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ABSTRACT

In steam-electric power plants, large volumes of surface waters are used for cooling the plant's condensers. There, approximately two thirds of the energy produced by the fuel is removed as waste heat. This heat is carried away by the cooling waters, is dispersed into the atmosphere or surface water bodies, and is lost for other potential uses. When condenser cooling systems such as towers or ponds are used, there is also a considerable net loss of water through evaporation.

Injection and storage of spent cooling waters underground would reduce the evaporative (consumptive) losses to the atmosphere. Later, these waters could be recovered for use in heating and in industrial or agricultural applications. The resulting conservation of energy and water may make such a project economically feasible in the near future as the costs of water and fuel increase.

In this paper, we review the use of ground water from a confined aquifer for this application and analyze a simple configuration of one withdrawal and one injection well to determine: (1) the areal extent of temperature changes caused by reinjection of spent cooling waters into the aquifer from which they originated; and (2) how long it would take for the water to become too hot to use for cooling.

INTRODUCTION

The present rate of water use in fossil-fueled and nuclear electric power plants is high and is expected to increase significantly in the future (see Table 1). Only a small portion of this demand is supplied from ground-water sources. In some areas the use of ground water would have advantages over surface water for cooling because ground water would offer a more reliable supply, a relatively constant temperature and quality, and a broader area for plant site selection (Smith, 1978). However, according to Murray and Reeves (1977, Table 9) the 1975 rate of ground-water use for thermoelectric power generation in the entire United States was only about 61 m^3/sec (1.4 x 10^9 gal/day).

About 99% of the water withdrawn by these plants is used for cooling; that is, to condense the spent steam from the generators and to dissipate waste heat produced during electric power generation (Murray and Reeves, 1977). In many cases, to avoid thermal pollution of surface water bodies, or to save water where it is expensive or scarce, cooling towers or ponds are employed. This allows the water to be used repeatedly in the power plant condensers and cooling system, but large volumes of water are lost to the atmosphere through evaporation. The volume of water consumed (permanently removed from its source) per unit waste heat varies with the power plant and cooling systems used and the meteorological conditions at the site. The average water consumption estimates given by Jury et al. (1979, Table 1) for the different cooling methods vary between 0.07 and 0.98 $m^3 \cdot sec^{-1} \cdot GW^{-1}$ (1.6 to 22.4 x 10^6 $gal \cdot day^{-1} \cdot GW^{-1}$), for dry and wet cooling tower systems, respectively. According to Davis and Velikanov (1979) in the next 10 to 15 years the average value for the total water consumption per power unit will be between 0.5 and 0.6 $m^3 \cdot sec^{-1} \cdot GW^{-1}$ (11.4 to 13.7 x 10^6 $gal \cdot day^{-1} \cdot GW^{-1}$). Thus, the average 1000-MW steam-electric power plant would consume annually about 15 to 18 x 10^6 m^3 (4.0 to 4.8 x 10^9 gal) of water. Snyder et al. (1979) estimated the 1975 total consumption rate by these type of plants in the conterminous United States (Table 1) to be about 75 m^3/sec (1.7 x 10^9 gal/day).

The amount of heat to be disposed by the cooling system depends on the thermal efficiency of the plant. The efficiency of a fossil-fueled plant (about 38%) is somewhat higher than that of most nuclear plants (about 33%). The alternate cooling system technologies have been discussed recently by Snyder et al. (1979) and Jury et al. (1979) and will not be reviewed here.

The large amount of sensible heat carried by the cooling waters could be used in district heating or in agricultural and industrial applications. All or some of these waters could be stored in aquifers for later use. [Researchers at Lawrence Berkeley Laboratory (1978) are investigating this potential use of aquifers.] To do this, the hot waters would be injected underground with minimal contact with the atmosphere. The heat storage efficiency of aquifers is high because of their low thermal conductivities and high specific heat capacities. Thus only small volumes of water would be lost through evaporation and most of the thermal energy contained in the cooling water would be conserved.

