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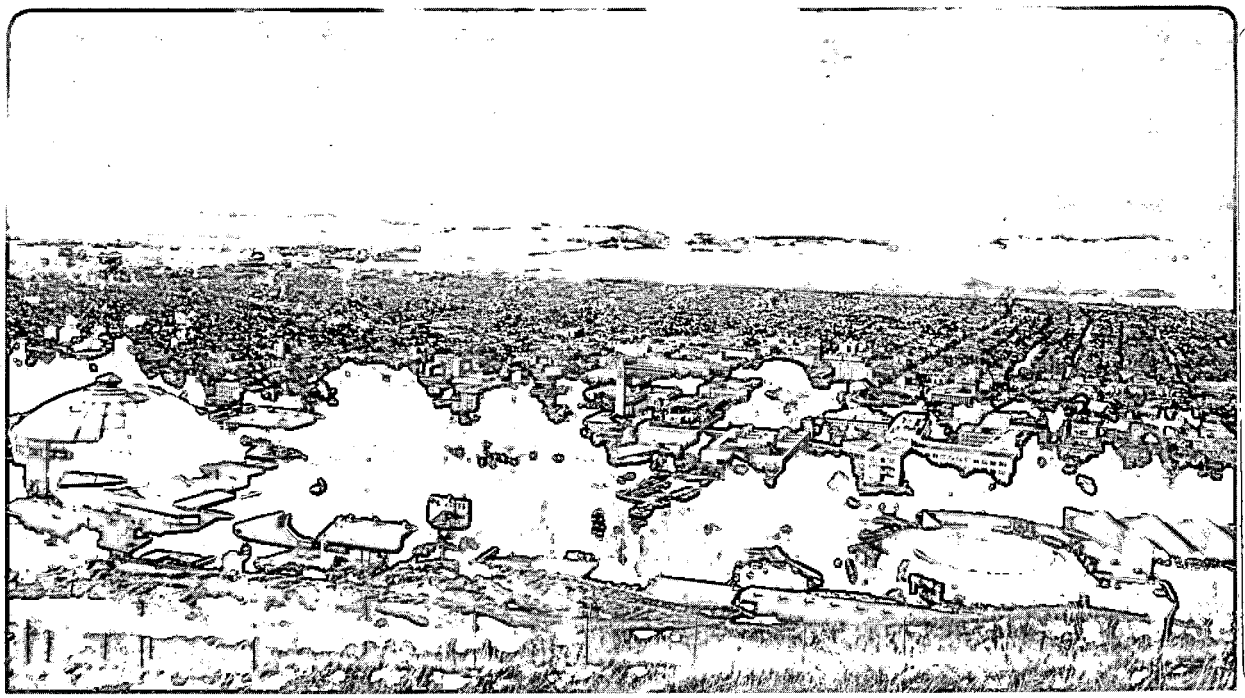

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Seasonal Storage of Thermal Energy in Unsaturated Soils: Modeling, Simulation, and Field Validation

C. Doughty, C. F. Tsang,* E. Korin,† and A. Nir†*

*Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

†Ben-Gurion University of the Negev
Beer-Sheva, Israel

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ABSTRACT

Most investigations on seasonal storage of thermal energy have concentrated mainly on cold and moderate climatic regions, and have emphasized aquifer storage. In warm, arid climatic zones, where the use of groundwater aquifers for this purpose is not feasible, unsaturated soil has been identified as one of the most suitable media. Our previous research programs used mathematical modeling to investigate both general concepts and a specific configuration for a storage facility in unsaturated soil. In the present project, a reduced-scale field experiment was performed in order to: a) validate the mathematical models of the storage system and study the relevant heat transfer processes in unsaturated soils; b) test the proposed technologies for the construction of the storage facility, including heat-exchanger emplacement and operational control; and c) provide cost estimates of the implementation of this method. The transfer of heat to the soil is achieved through a heat exchanger constructed of 0.03-m-diameter polybutylene pipe in a helical configuration 1 m in diameter and 6 m in length, which is inserted into a 10-m-deep well. A detailed description of the experimental procedures and technological developments are given in a companion paper (Bar-On et al., 1991), while the present paper emphasizes model development and validation. Two experimental storage cycles were performed and modeled, and a satisfactory match was obtained between the observed and predicted temperatures throughout the storage volume. The sensitivity to parameter estimates, modeling approximations, and parameter nonlinearity was also studied. On the basis of the accumulated knowledge and experience from this project, a pilot-scale experiment appears feasible.

