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# INVESTIGATION OF THE VERTICAL-FLOW AQUIFER THERMAL ENERGY STORAGE CONCEPT AND NUMERICAL SIMULATION OF THE DORIGNY FIELD EXPERIMENT

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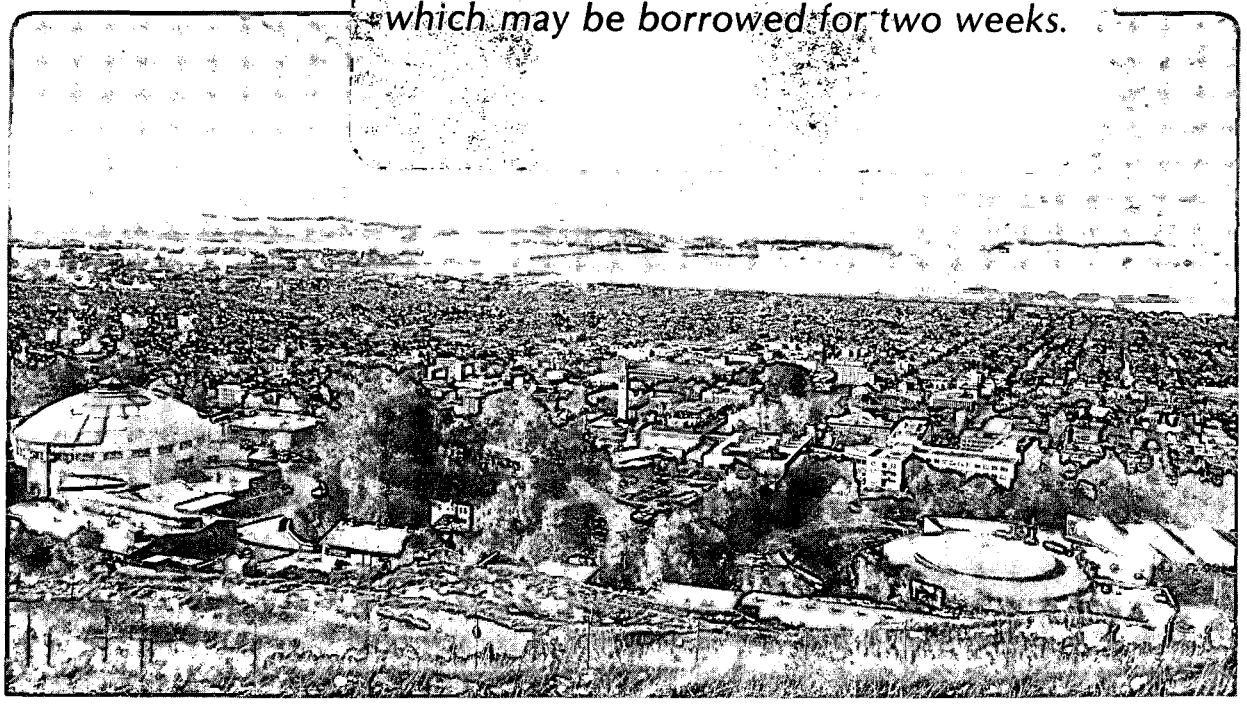

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# INVESTIGATION OF THE VERTICAL-FLOW AQUIFER THERMAL ENERGY STORAGE CONCEPT AND NUMERICAL SIMULATION OF THE DORIGNY FIELD EXPERIMENT

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## ABSTRACT

A mathematical modeling study of the vertical-flow aquifer thermal energy storage concept is made. A history match calculation of the Dorigny field experiment, part of the SPEOS project, is carried out using two simplified models. Then the main heat-loss mechanisms are isolated to study their relative importance. Finally, variations on the Dorigny experimental configuration are studied to examine the behavior of the vertical-flow storage system in general.

