Title
MODELING UNDERGROUND STORAGE IN AQUIFERS OF HOT WATER FROM SOLAR POWER SYSTEMS

Author
Tsang, Chin Fu

Publication Date
1977-05-01

Presented at International
Solar Energy Society (American
Section) "Solar World" meeting
Orlando, Florida, June 6-9, 1977.

LBL-6327 c.1
UC-94a

Energy and Environment Division

Modeling Underground Storage in Aquifers of Hot Water from Solar Power Systems

Chin Fu Tsang, Colin B. Goranson,
Marcelo J. Lippmann and
Paul A. Witherspoon

May 1977

Lawrence Berkeley Laboratory University of California/Berkeley

Prepared for the U.S. Energy Research and Development Administration under Contract No. W-7405-ENG-48

DISCLAIMER

Paper to be presented at the International Solar Energy Society (American Section), "Solar World" meeting at Orlando, Florida, 6-9 June 1977.

MODELING UNDERGROUND STORAGE IN AQUIFERS OF HOT WATER FROM SOLAR POWER SYSTEMS

Chin Fu Tsang, Colin B. Goranson, Marcelo J. Lippmann, Paul A. Witherspoon
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

The feasibility of storing hot water from solar energy collectors in underground aquifers is explored. Using a numerical model for computing heat and mass flow in a three-dimensional water-saturated porous medium, three cases are studied: a) daily storage, b) seasonal storage with semi-annual cycles and c) seasonal storage with annual cycles. The hydrodynamic and thermal behaviors of the storage system are analyzed and illustrated. In all the cases studied the energy retrieval is found to be over 80%.

INTRODUCTION

The development of practical and low-cost methods for storing large amounts of thermal energy is of fundamental importance for the utilization of solar energy. The basic function of a storage system is to act as a buffer between time-varying solar energy inputs and thermal and/or power demands. The present paper explores the novel concept of storing hot water from solar energy collectors into natural aquifers underground.

Aquifers are geologic formations which contain and conduct water. They may be found at depths ranging from a few meters to several kilometers. Confined aquifers are those which are bounded above and below by impermeable layers and are saturated by water under pressure. For many years these types of aquifers have been used for liquid waste disposal and for storing fresh water, oil products and gas[1,2]. However, their use for hot water storage is a relatively new concept suggested by Robbimov, Umarov and Zakhidov[3], Kazmann[2] and Meyer and Todd[4] in the early seventies.

The physical basis of the concept lies in: a) the low thermal conductivities of caprock and bedrock materials, b) the large volume of the aquifer (of the order of $10^7 m^3$), and c) the capability of storing water under high pressures. To estimate the feasibility and efficiency of such a storage system, the processes during injection and withdrawal cycles must be understood, such as:

1. Thermal behavior of and heat loss from the system during successive cycles of operation.
2. Pressure distribution in the aquifer during the process.
3. The possibility of compaction of the aquifer and overburden, with the resulting land subsidence phenomenon.
4. Rock-water chemical reactions and the resulting change in aquifer permeability.

It is only recently that sophisticated computer models have been developed to study these questions using the proper physical conditions and parameters, and to make realistic predictions of the energy recovery efficiency of aquifer storage systems. Furthermore, physical models and field experiments have been initiated[5,6] to test this concept. These will not only provide data to verify numerical models, but also give an indication of the feasibility and possible problems that may be encountered during the implementation of the aquifer storage concept.

In the present work, we will make use of a numerical model develped at the Lawrence Berkeley Laboratory[7,8,9] to investigate the problems of daily cyclic hot water storage, as well as seasonal (average) storage for a solar energy collection system. In the following section of the paper we will describe the computer program used in the calculations. Results will then be presented and discussed. The paper will conclude with a summary and some general comments.

