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Author
Tsang, C.-F.

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Chin Fu Tsang

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Chin Fu Tsang
Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

The concept of thermal energy storage in aquifers was suggested a few years ago. The idea is to store in aquifers large quantities of hot water produced (1) as a by-product of power plants, or (2) from solar energy collectors, and to retrieve the hot water for use when needed. Hence this method will, on the one hand, recover waste heat from power plants that is normally wasted, thus making possible the implementation of large-scale total energy systems. On the other hand, when used in conjunction with solar energy systems, aquifer energy storage provides a buffer between time-varying solar energy inputs and thermal or power demands.

It is only recently that sophisticated computer models have been developed to study this storage system using the proper physical conditions and parameters, and to make realistic predictions of the energy storage and retrieval efficiencies. Furthermore, field experiments are currently underway to test this concept. In the present paper analytical and numerical studies at the Lawrence Berkeley Laboratory are described. The hydrodynamic and thermal behaviors of the storage system are analyzed and illustrated. The ratio of energy retrieval over energy stored is predicted to be as high as 80%.

AQUIFER THERMAL ENERGY STORAGE

INTRODUCTION

The need for practical and low-cost methods of storing a large amount of thermal energy becomes apparent with the development of solar energy and the implementation of a total energy system. The basic function of a storage system is to compensate the time mismatch between periods of energy input and those of power demand.

One of the most promising solutions for long-term seasonal storage is in underground aquifers. 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. Their use for hot water storage was first suggested in 1971. Initial studies of this new idea were made by Robbimov, Umarov and Zakhidov (1971), Meyer and Todd (1973), and Hausz (1975). These early works involve mainly analytic or semi-analytic calculations as well as economic and institutional considerations.

In 1976 Tsang, Lippmann and Witherspoon presented the results of a three-dimensional numerical modeling of the fluid and thermal flow in an aquifer used for hot water storage, indicating a recovery-storage ratio greater than 80%. At about the same time, Molz and Warman performed their first set of field experiments on hot water storage and their data were analyzed and used in a numerical simulation study by Larsen, et al. In 1977, a number of other projects both in the U.S. and abroad were initiated to investigate or demonstrate the feasibility of the aquifer thermal energy storage concept. These were reviewed and discussed at a Workshop at the Lawrence Berkeley Laboratory (LBL) in May 1978.

Many of these projects will be described in the forthcoming Proceedings of the LBL Workshop. The present paper will concern itself with a review of the numerical modeling work performed at LBL over the last two years.*

In the following section of the paper the physical bases of the concept will be briefly described. Then a qualitative description will be made of a computer model developed at LBL and used in the present study. A careful validation of the model will be presented using three different examples for which either analytic or semi-analytic solutions are available. Then a detailed case study of the thermal and pressure behavior of an aquifer used for thermal energy storage will be discussed. Recent LBL calculations are then outlined and results described. The paper will be concluded with a summary and some general comments.

* Work performed in collaboration with M.J. Lippmann, T.A. Buscheck, D.C. Mangold, C.B. Goranson and P.A. Witherspoon.

PHYSICAL BASIS

The physical bases of the concept lie in the low heat conductivities of caprock and bedrock materials, and in the fact that aquifer volumetric capacity is normally of the order of cubic kilometers or 10^9 m^3. Thus large volumes of hot water may be stored. To estimate the feasibility and efficiency of such a storage system, the processes occurring during injection and withdrawal cycles must be understood, such as:

1. Thermal behavior and heat losses during the first and successive cycles.

2. Pressure distribution in the aquifer during the process. Possibility of compaction of the aquifer and overburden formations and the resulting land subsidence phenomenon.

3. Chemical reactions and the resulting change in aquifer permeability and porosity.

NUMERICAL MODEL "CCC"

The LBL numerical model used is called "CCC" which stands for "Conduction, Convection and Compaction." It is based on the so-called Integrated-Finite-Difference Method (Edwards, 1968; Sorey, 1975; Narasimhan and Witherspoon, 1976). 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 geothermal system is simulated using the one-dimensional consolidation theory of Terzaghi. Thus the following physical effects can be induced simultaneously in the same calculation:

1. Flow of hot and cold water with large viscosity and density differences.

2. Effects of temperature on fluid heat capacity, viscosity and density.

3. Heat convection and conduction in the aquifer.

4. Heat exchange between the porous aquifer and its contained fluids with the confining beds.

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 to a later study.

VALIDATION OF THE NUMERICAL MODEL

Three different examples are studied for which analytic or semi-analytic solutions are available.

The first example is the Theis solution which describes the change of pressure head with time in a well flowing at a constant rate. Our numerical results follow closely the standard solution in terms of the exponential integral (Figure 1). For comparison, numerical results obtained by a Linear Finite Element method (Pinder and Frind, 1972) are also shown. A Quadratic Finite Element method does not yield any improvements. Only when a Cubic Finite Element method is used are comparable results obtained.

The second example considered is the problem of evaluating the temperature distribution as a function of time and radial distance when cold water is injected into a hot reservoir. To solve the problem analytically, Avdonin assumed zero gravity and constant parameters. In Figure 2, the comparison between Avdonin's solution and our numerical results is shown. Again good agreements are found; the small deviation corresponds to the finite size of the mesh.

The third example is that of an injection-production doublet in which cold water is injected in one well and reservoir water is produced in another. The production temperature as a function of time obtained by Gringarten and Sauty (1975) is compared with our numerical results (Figure 3). The agreement is surprisingly good.

The quality of agreement for these three different examples gives us confidence in the numerical model we are going to use for our present study of hot water storage in aquifers.

Detailed Results of a "Typical" Case Study in Hot Water Storage

In this section we present in detail the results of a simple problem in which each cycle of 360 days is composed of four periods:

1. Summer (90 days) when supply exceeds the demand of space heating: storage of hot water in the aquifer.

2. Autumn (90 days) when supply and demand are approximately equal: the well is shut-in.

3. Winter (90) days when demand exceeds supply: hot water is produced from the aquifer.

4. Spring (90 days) when, again, supply and demand are approximately equal: the well is shut-in.

The rate of injection and production is kept the same, equal to 10^6 kg/day (181 gpm). The height of the aquifer is taken to be 100m. The injection and original aquifer temperatures are 120°C and 20°C respectively. The parameters used in the study are tabulated in Figure 4. These are realistic values taken from standard sources, Kappelmeyer and Haenel (1974), Helgeson and Kirkham (1974) and American Institute of Physics Handbook (1972).

The mesh design used is displayed in Figure 5. The thickness of the caprock, aquifer and bedrock are equal and were arbitrarily set at 100m. The well is positioned at zero radial distance, the mesh having radial symmetry around that axis. One remark has to be made here. In pressure (mass flow) calculations, mesh elements could be increased in size as one moves away from the well, without significantly affecting the accuracy of the results. However, in heat calculations the mesh elements should decrease in size as one moves away from the well, since the injected hot water will move a smaller radial distance in unit time steps. We have chosen a compromise, and equal radial distance steps are made in the mesh as shown in Figure 5. Furthermore, a finer mesh was used in an additional calculation to show the stability of our results against mesh changes. This will be illustrated in a later figure (Figure 10).

The calculated temperature distribution in the aquifer is shown in Figure 6, for two time periods (t is total time elapsed):

1. t = 90 days, after 90 days injection in the first cycle;

2. t = 270 days, after 90 days injection, 90 days rest and 90 days production.

The thermal front is not sharp due to heat conduction to the confining beds and the native water in the aquifer. It will be shown later that numerical dispersion appears not to affect our results significantly. Note that after 90 days of injection the 20°C isotherm (original reservoir temperature) is at about 30m from the well. The hydrodynamic front, i.e., the location of the injected water, is much farther away, however, at about 60m from the well. The thermal front lags behind this front representing the effect of the porous medium being heated and draining energy from the injected water.

Figure 7 presents the radial dependence of pressure distribution at the horizontal center line of the aquifer, the initial pressure being 1.38×10^6 N/m^2. After 90 days of injection the curve is essentially an inverse Theis solution with a "transition" at about 30m. This transition may be understood as the separation between native and the warmer injected waters with significantly different viscosity values on either side of the 30m point (see Figure 6). After 90 days of rest (t=180 days), the pressure distribution equilibrates to a smooth line. During the production period after this rest, a typical Theis curve is again seen.

The temperature distributions for different times within the aquifer are summarized in Figure 8, where, again, t represents total time elapsed. Only a few points need to be pointed out in this figure. The rest period after an injection period results in a diffused thermal front because of conduction and convection during pressure equilibration (Figure 7). During this period, the main effect is the loss of heat to the confining beds, resulting in a somewhat lower temperature. Figure 8 also presents the curve corresponding to 5 days into the next cycle (t= 365 days). The effect of the aquifer having already been heated during the first cycle is clearly seen, resulting in a more efficient hot water storage system for successive cycles.

To study how important numerical dispersion is in our results, we ran the problem again with a finer mesh. In one mesh design, we divided the aquifer vertically into 6 layers and radially into 2m steps; in another mesh the corresponding quantities are 4 layers and 1.5m steps. As shown in Figure 9, the changes in temperature values are negligible.