In this paper, we will analyze the aquifer temperature changes caused by the use of ground water for cooling thermoelectric power plants and reinjecting the heated water into the aquifer from which it originated. We will consider a simple doublet system, consisting of one production and one injection well, under different regional ground-water conditions. In particular, we are concerned with the length of time it takes for the injected water to affect the temperature of the water in the production well, which is called the breakthrough time. After that time, if water from the production well is sent through the plant's condensers, the efficiency of the plant will be impaired.

AQUIFER TEMPERATURE CHANGES

Temperature changes occur in an aquifer when ground water is extracted from one well, used in a plant cooling system, and reinjected into the aquifer through a second well (at a higher temperature). In this paper, we will examine the areal extent of these temperature changes and the length of time it takes for the ground water to become too hot to use for this purpose. We have made no attempt to study chemical reactions or precipitation that might occur when waters of different temperatures and chemical composition are injected into the aquifer.

When hot water is injected into an aquifer, a hydrodynamic front is created along which the injected water displaces the native ground water. The thermal front advances toward the production well more slowly than the hydrodynamic front because the injected water is cooled by the rock skeleton of the aquifer. Because of the difference in specific heat capacities between rock and water, the ratio of the volume of aquifer around the injection well where the native ground water has been displaced (V_A), to the volume where the temperature has been altered (V_T) is:

$$V_A/V_T = \frac{(1 - \phi)\ \rho_R C_R + \phi \rho_W C_W}{\phi \rho_W C_W} \qquad (1)$$

where ϕ is porosity, ρ is density, C is specific heat capacity, and the subscripts R and W refer to rock and water, respectively. We assume that (1) piston displacement occurs in the aquifer, (2) the wells penetrate the total aquifer thickness, and (3) there is no thermal conduction within or away from the aquifer. Thus, under these assumptions and for an aquifer with properties as given in Table 2, about 4.2 x 10^5 m^3 (1.11 x 10^8 gal) of warm water could be injected, and the heated volume would be restricted to a 30-m (98.4-ft) radius cylinder.

Classical heat conduction studies (e.g., Carslaw and Jaeger, 1959) have shown that conduction is relatively slow in typical geologic formations. Figure 1 shows the transient temperature profile radially away from a 30-m (98.4-ft) radius cylinder (r_o) kept at a constant temperature (T_o), embedded in a medium whose thermal diffusivity (κ) is equal to 16.5 x 10^{-3} cm^2/sec (6.39 x 10^{-2} ft^2/hr) and initial reference temperature is defined as zero. The figure shows that no temperature changes occur 500 m (1640.4 ft) away from the cylinder even after 100 years.

These results indicate that geologic materials with thermal properties like those of sandstones are good insulators. This makes it feasible to store hot water in aquifers and restrict the thermal changes to small areas around the injection wells.

If convection is incorporated in the analysis, as is necessary for the case of one injection and one production well, the heat transport through the materials is much faster. Tsang et al. (1977) have established that in the case of doublet systems placed in a confined aquifer with no natural regional ground water flow, the breakthrough time (t_B) at the production well is

$$t_B = (\phi/3)(\pi H D^2/Q)(V_A/V_T) \tag{2}$$

where H is aquifer thickness, D is distance between wells, Q is volumetric flow rate, and V_A/V_T is given in Equation 1.

For the case of no regional ground-water flow, the temperature of the produced water (T) after breakthrough may be approximated by (Tsang et al., 1977):

$$\frac{T - T_i}{T_o - T_i} = 0.338 \exp(-0.0023\, t/t_B) + 0.337 \exp(-0.1093\, t/t_B) + 1.368 \exp(-1.3343\, t/t_B) \qquad \text{for } t > t_B \tag{3}$$

where T_i is the temperature of the injected waters, T_o the initial ground-water temperature and t is time.

