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by

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Introduction

Aquifers have been suggested as one of the most promising solutions for long-term, low cost, seasonal storage of thermal energy. Aquifers are geologic formations which contain and conduct water. They are 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 were made by Rabbimov, Umarov and Zakhidov (1971); Meyer and Todd (1973); and Hausz (1974). These early works involve mainly analytic or semi-analytic calculations as well as economic and institutional considerations.

In 1976, Tsang, Lippmann, Goranson and Witherspoon, at LBL, presented the results of a three-dimensional numerical modeling of the fluid and heat flows in aquifers used for hot water storage. The results indicated a recovery storage ratio greater than 80%. At the same time, Molz et. al. (1978) completed their first set of field experiments on hot water storage. Their data were analyzed and used in a numerical simulation study by Papadopulos and Larson (1978). The present paper reviews the results of the numerical modeling work performed at LBL over the last one and a half years.

In the next section of the paper, the physical basis of the concept is briefly discussed and a qualitative description is given of a computer model developed at LBL and used in these studies. A careful validation of the model is then presented using three different examples for which either analytical or semi-analytical solutions are available. In the following section, the various cases for which calculations have been made are discussed and results described. The paper is concluded with a summary and some general remarks.

Mathematical Approach

The physical basis of the concept of aquifer thermal energy storage lies in the low heat conductivities of rock materials and also in the fact that aquifer volumetric capacity is normally on the order of $10^9 m^3$. Thus, large volumes of hot water may be stored under pressure. To estimate the feasibility and efficiency, as well as the optimal arrangements of such a storage system, the processes occurring during injection and withdrawal cycles must be understood. Processes of interest include: 1) thermal behavior and heat losses during successive cycles; 2) pressure changes throughout the aquifer including the possibility of the compaction of the aquifer and overburden formation which may result in land subsidence; and 3) chemical reactions and the resulting changes in aquifer permeability and porosity.

Most of our studies were made using a numerical model called "CCC" which stands for Conduction, Convection and Compaction. It is based on the so called Integrated Finite Difference Method (Edwards, 1972; Sorey, 1976; Narasimhan and Witherspoon, 1976). The model computes heat and mass flow in three-dimensional, water saturated, porous systems. Coupled with mass and energy flow is a calculation of the vertical deformation of the system using the one-dimensional consolidation theory of Terzaghi. Thus, the following physical effects are included in the calculations: a) effects of temperature on fluid heat capacity, viscosity and density; b) heat convection and conduction in the aquifer; c) effects of regional groundwater flow; d) spatial variations in aquifer properties; and e) gravitational effects.

For the validation of the numerical model, three different examples are used for which analytical or semi-analytical solutions are available. The first example is the Theis solution (1935) which describes the change of pressure head with time in a well flowing at a constant rate. Our numerical results follow closely the standard solutions in terms of the exponential integral (Figure 1). For comparison, numerical results obtained by a linear finite element method are also shown. A quadratic finite element method does not give any improvements. Only when a cubic finite element method is used are the results comparable to ours. The second example considered is a problem of evaluating the temperature distribution and radial distance as a function of time when cold water is injected into hot reservoirs. To solve the problem analytically, Avdonin (1964) 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 into one well and reservoir water is produced from 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.

Parameters Used and Mesh Design

In all our calculations we have assumed that the rate of injection and production is kept the same, equal to 10^6 kg/day (approximately 181 gpm).

The parameters used in the study are tabulated in Figure 4. These are property values taken from standard sources (Kappelmeyer and Haenel, 1974; Helgeson and Kirkham, 1974). We have performed calculations for both one-well and two-well systems. In the case of the single well, the mesh design is shown in Figure 5. The well is positioned at zero radial distance, the mesh having radial symmetry around that axis. One remark needs to be made here. In pressure 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 for equal time steps, the injected hot water will move a smaller radial distance (assuming constant flow rate). We have chosen a compromise by assuming equal radial distance steps 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. Another remark needs to be made concerning the design of the mesh in the caprock and bedrock. A very fine mesh is used close to the aquifer representing a rapid change in temperature in that region. A careless design will give a misleading value for the heat loss from the aquifer into the caprock and bedrock.

