PRELIMINARY MODELING OF AN AQUIFER THERMAL-ENERGY STORAGE SYSTEM

UNITED STATES GEOLOGICAL SURVEY

Open-File Report 84-811

Prepared in cooperation with the
UNIVERSITY OF MINNESOTA and
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Preliminary Modeling of an Aquifer Thermal-Energy Storage System

By Robert T. Miller

Abstract

The University of Minnesota, the Minnesota Geological Survey, and the U.S. Geological Survey are studying the feasibility of storing water at a temperature of 150 degrees Celsius in the Franconia-Ironton-Galesville aquifer. The Aquifer Thermal-Energy Storage project has a doublet-well design with a well spacing of approximately 250 meters. One well will be used for cool-water supply, and, the other, for hot-water injection.

The U.S. Geological Survey is constructing a model of ground-water flow and thermal-energy transport to aid in determining the efficiency of the Aquifer Thermal-Energy Storage system. A preliminary model of radial flow and thermal-energy transport was constructed, based on hydraulic and thermal properties of the Franconia-Ironton-Galesville aquifer determined in previous studies. The model was used to investigate the sensitivity of model results to various hydraulic and thermal properties and to study the potential for buoyancy flow within the aquifer and the effect of various cyclic injection-withdrawal schemes on the relative thermal efficiency of the aquifer.

Sensitivity analysis was performed assuming 8 days of injection of 150-degree-Celsius water at 18.9 liters per second, 8 days of storage, and 8 days of withdrawal of hot water at 18.9 liters per second. The analysis indicates that, for practical ranges of hydraulic and thermal properties, rock-heat capacity is the least important property and thermal dispersivity is the most important property used to compute temperature and aquifer thermal efficiency.

The amount of buoyancy flow was examined for several values of hydraulic conductivity and ratios of horizontal to vertical hydraulic conductivities. For the assumed base values of hydraulic and thermal properties, buoyancy flow was negligible. The greatest simulated buoyancy flow resulted from simulations in which horizontal hydraulic conductivity was increased to 10 times the base value, and the vertical hydraulic conductivity was set equal to the horizontal hydraulic conductivity.

The effects of various injection-withdrawal rates and durations on computed values of aquifer relative thermal efficiency and final well-bore temperature were studied for five 1-year hypothetical test cycles of injection and withdrawal. The least efficient scheme was 8 months injection of 150-degree-Celsius water and 4 months of withdrawal of hot water at 18.9 liters per second. The most efficient scheme was obtained with 6 months of injection of 150-degree-Celsius water at 18.9 liters per second and 6 months of withdrawal of hot water at 37.8 liters per second. The hypothetical simulations indicate that the subsequent calibrated model of the doublet-well system will be a valuable tool in determining the most efficient system operation.

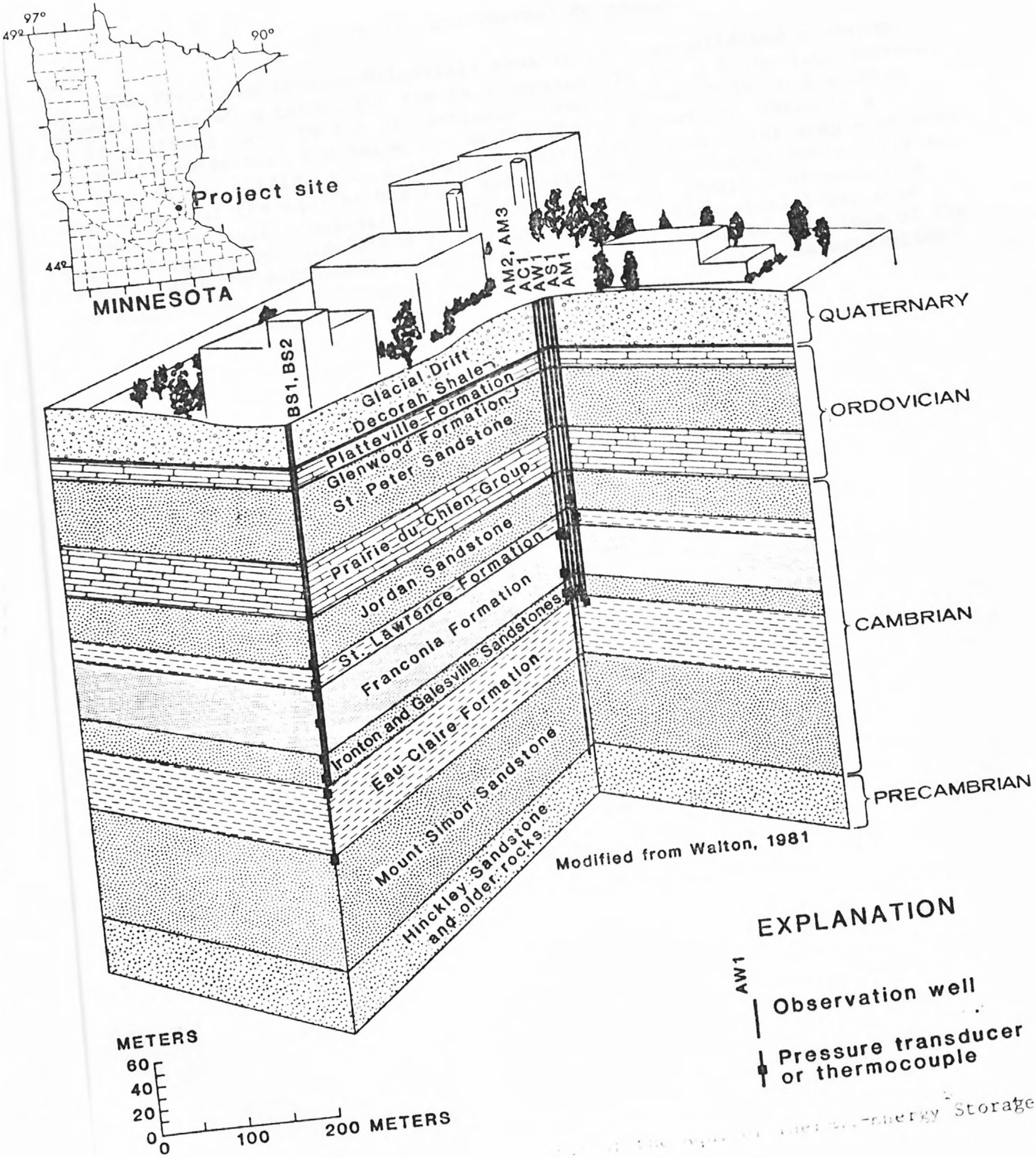
Introduction

In May 1980, the University of Minnesota, the Minnesota Geological Survey, and the U.S. Geological Survey began a cooperative study to evaluate the feasibility of storing water heated to 150 ^{o}C in the deep (180-240 m) Franconia-Ironton-Galesville aquifer and later recovering it for space heating. High-temperature water from the cooling system for the University's electrical-generation facilities would supply heat for injection. The Aquifer Thermal-Energy Storage (ATES) site and doublet-well system design are shown diagrammatically in figure 1. The injection-withdrawal wells are approximately 250 m apart. Water is pumped from one of the wells through a

Figure 1.--(caption on next page) belongs near here.

heat exchanger where heat is added or removed. Water then is injected back to the aquifer through the other well. The experiment planned for testing the ATES system includes a series of hot-water injection, storage, and withdrawal cycles. Each cycle will be 24 days long, and the length of each injection, storage, and withdrawal step of the cycle will be 8 days.

The U.S. Geological Survey is constructing a ground-water-flow and thermal-energy-transport model for evaluating the efficiency of the ATES system. This paper describes sensitivity analyses for individual preliminary model-input properties, the potential for buoyancy-flow effects, and hypothetical simulations of aquifer relative thermal efficiency.


97°
49°
90°
44°
Project site
MINNESOTA
BS1, BS2
AM2, AM3
AC1
AW1
AS1
AM1
Glacial Drift
Decorah Shale
Platteville Formation
Glenwood Formation
St. Peter Sandstone
Prairie du Chien Group
Jordan Sandstone
St. Lawrence Formation
Franconia Formation
Ironton and Galesville Sandstones
Eau Claire Formation
Mount Simon Sandstone
Hinckley Sandstone and older rocks
QUATERNARY
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
Modified from Walton, 1981
EXPLANATION
AW1
Observation well
Pressure transducer or thermocouple
METERS
60
40
20
0
0
100
200 METERS

Hydraulic and Thermal Properties

The Franconia-Ironton-Galesville aquifer is a consolidated sandstone, approximately 60 m thick; the top is approximately 180 m below land surface. It is confined above by the St. Lawrence Formation, which is an 8-m-thick dolomitic sandstone, and below by the Eau Claire Formation, which is a 30-m-thick shale (fig. 1). Initial hydraulic testing with inflatable packers indicates that the aquifer has four hydraulic zones with distinctly different values of hydraulic conductivity. The thickness and location of each zone were determined by correlating data from bore-hole geophysical logs, core samples, and the inflatable-packer tests. The stratigraphic relations of the hydraulic zones, their thicknesses, and horizontal hydraulic conductivities determined from these data are shown in table 1.

Table 1. Hydraulic zonation, thickness, and horizontal hydraulic conductivity determined from bore-hole geophysical logs, core samples, and inflatable-packer test data

Hydraulic zone	Thickness (m)	Horizontal hydraulic conductivity (m/d)
Franconia Formation:		
Upper..........................	14	0.6
Lower..........................	25	.03
Ironton Sandstone................	15	1.2
Galesville Sandstone............	6	.3

The average porosity for the Franconia-Ironton-Galesville aquifer is approximately 25 percent (Norvitch and others, 1973), and the average storage coefficient is 3.6×10^{-5} (Miller, 1983).

Values of rock thermal conductivity and rock-heat capacity are given in table 2 and represent averages from values given by Clark (1966) for different sandstones and shales that are similar in composition to the Franconia-Ironton-Galesville aquifer and the confining beds, St. Lawrence and Eau Claire Formations. Thermal dispersivity was estimated from the results of heat-storage testing by Sauty and others (1979).

Table 2. Summary of relevant system thermal properties

Rock thermal conductivity (aquifer and confining beds)	$=2.20 \times 10^5$	joules per meter per day per degree Celsius
Thermal dispersivity	= 3	meters
Rock-heat capacity	$= 1.81 \times 10^6$	joules per cubic meter per degree Celsius

Numerical Model and Mathematical Formulation

Early in the study, a preliminary two-dimensional, radial-flow, anisotropic, nonisothermal, ground-water-flow and thermal-energy-transport model was constructed. Sensitivity analyses were made for a range of selected hydraulic and thermal properties that are known or assumed to be characteristic of the aquifer. The preliminary model also was used for examining the relative efficiency of the aquifer for thermal-energy storage for different injection and withdrawal rates and duration.

The numerical model code was developed for the U.S. Geological Survey for calculating the effects of liquid waste disposal in deep saline aquifers (Intercomp, 1976). The model uses finite-difference techniques to solve simultaneously the equations of fluid and energy transport. The mathematical formulation of the model for radial flow is summarized below.

The equation of ground-water flow (continuity equation) for a fluid of variable density and viscosity, such as water at varying pressure and temperature, can be expressed as

$$\nabla \cdot \left[\rho \frac{k}{u} (\nabla p - \rho g \nabla z)\right] - q' = \frac{\partial}{\partial t}(n\rho)$$

where p is pressure, k is intrinsic permeability, ρ is density, u is viscosity, g is gravitational acceleration, n is porosity, q' is mass rate of flow per unit volume from sources or sinks (the injection rate for this experiment), z is the spatial dimension in the direction of g, and t is the time dimension. The operator for an axially symmetric cylindrical coordinate system is $(1/r)\cdot(\partial/\partial r) + (\partial/\partial z)$, where r is the radial dimension.

The equation describing the transport of thermal energy in ground-water system is

$$\nabla \cdot \left[\rho \frac{k}{u} H (\nabla p - \rho g \quad z)\right] + \nabla \cdot K \cdot \nabla T - q_L - q'H = \frac{\partial}{\partial t}\left[n\rho U + (1 - n)(\rho C_p)_R T\right]$$

where H is enthalpy, K is hydrodynamic thermal dispersivity (thermal conductivity plus hydrodynamic dispersivity), T is temperature, q_L is rate of heat loss across boundaries, U is internal energy, and $(\rho Cp)_R$ is the heat capactiy of the aquifer matrix (a product of its density and specific heat); all other terms are as defined in equation 1. Boundary conditions for this equation are (1) specified flux of heat at the well radius, associated with the source-sink term q', (2) heat convection at the model lateral boundary, and (3) heat conduction across the confining beds (Papadopulos and Larson, 1978).