BACKGROUND

Seasonal heat storage concepts and designs have undergone numerous tests and accumulated many years of operational experience in a variety of geologic storage media (International Conferences on Seasonal Thermal Energy Storage, 1981, 1983, 1985, 1988, 1990), including aquifers, caverns, and dry rock, as well as shallow partially-saturated soils, which are by far the least expensive to use and most widely available geologic storage media. These applications refer mainly to colder or moderate climatic zones, while only limited progress on the application of this concept is reported for warm climatic zones (WCZ) where shallow aquifers are rare, and when present are needed for water supply. While seasonal heat storage in WCZ may be expected to benefit from lower heat losses to the environment and higher solar inputs, the lower specific demand for domestic heat and shorter heating periods make the need for heat storage seem less urgent and the investment less attractive. Preliminary analysis indicates that this may not be the right conclusion (Nir and Benson, 1982). These zones, which include the southwest United States, parts of Australia, and the Mediterranean countries, are subject to intensive growth in population and in industrial and agricultural development. They should be expected to benefit from suitable methods of heat storage.

Although experience from other storage media and other climatic zones can serve as a useful base of knowledge for designing storage facilities in unsaturated soil, specific features of WCZ give rise to new physical processes in soils, which introduce additional heat transfer mechanisms, and thus require new technological approaches for the design of seasonal heat storage systems. This need motivated our previous mathematical modeling studies, in which a particular configuration for heat storage in shallow unsaturated soils was developed (Doughty et al., 1983; Nir, 1983; Nir et al., 1986). The objectives of the present combined experimental/modeling study are: (a) verification and validation of theoretical models; (b) use of the models for storage-facility design, construction, and operational control on a reduced field scale; (c) test of

proposed technologies for excavation, emplacement, operation, and control of the storage facility, especially those associated with the heat-exchange and water-transport pipes; (d) evaluation of total system operation; (e) collection and evaluation of input data for cost estimates; and (f) identification of possible environmental effects.

HEAT EXCHANGER CONFIGURATION AND MATHEMATICAL MODEL

The storage system design is envisioned to consist of multiple vertical heat exchangers, each constructed of flexible polybutylene tubing 0.03 m in diameter, shaped in a helical configuration of 1.3 m diameter and 18 to 24 m length, placed in a well. For the present experiment, a single reduced size exchanger of 1 m diameter helix and 6 m length was used. It was placed in a 10 m deep well, and equipped with temperature and moistures sensors. The well space was refilled with the excavated soil, which was then saturated with water. The heat-exchanger water circulation system is closed; water circulating through the heat exchanger does not come in contact with soil moisture. Figure 1 shows a schematic diagram of the heat exchanger.

The numerical simulator PT (Bodvarsson, 1982) was used to calculate conductive heat transfer in the soil, with either a constant or temperature-dependent thermal conductivity; moisture flow in the unsaturated-soil storage medium was not included. Theoretical calculations have been made (Bensabat et al., 1991a, b), indicating that this is a satisfactory approximation for a storage system under these experimental conditions, i.e., heat-exchanger inlet temperature in the range of 65 to 80°C, and heat storage in loess and silt soils with a high initial water content. Under other conditions, drying of the soil at the thermal front may cause a significant reduction in heat transfer coefficient, redistribution of solutes, and chemical and physical changes in soil properties.

In the heat exchanger itself, the heat transfer is by convection and conduction, with fluid flow modeled as simple piston displacement. The helical tubing is modeled by a cylindrical conduit of equivalent volume and surface area. This enables a two-dimensional (r-z) model to be used, which greatly reduces computational costs. The conditions under which this approximation is adequate have been studied by mathematical modeling: the temperature distribution around one turn of the helix is compared with that around the equivalent length of cylindrical conduit (Doughty et al., 1991). These studies had the added benefit of aiding in the design of the experiment by determining the optimal vertical distance between turns of the helix.