Results of Calculations

Calculations were made for the following cases:

1. Annual Cycle - Seasonal Storage

In this problem, each cycle of 360 days is composed of four periods: a) in summer, when supply exceeds demand, the hot water is stored in the aquifer; b) in fall, when supply and demand are approximately equal, the well is shut in; c) in winter, when demand exceeds supply, hot water is produced from the aquifer; and d) in spring, when supply and demand are approximately equal, the well is shut in. The calculated temperature distribution in the aquifer is shown in Figure 6 for two time periods: a) after ninety days of injection; and b) after ninety days of injection, ninety days of rest, and ninety days of production. The thermal front is not sharp because of heat conduction to the confining beds and to the aquifer system. It will be shown later that numerical dispersion is negligible in our results. Note, that after ninety days of injection, the 20° isotherm is about 30 meters from the well. The hydrodynamic front (the location of the injected water) is much farther away, approximately 60 meters from the well. The thermal front lags behind, representing the fact 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 1.3×10^6 Pascals. After ninety days of injection, the curve is essentially an inverse Theis solution with a transition at about 30 meters. This transition may be understood as a separation between native and the warmer injected water, with significantly different viscosity values, on either side of the 30 meter point (see Figure 6). After ninety days of rest, the pressure distribution equilibrates to a smooth line. During the production period after this rest a typical Theis curve is seen again. The radial dependence of the temperature distribution at the horizontal center line of the aquifer is shown in Figure 8 for different times in the first cycle. This figure also presents the curve corresponding to five days into the next cycle, showing the effect of the aquifer having already been heated during the first cycle and thus resulting in a more efficient hot water storage system for later cycles.

To study how numerical dispersion affected our results, we performed the calculation again with a finer mesh. In one mesh design we divided the aquifer vertically into six layers and radially into steps of 2 meters. In another design, the corresponding quantities are four layers and 1.5 meter 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 period for successive cycles. The efficiency is increased for each successive cycle as the aquifer is heated up, making it a better storage system. The process will reach a quasi-equilibrium when successive cycles do not change the temperature appreciably. By integrating the production temperature minus the original aquifer temperature over the production period, the energy recovered can be calculated. The percentage of energy recovered, shown in Figure 11, is this calculated energy divided by total injected energy for each cycle. Further details are shown in Figure 12, which indicates the energy balance for the first cycle: a) heat loss from all the boundaries of our caprock-aquifer-bedrock system; b) total energy injected; and c) total energy produced. It appears that the external heat loss is negligible. The difference between injected and produced energies is mainly used to heat up the aquifer, making it a better storage system.

2. Different Cycle Periods

In addition to the annual cycle described above, we also looked at the semi-annual cycle, that is: storage in the fall, production in winter for space heating; and storage in spring, production in summer for air conditioning. Very similar results were obtained. The corresponding percentage of energy recovered for successive cycles is shown in Figure 11.

3. Well Partially Penetrating the Aquifer

Calculations were also performed assuming the well to be open only for the upper half of the aquifer. Figure 13 shows the temperature contours in the aquifer after ninety days of injection and after ninety days of subsequent production. The buoyancy effect of low density hot water is clearly seen. The percentage of energy recovered for successive cycles is only slightly affected.

4. Storage of Water of Different Temperatures

We have looked at storage of water at 120°C, 220°C and 320°C. We found that as far as the 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.

5. Effect of a Clay Lens in the Aquifer

In this case the aquifer is divided into two parts by a clay lens with a radius of twenty meters. If the well is open only below the lens, the result of hot water injection and production is as shown in Figure 14 which displays the temperature contours after ninety days of injection and ninety days of subsequent production. The effect of the clay lens on these temperature contours is clearly demonstrated. However, it is found that the percentage of energy recovered is not much affected (Figure 11).