The radial-flow model simulates the St. Lawrence, Franconia, Ironton, Galesville, and the Eau Claire Formations. It consists of 16 variable-width node spacings in the vertical direction and 21 logarithmically increasing-width node spacings in the radial direction. The vertical spacings range from approximately 5 to 10 m. The smallest radial spacing is 0.18 m, and the largest is 26.8 m. The lateral model boundary represents one-half of the distance between production wells A and B (125 m) and is simulated as a constant head.

Injection and withdrawal of heated water is through 12 vertical nodes, which, when combined represent the Franconia-Ironton-Galesville aquifer. Radially, the nodes represent the diameter of the well bore (0.18 m). Injection and withdrawal at the well bore into and out of each horizontal layer is based upon the layer mobility alone. Mobility is proportional to the relative layer permeability-thickness product divided by the total well-bore interval permeability thickness (Intercomp, 1976).

The confining beds, the St. Lawrence and Eau Claire Formations, are simulated by two nodes each. Energy transport is by convection and conduction at the respective inner boundaries of these confining beds with the Franconia-Ironton-Galesville aquifer and by conduction at their respective boundaries opposite the aquifer. Energy transport at the model's lateral boundary is by conduction and convection.

The regional gradient within the study area for the Franconia-Ironton-Galesville aquifer is estimated to be approximately 0.0002 with a natural pore velocity of 0.005 m/d (Roman Kanivetsky, Minnesota Geological Survey, written commun., 1980). This low regional flow rate will not impact seriously results of the sensitivity analyses because of the short term of the simulations or modeling of the hypothetical long-term relative efficiency because storage periods are not simulated. Therefore, the natural flow system is not simulated by the model.

As described above, the ATES system will operate with a doublet-well system. The steady-state flowfield for a doublet-well system with well spacing equal to that of the ATES system (250 m) is shown in figure 2. The equipotential lines indicate that the preliminay model assumption of radial

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Figure 2.--(caption on next page) belongs near here.

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flow is less exact with increasing distance from the center of either well bore. The interpretation of the preliminary model results, in terms of representing the ATES doublet-well system, will be related to the radial distance that heat will move away from the well for the period of simulation; that is, the farther the heat moves away from the well, the less exact the assumption of radial flow. For the preliminary model simulations described in this report, all the heat was maintained within the boxed area around the injection well shown in figure 2. Figure 2 also shows the location of the preliminary model lateral boundary in relation to the doublet-well flowfield.

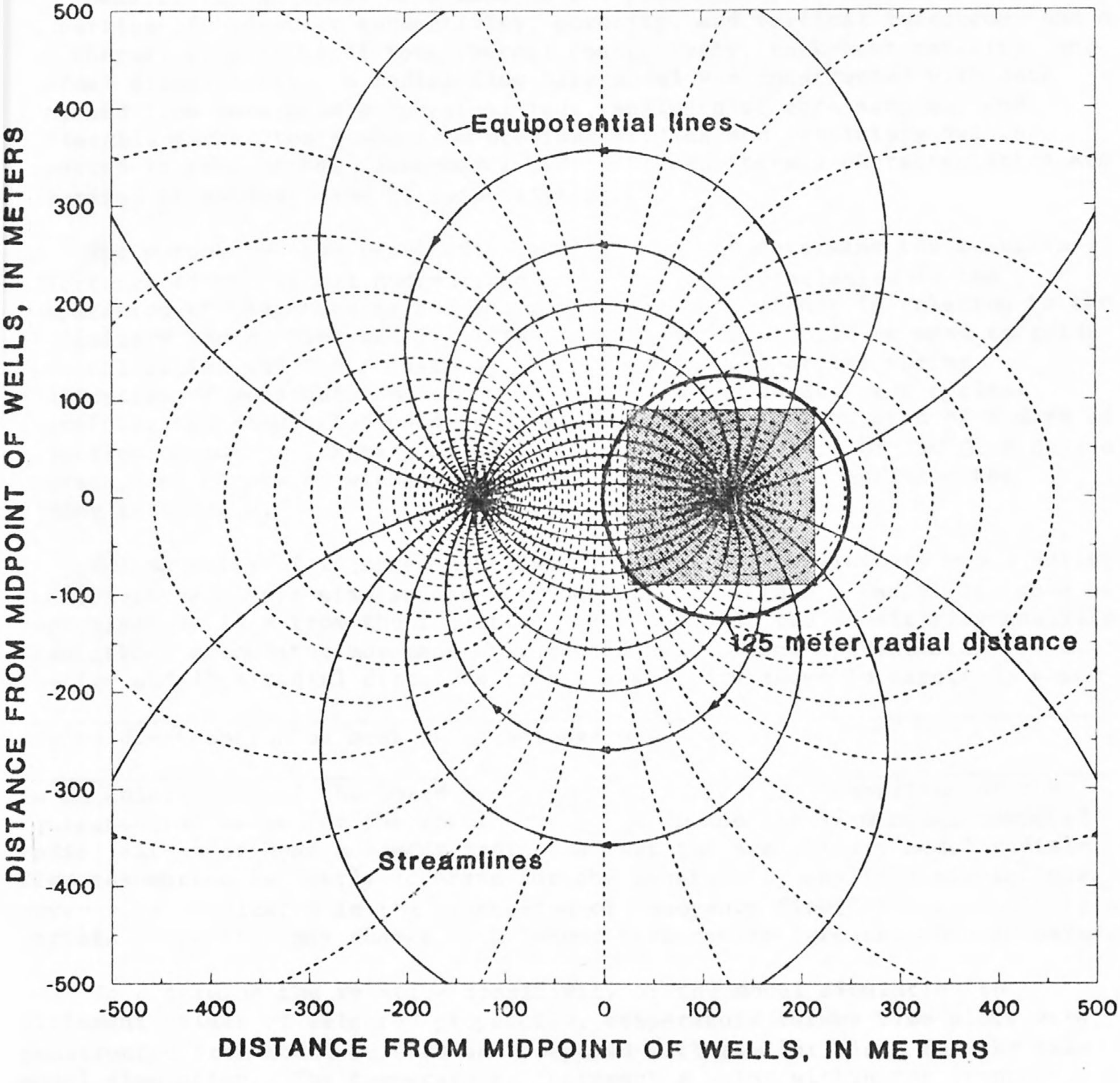

Figure 2. Flowfield showing a doublet-well system similar to the Aquifer Thermal-Energy Storage

Sensitivity Analysis

Sensitivity analyses were made on the preliminary model for the hydraulic properties of hydraulic conductivity, porosity, and vertical anisotropy and on the thermal properties of rock thermal conductivity, rock-heat capacity, and thermal dispersivity. A radial-flow base model was constructed with data obtained from bore-hole geophysical logs, analysis of core samples, and inflatable-packer tests and from previous studies and laboratory values reported in text books. Base-model hydraulic and thermal characteristics are described in tables 1 and 2, respectively.

The purpose of the sensitivity analysis was to determine the relative importance of individual hydraulic and thermal characteristics in the computation of temperatures and aquifer thermal efficiency in relation to the preliminary radial-flow model. This information then could be used to guide data collection and the adjustment of model-input properties during calibration of subsequent models with data from the 24-day test cycles. Therefore, the simulation used in sensitivity analysis consisted of 8 days of injection of water at a rate of 18.9 L/s and a temperature of 150°C, 8 days of storage, and 8 days of withdrawal at a rate of 18.9 L/s comprising the 24-day test cycle.

The majority of injected heat calculated by the preliminary model during sensitivity-analysis simulations was concentrated within a radial distance of approximately 14 m from the injection well. None of the sensitivity-analysis simulations calculated movement of injected heat beyond approximately 17 m. The 17- and 14-m radial distances from the well are shown in figure 3, which

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Figure 3.--(caption on next page) belongs near here.

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is an enlargement of the boxed area shown in figure 2. Comparison of the equipotential lines for the doublet-well system and the 17-m model-computed radial extent of heat movement indicates that the preliminary model radial-flow assumption is fairly accurate for the sensitivity-analysis simulations. However, as indicated in the discussion of "Buoyancy Flow," the sensitivity of certain properties may change with longer term cycles (greater than 60 days).

To determine the relative sensitivity of the model simulation to different values of selected properties, temperature versus time plots were constructed from model results and compared with similar plots for the base-model simulation. The temperatures represent a point within the Ironton-Galesville Formation at a radial distance of approximately 6.5 m from the production well. Aquifer thermal efficiency was calculated as a percentage by dividing the total heat produced during recovery by the total heat injected. The aquifer thermal efficiency of the base simulation is 51.0 percent. The following discussion of individual properties is ordered from least to most sensitive in the model simulation.

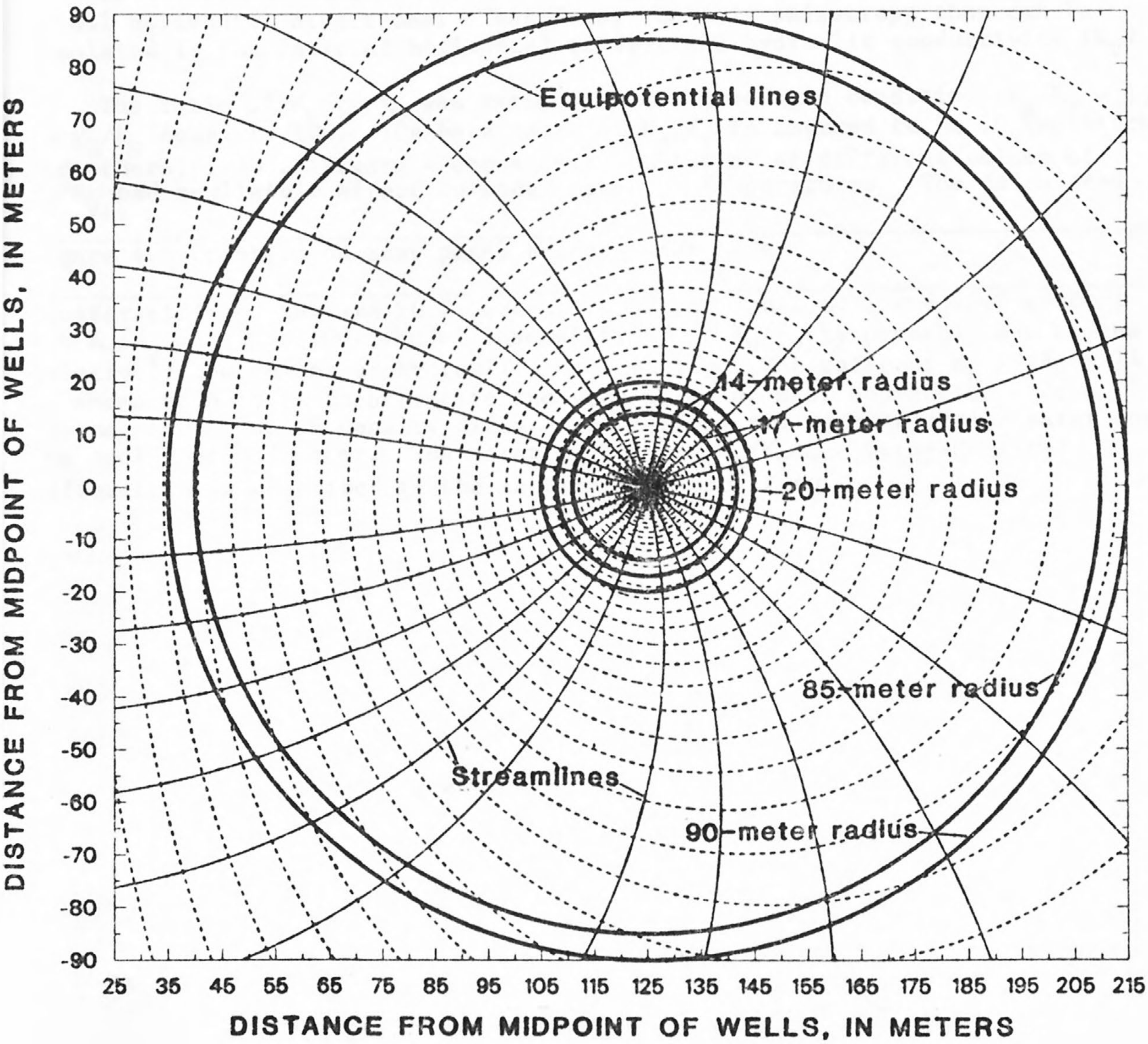

Figure 3. Flowfield showing an area near the injection well of a doublet-well system similar to the Aquifer Thermal-Efficiency Storage system.