NUMERICAL MODEL "CCC"

The numerical model employed is called "CCC" which stands for "Conduction, Convection and Compaction." It is based on the so-called Integrated-Finite-Difference Method[10,11,12]. The model computes heat and mass flow in three-dimensional water-saturated porous systems. Concurrent with the mass and energy flow, the vertical deformation of the aquifer system is simulated using the one-dimensional consolidation theory of Terzaghi. The governing equations used may be found in Reference 8 (see also Reference 13). Thus the following physical effects can be included simultaneously in the same calculations:

1. Flow of hot and cold water with large viscosity and density differences.
2. Effects of temperature on rock and fluid properties (e.g., heat capacity, viscosity and density).
3. Heat convection and conduction in the aquifer, caprock and bedrock.
4. Effects of gravity on fluid flow.

5. Effects of regional groundwater flow.
6. Combined effects of many injection and withdrawal cycles.
7. Spatial variations in aquifer properties.
8. Possible compaction and the associated land subsidence due to pressure changes during the injection-withdrawal history.

In the present paper, we have concentrated on a detailed calculation of the mass and energy flow, and left the problem of compaction and subsidence for a later study.

The numerical model has been successfully validated against three independent semi-analytical solutions previously published: a) Theis Solution[14], which describes the change, with time and space, of pressure in an infinite reservoir under production, b) Avdonin's solution[15] which gives the temperature distribution as a function of time and radial distance from a well when cold water is injected into a hot reservoir, c) Gringarten and Sauty's solution[16] which gives, for a production-injection doublet, the temperature variation at a production well when colder water is injected into the other well. The substantial agreement[7] of these three different examples with our model gives us considerable confidence in its validity.

CASES STUDIED

Three different cases are studied corresponding to three different cyclic periods:

1. Daily storage: hot water is injected for 12 hours during daytime and produced for 12 hours during nighttime.
2. Seasonal storage, semi-annual cycle: hot water is stored in spring for 90 days, pumped out to use for air-conditioning in summer for 90 days, then hot water is again stored in autumn for 90 days and finally pumped out to use for heating in winter for 90 days.
3. Seasonal storage, annual cycle: hot water is stored in summer for 90 days and used for 90 days in winter for heating. There is no injection or production during spring or autumn.

The rates of injection and production are kept the same, equal to 10^6 kg/day. It is estimated [17] that at this rate 170°C water would be able to meet the space heating or air-conditioning needs of approximately 2,000 people, assuming a 30% heat loss in transport lines. The parameters used in the calculations are tabulated in Table I, which are taken from standard sources. Fluid viscosity, density and heat capacity are assumed to be temperature-dependent, corresponding to those of pure water.

The mesh design used in the numerical model is shown in Figure 1 for the cases (2) and (3) of seasonal storage. The thicknesses of the caprock, aquifer, and bedrock are equal and are assumed to be 100 m. The well for injection and production is positioned at zero radial distance, the mesh having radial symmetry around that axis.

Two technical remarks have to be made here:

1. In pressure-fluid-flow calculations, mesh elements can be made to be increasing in size as radial distance increases, representing less and less pressure change. But in heat calculations, mesh elements should decrease in size as radial distance increases since the injected hot water will move a smaller radial distance in unit time steps. Figure 1 shows that we have chosen equal radial distance steps, $\Delta r = 2$m, up to 70 m from the well, which is beyond the farthest distance thermal fronts will reach in these studies. Element sizes are allowed to increase for distances greater than 70 m. We have made a study[7] of dependence of results on mesh size and have shown that with this fine mesh, numerical dispersion is minimized.
2. The caprock (and bedrock) is divided into 5 layers with thicknesses of 5, 5, 15, 35 and 40 m. We have made a study with two other caprock meshes: a) 2 layers of 50 m thickness each and b) 6 layers with thicknesses of 1, 1, 3, 5, 25 and 55 m. We found the 2-layer mesh underestimates the heat losses. The difference in heat conduction between the 5-layer and 6-layer mesh is less than 5%.

For the daily storage case we have chosen an aquifer 33 m thick. The mesh design is similar to that shown in Figure 1, with vertical dimensions reduced by a factor of 3 and horizontal dimensions reduced by a factor of 7.7.

RESULTS

The initial aquifer temperature, T_o, is assumed to be 20°C. We have performed calculations with injection temperature T_i assumed to be 120°C, 220°C and 320°C. It appears that the temperature of the produced water for different injection temperatures is very similar, with a scaling according to the factor $(T_i - T_o)$. Below we shall only show the results for $T_i = 220$°C.