6. Inhomogeneity of the Aquifer

If the aquifer is composed of two layers, one more permeable than the other, then the flow and the temperature contours will be changed. An example in which one region is twice as permeable as the other is shown in Figure 15. The water tends to flow into the higher permeable region as would be expected. However, again it is found that the percentage of annual recovery is not much affected (Figure 11).

7. Chilled Water Storage

In addition to the study of hot water storage, we have studied the concept of storage of winter chilled water (at say 4°C) to be used in summer for air conditioning. If we assume storage of 4°C water over ninety days in winter, and production for ninety days in summer, then the production temperature for successive cycles is shown in Figure 16. After a few cycles, the temperature is expected to be below 10°C for the whole production period.

8. Two Well System

In this case we study a system of two wells, where one well supplies the water that is heated and injected into the other well. In studies described above, the thermal front moves radially from the single well. However, in this case, because of the presence of the second well, the thermal front will be distorted. In Figure 17, the thermal fronts are shown as a function of the separation between the storage well and the supplying well. As indicated, if the two wells are at a reasonable distance apart, single well results are applicable. To study this case in more detail, we have performed a three-dimensional numerical modeling of the two well system. The mesh design is shown in Figure 18. A fine mesh is used near the storage well to ensure an adequate description of the temperature changes in that region. Results of our calculations are shown in Figure 19. Here, the effect of the supplying well and the gravitational buoyancy effect are clearly indicated. The production temperature as a function of production period in the first cycle is shown in Figure 20. For comparison, the corresponding single well curve is also plotted.

9. Possibility of Consolidation or Uplift

To demonstrate the capability of the model to calculate the consolidation or uplift effect, we have performed calculations based on two sets of arbitrarily chosen parameters. The results are illustrated in Figure 21 where we have assumed 10-day injection and production periods. One can see that consolidation and uplift are strongly parameter dependent.

Summary

In this paper, the hydrodynamic and thermal behavior of an aquifer used for thermal energy storage was studied and described for a number of possible situations. In all the cases studied, the percentage of energy recovery was surprisingly high, over 80% after only a few injection-production cycles. We have plans to simulate the production and injection history of an actual field experiment.

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 or permeability. Furthermore, water treatment is crucial to ensure the injectability of the storage well. Another effect which we plan to study is fingering caused by geological heterogeneities which would tend to reduce the energy recovery percentage.

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

Acknowledgements

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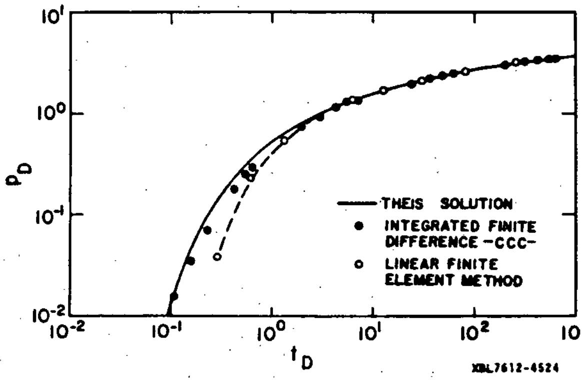

Figure 1. CCC compared to the Theis (1935) solution. Results obtained from the conventional finite element method are also shown.

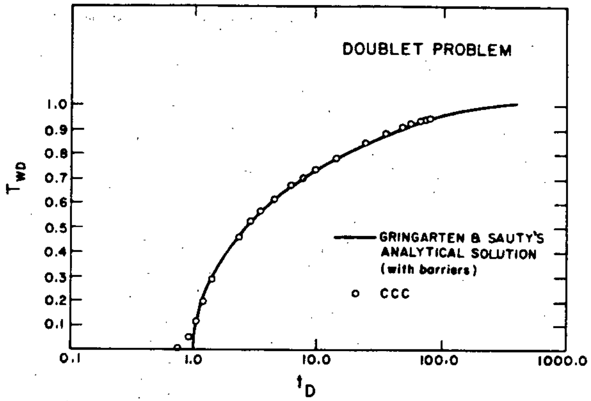

Figure 3. CCC compared to the Gringarten and Sauty (1975) doublet problem.

