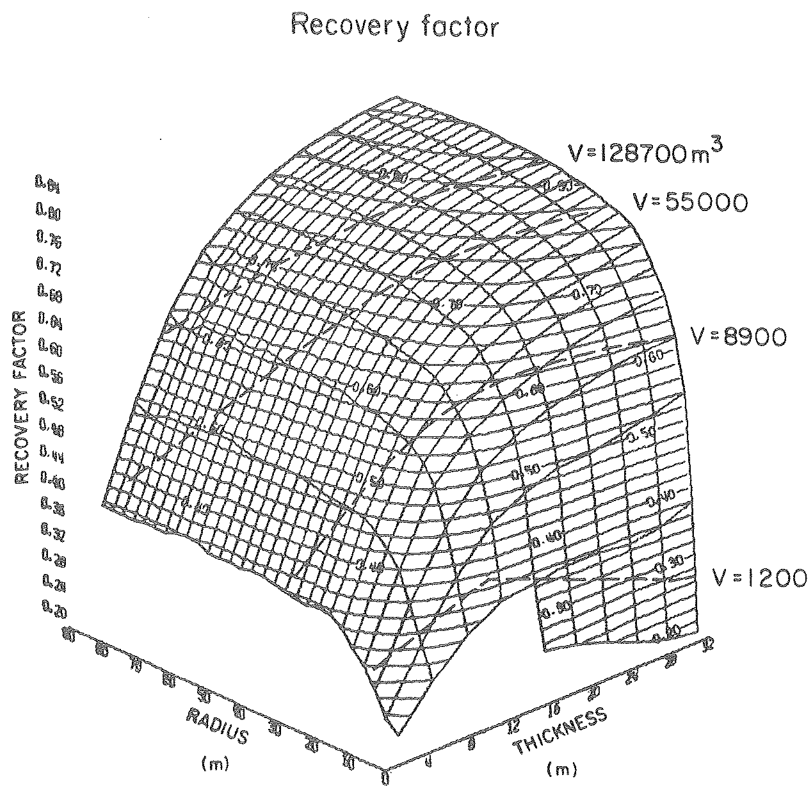

FIG. 1. The recovery factor as a function of aquifer thickness and storage radius. The latter is defined as the radius reached by the storage temperature front at the end of injection period.

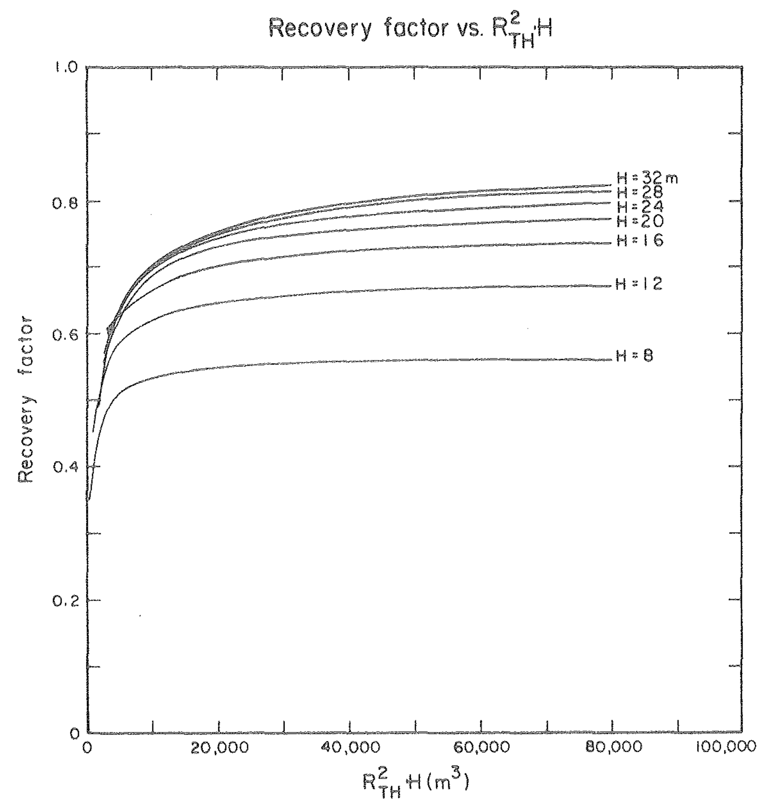

FIG. 2. The recovery factor as a function of storage volume, implicity given by $R^2_{th}H$ for different values of aquifer thickness H.