Figure 10 displays the water temperature at the well during the production periods for successive cycles. The efficiency is increased for each successive cycle as the aquifer is heated, making it a better storage system. The process will reach a quasi-equilibrium, when successive cycles do not change the temperature any further. The temperature at the end of each production cycle being the lowest, it is plotted as a function of cycles in Figure 11, showing the approach to a limiting value.

By integrating the production temperature minus the original aquifer temperature over the production period, the energy recovered can be calculated. The percentage of energy recovery shown in Figure 12 is this calculated energy divided by total injected energy for each cycle. A surprisingly high quasi-equilibrium energy recovery rate is found after the first three cycles. To look into further details, energy balance for the first cycle is shown in Figure 13, which indicates:

1. Heat loss from all the boundaries of our caprock-aquifer-bedrock system;

2. Total energy injected;

3. Total energy produced.

It appears that the external heat loss is negligible. The difference between injected and produced energies is used to heat the whole system (i.e., reservoir, caprock and bedrock).

Further Calculations

In the last section we described in some detail the results for a typical case. We shall summarize below our more recent calculations, some of which have already been reported (Tsang, et al., 1977 and 1978).

A. Refinement of Caprock Mesh. A careful study of the mesh design used for the caprock and bedrock has been completed. We have arrived at a better mesh (with finer grids in regions near the aquifer) which enables one to calculate conduction more accurately. However the conclusions given in the last section are essentially unchanged.

B. Well Partially Penetrating the Aquifer. Calculations were performed assuming the well to be open only for the upper half of the aquifer. Figure 14 shows the temperature contours in the aquifer after 90 days of injection and after 90 days of subsequent production. The buoyancy effect of lower-density hot water is seen cleary. However, the percentage of energy recovered for successive cycles is only slightly affected (see Figure 12).

C. Different Cycle Periods. In addition to the cycle period described in the last section, we also looked at (i) the semi-annual cycle: storage in Fall, production in Winter for space heating; storage in Spring and production in Summer for air-conditioning.

(ii) the daily cycle: storage for 12 hours and production for 12 hours. The corresponding percentage of energy recovered for successive cycles is also shown in Figure 12.

D. Storage of Water of Different Temperatures. We have looked at storage of water at not only 120°C but also 220°C and 320°C. We found that, as far as hydrodynamic and thermal behavior of the aquifer is concerned, the results appear to scale as (T_s-T_o), where T_s is the temperature of water stored and T_o is the original aquifer temperature.

E. Chilled Water Storage. Instead of storing hot water, the concept can be easily adopted to the storage of winter chilled water (at say, 4°C) to be used in summer for air-conditioning. If we assume storage at 4°C over 90 days in winter and production 90 days in summer, then the production temperature for successive cycles is shown in Figure 15. Field experiments of chilled water storage are currently being planned or carried out.

F. Inhomogeneity of the Aquifer. If the aquifer is composed of two layers, one more permeable than the other, then the flow and temperature fields will be changed. One example in which one region is twice as permeable as the other is shown in Figure 16. The effect of the higher permeable region is easily seen. However, it is found that the percentage of energy recovery for successive cycles is not much affected ($\gtrsim$ 80%).

G. Two-Well System. We have also modeled a two-well system where one well supplies the water that will be heated and stored in the other. A typical result is shown in Figure 17. It is found that for a given storage if the two wells are at a reasonable distance apart, single-well results are applicable.

SUMMARY

In this paper we discussed the physical bases for using aquifers for the storage of hot or chilled water. The hydrodynamic and thermal behaviors of such an aquifer thermal storage system were studied and described. First, detailed results with one particular set of geological conditions and storage requirements were presented. Calculations based on other conditions were then outlined and briefly discussed. In all cases studied the percentage of energy recovery was surprisingly high, over 85% after only a few injection-production cycles.

So far we have considered porous systems only. The existence of any fault or large connecting fractures will alter the picture. Chemical reactions will also be important because they may cause changes in porosity and permeability. Furthermore, water treatment is crucial to ensure the injectability of the storage well.

In spite of these reservations, the results in this paper point to the great potential of using aquifers for thermal energy storage. Problems outlined above may be minimized by careful engineering. Field experiments currently carried out are important to verify the high recovery percentage predicted by these modeling studies.

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FIGURE CAPTIONS

Figure 1. Validation of LBL computer model "CCC". Case 1: Theis (1935) solution (pressure drawdown for a constant flow rate at the well). Also shown are the results obtained from conventional finite element method. Axes are in standard dimensionless pressure and time units, defined in Theis (1935). (XBL 7612-4524)

Figure 2. Validation of LBL computer model "CCC". Case 2: Avdonin (1964) solution (temperature distribution in aquifer, on injection of water colder than native water in aquifer. 2×10^4 cm^3/sec injected into an aquifer 200m in thickness with 20% porosity. (XBL 7612-4521)

Figure 3. Validation of LBL computer model "CCC". Case 3: Gringarten doublet problem (production temperature variations for a two-well system with one well injecting cold water and the other producing heated water). Dimensionless temperature and time on the axes are defined in Gringarten and Sauty (1975). (XBL 7612-4522)

Figure 4. Parameters used in hot water storage model. Parameters shown are for indicated materials and were obtained from tables published by O. Kappelmeyer and P. Haenel (1974), Helgeson and Kirkham (1974) and American Institute of Physics Handbook (1972).

Figure 5. Mesh design for simulation of our sample hot water storage problem. The problem has radial symmetry with well at the zero radial distance. The aquifer 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°C. The aquifer region beyond radial distance of 134m is kept at constant temperature and constant pressure. (XBL 7611-4496)

Figure 6. Temperature distribution in aquifer after 90 days of injection, 90 days of rest, and 90 days of production (Cycle 1) for variable fluid parameters with gravity. Well fully penetrating the aquifer. In the figure, t represents total time elapsed. (XBL 7612-4526)

Figure 7. Pressure distribution in aquifer as a function of distance from well: Cycle 1, full penetration. (XBL 7612-4525)

Figure 8. Temperature distribution in aquifer as a function of radial distance for indicated times. (XBL 7611-4491)

Figure 9. Effect of mesh size on calculated temperature. (XBL 7612-10938)

Figure 10. Temperature at the well versus production time for each cycle. Variable fluid parameters, gravity included, well fully penetrating aquifer. (XBL 7611-4492)

Figure 11. Temperature at the end of each production period versus cycle. (XBL 7712-11126)

Figure 12. Energy recovered from aquifer versus cycle. (XBL 7712-11225)

Figure 13. Energy balance for 1 cycle (variable parameters, full penetration, gravity included). Indicated are energy injected, energy recovered, and energy lost through all boundaries. Note that energy lost is negligible.

Figure 14. Temperature distribution in aquifer after 90 days of injection and 90 days of production (Cycle 1) for variable fluid parameters with gravity. Well partially penetrating the aquifer. In the figure, t represents total time elapsed. (XBL 7712-11224)

Figure 15. Chilled water storage: Temperature at the well versus production time for each of the Cycles 1 to 5. (XBL 783-7508)

Figure 16. Isotherms for inhomogeneous reservoir after the 90 days injection period and after 90 days of subsequent production. The permeability in the shaded layer is twice that of the upper layer. (XBL 785-2517)

Figure 17. Isotherms for a two-well system (after 90 days of injection), plane and cross section views. (XBL 785-2508)