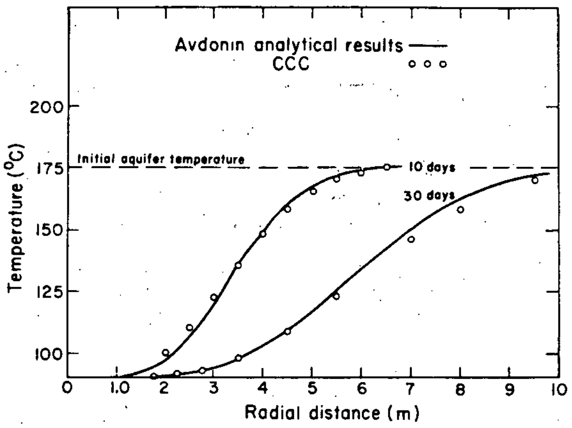

Figure 2. CCC compared to Avdonin (1964) solution. Water injected at 2×10^4 cm^3/sec into an aquifer 200m thick with 20% porosity.

MATERIAL	POROSITY	DENSITY kg m^{-3}	HEAT CAPACITY J kg^{-1} °C^{-1}	THERMAL CONDUCTIVITY J $s^{-1}m^{-1}$°C^{-1}	PERMEABILITY m^2	SPECIFIC STORAGE $KN^{-1}m^2$
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 C(J kg^{-1}°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. Material and fluid parameters used in the hot water storage model.

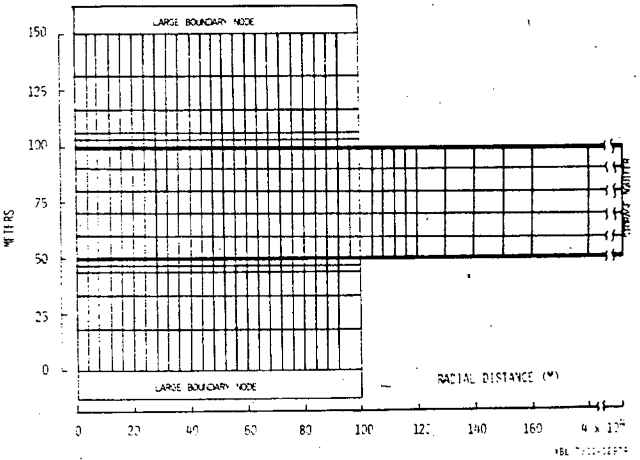

Figure 5. CCC mesh design for hot water storage: radial symmetry with well at zero radial distance.

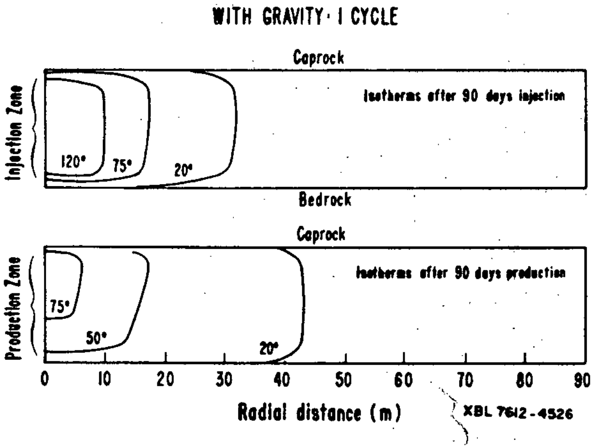

Figure 6. Temperature distribution in the aquifer after 90 days of injection, 90 days of rest, and 90 days of production (Cycle 1); t represents total time elapsed.