## 1. INTRODUCTION

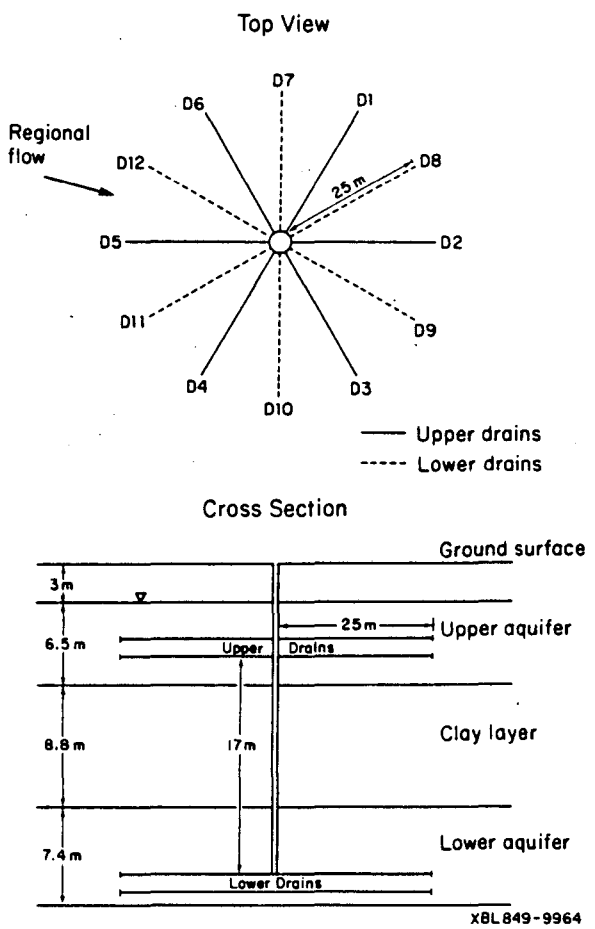
Natural convection is a serious problem for aquifer thermal energy storage (ATES) systems that use a vertical well to inject hot or cold water horizontally into an aquifer. The density difference between the injected and native waters causes the vertical thermal front to tilt, resulting in large heat dissipation. To avoid this problem, the SPEOS (Stockage Pilote d'Energie Par un Ouvrage Souterrain) project, sponsored by the International Energy Agency, has developed the vertical-flow ATES concept. The basic design includes a vertical central well with two levels of horizontal radial drains separated by a vertical interval. During the summer injection period, water is continuously extracted from the lower-level "supply" drains, heated by heat exchangers located in the central well, and then injected into the upper-level "storage" drains. This design creates a vertical fluid flow field and a horizontal thermal front, thus minimizing the effect of natural convection. The resulting plume has a compact shape with a small surface to volume ratio, and minimal heat loss. During the winter production period, the flows are reversed and heat is extracted from the produced water and used for space heating. The efficiency of an ATES system is quantified by the recovery factor, defined as the ratio of energy produced to energy injected.

Between 1982 and 1984 a field experiment using the vertical-flow ATES concept was conducted on a shallow water-table aquifer at Dorigny, near Lausanne, Switzerland (1). Two cycles, each consisting of an injection, storage, and production period, were carried out. Approximately 15,000 $m^3$ of water was injected each cycle. The average injection temperature was 60 °C for the first cycle and 70 °C for the second.

Lawrence Berkeley Laboratory (LBL) has carried out a mathematical modeling study of the vertical-flow ATES concept. First, a history match calculation of the first cycle of the Dorigny experiment is compared to the field results. Next, the main heat-loss mechanisms for the Dorigny experiment are isolated in order to study their relative importance for the system, and parameter sensitivity studies are made. Finally, calculations are done for several variations on the Dorigny experiment, to examine the general feasibility of the vertical-flow ATES concept.