For case 2, seasonal storage, semi-annual cycle, we have performed calculations not only for a well fully penetrating the aquifer, but also for a well partially penetrating it for 50 m. Figure 2 displays the temperature contours within the aquifer for the partial penetration case (a) at the end of the injection period of the first cycle and (b) at the end of the production period of the same cycle. The thermal front is not sharp due to heat conduction within the aquifer and with the confining beds. This is seen more clearly in Figure 3 which displays the temperature near the center of the aquifer as a function of radial distance for the case of the well fully penetrating the aquifer. Curves for different times are shown for the first cycle. Note that after 90 days of injection, the 20°C isotherm is about 30 m from the well. The hydrodynamic front, i.e., the location of the injected water, is however much farther away, at about 60 m from the well. The thermal front lags behind this front representing the effect of the porous sandstone medium being heated up and taking energy away from the injected water. From Figure 3 one can also see that at the end of the first cycle (t = 180 days), the aquifer has been heated up, resulting in a more efficient hot water storage system for the second and successive cycles.

Figure 4 represents the production temperature at the well during the production period for successive cycles for the case of semi-annual cycle with full penetration. The recovery temperature is increased for each successive cycle as the aquifer is heated up, making it a more efficient hot water storage system. The process will reach quasi-equilibrium when later cycles do not change the temperature appreciably.

The results for semi-annual cycles with full penetration are summarized in Table II. It can be seen that energy recovered (which may be calculated from the integral of temperature over time in Figure 4) improves with each successive cycle. The heat lost is also shown and is two orders of magnitude smaller than the energy recovered. The difference between energy injected and recovered is the energy diffused to heat up the aquifer, making it a better storage system for the following cycle. The last line gives the minimum recovery temperature during production. This corresponds to the lowest temperature found at the end of each production period, as shown in Figure 4.

Table III summarizes the results for the first two cycles in the daily storage case. The energy recovery efficiency is surprisingly high, since there is not enough time for substantial thermal diffusion to take place. Hydrodynamic dispersion in the porous medium, which is ignored in the present calculation, may reduce the efficiency, but its magnitude and effects are site-dependent.

For all cases studied, the percentage of energy recovered (i.e., recovered energy divided by total injected energy) and the minimum production temperature during each cycle are plotted against cycle number in Figures 5 and 6, respectively.

SUMMARY AND CONCLUSIONS

In the present paper we have made a study of hot water storage in aquifers. Three typical cases are analyzed using a numerical model developed at the Lawrence Berkeley Laboratory. The thermal and fluid flow behaviors of the aquifer system are analyzed and illustrated. In all these cases, the energy recovery efficiencies are surprisingly high, over 85% after only a few injection-production cycles. In the case of daily storage, the efficiency is about 97%. The presence of natural regional flow will tend to reduce these high values since it will sweep the hot water away from the well. However, it is found that this regional flow is usually very small, about 1 m/year for deep aquifers, in which case its effects will be insignificant. For shallow aquifers with a large regional flow, methods have been developed to design a system of wells to shield the hot water storage well from regional flow. In situations where regional flow has been measured, our model can include it in the calculations. The other factor that will reduce the energy recovery but cannot be computed by our model is the hydrodynamic dispersion, which is the dispersion of hot water fronts due to irregular paths taken by the fluid as it passes through the porous medium. (We are not aware of a general accepted technique which can calculate this dispersion, and which adequately reproduces existing laboratory and field data.)

So far we have assumed a simple system. The existence of any large connecting fractures will alter the picture considerably and requires further investigation. Chemical reactions will also be important because they may cause changes in porosity and permeability. It will be straight-forward to incorporate chemistry into our numerical model.

In spite of all these reservations, the results in this paper point to the great potential of using aquifers for hot water storage. Problems outlined above may be minimized by careful engineering. Field experiments currently being carried out will be important to verify the high efficiencies predicted by these calculations. To complete the understanding of the aquifer storage concept, flow through the wellbore and pumping methods for injection and production have to be studied. However, on these we can draw on the vast experiences in the fields of hydrogeology, petroleum engineering and geothermal energy.