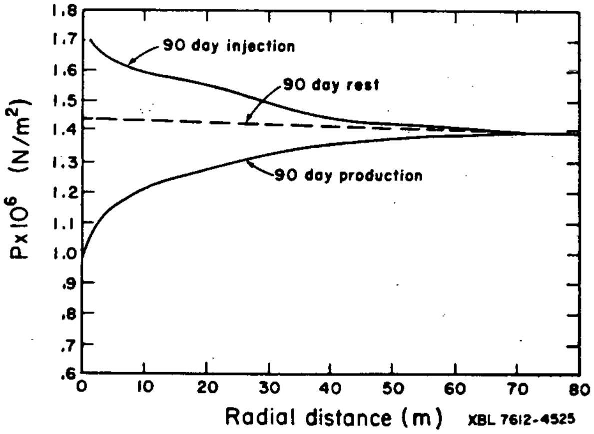

Figure 7. Pressure distribution in the aquifer as a function of distance from the well (Cycle 1), full penetration.

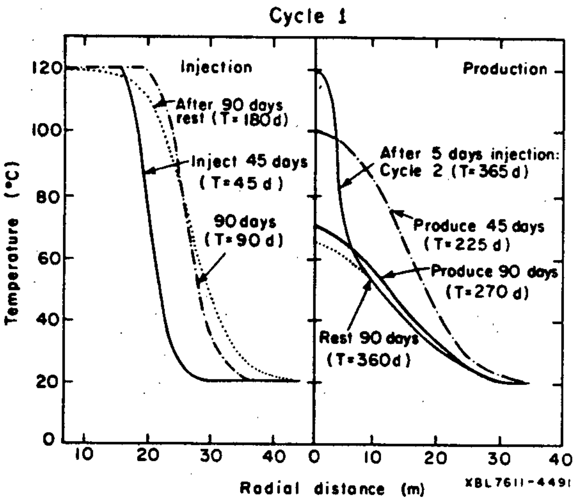

Figure 8. Temperature distribution in the aquifer as a function of radial distance for indicated times.

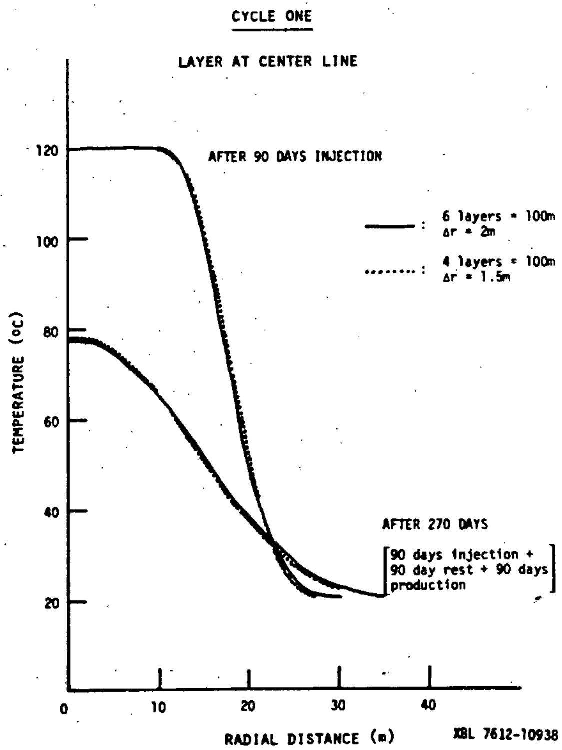

Figure 9. Effect of mesh size on calculated temperature.

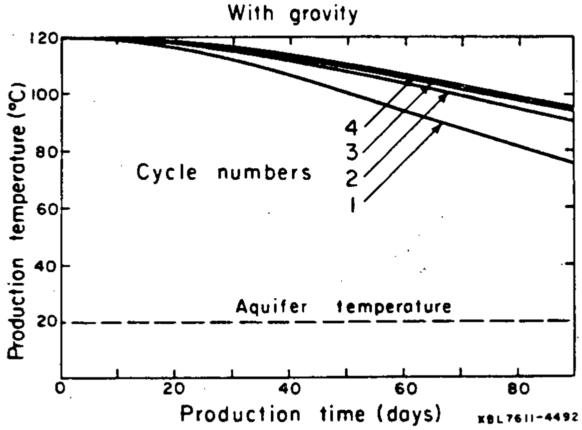

Figure 10. Temperature at the well versus production time for each cycle: full penetration case.