Hydraulic and Thermal Properties

Ratio of Horizontal to Vertical Hydraulic Conductivity

In the radial-flow model, horizontal hydraulic conductivity (K_H) is equal in all horizontal directions. Therefore, the only anisotropy that can be simulated is the ratio of horizontal to vertical hydraulic conductivity (K_V).

The ratio of K_H to K_V was varied from an isotropic condition ($K_H/K_V = 1$) to K_H/K_V equal to 100. The base value of K_H/K_V is assumed to be 10 (Norvitch and others, 1973). Figure 4 shows that simulation of different values of K_H/K_V had negligible effect on model-computed temperatures. The calculated

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Figure 4.--(caption on next page) belongs near here.

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aquifer efficiencies are 50.7 percent for K_H/K_V equal to 1 and 50.9 percent for K_H/K_V equal to 100. Model insensitivity to K_H/K_V is probably due to the relatively low values of hydraulic conductivity. The ratio of K_H to K_V will be shown to be more important in the simulation of heat convection at the thermal front due to density differences between the warm injection water and the cooler ground water. The relation between K_H/K_V and water-density differences is described in the section "Buoyancy Flow."

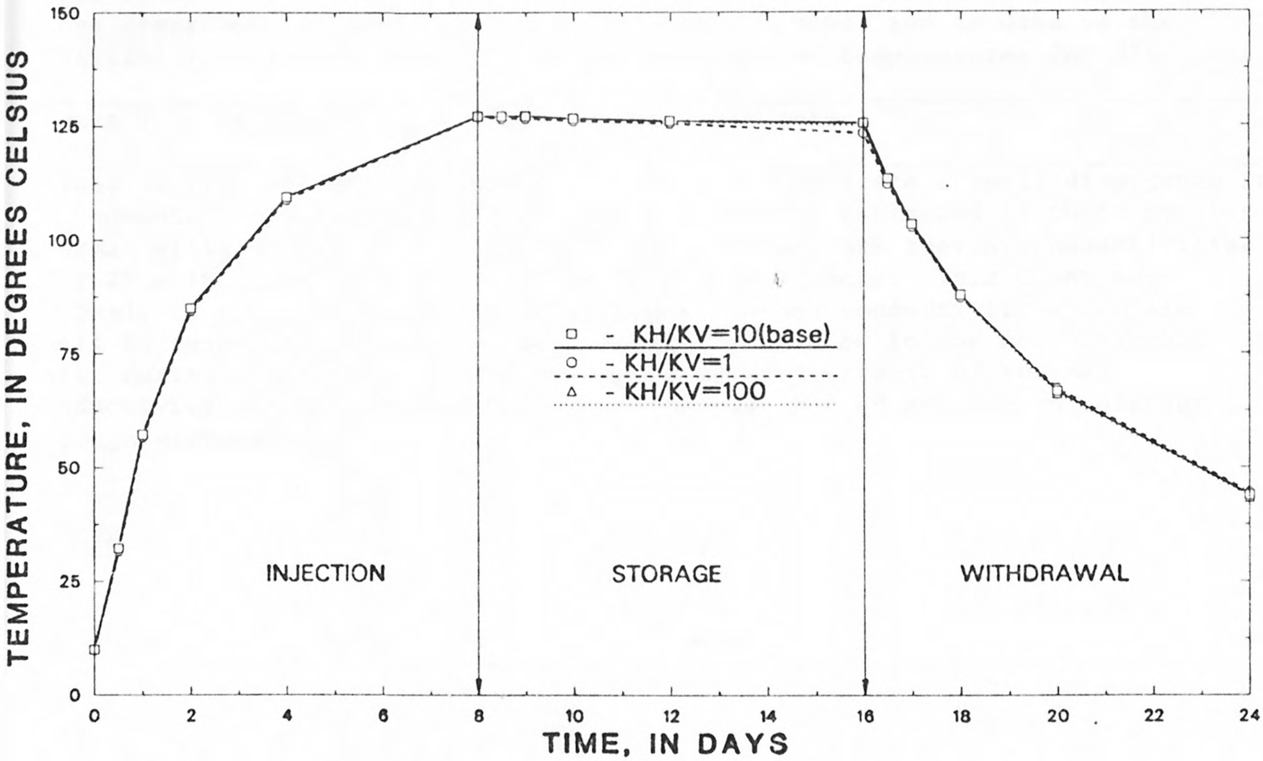

Figure 4. Model-computed temperatures for different values of the ratio of K_H/K_V.

Rock Thermal Conductivity

The values of rock thermal conductivity were varied in the model according to the approximate values given in Clark (1966) for sandstones comparable in composition to those in the Franconia-Ironton-Galesville aquifer. The reduction of rock thermal conductivity with temperature increase, as reported by Birch and Clark (1940), Sommerton and others (1965), and Clark (1966), is not accounted for in the computer code. This should not be a problem because the reduction of rock thermal conductivity described by these authors is small for the injection temperature (150°C), is within the range described for sandstone aquifers (Clark, 1966), and is used in the sensitivity analysis. Figure 5 shows the computed temperatures for different

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values of rock thermal conductivity. The plots indicate a small divergence in the computed temperatures during storage, which is reflected in their aquifer thermal efficiencies of 51.8 and 50.3 percent for rock thermal conductivities of 1.25×10^{-5} and 3.14×10^{-5} (J/m)/d/°C respectively. This divergence probably is due to the effects of the rock thermal conductivity which are small in comparison to the effects of heat convection in the moving ground water during injection. Therefore, the simulated effects of thermal conductivity are not observed until the storage period and remain constant through withdrawal.

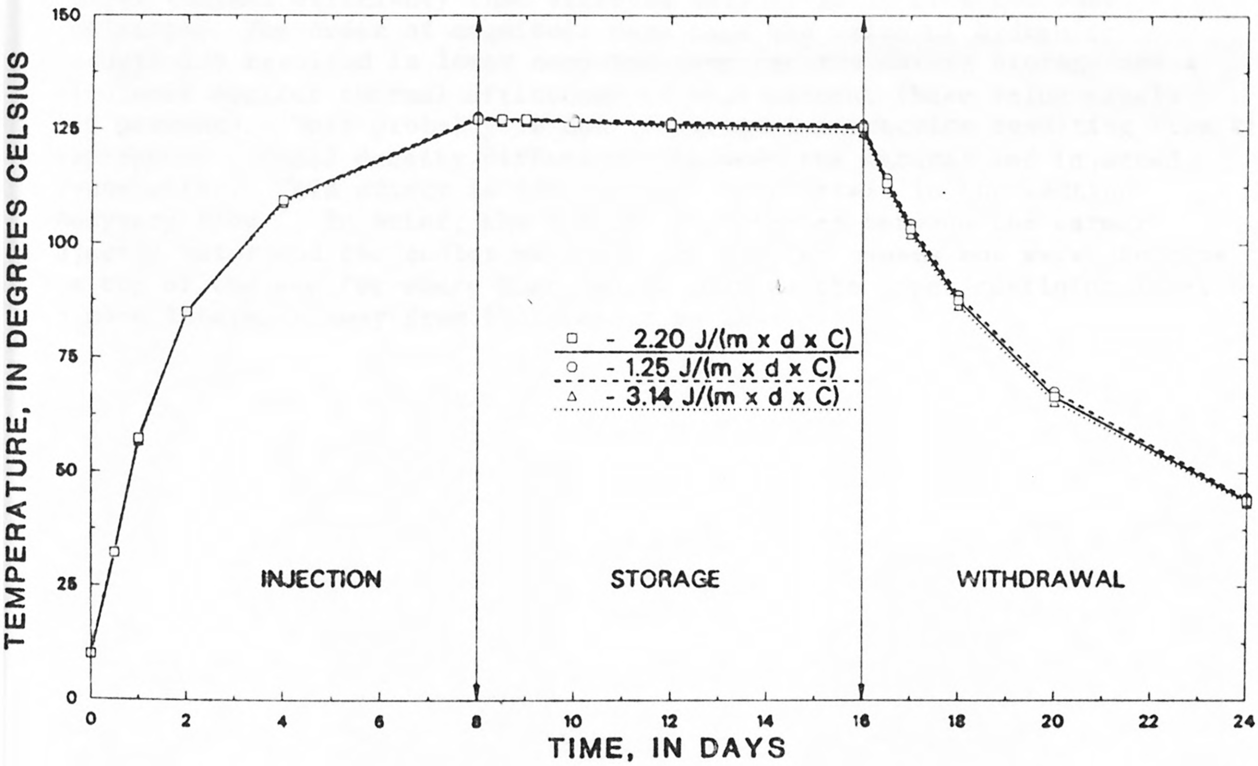

Figure 5. Model-computed temperatures for different values of rock thermal conductivity times 10^5.

Horizontal Hydraulic Conductivity

Values of horizontal hydraulic conductivity (fig. 6) that are an order of

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magnitude greater than and less than the assumed base values (table 1) were simulated in the model; the ratio of K_H to K_V was set equal to 10. The order of magnitude less than the value resulted in computed temperatures and an aquifer thermal efficiency that differed only slightly from the base simulation. The order of magnitude more than the value of hydraulic conductivity resulted in lower computed temperatures during storage and a calculated aquifer thermal efficiency of 49.5 percent (base value equals 51.0 percent). This probably is due to vertical convection resulting from the temperature-induced density differences between the natural and injected ground water. This effect is discussed in more detail in the section "Buoyancy Flow." In brief, the density differences between the warmer injected water and the cooler water in the aquifer causes hot water to move to the top of the aquifer where heat can be lost to the upper confining layer or to move laterally away from the production well.

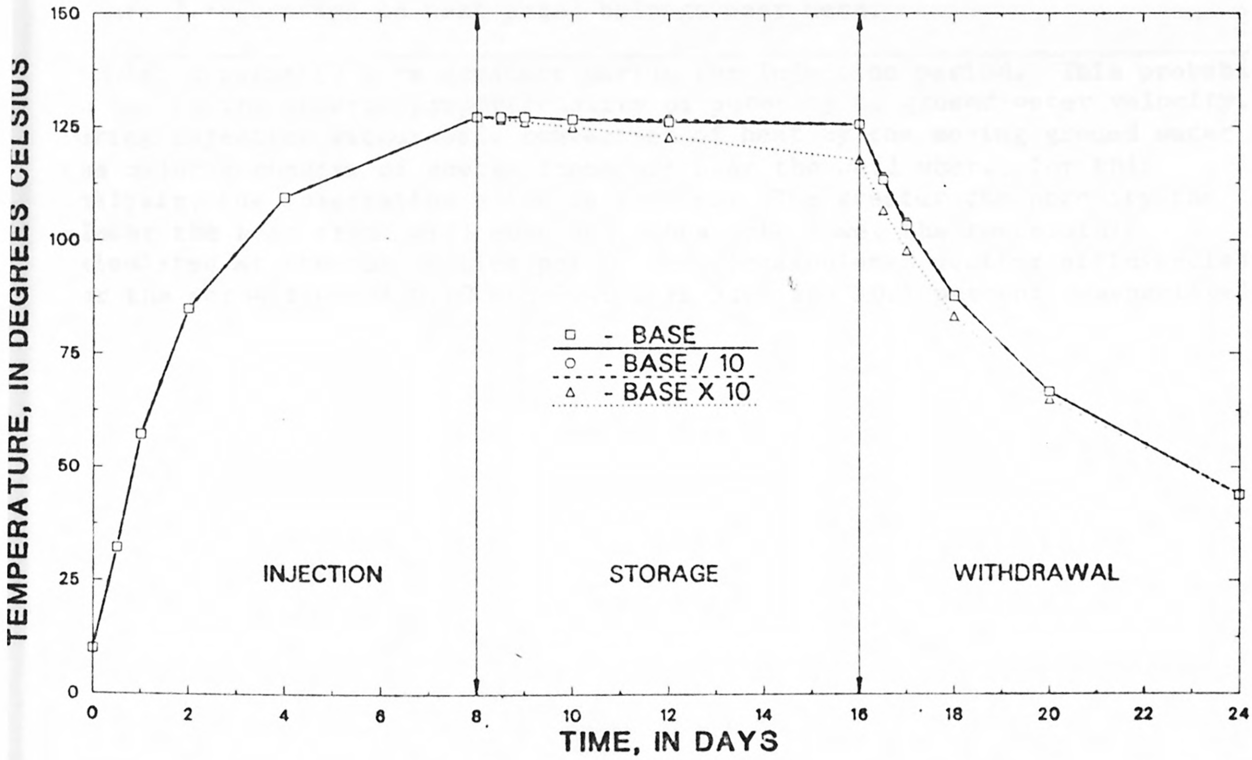

Figure 6. Model-computed temperatures for different values of horizontal hydraulic conductivity.