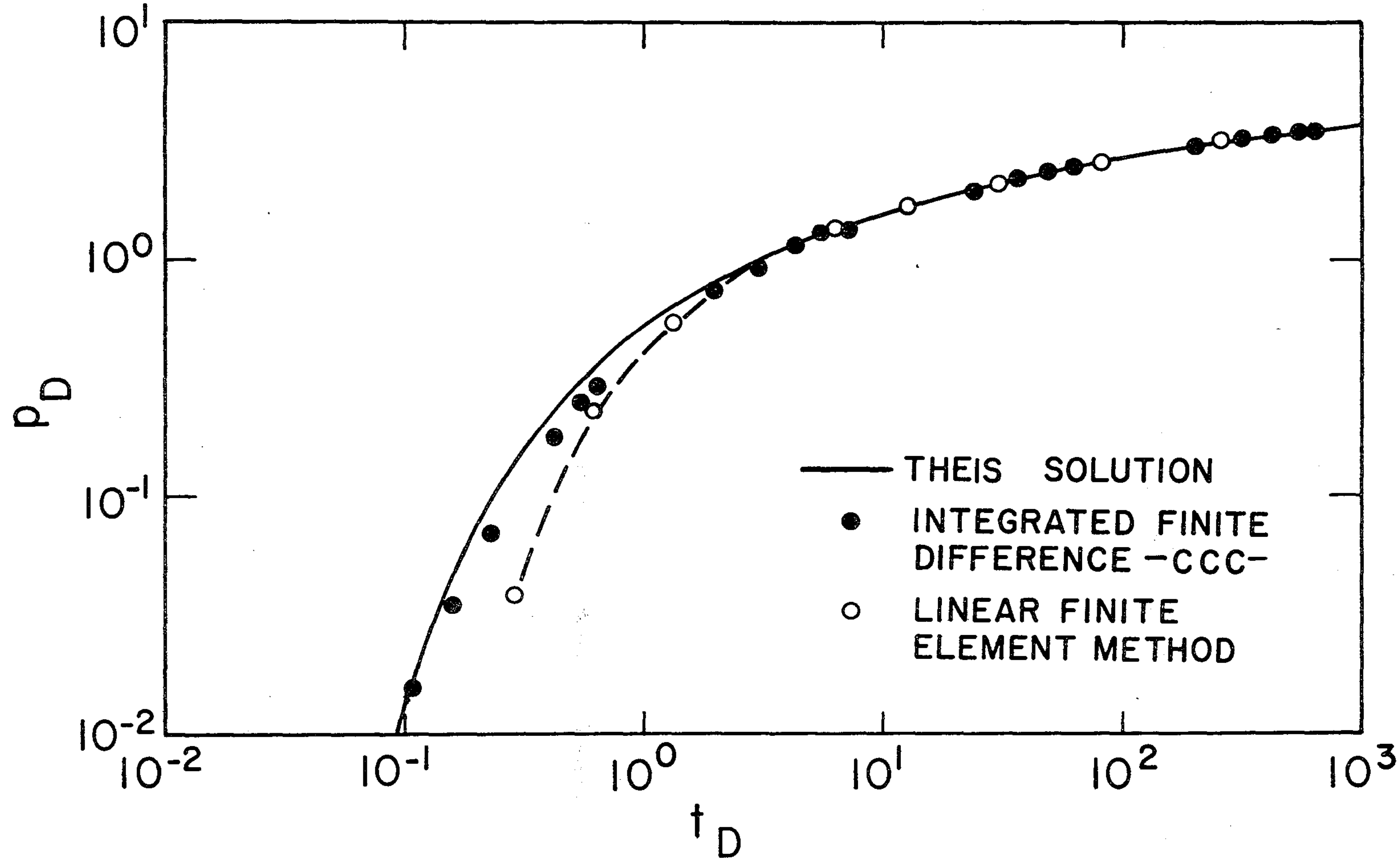

Figure 1

XBL 7612-4524

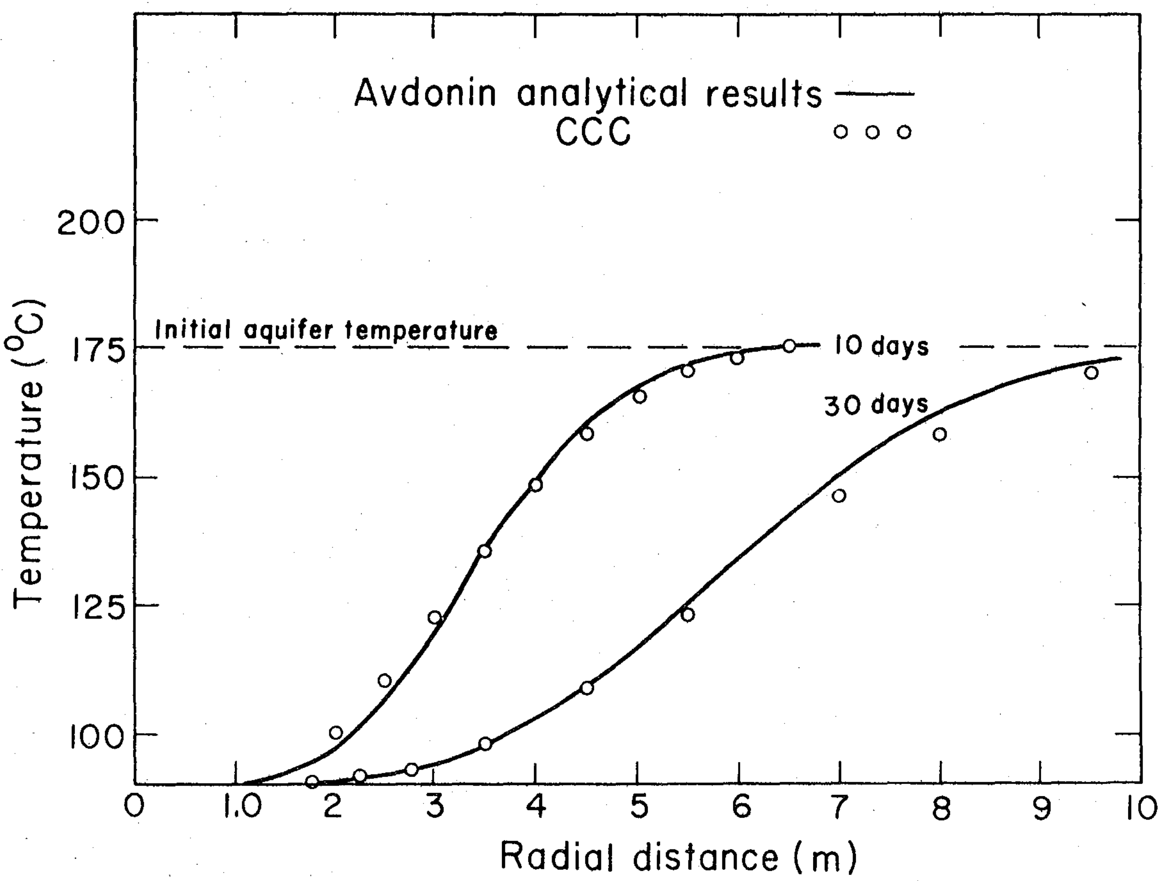

Figure 2

XBL 7612- 4521

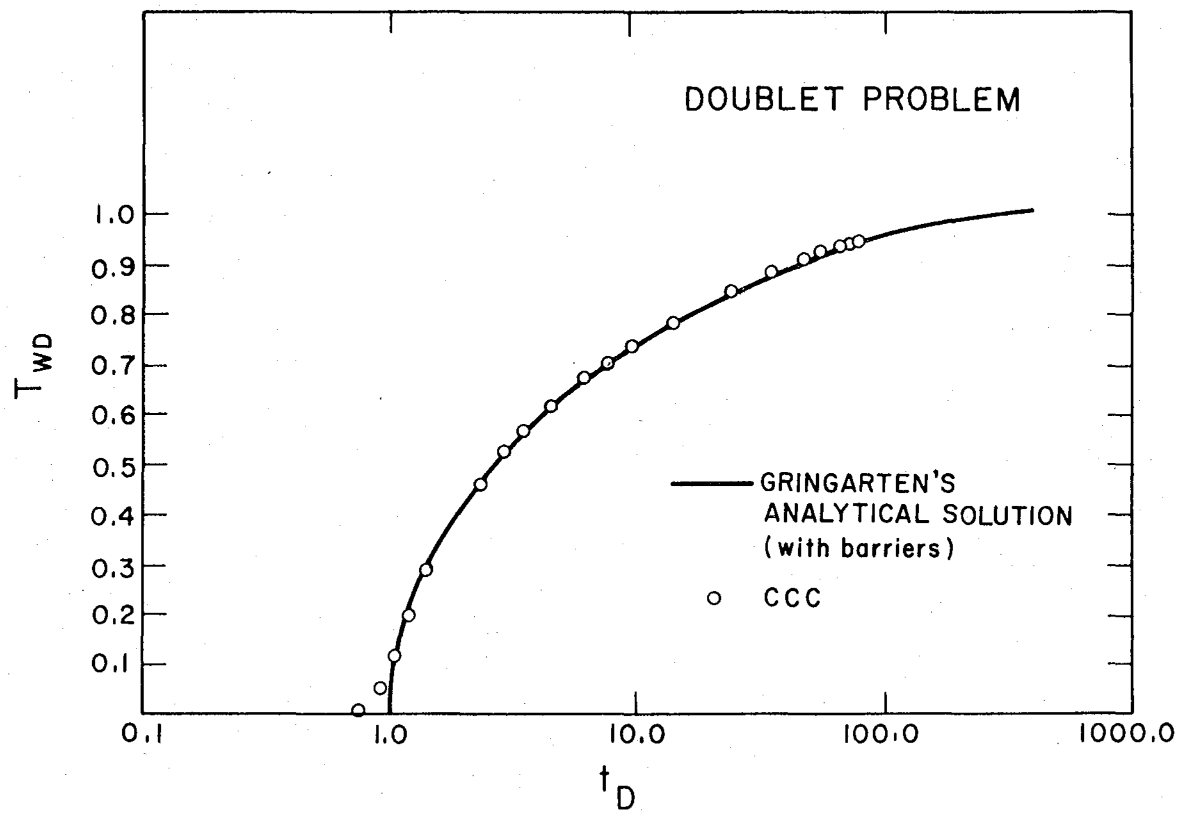

Figure 3

XBL 7612-4522

MATERIAL	POROSITY	DENSITY kg m^{-3}	HEAT CAPACITY J $kg^{-1} {}^{\circ}C^{-1}$	THERMAL CONDUCTIVITY J $s^{-1} m^{-1} {}^{\circ}C^{-1}$	PERMEABILITY m^2	SPECIFIC STORAGE m^{-1}
Reservoir (Sandstone)	0.20	2.6×10^3	9.70×10^2	2.894	1×10^{-13}	1×10^{-6}
Caprock Bedrock (Mudstone)	1×10^{-20}	2.7×10^3	9.30×10^2	1.157	1×10^{-40}	1×10^{-15}