REFERENCES

(1) D. L. Katz, K. H. Coates, "Underground Storage of Fluids," Ulrich's Books, Inc., Mich., 1968.

(2) R. G. Kazmann, "Exotic Uses of Aquifers," Pro. Am. Soc. Civil Eng., V. 93, No. IR3, p.8352, 1971.

(3) R. T. Robbimov, G. Ya. Umarov and R. A. Zakhidov "Storage of Solar Energy in a Sandy-Gravel Ground," Geliotekhnika, V. 7, No. 5, p.57-64, 1971. English translation in "Applied Solar Energy (USSR)".

(4) C. F. Meyer, D. K. Todd, Envir. Sci. Tech., V. 7, No. 6, p.512-516, 1973.

(5) F. J. Molz, J. C. Warman, T. E. Jones, "Transport of Water and Heat in an Aquifer Used for Hot Water Storage-Experimental Study," Am. Geophy. Union Fall Ann. Meeting, Dec. 6-10, 1976, San Francisco, CA.

(6) G. DeMarsily, Laboratoire d'Hydrogeologie Mathematique, Ecole Nationale Superieure Des Mines de Paris, private communication, 1977.

(7) C. F. Tsang, C. B. Goranson, M. J. Lippmann and P. A. Witherspoon, "Numerical Modeling of Cyclic Storage of Hot Water in Aquifers," AGU Fall Ann. Meeting, San Francisco, CA, Dec. 6-10, 1976, Lawrence Berkeley Lab., LBL-5929.

(8) M. J. Lippmann, C. F. Tsang and P. A. Witherspoon, "Analysis of the Response of Geothermal Reservoirs under Injection and Production Procedures," SPE-6537, Soc. Pet. Engs. of AIME, 47th Cal. Meeting, Bakersfield, CA., April 13-15, 1977.

(9) M. J. Lippmann, T. N. Narasimhan and P. A. Witherspoon, "Numerical Simulation of Reservoir Compaction in Liquid Dominated Geothermal Systems," Pro. 2nd Intl. Sym. on Land Subsidence Anaheim, CA, Dec. 10-17, 1976, Lawrence Berkeley Lab., LBL-4462.

(10) A. L. Edwards, "TRUMP: A Computer Program for Transient and Steady State Temperature Distribution in Multidimensional Systems," Lawrence

Livermore Lab., UCRL-14754, Rev. 3., 259 p., 1972.

(11) M. L. Sorey, "Numerical Modeling of Liquid Geothermal Systems," Ph.D. Thesis, Univ. of Calif., Berkeley, 65 p., 1975.

(12) T. N. Narasimhan, P. A. Witherspoon, Water Resources Res., V. 12, No. 1, p.57-64, 1976.

(13) P. A. Witherspoon, S. P. Neuman, M. L. Sorey and M. J. Lippmann, "Modeling Geothermal Systems," Int. Mtg. on "Geothermal Phenomena and Its Applications," Accademia Nazionale dei Lincei, Rome, 1975, Lawrence Berkeley Lab. Rep., LBL-3263, 68 p., 1975.

(14) C. V. Theis, "The Relationship Between the Lowering of Piezometric Surface and the Rate and Duration of Discharge Using Ground-Water Storage," Trans. Amer. Geophy. Union, V. 519, 1935.

(15) N. A. Avdonin, Neft'i Gaz, V. 3, p.37-41, 1964.

(16) A. C. Gringarten, J. P. Sauty, J. Geophy. Res., V. 80, No. 35, p.4956-4962, 1975.

(17) C. F. Meyer, Water Res. Bu., V. 12, p.237, 1976.

Work done under the auspices of U. S. ERDA.

TABLE I.

Property parameters used in hot water storage model.