Porosity

A range of porosity values was selected from published data (Clark, 1966; Norvitch and others, 1973); the laboratory analysis of core samples; natural gamma, gamma-gamma, and neutron borehole geophysical data; and analyses of cores of the Franconia and Ironton and Galesville Formations in southern Minnesota (Minnesota Gas Co., oral commun., 1980). The values ranged from 0.10 to 0.40. The median value, 0.25, was assumed to be the base value. Differences in model-calculated temperature (fig. 7) for the values of

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simulated porosity were greatest during the injection period. This probably is due to the inverse proportionality of porosity to ground-water velocity. During injection-withdrawal, convection of heat by the moving ground water is the major mechanism of energy transport near the well where, for this analysis, the observation point is located. The greater the porosity the slower the heat front will move and, thus, the lower the temperature calculated at the observation point. Model-calculated aquifer efficiencies for the porosities of 0.10 and 0.40 were 51.5 and 50.1 percent, respectively.

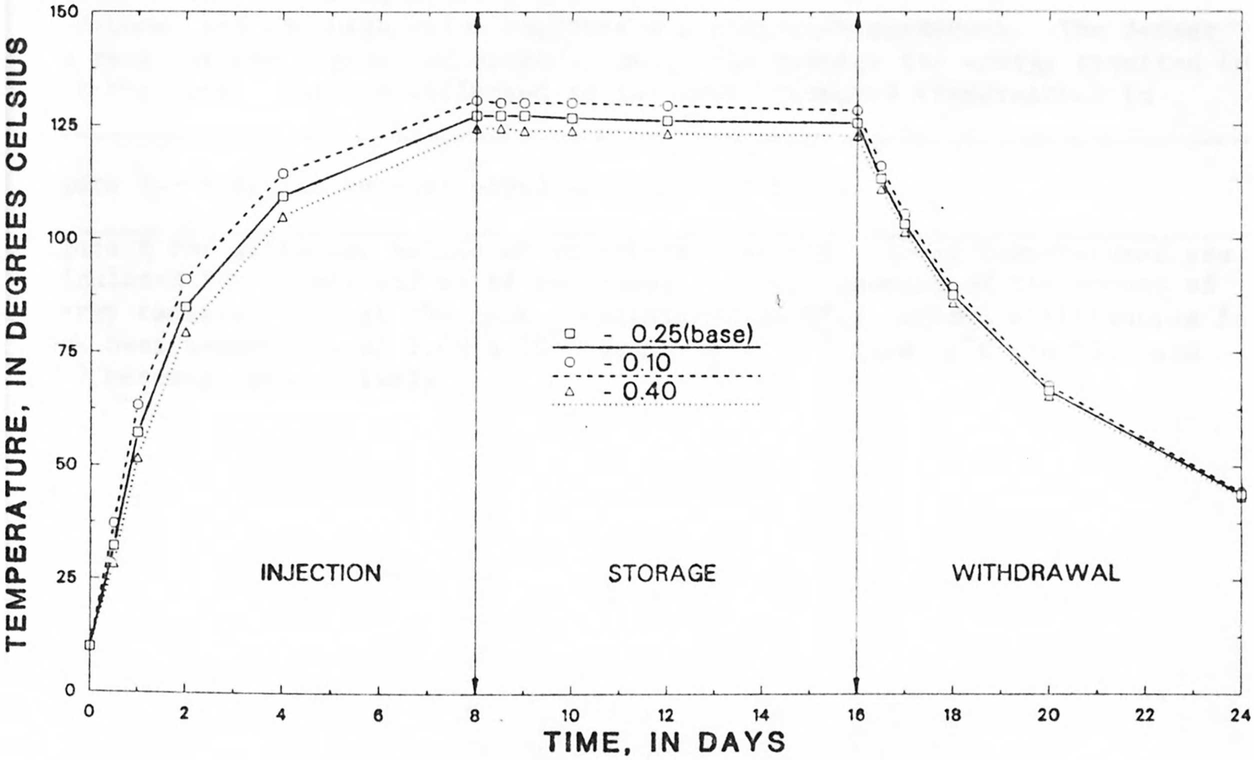

Figure 7. Model-computed temperatures for different values of aquifer porosity.

Rock-Heat Capacity

Rock-heat capacity is the product of rock density and rock specific heat and is the ability of the rock to store heat. Ranges of heat capacity were obtained from Sommerton and others (1965) and were calculated by using data from Sommerton and others (1965), Clark (1966), Hellgeson and others (1978), and Robie and others (1978) and from methods described by Martin and Dew (1965). The base value for rock-heat capacity represents a sandstone with a composition similar to sandstones in the Franconia-Ironton-Galesville aquifer. The low value of rock-heat capacity represents a quartz-rich sandstone, and the high value represents a clay-rich sandstone. The denser the rock, or the higher the specific heat, the greater the energy required to heat the rock. This is reflected in the model-computed temperatures in

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figure 8 for different values of rock-heat capacity. Lower temperatures are calculated for higher values of rock-heat capacity because of the amount of energy required to heat the rock. Calculated aquifer thermal efficiencies for rock heat capacities of 1.00×10^{-6} and 2.68×10^{-6} $(J/m^3)/^oC$ are 51.7 and 50.3 percent, respectively.

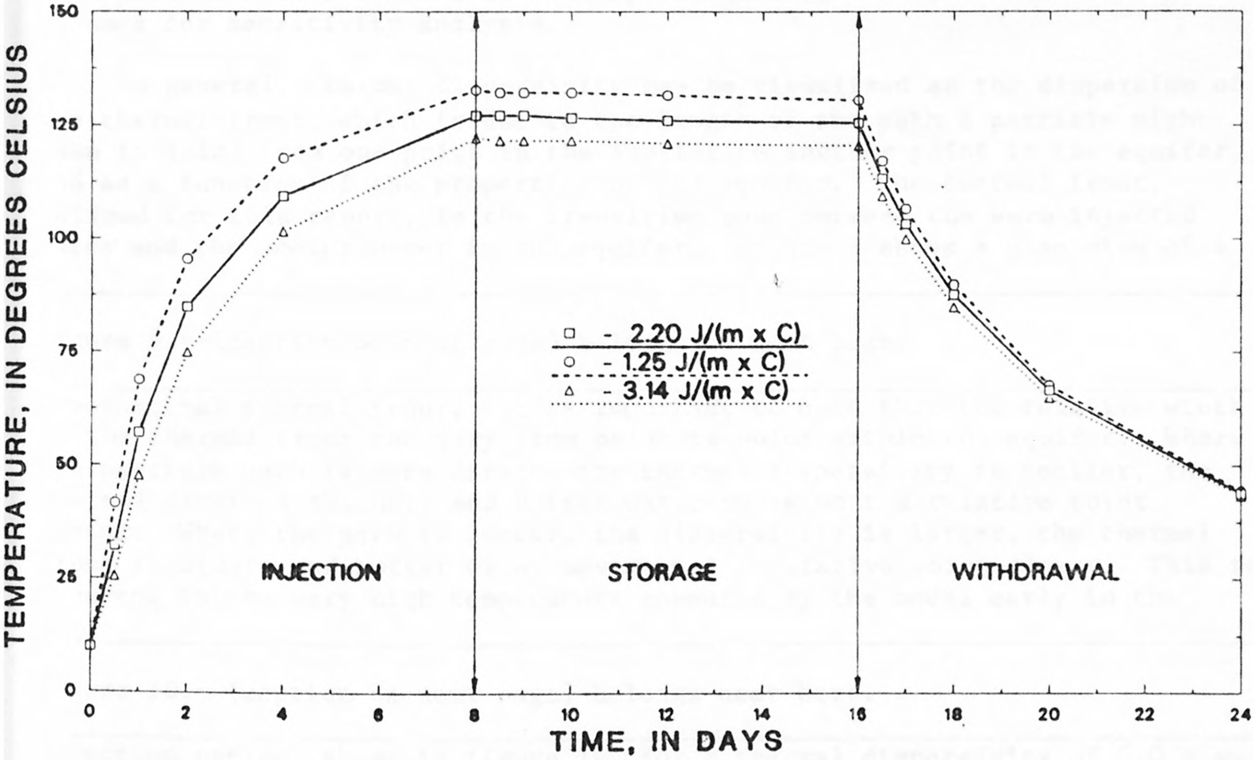

Figure 8. Model-computed temperatures for different values of rock-heat capacity.

Thermal Dispersivity

The model was most sensitive to thermal dispersivity which, unfortunately, is the most difficult property to measure in the ground-water-flow system. Although the body of data is not large, Sauty and others (1979) concluded from heat-injection tracer tests and model studies that thermal dispersivity is probably of the same order of magnitude as dispersivities measured by means of chemical tracers. Sauty and others (1979) also described thermal dispersivity as a function of scale, suggesting a value of 0.1 m for a heat-storage radius of 10 m in isotrophic aquifers. A base value of 3 m was assumed for sensitivity analysis.

In general, thermal dispersivity may be visualized as the dispersion of the thermal front, which is due to the length of the path a particle might take in going from one point in the aquifer to another point in the aquifer, and as a function of the properties of the aquifer. The thermal front, defined for this report, is the transition zone between the warm injected water and the cooler water in the aquifer. Figure 9 shows a plan view of a

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hypothetical thermal front. It is important to note that the relative width of the thermal front can vary from point to point within the aquifer. Where the particle path is more direct, the thermal dispersivity is smaller, the thermal front is thinner, and hotter water moves past a relative point faster. Where the path is longer, the dispersivity is larger, the thermal front is wider, and hotter water moves past a relative point slower. This is apparent in the very high temperature computed by the model early in the

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injection period, shown in figure 10, for a thermal dispersivity of 0.0 m and in the much lower temperature computed for a thermal dispersivity of 6.0 m.

Thermal dispersivity also has the greatest effect on the model-computed aquifer thermal efficiencies. A dispersivity of 0.0 m results in an efficiency of 66.8 percent, and a dispersivity of 6.0 m results in an efficiency of 43.4 percent.

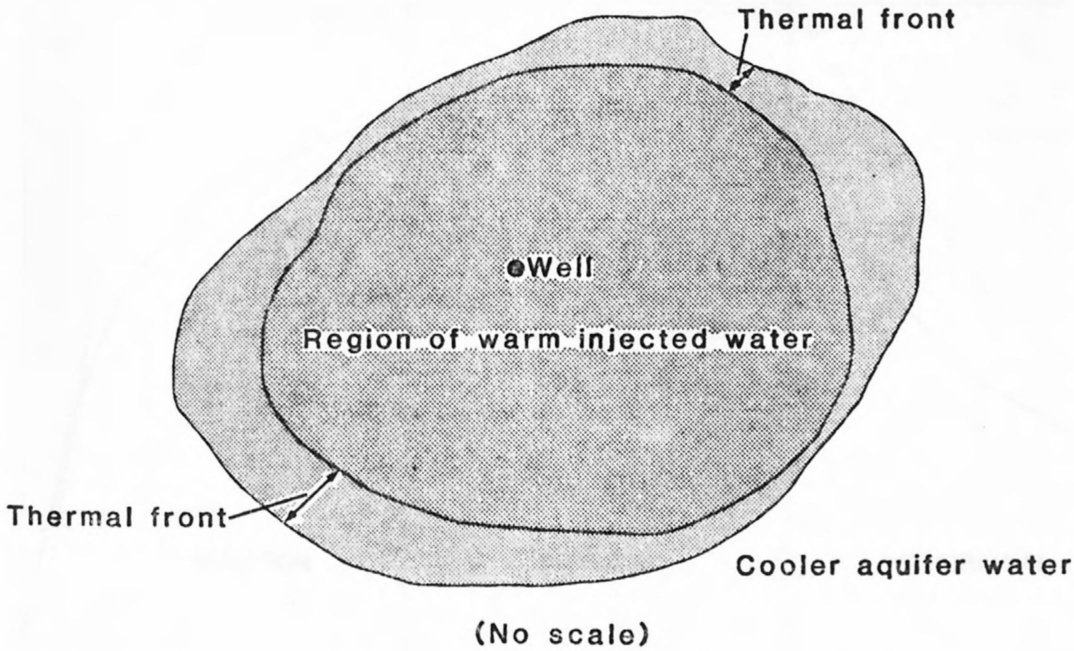

Figure 9. Plan view of hypothetical thermal front.