With the presence of regional ground-water flow, the breakthrough time (given by Equation 2) will be affected. Under these conditions, it is no longer possible to obtain a closed-form solution for the breakthrough time (Gringarten and Sauty, 1975). Nevertheless, for the special cases where the regional flow is parallel to a line between the doublet wells, the following expressions are obtained:

for $v_o > 0$

$$t_B = (D/v_o)(V_A/V_T)\left[1 + \frac{A}{\sqrt{1+4A}} \ln\left(\frac{1-\sqrt{1+4A}}{1+\sqrt{1+4A}}\right)^2\right] \tag{4A}$$

for $v_o < 0$ and $|v_o| < 2Q/(\pi\phi HD)$

$$t_B = (D/v_o)\,(V_A/V_T)\left[1 + \frac{4A}{\sqrt{-1-4A}} \tan^{-1}\left(\frac{1}{\sqrt{-1-4A}}\right)\right] \tag{4B}$$

where $A = Q/2\pi\phi HDv_o$ and v_o is the regional tracer velocity, being positive in the direction of the vector connecting the injection and production wells. When the regional velocity is negative and its magnitude is greater than

$2Q/(\pi\phi HD)$, the injected water will never reach the production well.

We studied the effect of natural ground-water flow fields with velocities up to 100 m/yr (328.1 ft/yr) using a computer model developed by Gringarten and Sauty (1975). This code computes heat transport in porous media, assuming a steady-state mass flow field.

For this purpose, we considered different distances (D) between wells and regional ground-water regimes. We assumed a volumetric flow rate of 10^4 m^3/day (2.64 x 10^6 gal/day); Table 2 gives the other parameters used. Thermal conductivities along the vertical and horizontal directions were neglected. The results obtained are given in Table 3. The direction of the regional ground-water flow is given by the angle α measured counterclockwise between the vector of regional ground-water velocity and the vector connecting the injection and production wells (Fig. 2). Figures 3 and 4 illustrate the results. The solid lines indicate the position of the thermal front at different times; the dashed lines show the flow lines between the wells.

For the cases shown in Table 3 where there is no regional flow, or where α is 0^o or 180^o (indicating that the flow is parallel to the line between the doublet wells), there are small differences (less than 5%) between the breakthrough times calculated by the computer code and those obtained from evaluating Equations 2 and 4. The analytical solutions are exact whereas the computer values depend on the discretization (number of flow channels) used in the model.

The results in Table 3 show that when the doublet system is in operation, the regional flow will not affect the breakthrough times appreciably unless (1) the direction of flow is from the injection well toward the production well ($\alpha = 0^o$) or in the opposite direction ($\alpha = 180^o$); or (2) the magnitude of velocity (v_o) is greater than 10 m/yr (32.8 ft/yr). Careful design of the well pattern including the use of screening and bounding wells will significantly reduce the effects of the regional ground-water flow (Tsang and Witherspoon, 1975; Whitehead and Langhetee, 1978). If necessary, the magnitude (and direction) of the natural flow could be changed locally by using strategically placed wells, but the velocity of the regional flow will be less than 10 m/yr (32.8 ft/yr) in most confined porous aquifers.

CONCLUSIONS

Using simple well configuration, the parameters given in Table 2, and injection/production rates of 3.65×10^6 m^3/yr (2.64×10^6 gal/day), it will take between two and eight years before the temperature of the extracted water begins to increase. This period appears quite short compared with the design life of a typical power station (about 30 years). However, increasing the distance between the wells or extracting some of the stored hot water will significantly increase the breakthrough times. (For example, Equation 2 shows that t_B is related to the square of the distance.)

In actual field tests a much larger number of wells could be used. The wells could be arranged in patterns similar to those being used in tertiary oil recovery operations. The analysis of the different well configurations would be more complex than in the case of a simple doublet system but could be easily performed by computer codes similar to the one used here.

Even though the flow rate used in the examples is quite small, the use of ground water in power plants for cooling and underground storage of the heated water should be thoroughly investigated in the field.