	Reservoir (Sandstone)	Caprock-Bedrock (Mudstone)
Porosity	0.20	1×10^{-20}
Density $kg\ m^{-3}$	2.6×10^{3}	2.7×10^{3}
Heat Capacity $J\ kg^{-1}\ {}^{\circ}C^{-1}$	9.70×10^{2}	9.30×10^{2}
Thermal Conductivity $J\ s^{-1} m^{-1} {}^{\circ}C^{-1}$	2.894	1.157
Permeability m^{2}	1×10^{-13}	1×10^{-40}
Specific Storage $N^{-1}\ m^{2}$	1×10^{-3}	1×10^{-12}

FLUID PARAMETERS			
Viscosity (cp)	T(°C)	Heat Capacity $(J\ kg^{-1}\ {}^{\circ}C^{-1})$	T(°C)
1.005	20	4.127×10^{3}	25
5.45×10^{-1}	50	3.894×10^{3}	75
2.80×10^{-1}	100	3.652×10^{3}	125
1.82×10^{-1}	150	3.341×10^{3}	200
1.35×10^{-1}	200		
Expansivity $({}^{\circ}C^{-1})$ 3.17×10^{-4}			

TABLE II.

Energy Balance for each cycle for the case of seasonal storage with semi-annual cycle (full penetration). Results for cycles 2 and 4 are not shown.

	CYCLE 1	CYCLE 3	CYCLE 5
Energy Injected (Joules)	5.71×10^{13}	5.71×10^{13}	5.71×10^{13}
Energy Recovered (Joules)	4.96×10^{13}	5.144×10^{13}	5.2×10^{13}
Energy Loss from Aquifer (Joules)	5.35×10^{11}	7.7×10^{11}	9.1×10^{11}
Energy Diffused to Heat up Aquifer (Joules)	7.10×10^{12}	4.9×10^{12}	4.2×10^{12}
Percentage of Energy Recovered	86.8%	90.0%	91.1%
Production Temperature at End of Cycle	124°C	147°C	155°C

- Full Penetration -

1 Cycle = 180 days
$T_i = 220°C$
$T_o = 20°C$
$Q = 1 \times 10^{6}$ kg/day
H = 100 m
$\Delta R = 2$ m
No. of Layers = 4

TABLE III.

Energy Balance for each cycle for the case of daily storage (full penetration).

	CYCLE 1	CYCLE 2
Energy Injected (Joules)	3.17×10^{11}	3.17×10^{11}
Energy Recovered (Joules)	3.07×10^{11}	3.097×10^{11}
Energy Loss from Aquifer (Joules)	1.667×10^{8}	2.24×10^{8}
Energy Diffused to Heat up Aquifer (Joules)	9.83×10^{9}	7.08×10^{9}
Percentage of Energy Recovered	96.8%	97.7%
Production Temperature at End of Cycle	170°C	181°C