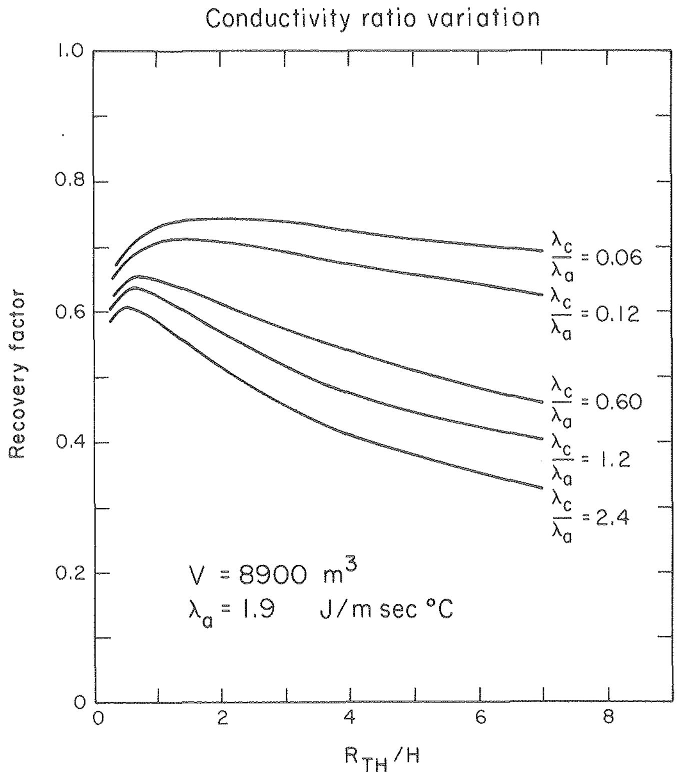

FIG. 3. The recovery factor as a function of aspect ratio, storage radius over aquifer thickness (R_{th}/H), for different aquifer and aquitard thermal conductivities (λ_a and λ_c). (XBL 803-6873)

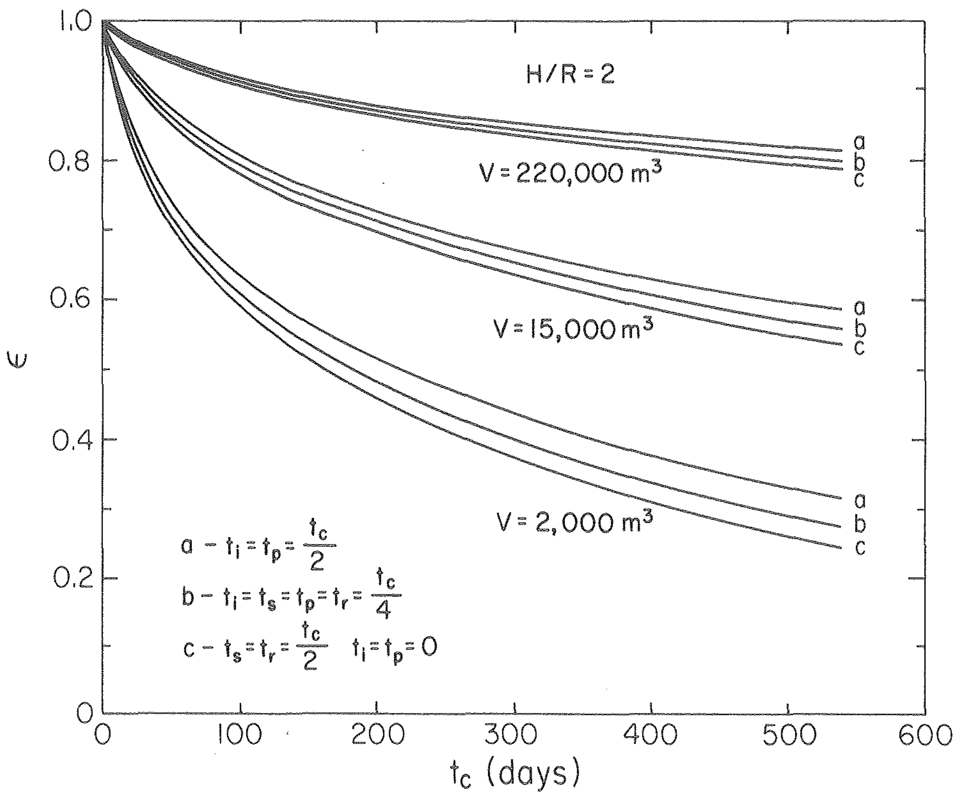

FIG. 4. The recovery factor as a function of cycle time periods (t_{cycle}). (XBL 807-1385)