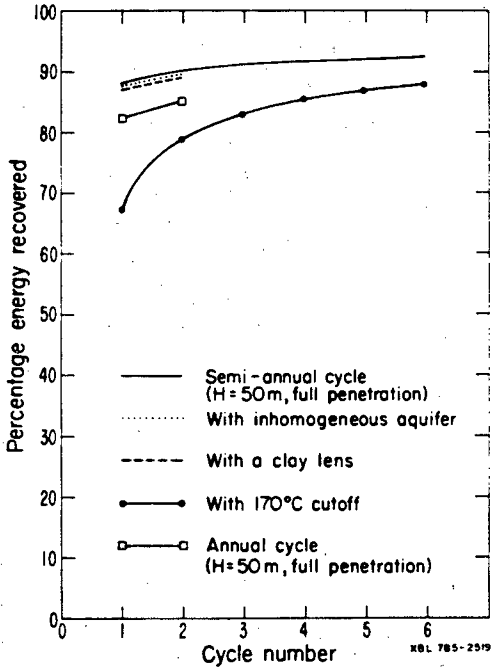

Figure 11. Energy recovered for different cycles.

FIRST CYCLE

Ti = 120°C

To = 20°C

Δr = 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 12. Energy balance for first cycle. Note that energy lost through boundaries is negligible.

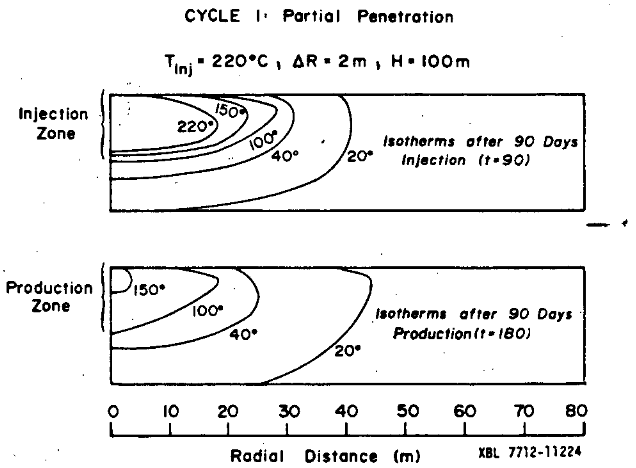

Figure 13. Isotherms for partial penetration after 90-day injection and production periods (Cycle 1).

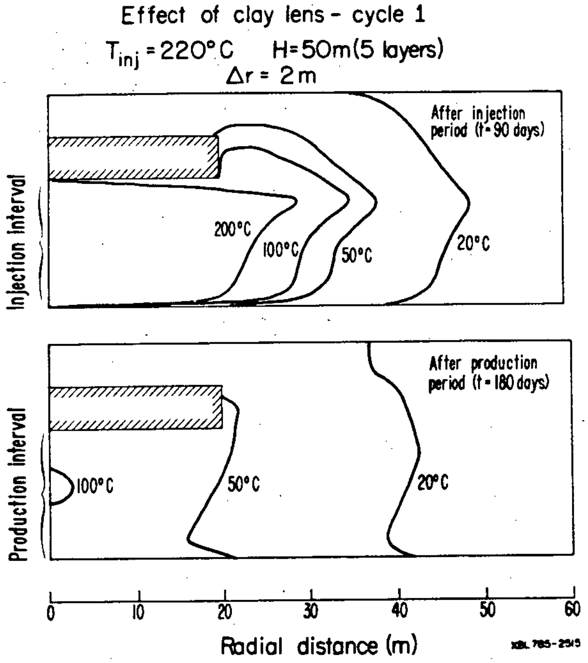

Figure 14. Effect of a clay lens (Cycle 1): 90 day production and injection periods.