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 (°C^{-1}) 3.17×10^{-4}			

Figure 4

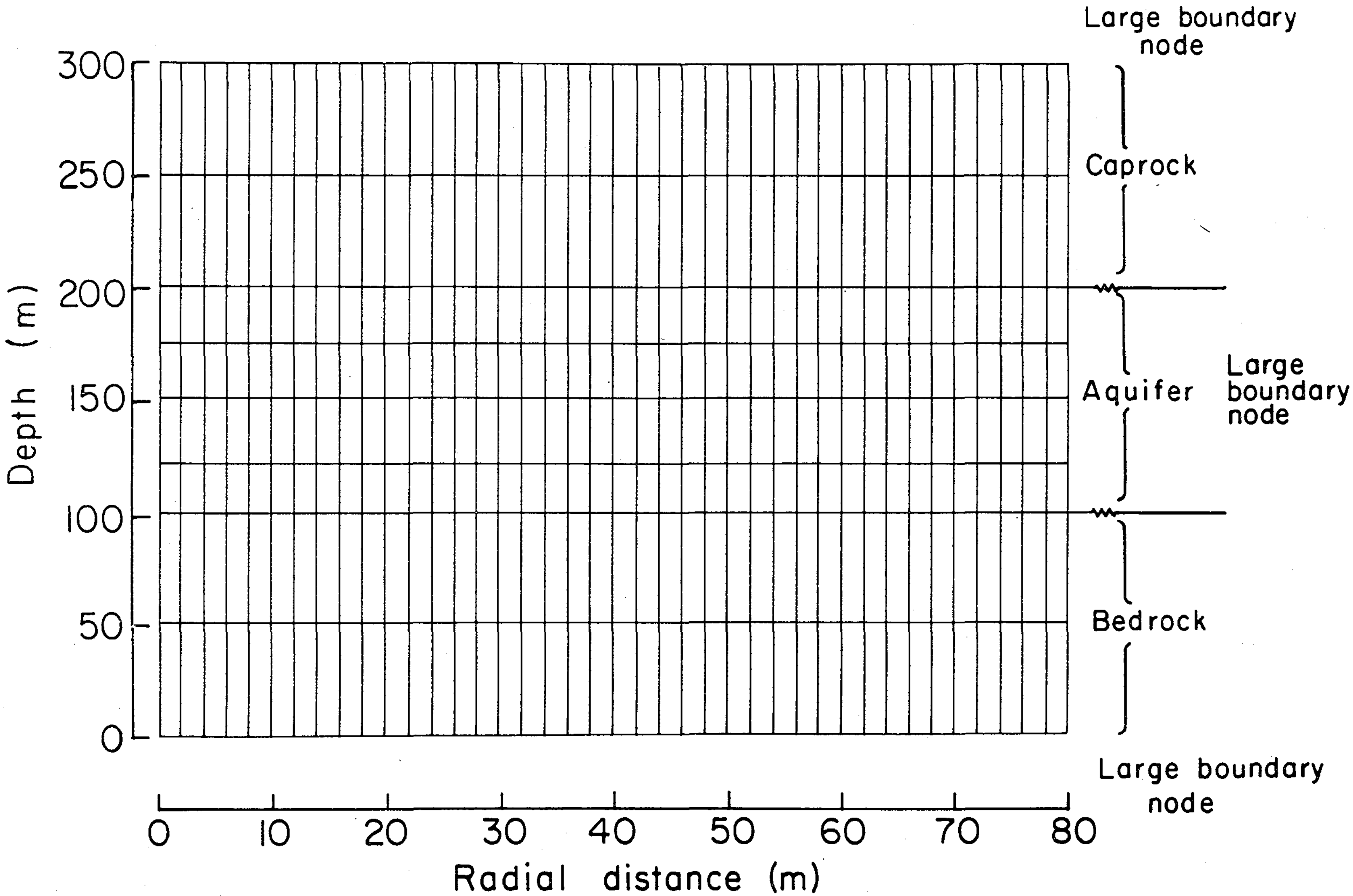

Figure 5

XBL 7611-4496

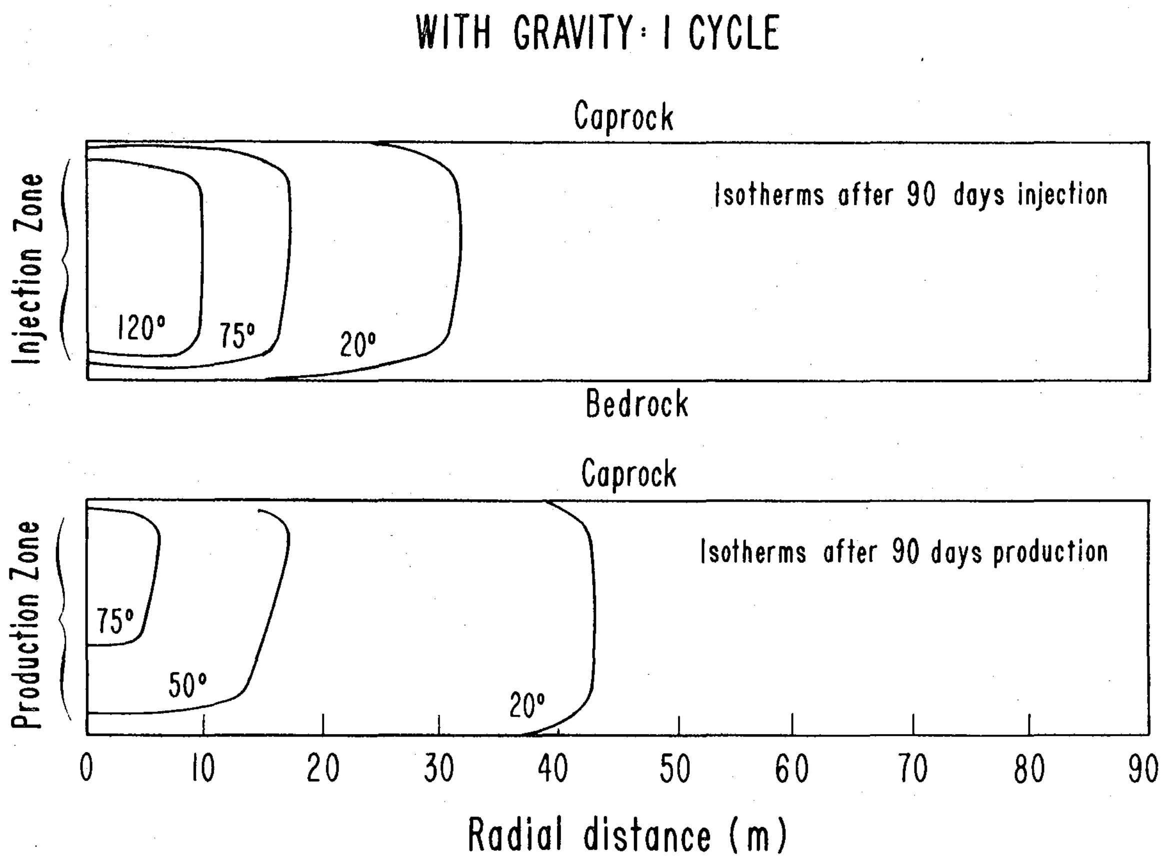

Figure 6

XBL 7612-4526

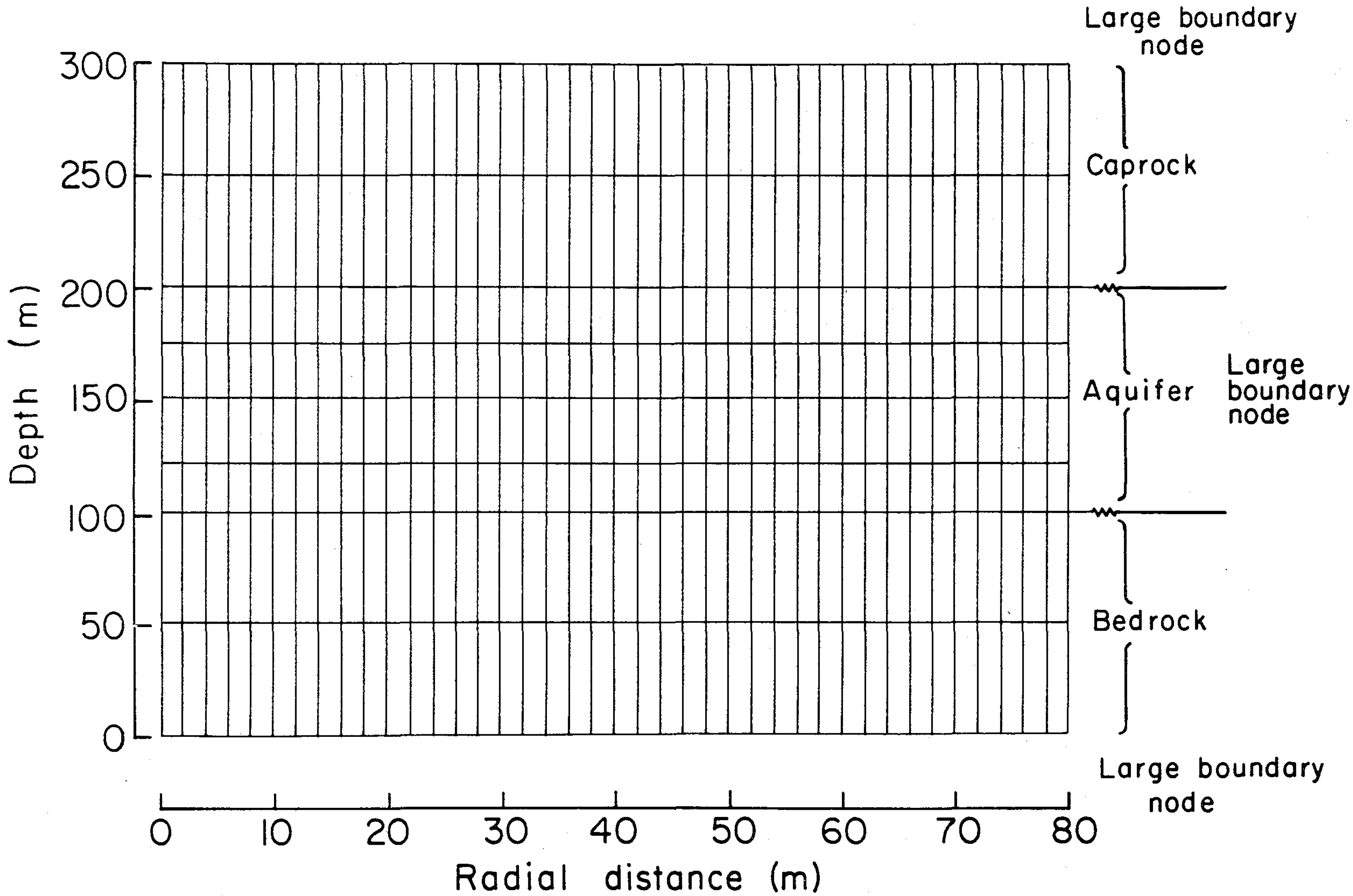

Figure 5

XBL7611-4496