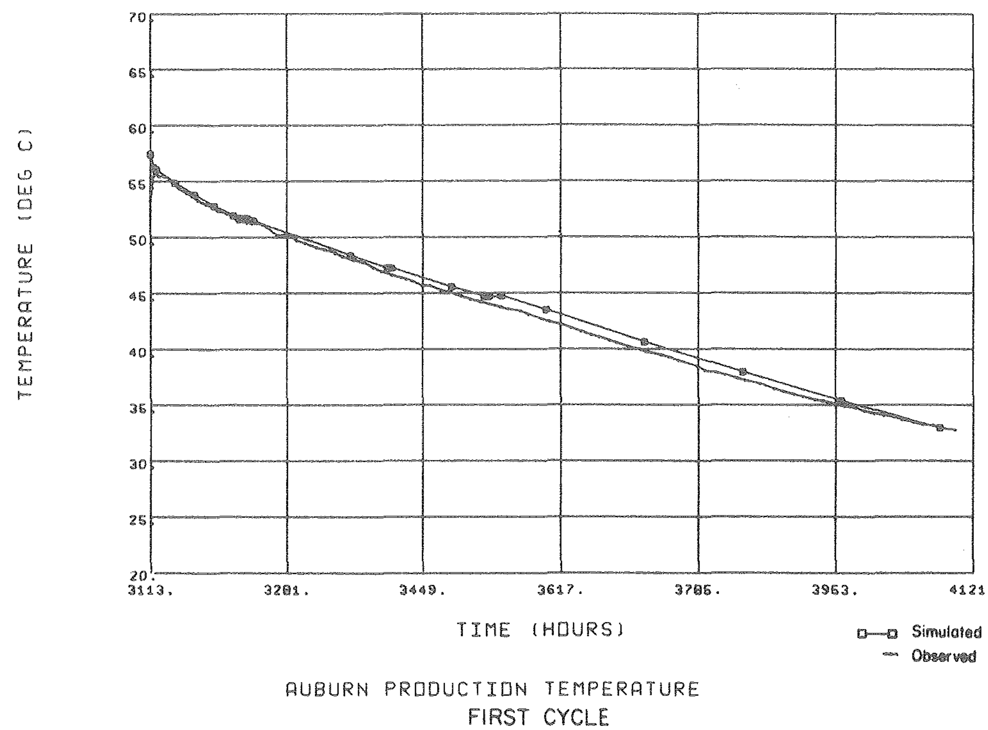

FIG. 5. Observed and simulated production temperatures as a function of time for the first cycle.

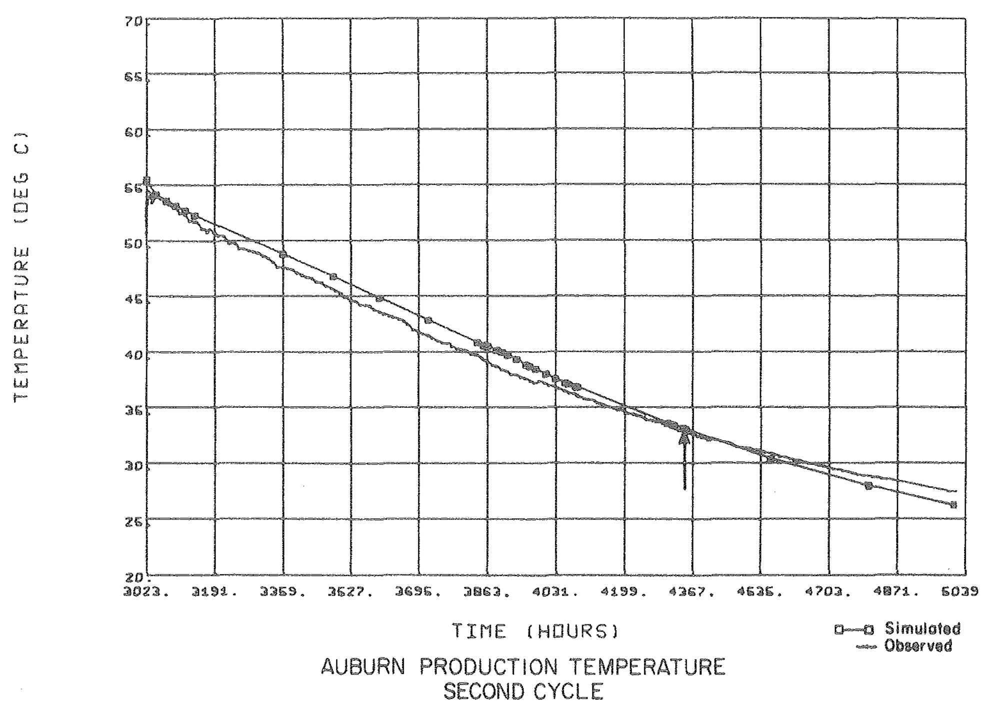

FIG. 6. Observed and simulated production temperatures as a function of time for the second cycle.