- Daily Cycle -

1 Cycle = 1 day
$T_i = 220°C$
$T_o = 20°C$
$Q = 1 \times 10^{6}$ kg/day
H = 33 m
$\Delta R = 0.26$ m
No. of Layers = 4

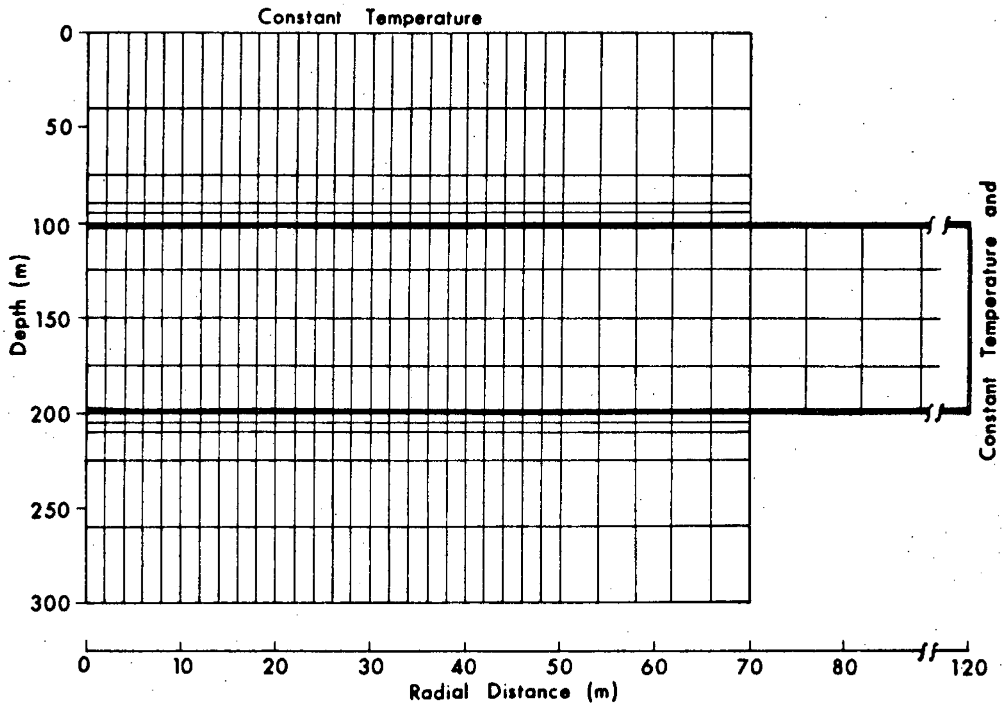

Figure 1.

Mesh design for Case 2 and Case 3. The problem has radial symmetry with well at the zero radial distance. The aquifer (depth: 100-200m) is confined by impermeable caprock and bedrock. The top of the caprock and the bottom of the bedrock are kept at constant temperature of 20°. Mesh design for Case 1 is obtained from this mesh by scaling vertically by 1/3 and radially by 0.13.

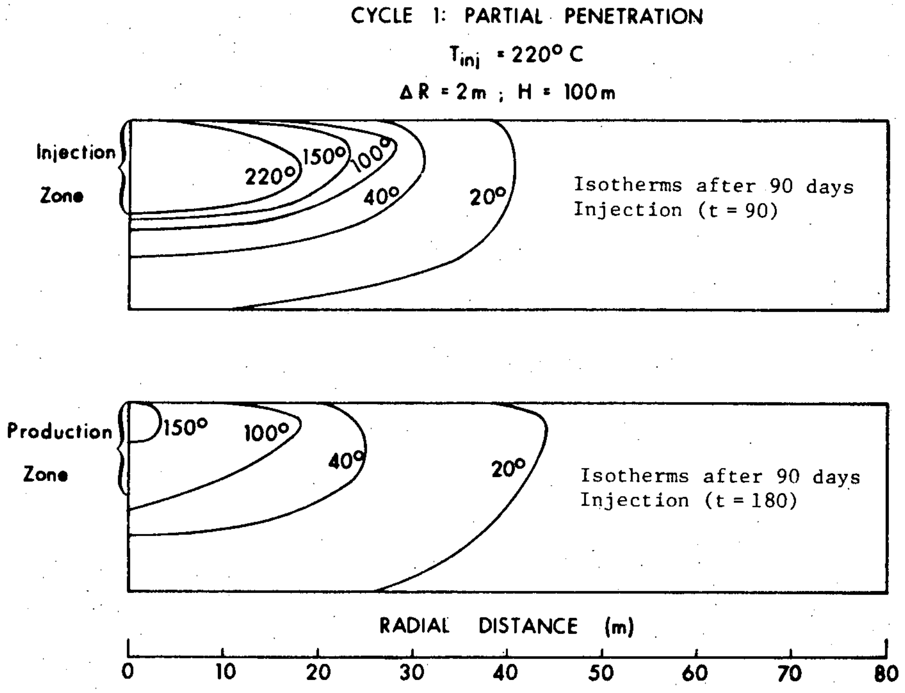

Figure 2.

Temperature contours in the aquifer after 90 days of injection; and after 90 days of production in Cycle 1, for the case of semi-yearly cycle, seasonal storage. The well penetrates the upper 50 m of the aquifer. Numbers labeling the contours are in degrees Centigrade.