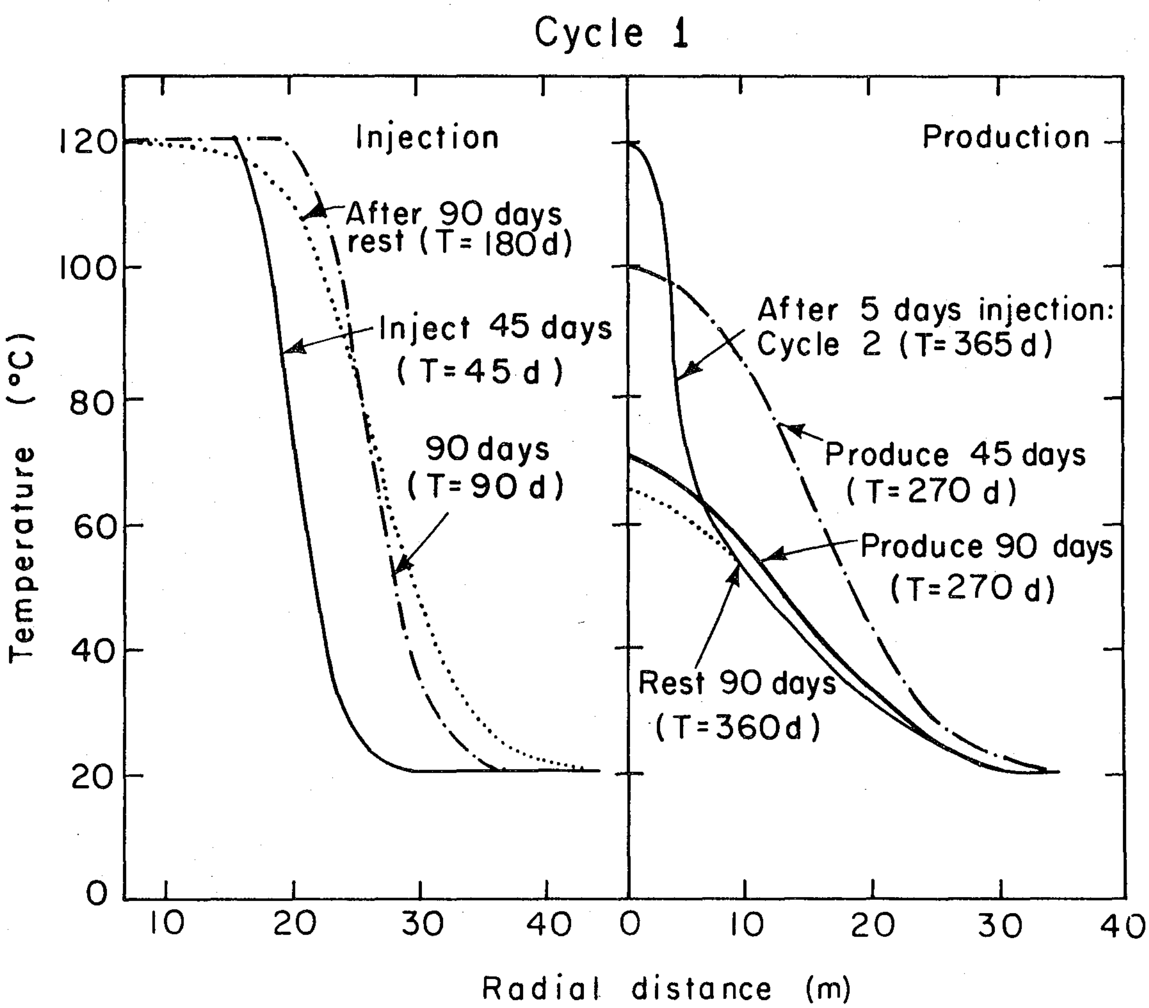

Figure 8

XBL 7611-4491

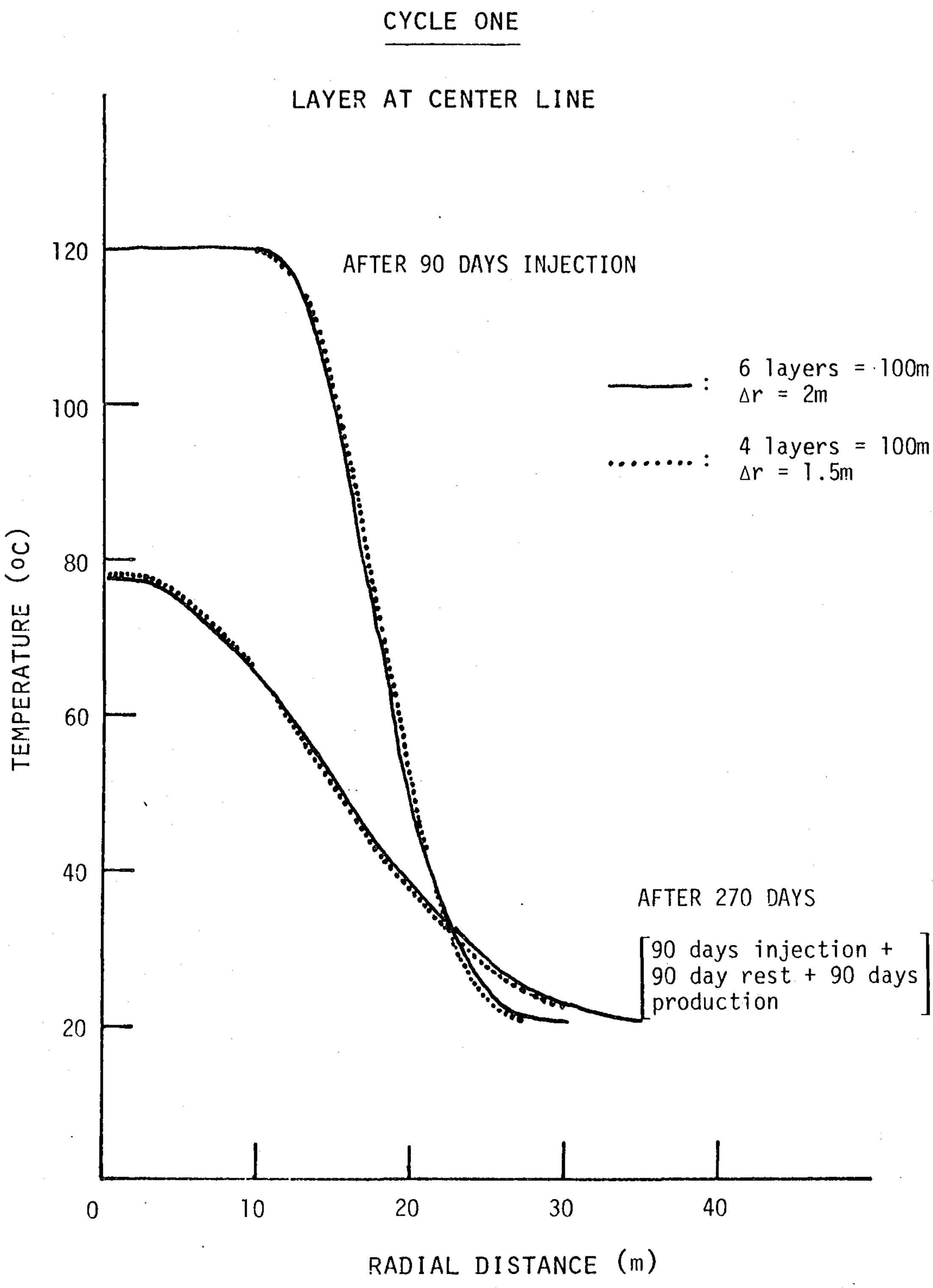

Figure 9

XBL 7612-10938

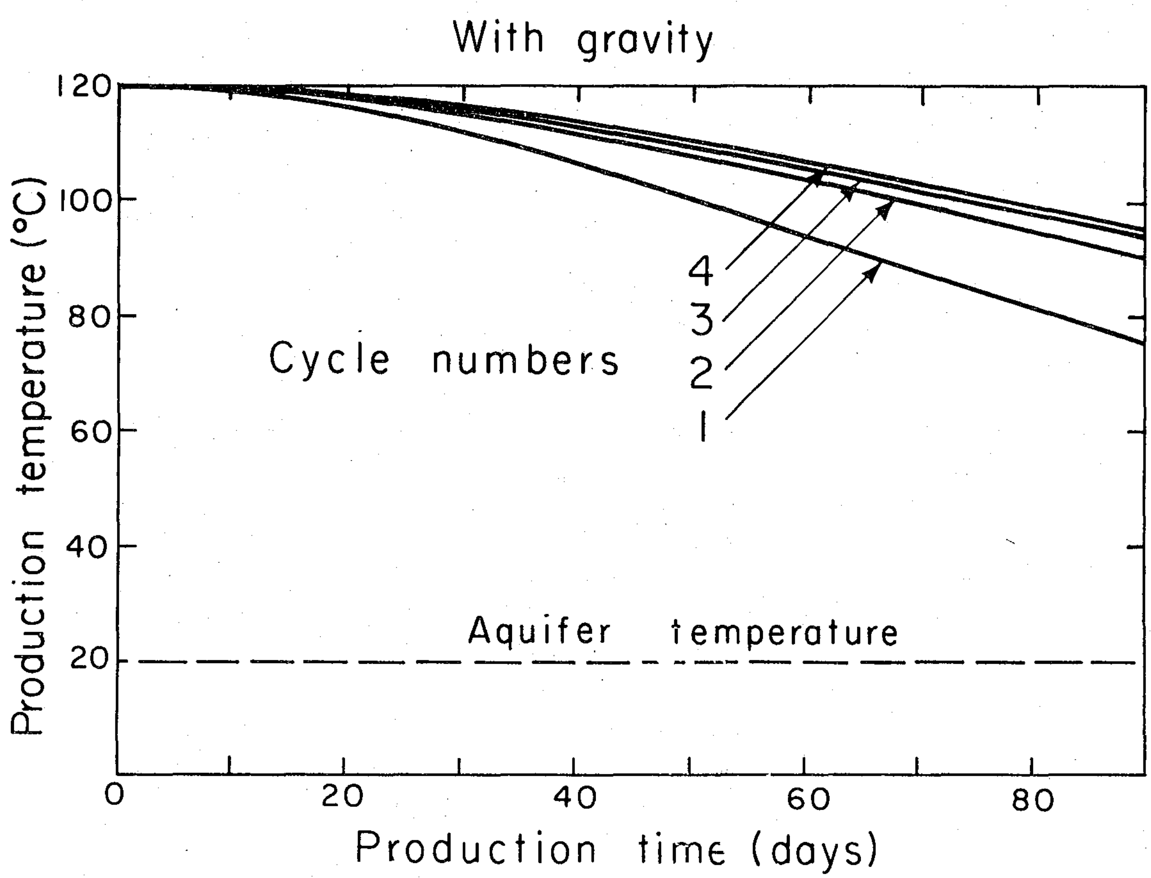

Figure 10

XBL 7611-4492

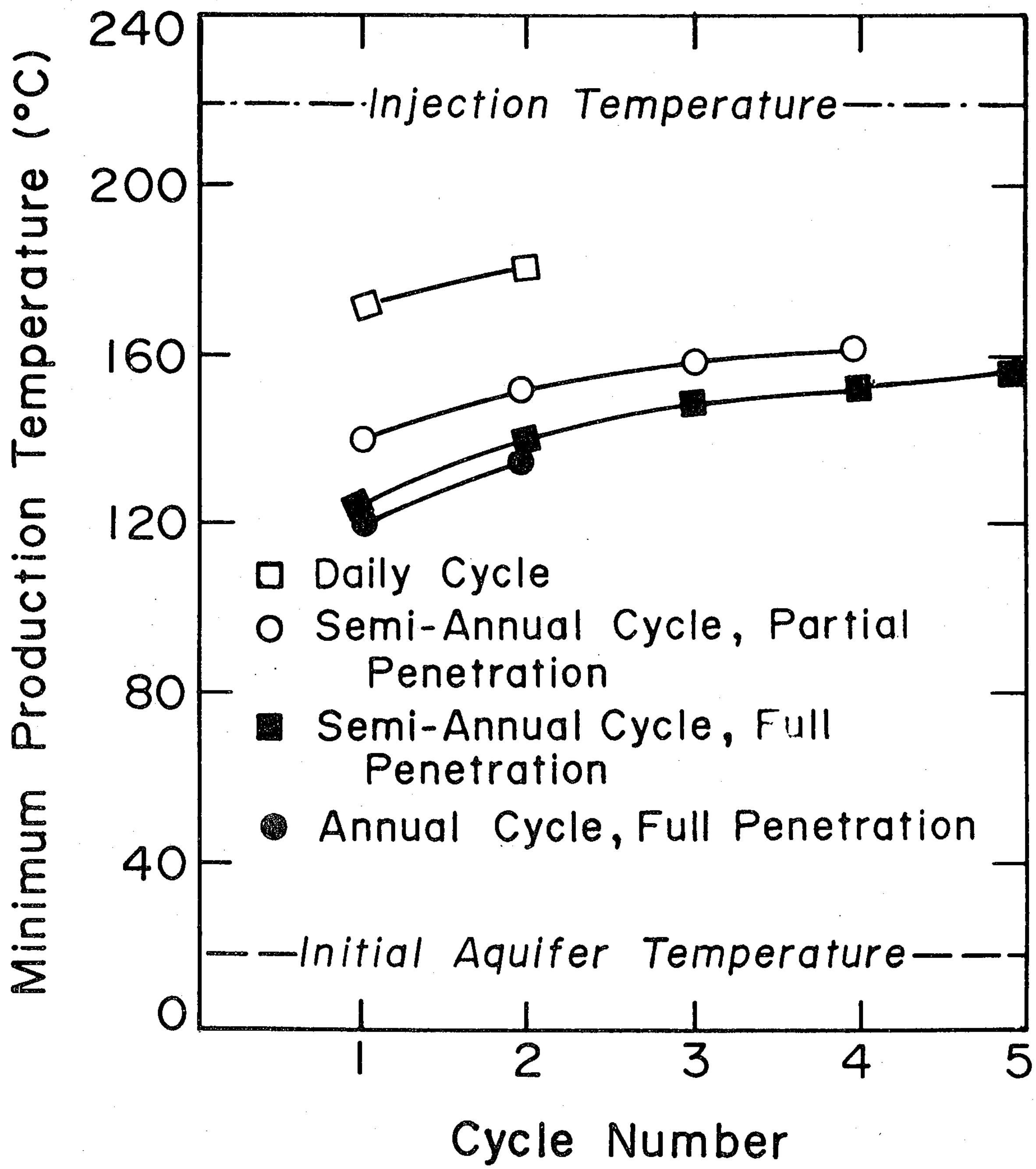

Figure 11 XBL 7712-11126