According to Davis and Velikanov (1979), in the average 1000-MW steam-electric plant about 900 x 10^6 m^3/yr (651 x 10^6 gal/day) of water flow through the condensers. A possible reduction in evaporation losses and conservation of energy could make this procedure economically feasible, especially in arid regions.

The temperature changes resulting from the injection of hot water into confined aquifers are reasonably localized around the injection wells. When the operation of the doublet well system is finally stopped and the stored water is not extracted, the plume of hot water will drift in the direction of the natural ground-water flow. As the hot water drifts, it will give up heat to the granular skeleton of the aquifer and become cooler, restricting the major temperature effects to the doublet area.

NOMENCLATURE

Symbol	Description	Dimensions
C	Specific heat capacity	$L^2 \cdot t^{-2} \cdot T^{-1}$
D	Distance between wells	L
H	Aquifer thickness	L
r	Radius, radial distance	L
Q	Volumetric flow rate	$L^3 \cdot t^{-1}$
T	Temperature	T
t	Time	t
t_B	Breakthrough time	t
V_A	Volume of aquifer where the original ground water has been displaced	L^3
V_T	Volume of aquifer where the ground-water temperature has been changed	L^3

Symbol	Description	Dimensions
v_o	Regional groundwater velocity	$L \cdot t^{-1}$
α	Angle measured counterclockwise between the vector connecting the injection and production wells and the regional groundwater velocity vector	--
κ	Thermal diffusivity	$L^2 \cdot t^{-1}$
ρ	Density	$M \cdot L^{-3}$
ϕ	Porosity	--

Subscripts

i	Injection
o	Initial
R	Rock
W	Water

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REFERENCES CITED

Carslaw, H. S., and Jaeger, J. C., 1959. Conduction of heat in solids, 2nd ed. Oxford, Clarendon Press, 510 p.

Davis, G. H, and Velikanov, A. L., 1979. Hydrological problems arising from the development of energy--a preliminary report. UNESCO, Technical Papers in Hydrology, v. 17, 32 p.

Gringarten, A. C., and Sauty, J. P., 1975. A theoretical study of heat extraction from aquifers with uniform regional flow. Jour. Geophys. Res., v. 80, no. 35, pp. 4956-4962.

Jury, W. A., Sinai, G., and Stolzy, L. H., 1979. Future sources of cooling water for power plants in arid regions. Water Resour. Bull., v. 15, no. 5, pp. 1444-1458.

Lawrence Berkeley Laboratory, 1978. Thermal Energy Storage in Aquifers Workshop, Proceedings, May 10-12, Berkeley, California. Berkeley, Lawrence Berkeley Laboratory Report LBL-8431.

Murray, R. C., and Reeves, E. B., 1977. Estimated use of water in the United States in 1975. U. S. Geol. Survey Circ. 765, 39 p.

Smith, E. M., 1978. Ground-water use for nuclear plants. Ground Water, v. 16, no. 5, pp. 352-354.

Snyder, D. M., Mao, K. T. and Glynn, R. D., Jr., 1979. Water use for electric power generation (Paper presented at the Engineering Foundation Conference on Improved Hydrologic Forecasting--Why and How, Asilomar, CA., March 25-30, 1979). Amer. Soc. Civil Engr. (in press).

Tsang, C. F., Lippmann, M. J., and Witherspoon, P. A., 1977. Production and reinjection in geothermal reservoirs. Geoth. Res. Coun. Trans., v. 1, pp. 301-303.

Tsang, C. F., and Witherspoon, P. A., 1975. An investigation of screening geothermal production wells from effects of reinjection, in Kruger, P., and Ramey, J. J., Jr., eds., Geothermal reservoir engineering. Stanford, Stanford Geothermal Program Rpt. SGP-TR-12, pp. 62-64.

Whitehead, W. R., and Langhetee, E. J., 1978. Use of bounding wells to counteract the effects of preexisting groundwater movement. Water Resour. Res., v. 14, no. 2, pp. 273-280.