## 2. THE DORIGNY EXPERIMENT

A sketch of the experimental configuration at the Dorigny site is shown in Figure 1. The water table, three meters below the ground surface, and the direction of the regional flow are shown. Ambient groundwater temperature is 12 °C. The




1. Schematic diagram of the Dorigny field experiment.

upper supply drains and lower storage drains are separated by a vertical distance of 17 m. A low permeability clay layer, discovered after the initiation of the experiment, lies between the two sand layers where the drains are located, effectively dividing the system into two aquifers. During injection, hot water spreads laterally around the upper drains and does not move downward through the clay lyer. This creates an elongated plume (the thickness of the upper aquifer is only 6.5 m) with a large surface to volume ratio and high heat loss.

Between July and December 1982, 14,743 $m^3$ of water at an average temperature of 59.3 °C was injected. From mid-January to April 1983, 18,280 $m^3$ of water was extracted at temperatures ranging from 40 to 20 °C. Water was extracted at equal rates from the six storage drains except between February 5th and 25th, when the two drains most upstream (D5 and D6) were closed. In total, 41% of the injected energy was produced (a recovery factor of 0.41) and the volume extracted was 1.24 times the volume injected.

## 3. THE MATHEMATICAL MODEL

The mathematical model PT (2), developed at LBL, is used in these studies. PT calculates the coupled liquid and heat flows in a water-saturated porous or fractured-porous medium. One-dimensional consolidation of the rock matrix can be considered as well, using the theory of Terzaghi (3). The mass and energy equations are coupled through the fluid flow in the convection term of the energy equation, and the pressure- and temperature-dependent fluid and rock properties. The rock matrix and fluid are considered to be in point local thermal equilibrium at all times. Energy changes due to fluid compressibility, acceleration, and viscous dissipation are neglected. The following physical effects are included in PT calculations: (a) heat convection and conduction; (b) regional groundwater flow; (c) multiple heat and/or mass sources and sinks; (d) step-wise constant pressure or temperature boundaries; (e) hydrologic or thermal barriers; (f) gravitational effects (buoyancy); (g) complex geometries due to heterogeneous materials; and (h) anisotropic permeability and thermal conductivity. The discretized equations used in PT are based upon the Integral-Finite-Difference method (4). This method treats one-, two-, or three-dimensional problems equivalently. An efficient sparse solver (5) is used to solve the linearized mass and energy matrix equations. The equations are solved implicitly to allow for large time steps. PT adjusts the time step automatically, so that the temperature or pressure changes in any node during one time step are within user-specified limits. Mass and energy balances are calculated for each node every time step. PT has been verified against a number of analytical solutions and validated against a series of field experiments (6).

In theory, PT can be used with an arbitrarily detailed three-dimensional calculational mesh to represent complicated field conditions accurately. However, a mesh with many elements may require prohibitively large amounts of computer memory and time, so simplifications are often necessary. Two simplified approaches are taken for this study, in order to reduce the problem to a manageable size. The material properties summarized in Table 1 are taken from (1).

### Single-Layer Areal Model

Because of the presence of the clay layer, the heat and fluid flow in the upper aquifer around the storage drains can be modeled independently of the flows around the lower supply drains. The upper aquifer is modeled as a single homogeneous layer of uniform thickness. A semianalytical solution for conductive heat losses to the underlying clay layer is included in the numerical model. The clay layer is assumed to be infinitely thick in this treatment, which is a reasonable assumption for the time duration of the first cycle. (Conduction penetration depth is 8.6 m for the 256 day cycle.) Heat losses to the ground surface through the unsaturated zone overlying the upper aquifer are expressed by a linear "radiation" heat flow, $Q = h(T - T_0)$. The effective heat transfer coefficient $h$, which combines the effects of the unsaturated zone and the ground surface, is used as a fitting parameter to match the experimental and calculated recovery factors. The measured seasonal variation in ground surface temperature, $T_0$, is incorporated into the model as well.