PREPARATION FOR THE FIELD EXPERIMENT

The initial stages of this project include: (a) construction of a field scale test facility; (b) determination of local soil thermal properties; (c) simulation of the planned experiment using local parameter values to aid in experimental design; (d) estimation of the sensitivity of the model to the adopted approximations; (e) selection of technical approaches of storage well excavation, heat exchanger construction and insertion, sensor location and data collection; and (f) additional theoretical studies of the heat transfer process. A detailed description of this work is given by Bensabat et al. (1988) and Doughty et al. (1991).

To determine the local soil thermal properties, two observation wells were drilled and equipped with temperature sensors. Several typical temperature depth profiles are shown in Figure 2. These measured temperature profiles may be used to estimate the value of soil thermal diffusivity by comparison to an analytical solution for the temperature profile in a homogeneous semi-infinite medium with a seasonally-varying surface temperature. The calculated profiles shown in Figure 2 assume a thermal conductivity of 1.8 W/mK. We consider this to be a first approximation only, as data from only a limited time period (3 months) were used. Furthermore, this method only provides information on the thermal conductivity at ambient temperatures, while the actual values of thermal conductivity at the elevated temperatures of the experiment are unknown. The experiment itself can be used to estimate values of thermal conductivity at higher temperatures, by comparing observed and calculated temperature distributions in the soil at the end of the heat-charging period. To identify locations where thermistors should be placed (i.e., where the temperature field is most sensitive to the value of thermal conductivity), the planned experiment was modeled using two different values of thermal conductivity. The differences between the resulting temperature distributions, shown in Figure 3, indicates that the thermistors should be located near the helix, where these differences are largest.

THE FIELD EXPERIMENT: COMPARISON WITH MODELS

The first experimental test consisted of a 9 month charge and a 1 month discharge period beginning in February 1989. The second test, performed in February 1990, consisted of a charge period of 35 days, at higher temperatures and flow rates and with better control capability than those of the first test. The results of the first test were used to evaluate the basic mathematical model and the benefits of added modeling details, and to test the sensitivity of the calculated results to thermal conductivity. Based on these studies, an improved model was developed, which was then compared with the results of the second test. Additionally, the validation procedure included model verification against analytical solutions, an independent estimate of thermal parameters, and analytical and numerical analysis of the heat transfer processes (Doughty et al., 1991).

The heat-exchanger inlet temperature and flow rate for the numerical model of the 1989 test are shown in Figure 4. Hourly variations of 5–10°C and ~10 l/hr have been averaged out. Results of the 1989 test and the calculation made with the base model (Case A) are shown in Figures 5 and 6. Case A uses uniform constant values of thermal conductivity (1.8 W/mK) and heat capacity (2.35 MJ/m^{3}K). Figure 5 shows observed and calculated time sequences of temperature for two sensor locations. The experimental test was interrupted several times due to electrical breakdowns. This provided an unintentional test of the high-frequency thermal response of the system. Figure 5 indicates that the response was well reproduced by the calculation for the outlet temperature; other sensor locations show similar agreement. Figure 6 shows the observed temperatures superposed on the calculated temperature contour lines at the end of the 1989 charge period. The simulation results of the base model are generally within 2–4°C of the observed values, and in most cases underpredict them.

To enable a convenient comparison between the output of various versions of the model and the field observations, we consider the time-average of the fractional difference between the observed and calculated temperatures

$$<\Delta T_{frac}> = <\frac{(T_{obs}-T_{calc})}{(T_{obs}-T_{obs}^{init})}>$$

where T_{obs} and T_{calc} are observed and calculated temperatures, respectively, T_{obs}^{init} is the observed temperature at the start of the experiment, and < > denotes the time-average for days 160–290 for the 1989 test, and the time-average for days 30–70 for the 1990 test. $<\Delta T_{frac}>$ is calculated for three temperature points (see Figure 6):