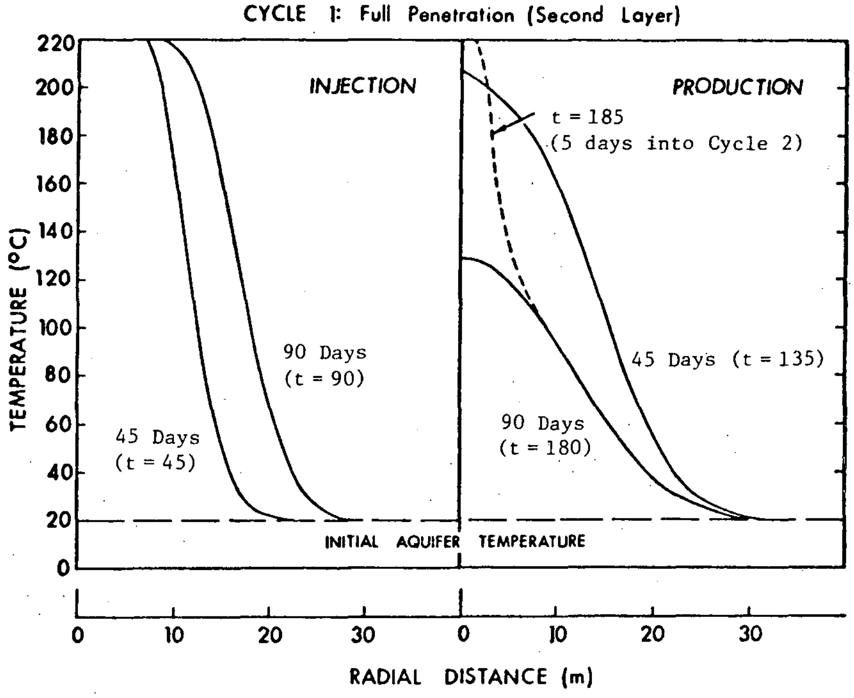

Figure 3.

Temperature profile within the aquifer 37.5 m from the caprock, as a function of radial distance from the well, for indicated times. t represents total time elapsed in days.

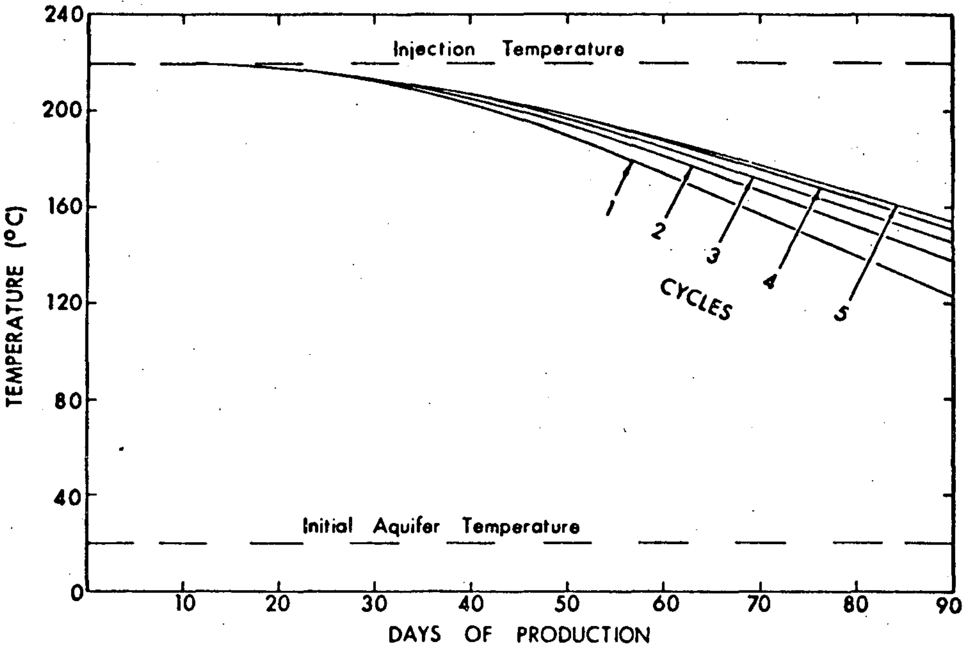

Figure 4.