TABLE 1. WATER WITHDRAWALS AND CONSUMPTION FOR STEAM-ELECTRIC GENERATION IN THE CONTERMINOUS UNITED STATES

	Withdrawals			Consumption		
	1975	1985	2000	1975	1985	2000
Fresh water						
(in m^3/sec)	3894	4155	3506	62	178	462
(in 10^9 gal/day)	(88.9)	(94.8)	(80.0)	(1.4)	(4.1)	(10.5)
Saline water						
(in m^3/sec)	1904	3805	4928	13	36	109
(in 10^9 gal/day)	(43.5)	(86.9)	(112.5)	(0.3)	(0.8)	(2.5)

Source: Modified from Snyder et al. (1979, Table 2).

TABLE 2. PARAMETERS USED IN THE EXAMPLES

Aquifer thickness (H) = 50 m (164.0 ft)

Porosity (ϕ) = 0.20

Volumetric heat capacity of water ($\rho_W C_W$) = 1.0 cal$\cdot$°C$^{-1}\cdot$cm^{-3} (62.5 Btu$\cdot$°F$^{-1}\cdot$ft^{-3})

Volumetric heat capacity of rock ($\rho_R C_R$) = 0.5 cal$\cdot$°C$^{-1}\cdot$cm^{-3} (31.2 Btu$\cdot$°F$^{-1}\cdot$ft^{-3})

TABLE 3. RESULTS OF DOUBLET SYSTEM

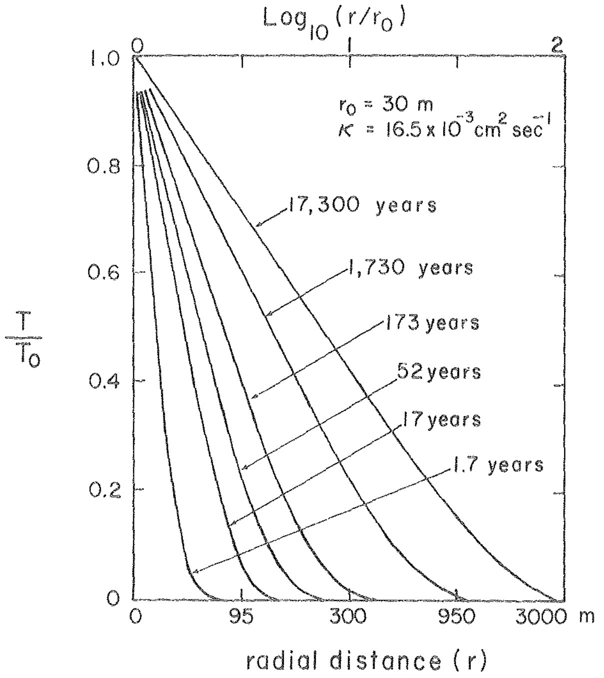
Distance between wells (m)	Distance between wells (ft)	Regional ground-water velocity (m/yr)	Regional ground-water velocity (ft/yr)	α (degrees)	Breakthrough time (years) Numerical	Breakthrough time (years) Analytical
500	1640	0	0	-	2.05	2.15
500	1640	100	328	270	2.14	-
500	1640	100	328	0	1.8	1.84
500	1640	100	328	180	2.5	2.60
750	2461	0	0	-	4.6	4.83
1000	3281	0	0	-	8.2	8.59
1000	3281	10	33	270	8.2	-
1000	3281	100	328	270	8.9	-

Figure 1. Temperature in the region bounded internally by a cylinder of radius $r = r_o$, with zero initial temperature and constant surface temperature, T_o (modified from Carslaw and Jaeger, 1959, Fig. 41).

Figure 2. Angle (α) between the vector of the regional ground-water velocity (v_o) and the vector from the injection well to the production well.