Ch0 – The heat exchanger outlet temperature ($r = 0.5$ m, $z = 4$ m)
Ch6 – The deepest temperature sensor inside the heat exchanger ($r = 0.3$ m, $z = 9$ m)
A7 – The deepest temperature sensor outside the heat exchanger ($r = 1.68$ m, $z = 7$ m)

Although the *in situ* value of soil thermal conductivity λ was estimated from the soil temperature profile studies mentioned above, the actual value of λ within the heat exchanger may be different from it due to variations in temperature, moisture content, and soil density resulting from the excavation and refilling procedure. It was therefore considered worthwhile to treat λ as an unknown parameter and model the 1989 storage cycle using a range of values for it. Results of such a sensitivity study are shown in Table 1. In each case, λ is constant in time and space. Increasing λ by 25% above the base-case (Case A) value results in larger fractional temperature differences (Case B), while decreasing it by 20% results in smaller differences (Case C). Recent soil temperature profile analyses, using data from a longer time period (1 year) than were used in the previous studies, yield values of λ closer to the lower value.

Three additional mechanisms, described below, can be included in PT to more accurately reflect physical processes occurring during the storage cycles. (The results of calculations that include these effects are summarized in Table 2).

1) It is generally accepted in the soil physics literature that soil thermal conductivity increases with temperature. For simplicity we consider a linear variation with a base value of λ at $T = 22$°C of 1.8 W/mK (Case D). Case D produces larger fractional temperature differences than the base case (Case A). This is not surprising in view of Table 1, which shows that using a larger constant base value of λ also increases fractional temperature differences. For a temperature-dependent λ case to yield decreased fractional temperature differences, the value of λ at 22°C must be smaller.

2) Soil heat capacity C varies with soil moisture content, which is larger within the heat exchanger because the backfilled soil was saturated with water during heat exchanger construction. Allowing C to vary in space has a very small affect on fractional temperature difference (Case E).

3) In the original modeling, the center pipe was assumed to be perfectly insulated between the ground surface and the top of the heat exchanger (depth 0 to 4 m). Using realistic thermal properties for the insulation allows a small part of the heat stored to be deposited in the shallow soil overlying the heat exchanger. Including this effect decreases the fractional temperature differences (Case F). For the 1990 cycle, which was conducted with higher heat exchanger inlet temperature and flow rate, the fractional temperature differences are somewhat higher (Case F-90).

The results of a new model, combining all the improvements shown in Table 2, and using a smaller base value for thermal conductivity, as indicated in Table 1, are shown in Table 3 for both the 1989 and 1990 storage cycles. The fractional temperature differences are much improved relative to the base case for the 1989 cycle (compare Cases A and G). For the 1990 cycle, the effect of decreasing the base value of λ, and using $\lambda(T)$ and $C(r, z)$ has mixed results (compare Cases F-90 and G-90), but for the most important parameter, heat-exchanger outlet temperature, the fractional temperature difference is much smaller.

DISCUSSION OF RESULTS

The problems which were of major concern at the outset of the experimental program related to the availability and reliability of large-diameter well drilling, heat exchanger construction and emplacement techniques, and the stability of the heat transfer process in unsaturated soils. Satisfactory drilling, construction, and emplacement technologies were developed and utilized, and are discussed in the companion paper by Bar-On et al. (1991). The heat transfer process did not indicate any significant deterioration during the 9 month charging period within the present precision of observation. In addition, there was no indication that heat transfer improved following a soil-wetting operation that was done during the last part of the charge period. The stability of the heat transfer implies that the moisture content remains near-constant, which may be ascribed to the type of soil (silty clay) and to its initial full saturation in the well interior. This justifies the modeling approach, which does not include the coupling of heat, water, and solute transfer. There remains an uncertainty about this problem in a multi-year operation, and therefore the soil-wetting option should not be discarded on the basis of this experience. Furthermore, the possible accumulation of solutes at the hot boundary deserves further theoretical and experimental investigation.