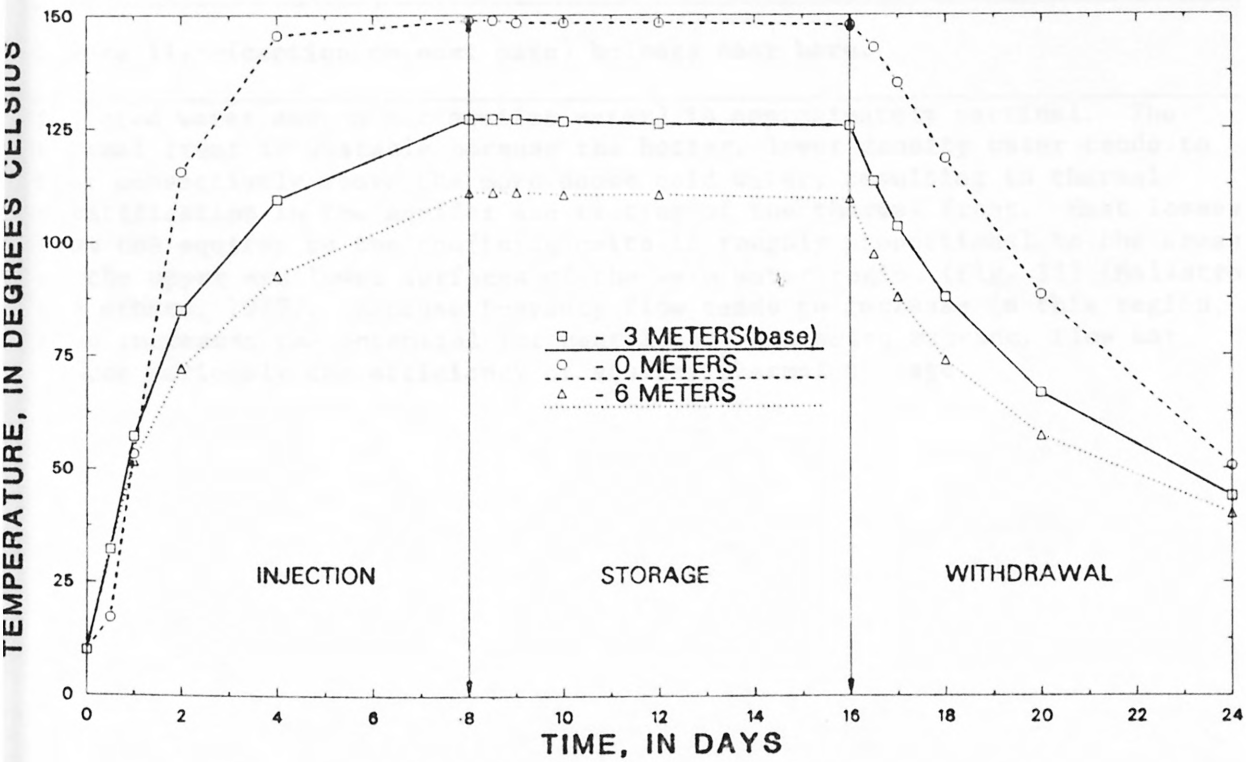

Figure 10. Model-computed temperatures for different values of thermal dispersivity.

Buoyancy Flow

Hellstrom and others (1979) described the effects of thermal convection, or buoyancy flow, which were due to the differences in density of the injected hot water and the cooler water in the aquifer. Their work was related to heat storage in shallow glacioalluvial aquifers, which generally have permeabilities higher than values reported for the Franconia-Ironton-Galesville aquifer. Figure 11 illustrates the effects of buoyancy flow. During early injection, the thermal front (transition zone between the hotter

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injected water and colder aquifer water) is approximately vertical. The thermal front is unstable because the hotter, lower density water tends to rise convectively above the more dense cold water, resulting in thermal stratification in the aquifer and tilting of the thermal front. Heat losses from the aquifer to the confining units is roughly proportional to the areas of the upper and lower surfaces of the warm water region (fig. 11) (Hellstrom and others, 1979). Because buoyancy flow tends to increase in this region, it also increases the potential for heat loss. Excessive buoyancy flow may reduce seriously the efficiency of aquifer thermal storage.

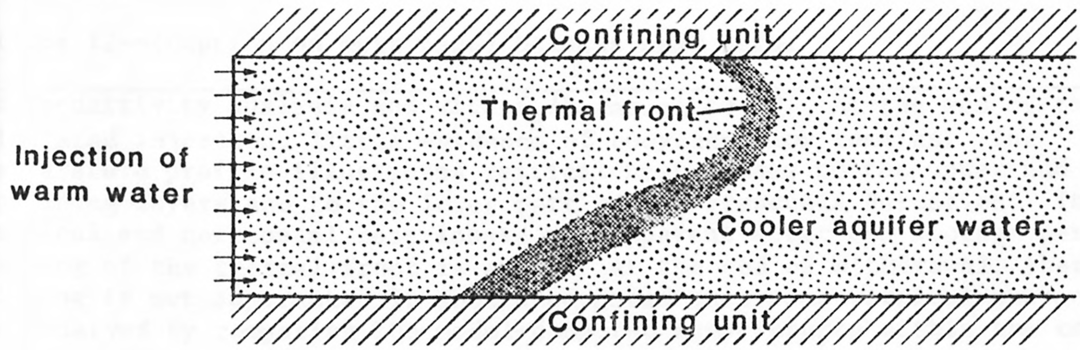

Figure 11. Horizontal injection of warmer water in an aquifer with excessive thermal stratification illustrating tilting of the thermal front, or buoyancy flow (Hellstrom and others, 1979).

To examine the potential for buoyance flow and its possible effect on the thermal efficiency of the Franconia-Ironton-Galesville aquifer, the preliminary nonisothermal, radial-flow, energy-transport model was used to simulate the 24-day test cycle from which temperature versus depth plots were constructed for selected values of K_H and K_H/K_V. As in previous simulations, the observation point for model-computed temperatures is 6.5 m radially from the injection well. The 24-day test cycle was simulated in the same way as in the sensitivity analysis with 8 days of injection of water at 18.9 L/s of 150°C water and followed by 8 days of storage and 8 days of withdrawal at 18.9 L/s. To examine the effect of buoyancy flow due to natural convection and due to forced convection during injection and withdrawal, vertical temperature profiles were constructed for the end of simulated injection, storage, and withdrawal periods.

Figure 12 illustrates the temperature profile at a radial distance of 6.5 m from the injection well for the base conditions (tables 1, 2) used in

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the sensitivity analysis and with K_H/K_V equal to 10. At the end of the simulated injection, little evidence of buoyancy flow remains. The temperature profile illustrates vertical heat losses to the upper and lower confining layers and to the lower part of the Franconia Formation. The vertical and horizontal heat losses are apparent after the storage period, but tilting of the thermal front is small. At the end of withdrawal, thermal tilting is not apparent. It should be noted that some vertical convection can be observed by comparing the model-computed temperatures within the confining layers. At the end of the withdrawal period, the temperature in the upper confining layer, the St. Lawrence Formation, is warmer than the temperature in the lower confining layer, the Eau Claire Formation, even though the temperature in the Ironton-Galesville Formation is hotter than the temperature in the upper part of the Franconia Formation. It also should be noted that temperatures in the lower part of the Franconia Formation continued to increase during withdrawal, indicating that heat conduction from above and below is greater than forced convection from pumping into or out of this part of the formation. If heat injected or conducted to the lower part of the Franconia Formation is not recoverable, then the efficiency of the aquifer thermal-storage system could be reduced significantly.

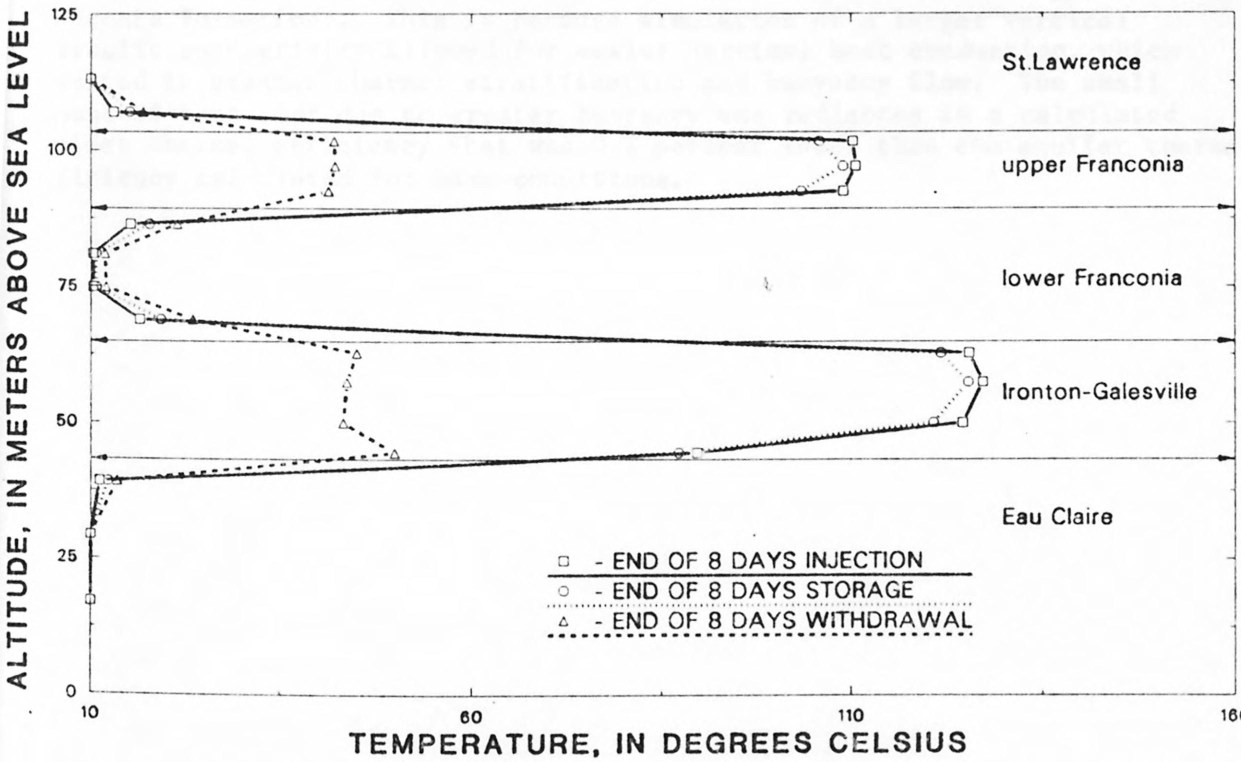

Figure 12. Model-computed temperature profiles at the end of simulated injection, storage, and withdrawal for assumed base conditions.

Figure 13 illustrates the model-computed temperature profile for

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conditions similar to those in figure 10 except that horizontal and vertical hydraulic conductivities are equal. The computed temperature profiles in figure 13 are similar to figure 10 except for a slightly larger tilt in the thermal front after the storage period and slightly higher temperatures in the upper confining layer (St. Lawrence Formation) and the lowermost point (lower Franconia Formation). This is because simulation of a larger vertical hydraulic conductivity allowed for easier vertical heat conduction, which resulted in greater thermal stratification and buoyancy flow. The small amount of heat lost due to greater buoyancy was reflected in a calculated aquifer thermal efficiency that was 0.2 percent lower than the aquifer thermal efficiency calculated for base conditions.