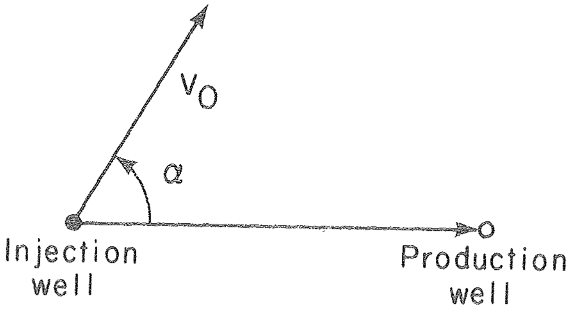
Figure 3. Doublet well system (D = 500 m) under different regional ground-water conditions. Solid lines indicate the position of the thermal front at different times; the dashed lines show the flow lines between the wells.

Figure 4. Doublet well system (D = 1000 m) under different regional ground-water conditions. Solid lines indicate the position of the thermal front at different times; the dashed lines show the flow lines between the wells.



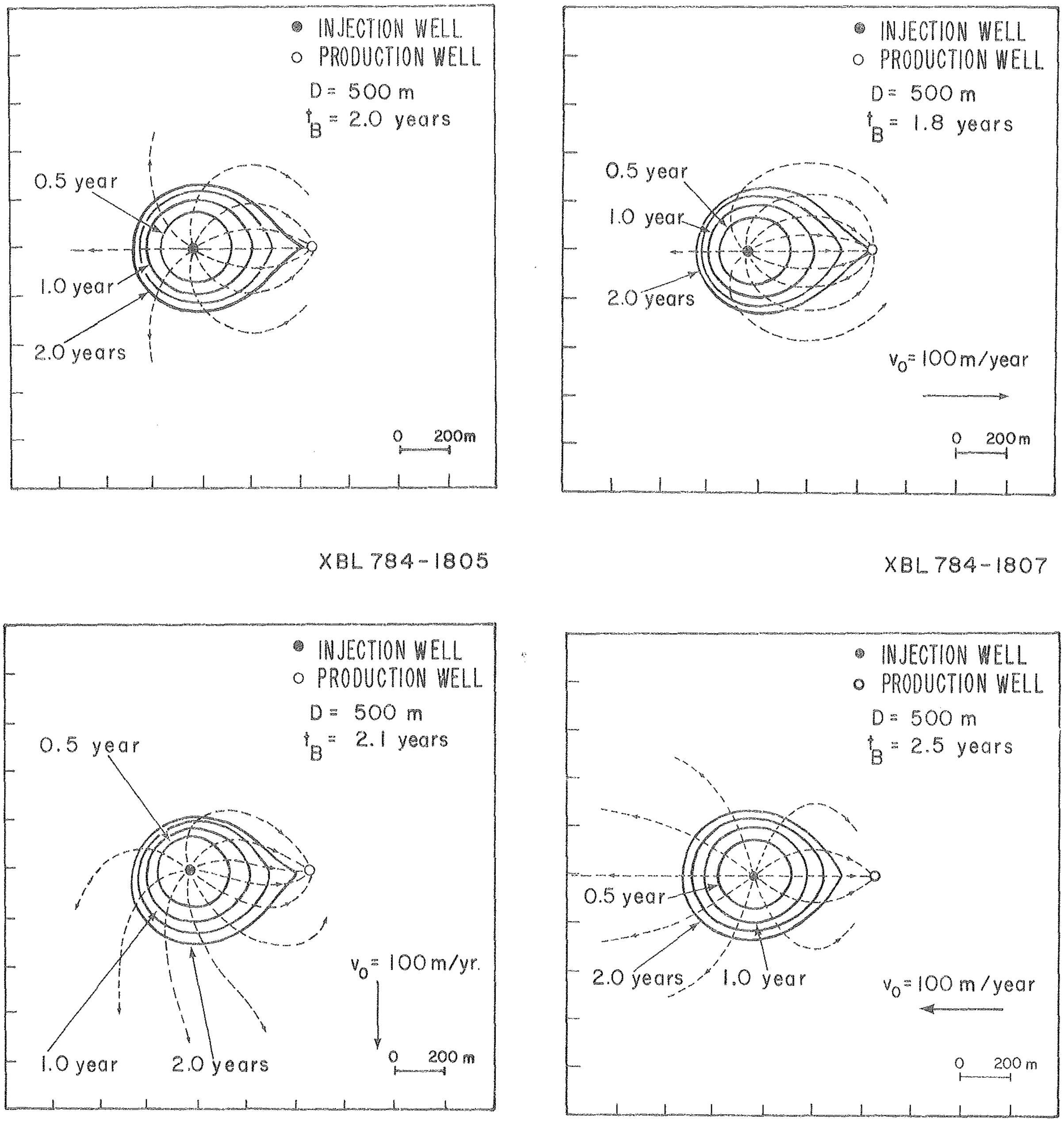
XBL 784-1803

Figure 1. Temperature in the region bounded internally by a cylinder of radius $r = r_0$, with zero initial temperature and constant surface temperature, T_0 (modified from Carslaw and Jaeger, 1959, Fig. 41).



XBL 802-8182