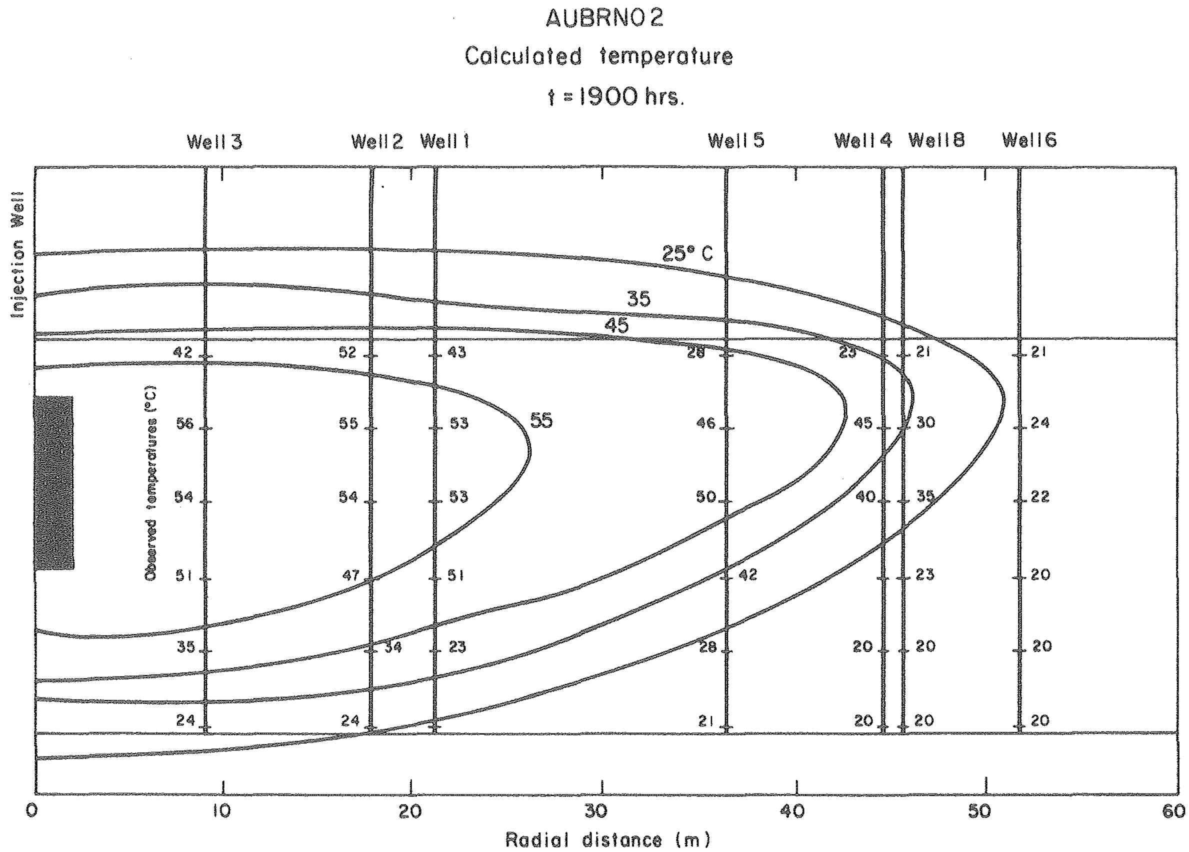

FIG. 7. Simulated temperature contours in a vertical cross section of the aquifer at the end of the injection period of the first cycle. Observed temperatures are also indicated.