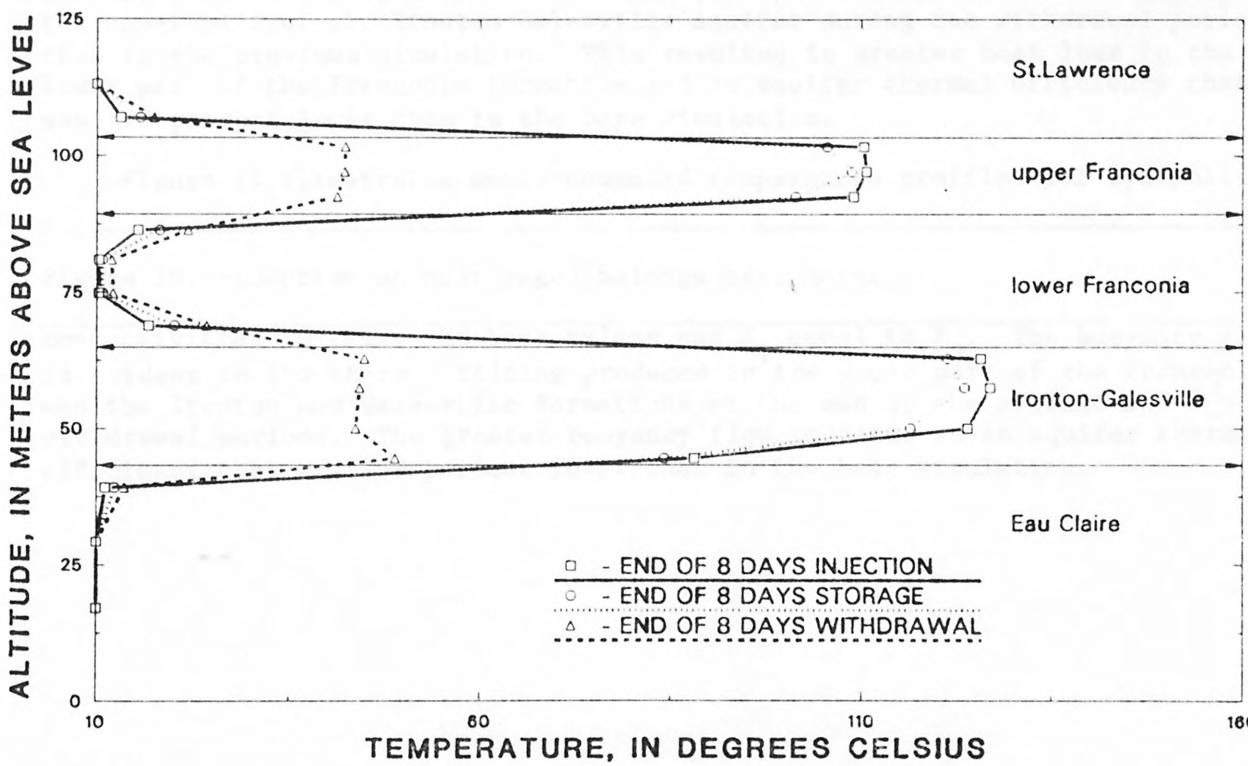

Figure 13. Model-computed temperature profiles at the end of simulated injection, storage, and withdrawal for base conditions and K_H equal to K_V.

To further examine the effects of buoyancy flow within the possible range of hydraulic conductivity for the aquifer, hydraulic conductivity was simulated as 10 times the base value with K_H/K_V equal to 10 (fig. 14). The

Figure 14.--(caption on next page) belongs near here.

computed temperature profiles at the end of the storage period are similar to those in figures 12 and 13 except in the Ironton-Galesville aquifer, where the thermal front is moderately tilted. Also, computed temperatures are higher in the upper part of the Ironton-Galesville aquifer during the withdrawal period than in the previous simulation. This resulted in greater heat loss to the lower part of the Franconia Formation and an aquifer thermal efficiency that was 1.3 percent lower than in the base simulation.

Figure 15 illustrates model-computed temperature profiles for hydraulic

Figure 15.--(caption on next page) belongs near here.

conductivities 10 times the base values and K_V equal to K_H. The buoyancy flow is evident in the thermal tilting produced in the upper part of the Franconia and the Ironton and Galesville Formations at the end of the storage and withdrawal periods. The greater buoyancy flow resulted in an aquifer thermal efficiency that was 2.9 percent lower than in the base simulation.

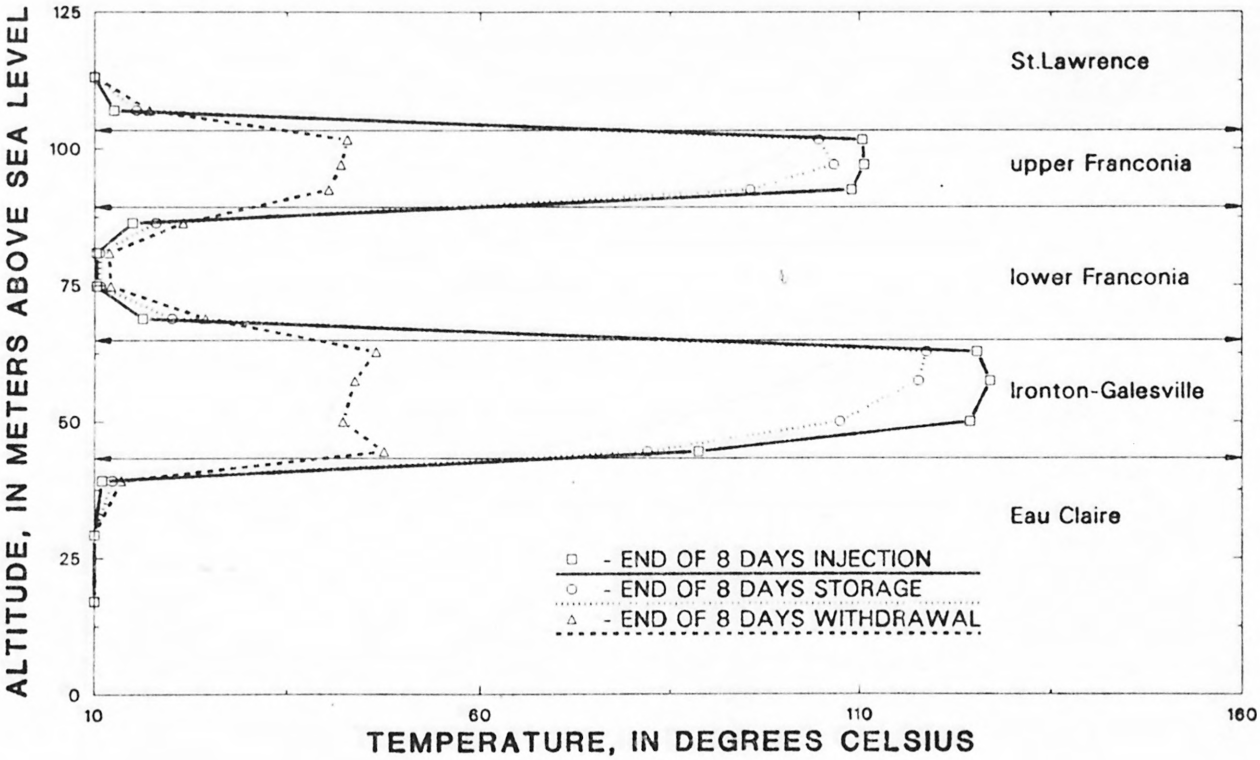

Figure 14. Model-computed temperature profiles at the end of simulated injection, storage, and withdrawal for hydraulic conductivities equal to 10 times the base value.

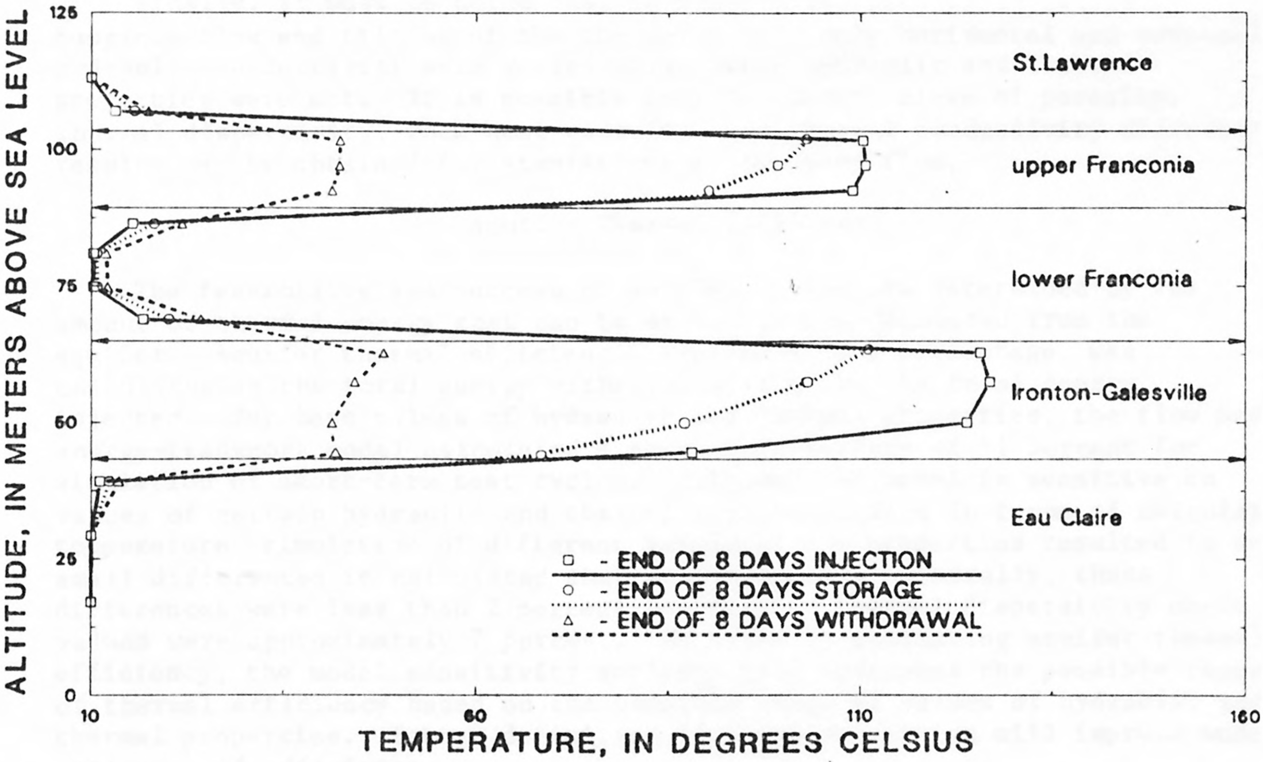

Figure 15. Model-computed temperature profiles at the end of simulated injection, storage, and withdrawal for horizontal hydraulic conductivities equal to 10 times the base value and K_V equal to K_H.

It is important to note that the temperature in the lower Franconia Formation continued to increase throughout the simulated test cycle for each of the assumed conditions. As stated earlier, losses to the lower part of the Franconia Formation may result in a significantly lower thermal efficiency of the formation. A method for possible reduction of heat loss to this part of the aquifer may be screening only the permeable parts of the upper part of the Franconia and the Ironton and Galesville Formations and, thus, not injecting hot water directly into the lower part of the Franconia Formation.

Finally, it must be noted that in simulations used to investigate buoyancy flow and tilting of the thermal front, only horizontal and vertical hydraulic conductivity were varied while other hydraulic and thermal properties were not. It is possible that for other values of porosity, thermal dispersivity, rock-heat capacity, and thermal conductivity different results may be obtained for simulations of buoyancy flow.

Aquifer Thermal Efficiency

The feasibility and success of an ATES system are determined by the amount of thermal energy that can be stored in and recovered from the aquifer. Aquifer thermal efficiency, expressed as a percentage, was calculated as the total energy withdrawn divided by the total energy injected. For base values of hydraulic and thermal properties, the flow and energy-transport model calculated a thermal efficiency of 51 percent for simulation of short-term test cycles. Although the model is sensitive to values of certain hydraulic and thermal characteristics in terms of calculated temperature, simulation of different values of the properties resulted in only small differences in calculated thermal efficiency. Generally, these differences were less than 2 percent, except for thermal dispersivity where values were approximately 7 percent. In terms of estimating aquifer thermal efficiency, the model sensitivity analysis only indicates the possible range of thermal efficiency based on the possible range of values of hydraulic and thermal properties. Better definition of these properties will improve model estimates of efficiency.

The sensitivity analysis indicates the properties that need to be defined more precisely to make the model estimate as accurate as possible. However, in addition to the physcial properties of the aquifer system, operational factors also will affect the thermal efficiency of the ATES system. These factors include temperature of injected water, rate of injection and withdrawal, and duration of injection, storage, and withdrawal. To test the effects of these factors on thermal efficiency, a series of model simulations were performed in which these factors were varied, and the results were compared. Base values of hydraulic and thermal properties were used in all these simulations.

As described above, the ability of the preliminary radial-flow model to simulate the ATES doublet-well system is related to the radial distance that heat will move away from the well for the period of simulation. Model computed temperatures for the short-term cycle simulations (fig. 16) indicate

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Figures 16.--(caption on next page) belongs near here.

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that injected heat was contained within a radial distance of approximately 20 m. This radial distance is shown in figure 3. Comparison of the equipotential lines for the doublet-well system and the 20-m, model-computed radial extent of heat indicates that the short-term cycle simulations are fairly representative of the doublet-well system.