Temperature at the well versus production time for each cycle. The case shown is for seasonal storage with semi-yearly cycle, well fully penetrating the aquifer.

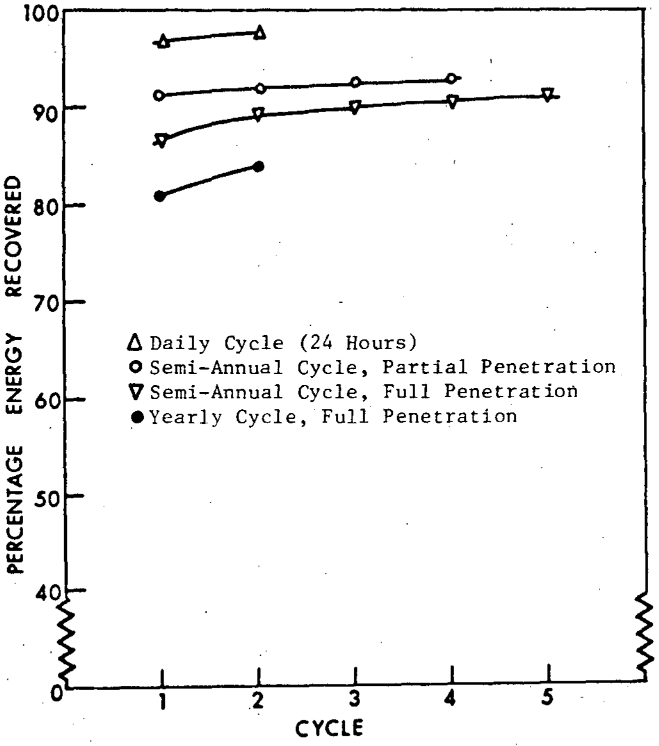

Figure 5.

Percentage of energy recovered over energy injected versus cycle number.

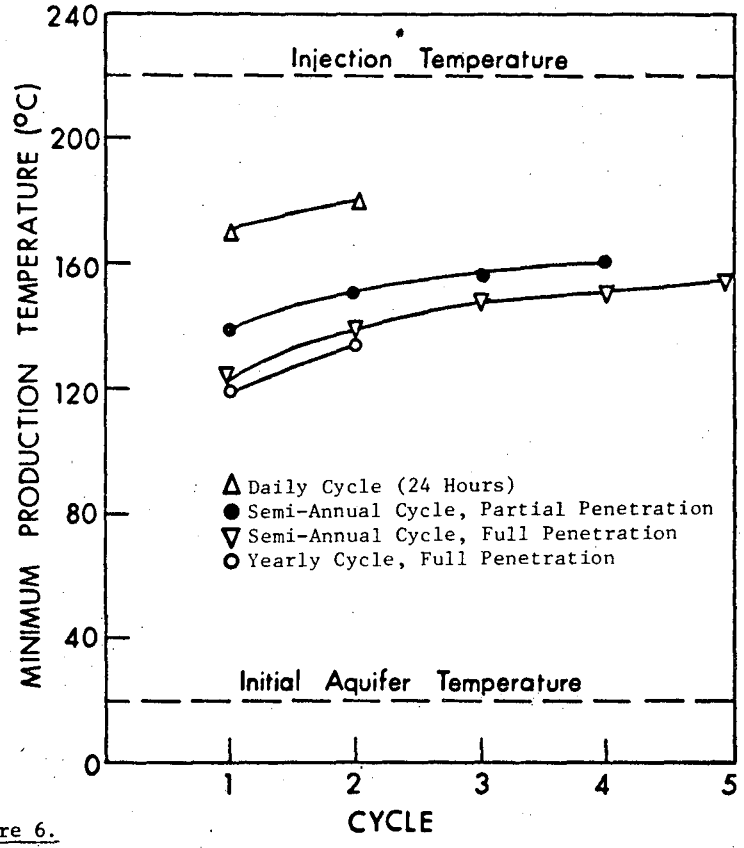

Figure 6.

Temperature at the end of each production period (minimum production temperature) versus cycle number.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720