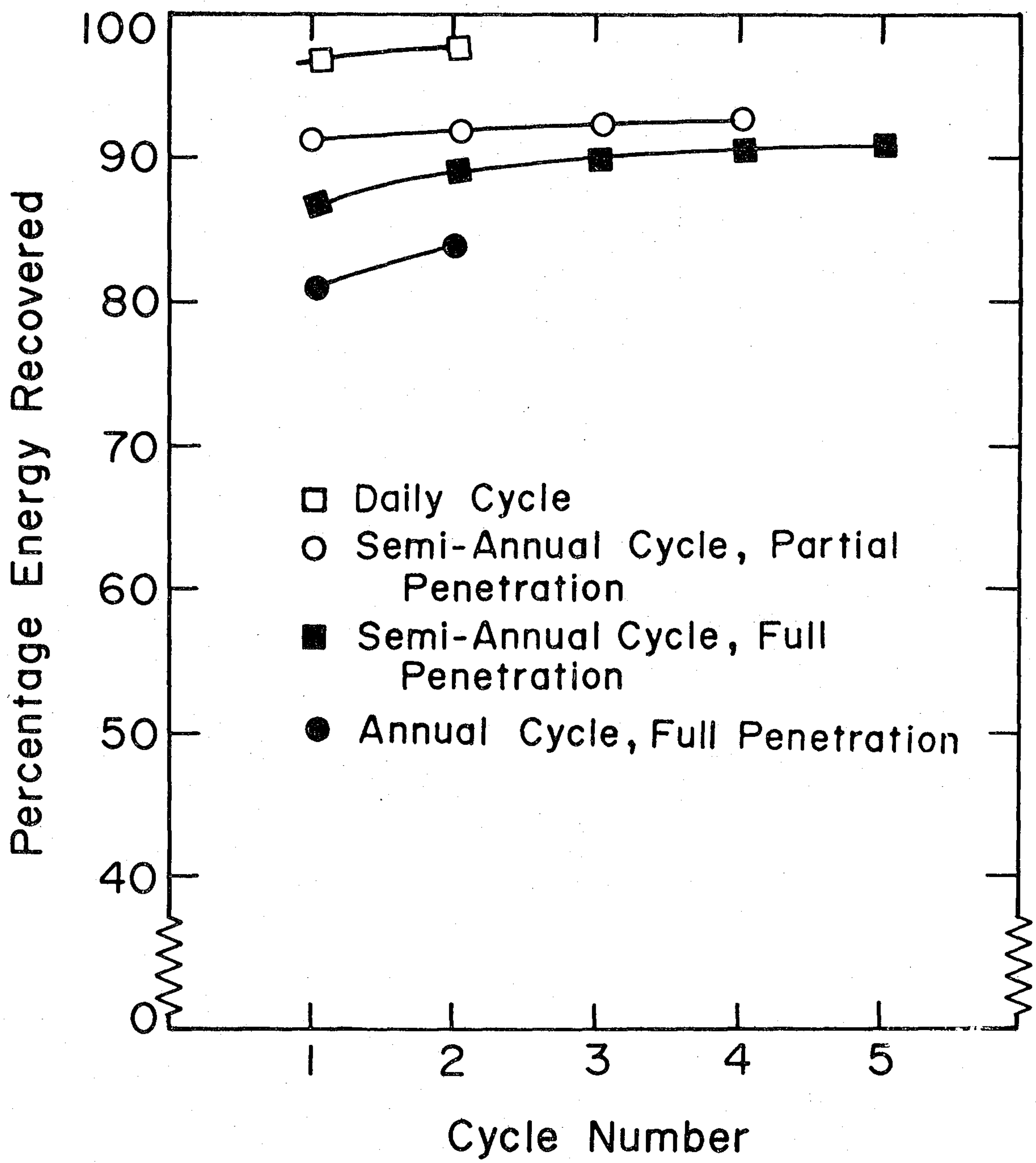

Figure 12

XBL 7712-11225

FIRST CYCLE

$Ti = 120°C$

$To = 20°C$

$\Delta r = 1.5m$; 4 layers

Heat Loss Through Boundaries in One Complete Cycle	=	7.67×10^{7} Joules
Total Energy Injected	=	3.97×10^{13} Joules
Total Energy Recovered	=	3.50×10^{13} Joules