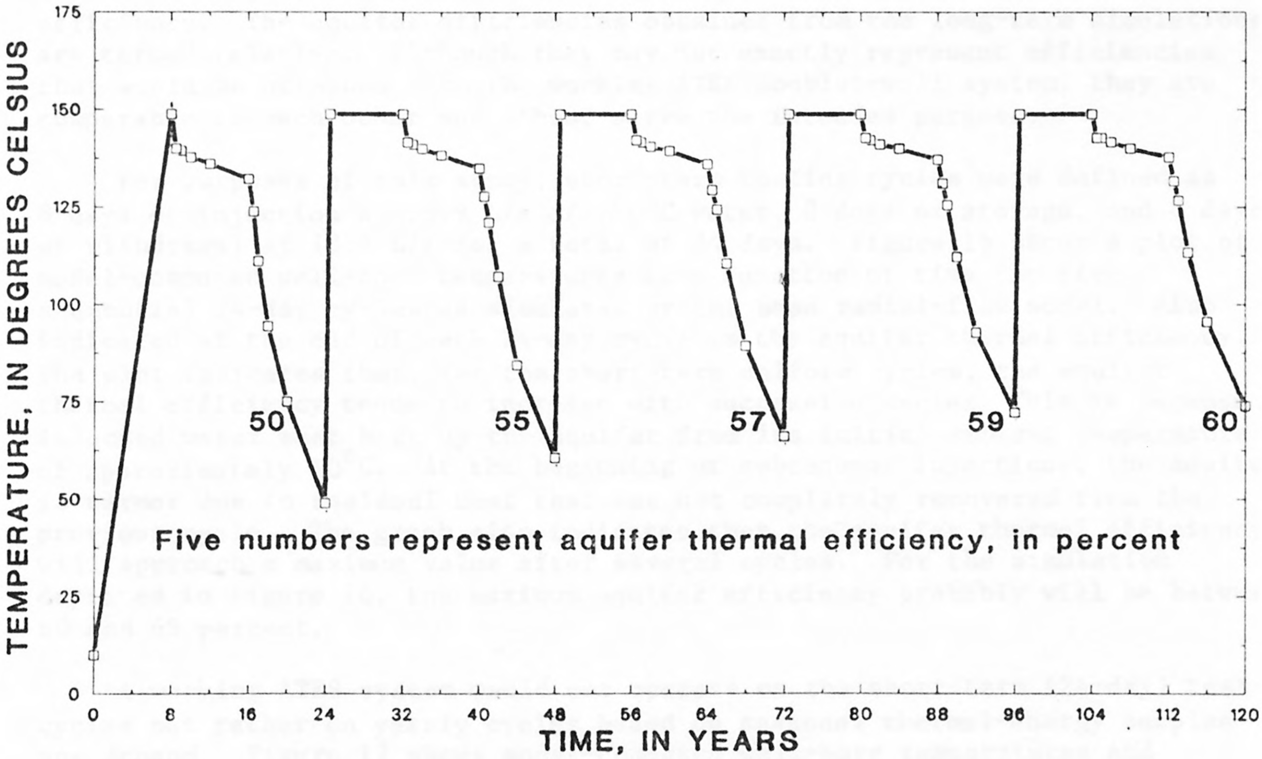

Figure 16. Model-computed well-bore temperatures and aquifer thermal efficiencies for five sequential 24-day test cycles.

Longer term simulations indicate that heat will be contained within an 85-m radial distance for the 6-month injection periods and a 90-m radial distance for the 8-month injection periods (fig. 17-20). These two radial distances are plotted on figure 3. A comparison of the 85- and 90-m radial distances with the equipotential lines for the doublet-well system indicates that the preliminary model radial-flow assumption may not represent adequately the doublet-well system for the longer term cycles. However, the usefulness of the results of the preliminary model long-term simulations is not affected because the purpose of the simulations is to describe how the operational factors of injection and withdrawal rates and duration can affect the aquifer efficiency. The aquifer efficiencies obtained from the long-term simulations are termed relative. Although they may not exactly represent efficiencies that would be obtained from the working ATES doublet-well system, they are comparable to each other and, thus, serve the intended purpose.

For purposes of this study, short-term testing cycles were defined as 8 days of injection at 18.9 L/s of 150°C water, 8 days of storage, and 8 days of withdrawal at 18.9 L/s for a total of 24 days. Figure 16 shows a plot of model-computed well-bore temperatures as a function of time for five sequential 24-day cycles as simulated by the base radial-flow model. Also indicated at the end of each 24-day cycle is the aquifer thermal efficiency. The plot indicates that, for the short-term uniform cycles, the aquifer thermal efficiency tends to increase with successive cycles. This is because injected water must heat up the aquifer from its initial ambient temperature of approximately 10°C. At the beginning of subsequent injections, the aquifer is warmer due to residual heat that was not completely recovered from the previous cycle. The graph also indicates that the aquifer thermal efficiency will approach a maximum value after several cycles. For the simulation depicted in figure 16, the maximum aquifer efficiency probably will be between 60 and 65 percent.

A working ATES system would not operate on the short-term (24-day) test cycles but rather on yearly cycles based on seasonal thermal-energy surplus and demand. Figure 17 shows model-computed well-bore temperatures and

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Figure 17.--(caption next page) belongs near here.

relative thermal efficiencies for five continuous 1-year cycles of 8 months of injection at 18.9 L/s of 150°C water and 4 months or withdrawal at 18.9 L/s. The model conditions are similar to those previously described for five 24-day cycles. Relative thermal efficiencies of the aquifer range from 34 to 39 percent, and well-bore temperatures at the end of withdrawal range from approximately 80° to 105°C.

Figure 18 shows model-computed well-bore temperatures and relative

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Figure 18.--(caption next page) belong near here.

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thermal efficiencies of the aquifer for conditions similar to those shown in figure 17 except that the withdrawal rate is 37.7 L/s. The relative thermal efficiency of the aquifer ranges from 52 to 61 percent, and the well-bore temperature at the end of each cycle ranges from approximately 45° to 75°C.

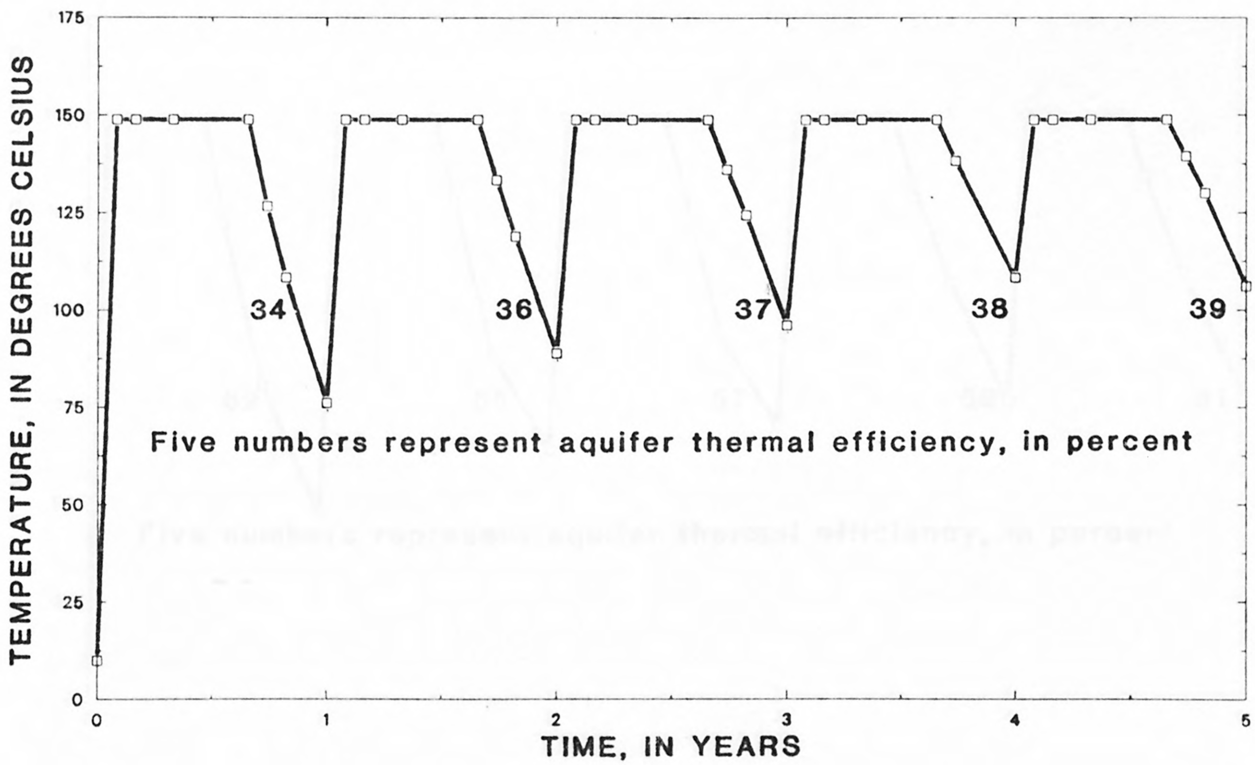

Figure 17. Model-computed well-bore temperatures and aquifer relative thermal efficiencies for five sequential 1-year cycles each consisting of 8 months of injection at 18.9 L/s of 150°C water and 4 months of withdrawal at 18.9 L/s.

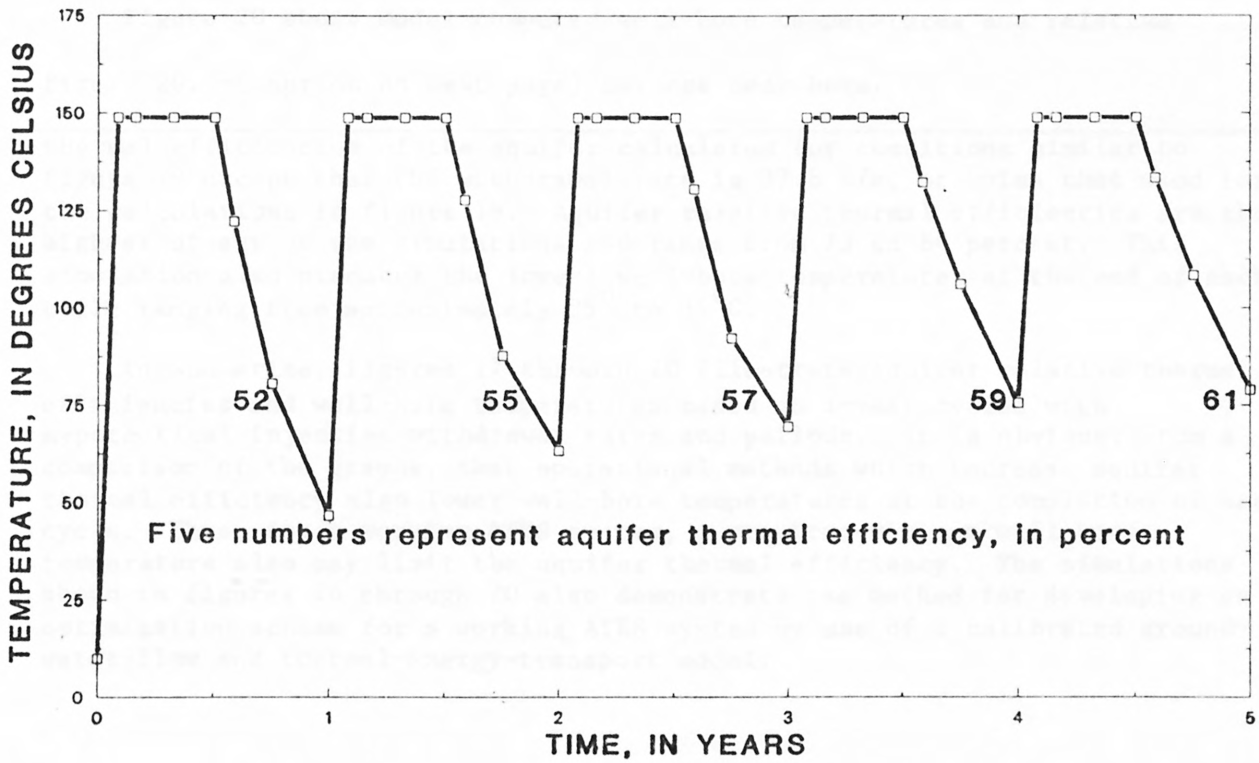

Figure 18. Well-bore temperatures and calculated aquifer relative efficiencies for five hypothetical 1-year cycles of 8 months of injection at 18.9 L/s of 150°C water and 4 months of withdrawal at 37.7 L/s.