Figure 2. Angle (α) between the vector of the regional ground-water velocity (v_0) and the vector from the injection well to the production well.



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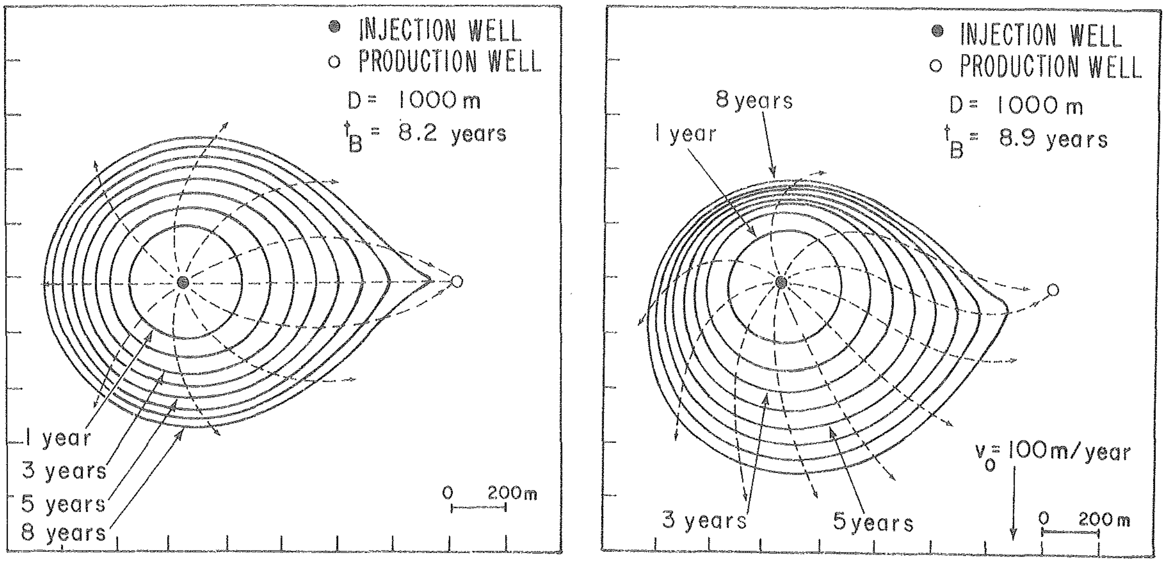
XBL 784-1807

XBL 784-1811

XBL 784-1804

Figure 3. Doublet well system (D = 500 m) under different regional ground-water conditions. Solid lines indicate the position of the thermal front at different times; the dashed lines show the flow lines between the wells.



XBL 784-1806

XBL 784-1808

Figure 4. Doublet well system (D = 1000 m) under different regional ground-water conditions. Solid lines indicate the position of the thermal front at different times; the dashed lines show the flow lines between the wells.