Figure 13

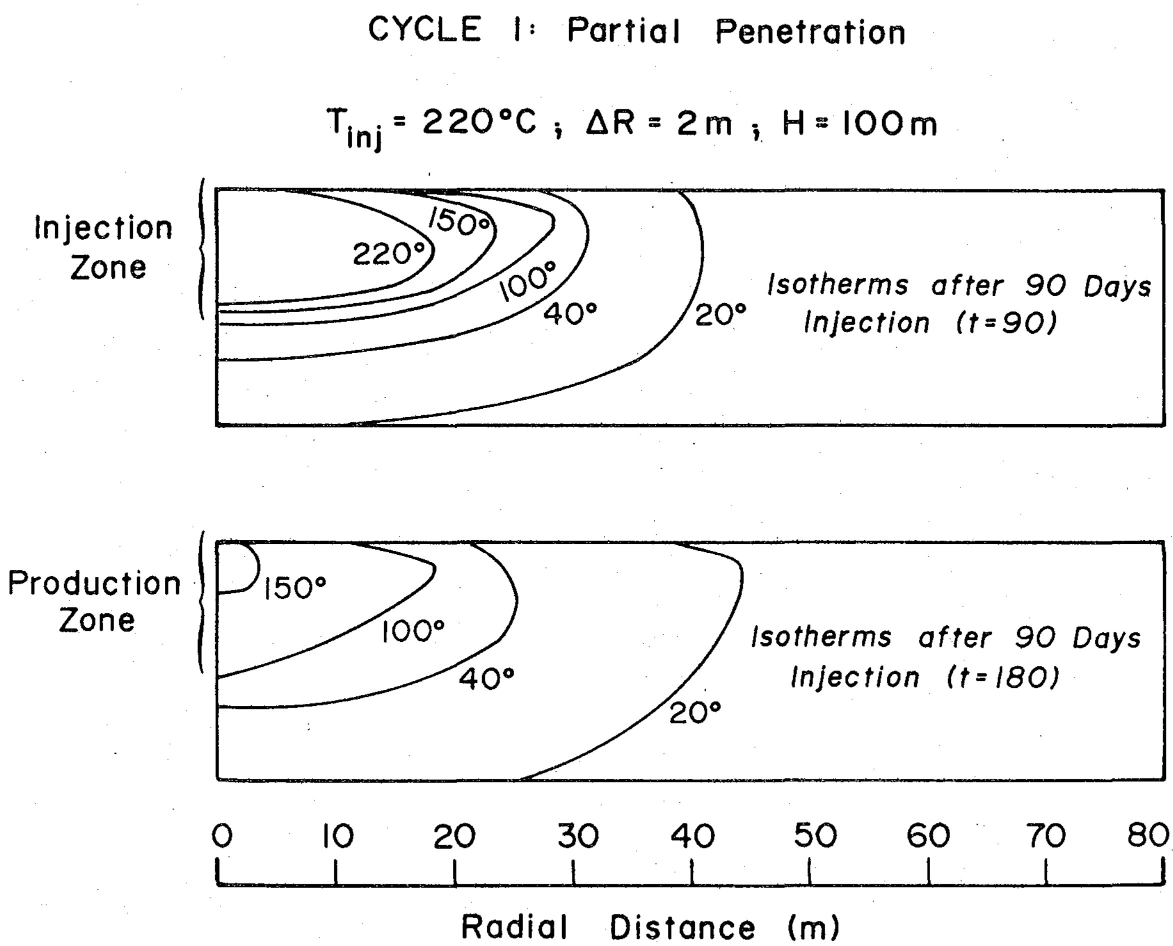

Figure 14 XBL 7712-11224

Production Temperature v.s. Time for Cycles 1 to 5

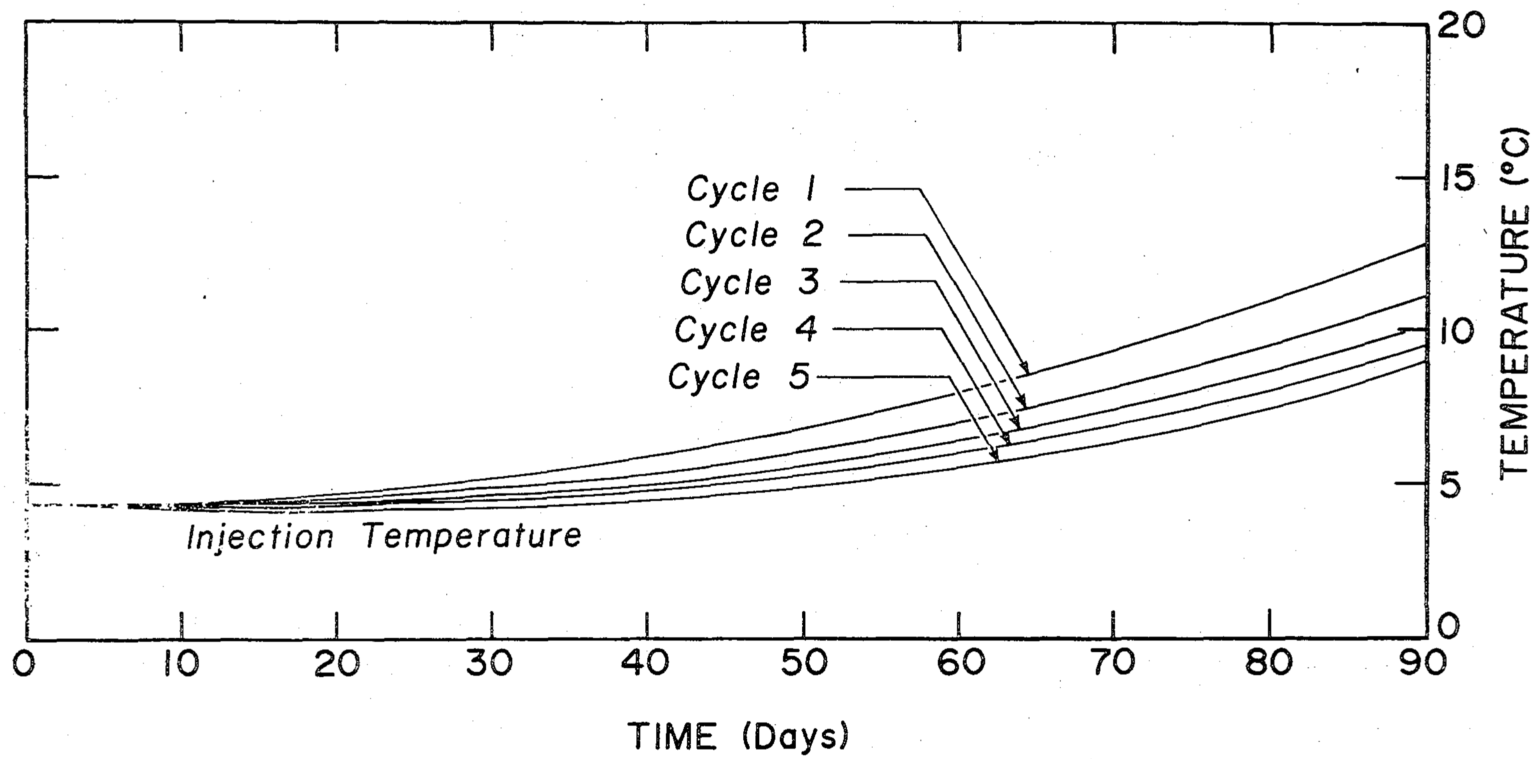