MODELING A FULL-SCALE WELL

Based on the results of the experiments, a multi-year simulation for a full-scale pilot project was carried out using the base model. The simulation considers a storage well in a multiple storage-well field (thus minimizing edge effects). It indicates a discharge capability of 6 MWh per annual storage cycle, with an energy recovery of 70%, for a nominal size heat exchanger of 18 m length and 1.3 m diameter, with inlet temperatures of 65°C during the charge period and 20°C during the discharge periods, and a 36°C minimum outlet temperature during discharge. Results of the simulation are shown in Figure 7.

The energy output can be increased by changes in operating conditions such as a) higher inlet temperature; b) lower minimum usable outlet temperature (e.g. for agricultural uses or with heat pump coupling); c) longer heat exchanger and siting at a greater depth; and d) incorporation of phase change material. The resulting capability of thermal energy supply for a 4000 m^2 storage field (110 wells) would be between 500 to 1000 MWh per storage season, depending on the operating conditions, after an initial transient period of three years. This size can be considered to be the basic module, which can be expanded by adding similar units according to local conditions of supply and demand.

The model used for the present work can be used to aid in the construction of a pilot plant facility of one or two full-size storage wells, with the objective of testing the predicted operational performance and the improved methods of heat exchanger construction and emplacement. Such a program can be carried out with a moderate investment at the present experimental site, which is equipped with test instrumentation and facilities for the accommodation of two additional wells. An alternative site could be located close to an existing supply of alternative energy, such as solar, geothermal, or industrial waste heat, and a potential user of this stored heat.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The combined experimental/modeling effort of the project has been found very useful, both from the point of view of the experimenters and the modelers. Modeling results have been used to aid in experimental planning and design. Experimental results have both allowed validation of model results and provided insight into the importance of various physical processes. The project achieved its primary objectives, which were to: a) investigate seasonal thermal energy storage in an unsaturated soil under semi-arid climatic conditions; b) demonstrate a validation procedure for the conceptual and mathematical models of the storage system; c) develop and test heat-exchanger construction and emplacement techniques; d) test theories of heat and mass transfer in the unsaturated zone; e) make an initial cost estimate of this heat storage method.

The results of the research project suggest that unsaturated soils can provide thermal energy storage without causing environmental problems; however, further multi-year observations are needed. The mathematical models have been shown to provide a useful tool for the design of the storage system. Several possible improvements in engineering design, construction methods, and cost reduction have been indicated. The theoretical investigation of heat and mass transfer in unsaturated soils has indicated that moisture transport is negligible under conditions of the present experiment (Bensabat et al., 1991b), and that the model approximation of conductive heat flow is appropriate. It also has motivated further laboratory experiments, with results being of potential significance not only for seasonal thermal storage in soils, but also for the disposal/isolation of hot chemical or nuclear waste products in such environments.

Furthermore, there is a need for additional theoretical and laboratory studies on long-term geochemical effects on the heat transfer in the unsaturated zone at the hot boundary. The potential benefit of heat pump use and cold storage coupling should be included in future investigations.

ACKNOWLEDGEMENTS

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Table 1. Sensitivity studies

Case	λ (W/mK)	Comments	$<\Delta T_{frac}>$ (%)		
			Ch0	Ch6	A7
A	1.8	Base case Most calculated T's too low	4.1	5.8	3.6
B	2.25	Worse than A	9.0	9.8	5.4
C	1.44	Better than A	-1.1	2.4	2.2

Table 2. Model improvements

Case	Description	$<\Delta T_{frac}>$ (%)		
		Ch0	Ch6	A7
D	$\lambda(T)$: linear variation $d\lambda/dT = 0.009$ W/mK^2, $\lambda(22) = 1.8$ W/mK	5.7	7.5	3.3
E	$C(r,z)$ duct interior $C = 3.2$ MJ/m^{3}K elsewhere $C = 2.35$ MJ/m^{3}K	4.1	5.8	3.5
F	Shallow heat flow included	3.3	5.1	3.0
F-90	1990 test, same model as F	5.0	3.7	1.8

Table 3. New model

Case	Description	$<\Delta T_{frac}>$ (%)		
		Ch0	Ch6	A7
G	Combine all three improvements $d\lambda/dT = 0.009$ W/mK^2, $\lambda(22) = 1.35$ W/mK	-1.0	2.5	0.4
G-90	1990 test, same model as G	2.6	4.2	2.3

Note: Cases A, B, C, D, E, F, and G correspond to the 1989 test.
Cases F-90 and G-90 correspond to the 1990 test.