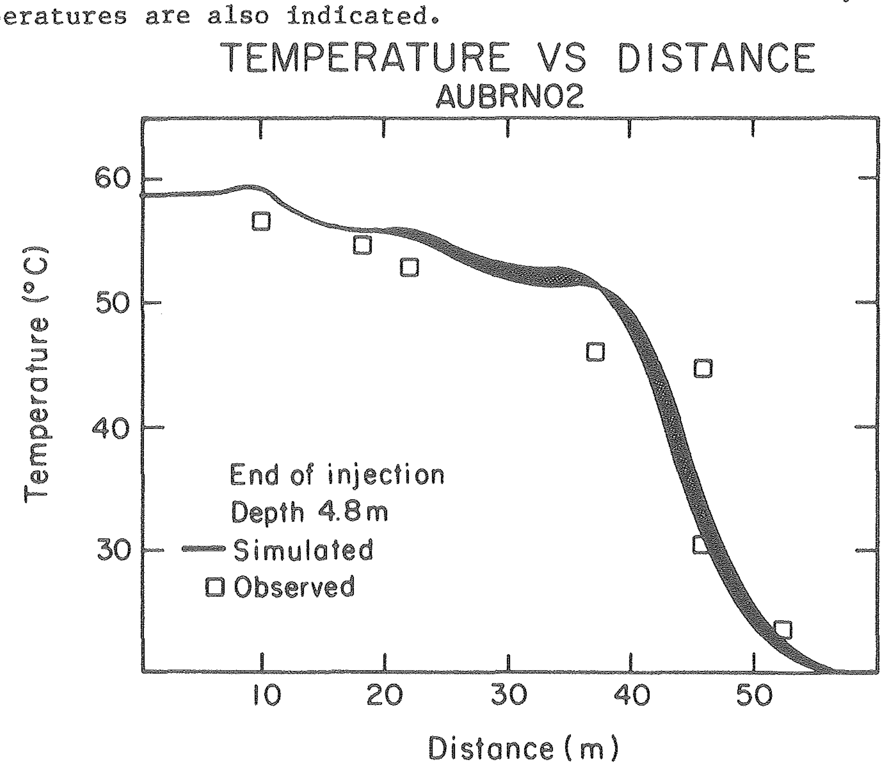

FIG. 8. Temperature versus radial distance at the end of injection period for the first cycle. Shaded curve indicates simulated values, boxes show observed values.

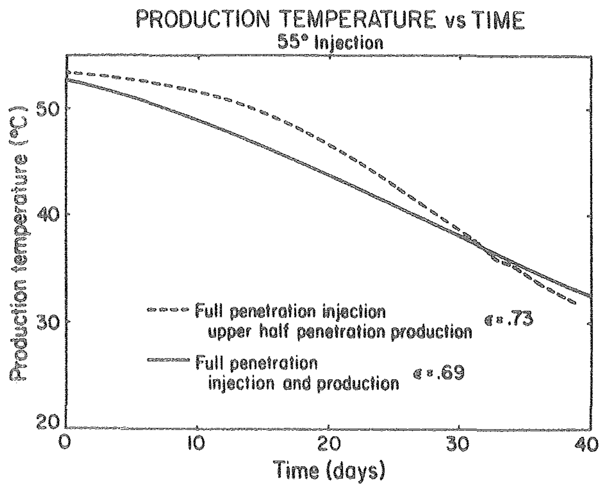

FIG. 9. Production temperature versus time for the storage of 55°C water for two well penetration arrangements (ε is the energy storage-recovery factor).

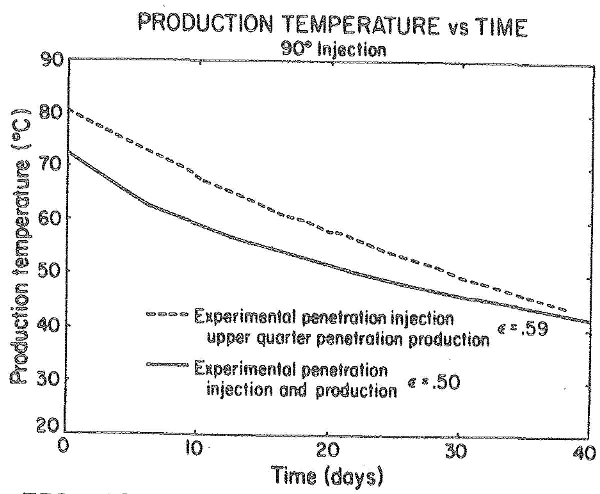

FIG. 10. Production temperature versus time for the storage of 90°C water for two well penetration arrangements. (ε is the energy storage-recovery factor).

K_a \ T_{inj}	36°C	55°C	70°C	90°C
15d	0.69	0.68		0.58
52d	0.67	0.57 (1/2) 0.62	0.46	0.34 (1/2) 0.42 (1/3) 0.44
		(60-60-60) 0.65 (60-120-60) 0.57		(60-60-60) 0.42 (1/2) 0.51
175d		0.31 (1/2) 0.39 (1/3) 0.41	0.24 (1/2) 0.31 (1/3) 0.34	

Unless otherwise indicated:

$(t_{inj}, t_{store}, t_{prod})$ = (90-90-90) days

T_o = 20°C

(1/2) or (1/3) indicates production from the upper 1/2 or upper 1/3 of the aquifer thickness respectively.

TABLE 1. Recovery Factor calculated with numerical model "CCC" for different injection temperatures and aquifer permeabilities.