Figure 15

XBL 783-7508

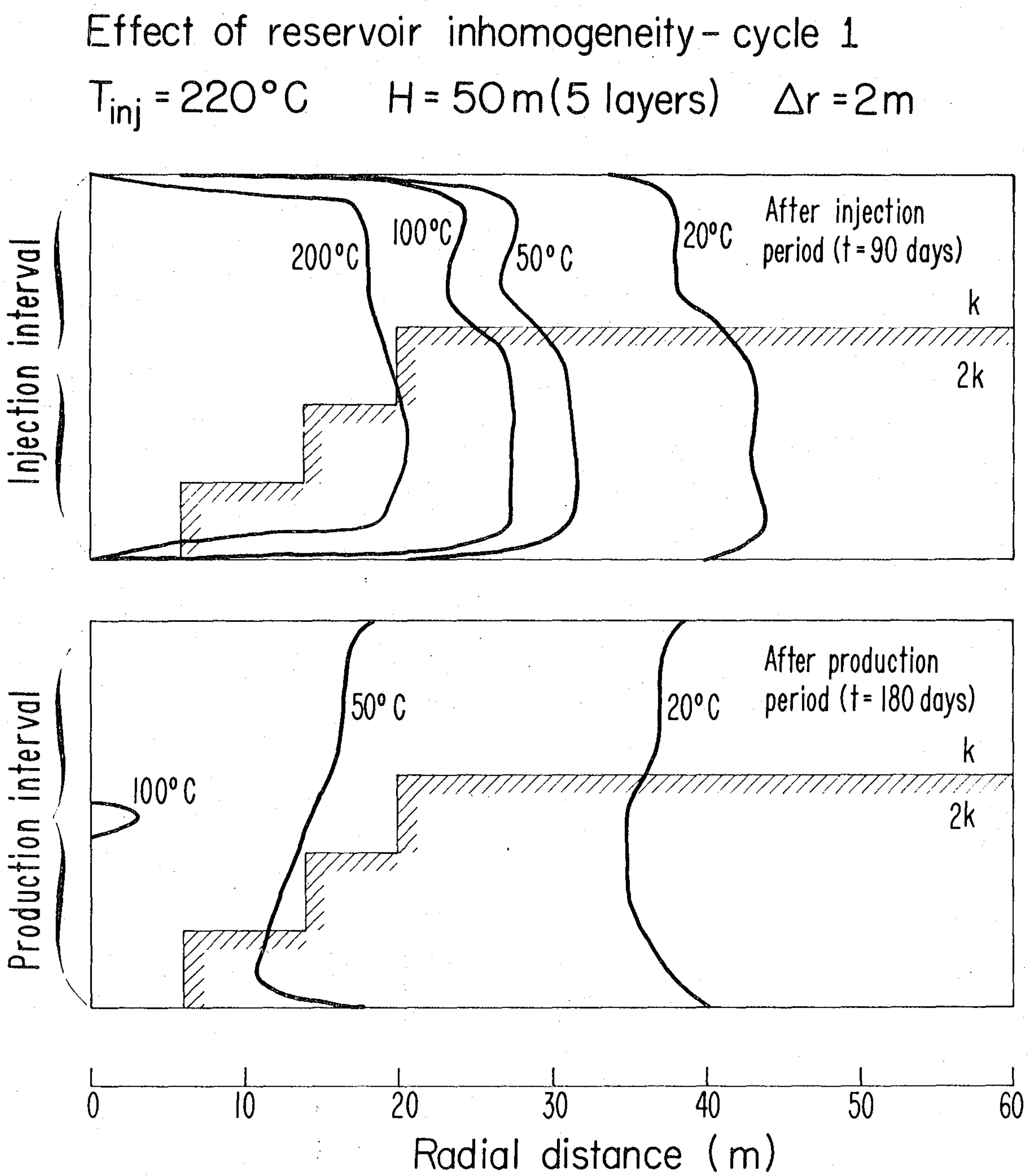

Figure 16

XBL 785-2517

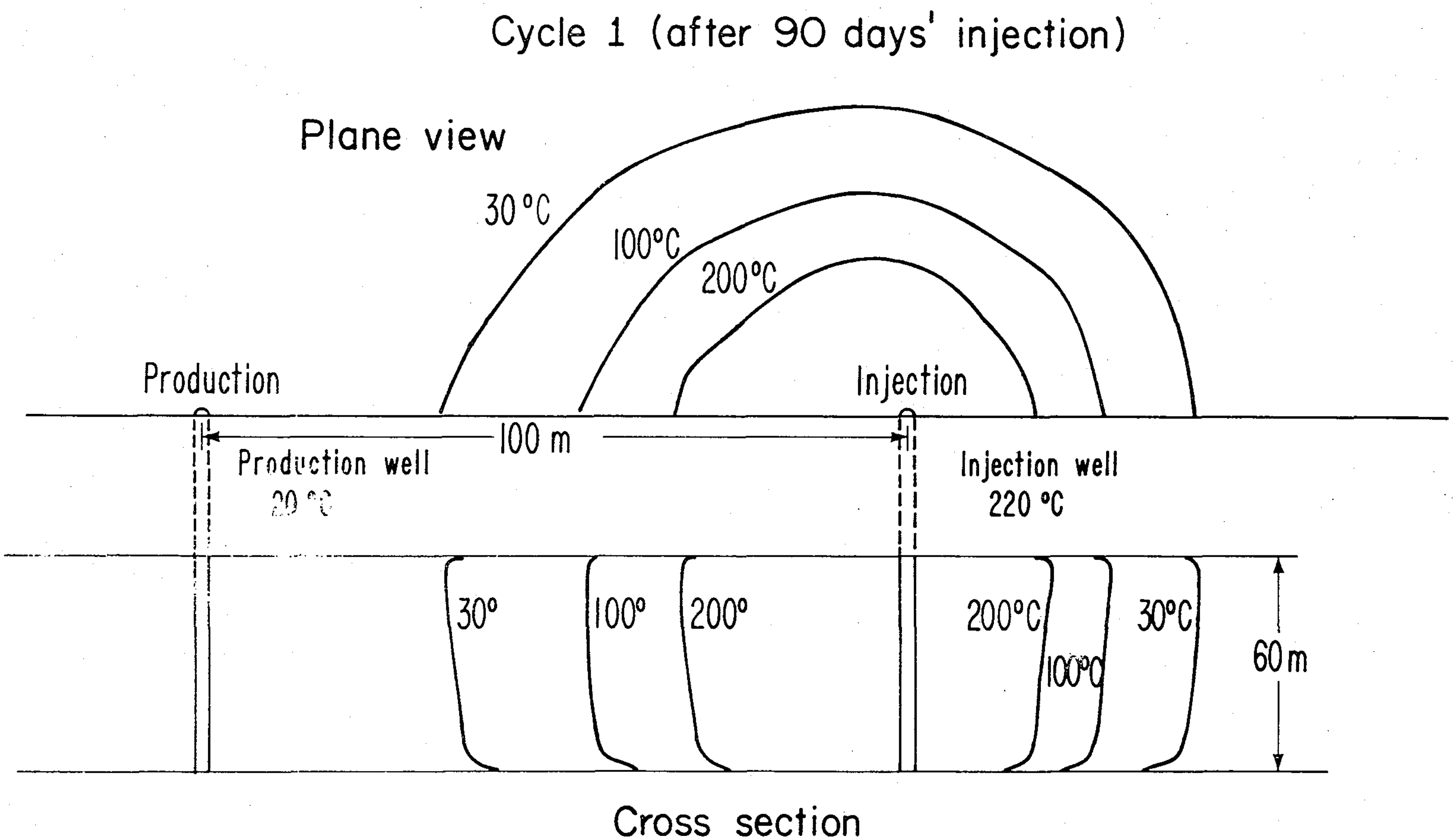

Figure 17

XBL 785-2508