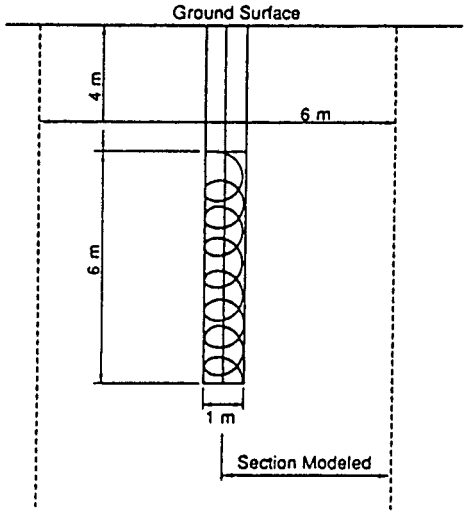

Figure 1. Schematic diagram of the helical heat exchanger.

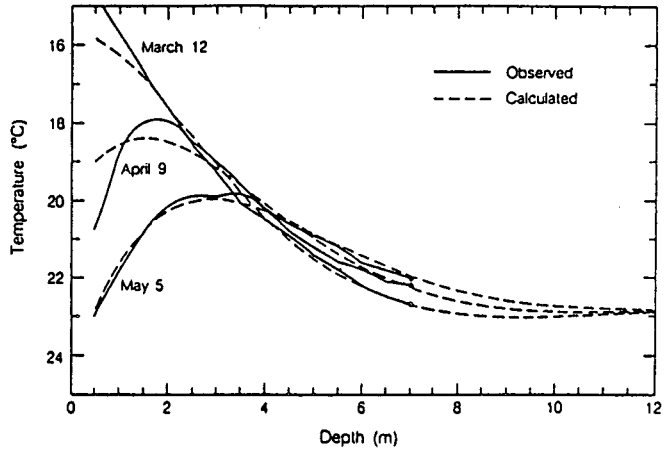

Figure 2. Observed vertical temperature profiles prior to the experiment, and the profiles calculated analytically assuming a thermal conductivity of 1.8 W/mK.

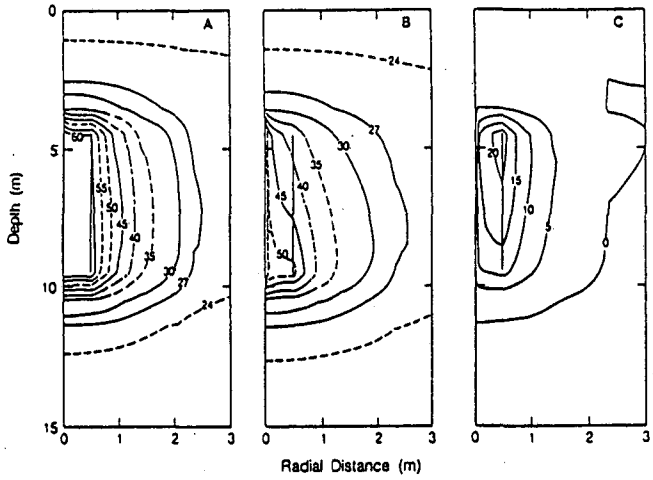

Figure 3. Computed temperature distribution after two months of charge for thermal conductivity of 0.8 W/mK (frame A) and 1.8 W/mK (frame B), and the difference between the two (frame C) (all contours labeled in °C).

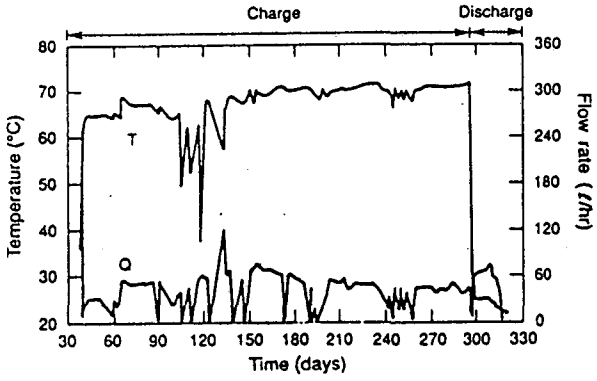

Figure 4. Inlet temperature and flow rate for the 1989 test.