Figure 19 shows model-computed well-bore temperatures and aquifer

Figure 19.--(caption on next page) belongs near here.

relative efficiencies calculated for five continuous 1-year cycles each consisting of 6 months of injection at 18.9 L/s of 150°C water and 6 months of withdrawal at 18.9 L/s. Relative thermal efficiency of the aquifer at the end of each cycle ranges from 51 to 59 percent, and the well-bore temperature at the end of each cycle ranges from approximately 45° to 70°C.

Figure 20 shows model-computed well-bore temperatures and relative

Figure 20.--(caption on next page) belongs near here.

thermal efficiencies of the aquifer calculated for conditions similar to figure 19 except that the withdrawal rate is 37.8 L/s, or twice that used for the calculations in figure 19. Aquifer relative thermal efficiencies are the highest of any of the simulations and range from 73 to 84 percent. This simulation also produces the lowest well-bore temperatures at the end of each cycle ranging from approximately 25° to 35°C.

To summarize, figures 17 through 20 illustrate aquifer relative thermal efficiencies and well-bore temperatures based on 1-year cycles with hypothetical injection-withdrawal rates and periods. It is obvious, from a comparison of the graphs, that operational methods which increase aquifer thermal efficiency also lower well-bore temperatures at the completion of each cycle. Thus, for a working ATES system, a required minimum well-bore temperature also may limit the aquifer thermal efficiency. The simulations shown in figures 16 through 20 also demonstrate one method for developing an optimization scheme for a working ATES system by use of a calibrated ground-water-flow and thermal-energy-transport model.

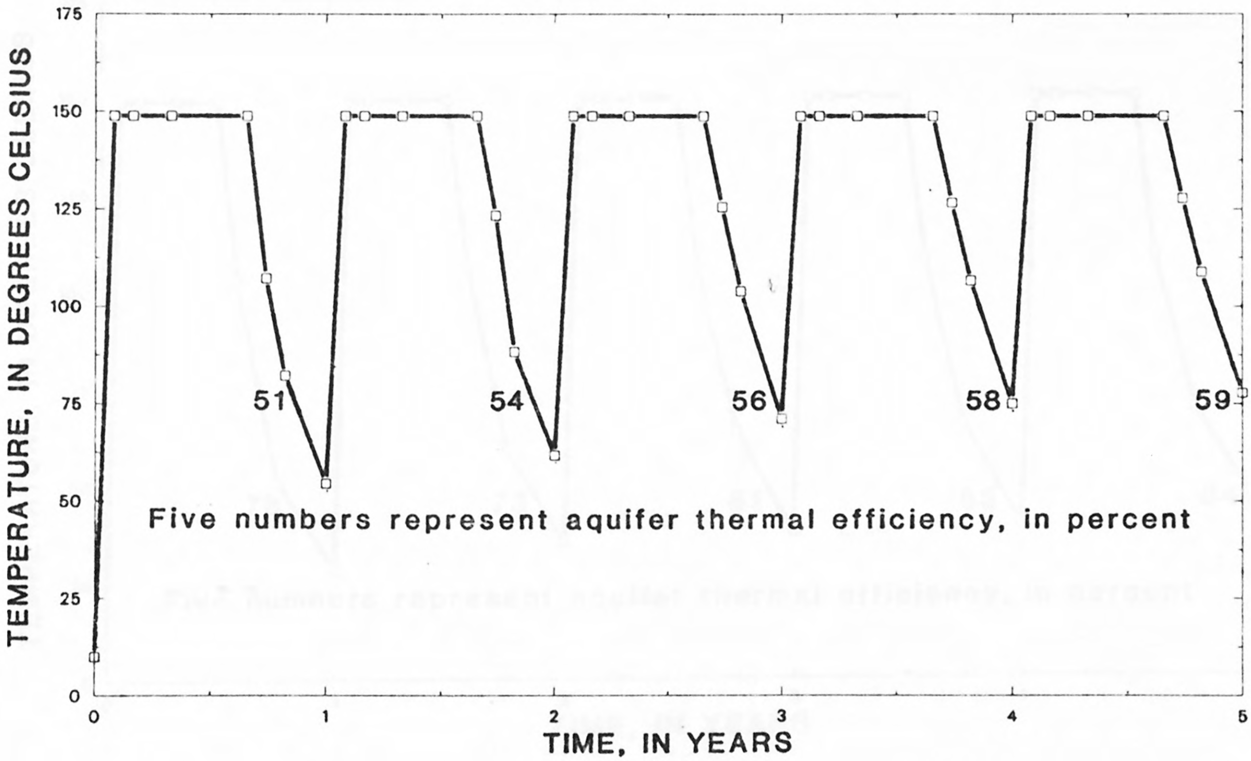

Figure 19. Well-bore temperatures and calculated aquifer relative efficiencies for five hypothetical 1-year cycles of 6 months of injection at 18.9 L/s of 150°C water and 6 months of recovery at 18.9 L/s.

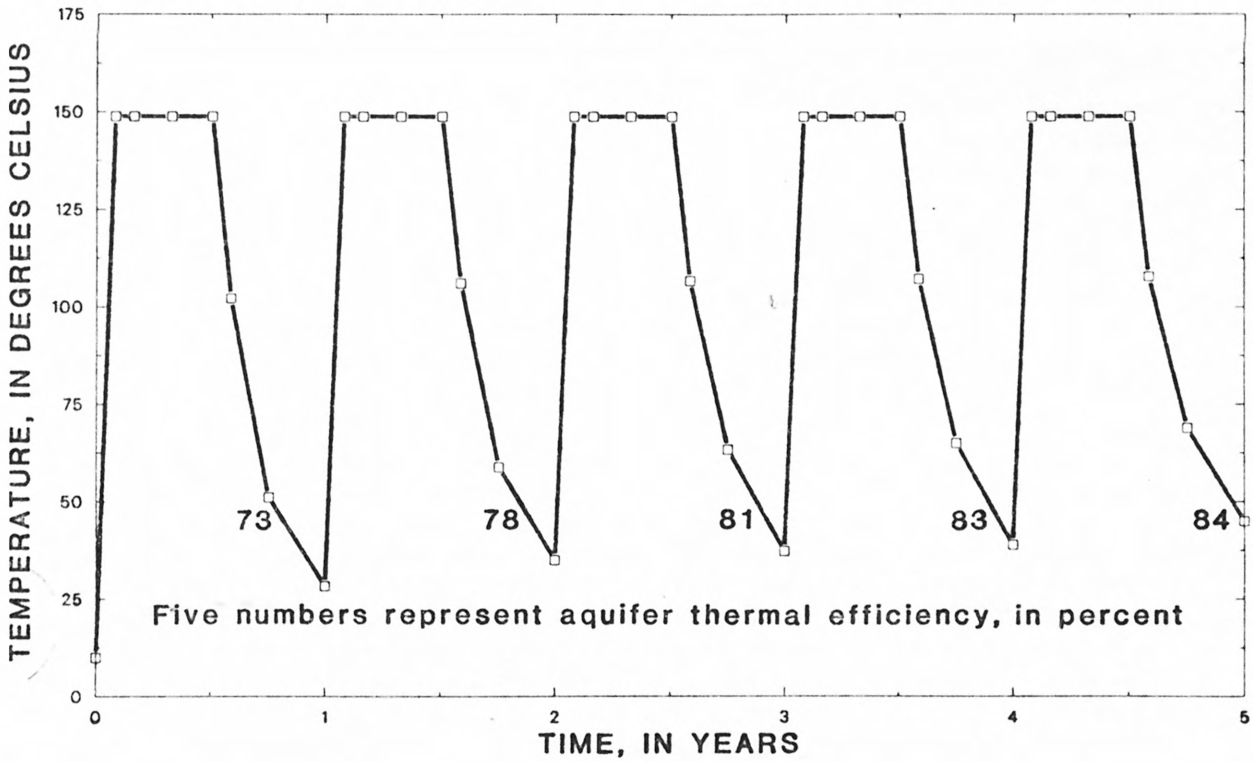

Figure 20. Well-bore temperatures and calculated aquifer relative efficiencies for five hypothetical 1-year cycles of 6 months of injection at 18.9 L/s of 150°C water and 6 months of withdrawal at 37.8 L/s.

Finally, a similarity between the relative thermal efficiencies of the aquifer in figures 16 and 19 should be noted. Each curve represents a different hypothetical cyclic scheme in terms of time and rate. The only common factor between them is the injection temperature and the total volume of water injected and withdrawn. Relative thermal efficiencies for the simulation depicted in figure 16, however, are calculated at a significantly reduced time scale (by a factor of approximately 15), which suggests that it may be possible to obtain adequate estimates of aquifer thermal efficiency and well-bore temperatures with reduced time-scale simulations.

Summary

In May 1980, the University of Minnesota began an ATES study on the St. Paul campus. The ATES system uses a doublet-well design with an injection-withdrawal well spacing of approximately 250 m. Hot water (150°C) will be injected into the deep (180-240 m) Franconia-Ironton-Galesville aquifer, a consolidated sandstone. The aquifer is confined above by the St. Lawrence Formation, a dolomitic sandstone, and below by the Eau Claire Formation, a shale. Short-term testing will consist of 8 days of injection at 18.9 L/s of 150°C water, 8 days of storage, and 8 days of withdrawal of heated water at 18.9 L/s.

The U.S. Geological Survey is constructing a ground-water-flow and thermal-energy-transport model to aid in evaluation of the ATES concept. A preliminary radial-flow model for ground-water flow and thermal-energy transport was constructed with a code developed for the U.S. Geological Survey for calculating the effects of liquid waste disposal in deep saline aquifers. Vertically, the model consists of 16 layers ranging in thickness from approximately 5 to 10 m, which simulates the aquifer and the confining layers. The radial spacings range from 0.18 to 26.8 m. The smallest radial spacing represents the well bore, and the largest radial spacing is one-half of the distance between the doublet wells, or a radius of 125 m.

Sensitivity analysis was made on the preliminary radial-flow and thermal-energy transport model for hydraulic conductivity, porosity, K_H/K_V, rock thermal conductivity, rock-heat capacity, and thermal dispersivity. Each simulation consisted of 8 days injection at 18.9 L/s of 150°C water, 8 days of storage, and 8 days of withdrawal at 18.9 L/s for one complete 24-day cycle. Individual model properties were varied for the assumed base values and plots of model-computed temperature versus time were constructed for a radial distance of 6.5 m from the well bore. Resulting curves then were compared with each other and with curves for other model properties to determine model sensitivity in terms of calculated temperature and aquifer thermal efficiency. Model results indicate that hydraulic and thermal properties may be ranked in terms of increasing model sensitivity as follows: K_H/K_V, rock thermal conductivity, hydraulic conductivity, porosity, rock-heat capacity, and thermal dispersivity.

The preliminary radial-flow and thermal-energy-transport model also was used to study the potential effects of thermal convection, or buoyancy flow, due to density differences between the cooler natural-temperature ground water and the heated injection water. The preliminary model simulated 8 days of injection of 150 $^{\circ}C$ water at 18.9 L/s, 8 days of storage, and 8 days of withdrawal at 18.9 L/s. Values of K_H and K_H/K_V were varied individually by an order of magnitude. Vertical profile plots of temperature were constructed at the end of injection, storage, and withdrawal at a radial distance of 6.5 m. Tilting of the thermal front caused by buoyancy flow was not apparent in the temperature profile plots at the end of injection, storage, or withdrawal for the assumed base values of hydraulic and thermal properties. Simulating horizontal K_H at 10 times the base value and K_V equal to K_H resulted in significant tilting of the thermal front at the end of storage and withdrawal, indicating the importance of accurate data collection and analyses for these two hydraulic properties.

The preliminary radial-flow and thermal-energy-transport model also was used to examine the effects on aquifer thermal efficiency of hypothetical test cycles consisting of various periods of injection and withdrawal of hot water and varying withdrawal rates. Simulations consisted of five injection-withdrawal cycles of 1 year each representing a total of 5 years of system operation. In all simulations, injection was 18.9 L/s of 150 $^{\circ}C$ water. Aquifer thermal efficiency was calculated as total energy withdrawn divided by total energy injected. The least efficient cycle simulated consisted of 8 months of injection at 18.9 L/s and 4 months of withdrawal at 18.9 L/s. The aquifer efficiency computed at the end of the fifth cycle was 39 percent, and the final well-bore temperature was 130 $^{\circ}C$. The most efficient simulation consists of 6 months of injection at 18.9 L/s and 6 months of withdrawal at 37.8 L/s. The computed efficiency after five cycles was 84 percent, and the final well-bore temperature was 46 $^{\circ}C$.

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