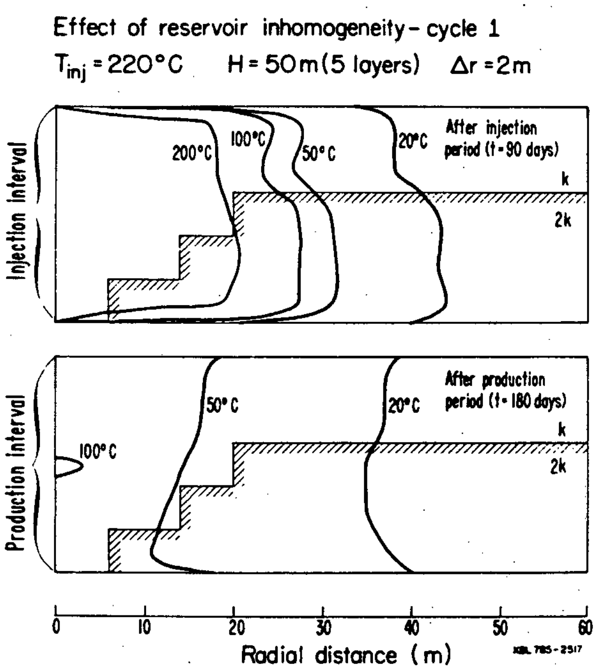

Figure 15. Effect of reservoir inhomogeneity (Cycle 1): 90 day production and injection periods.

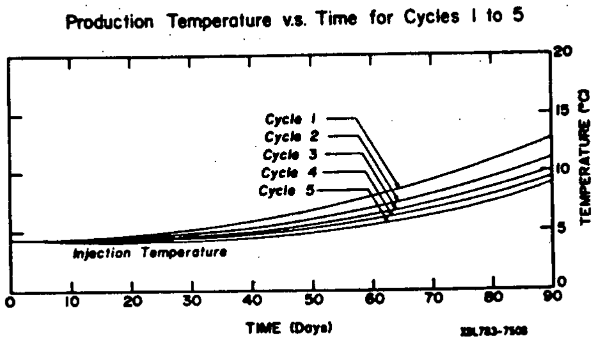

Figure 16. Chilled water storage: temperature at the well versus production time for five cycles.

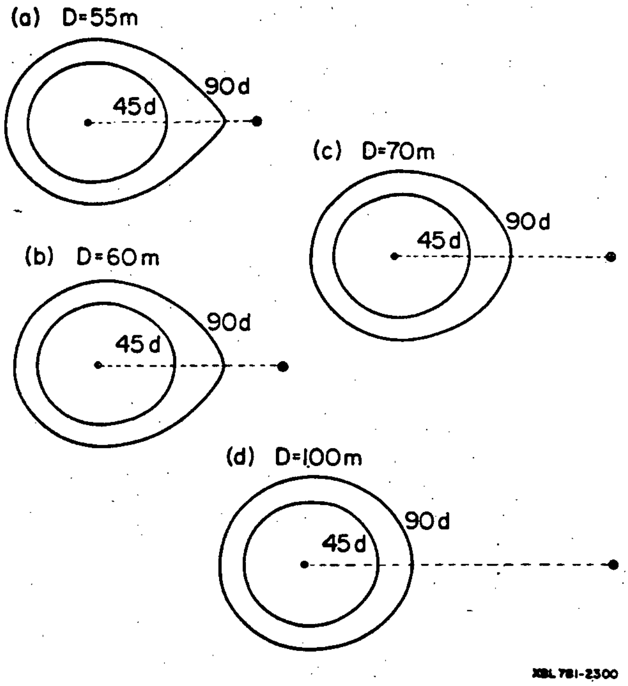

Figure 17. Effect of separation distance between storage and supplying wells at 45 and 90 days.

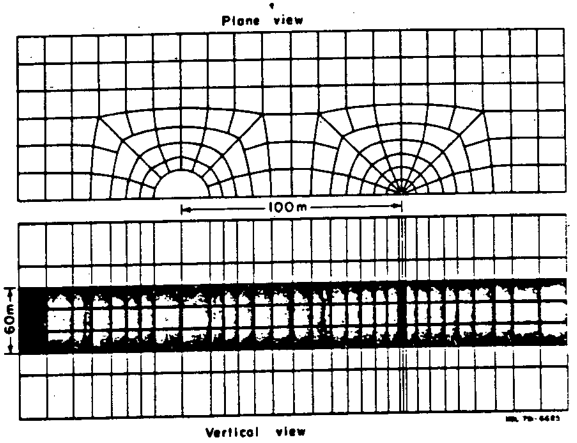

Figure 18. CCC doublet: mesh design.