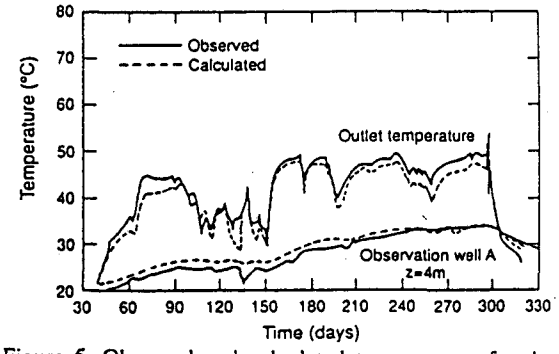

Figure 5. Observed and calculated temperatures for the 1989 test, for the heat exchanger outlet and at a depth of 4 m in observation well A.

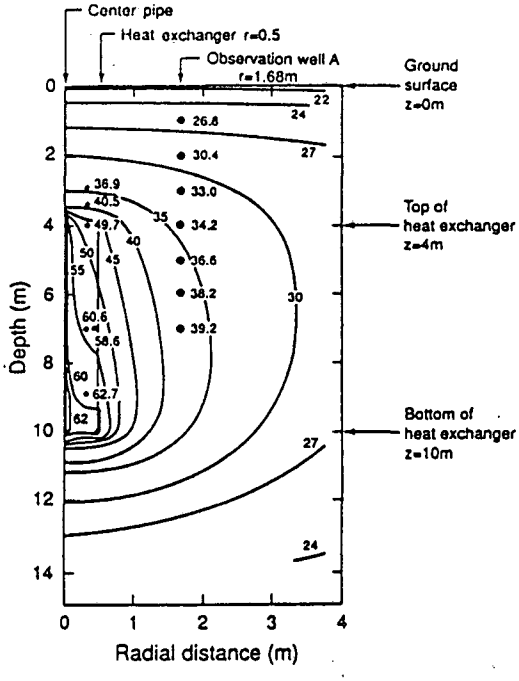

Figure 6. Calculated temperature distribution at the end of the 1989 charge period, and the observed temperatures at sensor locations. The heat exchanger outlet location is at $r = 0.5$ m, $z = 4$ m.

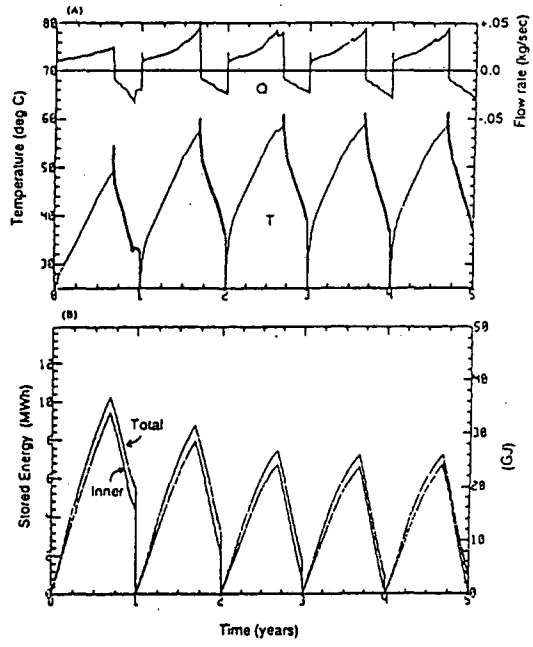

Figure 7. Results of the 5-year simulation for an operational well. Frame A shows the heat-exchanger outlet temperature (T) during the charge and discharge (bold) periods, and water circulation rate (Q). Frame B shows stored energy in the soil; note the 3-year transient.

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BERKELEY, CALIFORNIA 94720