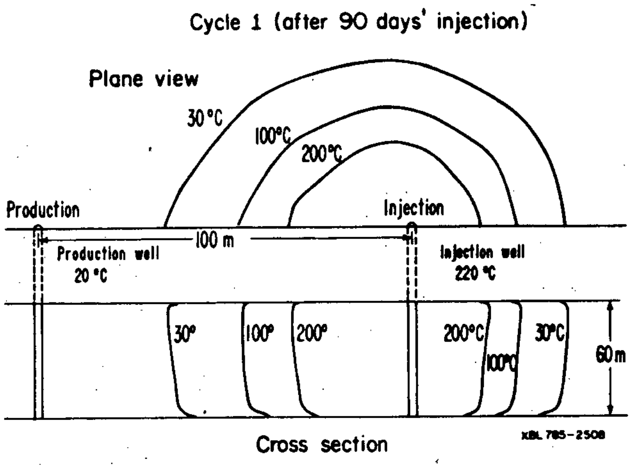

Figure 19. Isotherms for a two-well system after 90 days of injection. Plane and cross section views.

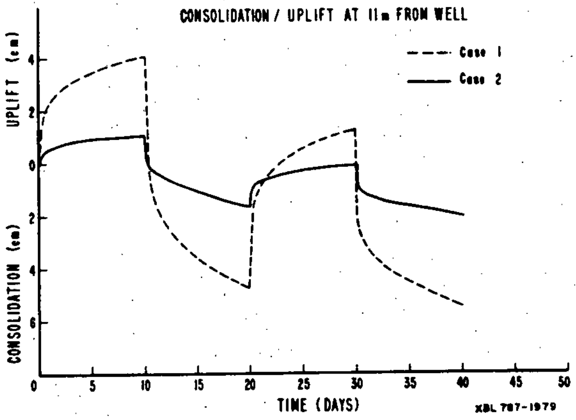

Figure 21. CCC Consolidation/Uplift: Case 2 has C_s and C_c values 1/5 of Case 1. (C_s and C_c are slopes of void ratio versus the logarithm of effective stress corresponding to recompression and virgin curves, respectively.)

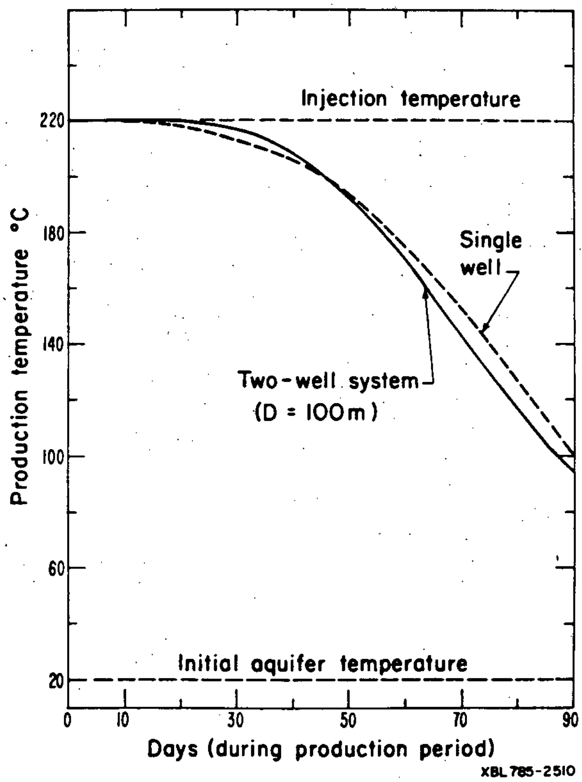

Figure 20. Production temperature during production period for a two-well system and the corresponding single-well case.

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