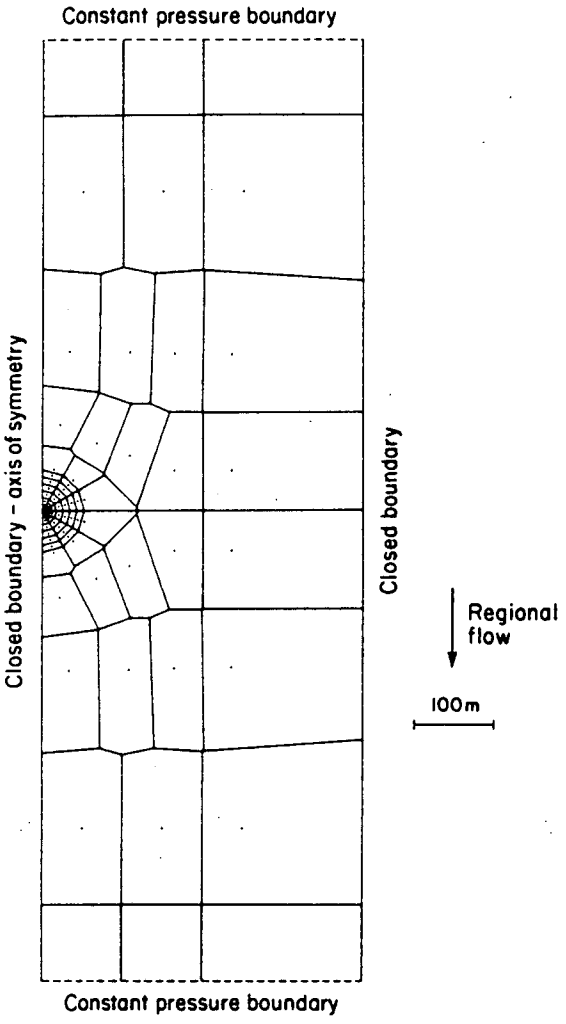
The regional groundwater flow at the Dorigny site is determined from water level and hydraulic conductivity measurements to be 0.1 m/day. It is included in the areal model by creating constant-pressure boundary elements in the calculational mesh, upstream and downstream of the storage drains, at different pressures. The mesh used for the areal model, shown in Figure 2, is generated using the computer code OGRE (7), developed at LBL. The mesh is designed to be finely discretized within the region where thermal effects are significant. The radial extent of the injected plume (31 m) and its displacement due to regional flow (0.04 m/day) are calculated based on energy conservation.

Table 1. Material properties used in the mathematical modeling studies.

| Layer | Property | Value |
|---|---|---|
| Upper Aquifer | Horizontal Permeability | $k_h = 8.16 \times 10^{-12}$ $m^2$ |
| | Vertical Permeability | $k_v = 1.27 \times 10^{-13}$ $m^2$ |
| | Thermal Conductivity | $\lambda = 2.5$ W/m °C |
| | Heat Capacity | $C = 3 \times 10^6$ J/$m^3$ °C |
| Clay Layer | Horizontal Permeability | $k_h = 3.77 \times 10^{-12}$ $m^2$ |
| | Vertical Permeability | $k_v = 6.41 \times 10^{-15}$ $m^2$ |
| | Thermal Conductivity | $\lambda = 2.1$ W/m °C |
| | Heat Capacity | $C = 2.5 \times 10^6$ J/$m^3$ °C |
| Lower Aquifer | Horizontal Permeability | $k_h = 8.16 \times 10^{-12}$ $m^2$ |
| | Vertical Permeability | $k_v = 1.27 \times 10^{-12}$ $m^2$ |
| | Thermal Conductivity | $\lambda = 2.5$ W/m °C |
| | Heat Capacity | $C = 2.5 \times 10^6$ J/$m^3$ °C |
| Unsaturated Zone | Horizontal Permeability | $k_h = 1.26 \times 10^{-14}$ $m^2$ |
| | Vertical Permeability | $k_v = 1.26 \times 10^{-16}$ $m^2$ |
| | Thermal Conductivity | $\lambda = 2.1$ W/m °C |
| | Heat Capacity | $C = 2 \times 10^6$ J/$m^3$ °C |

Notes:

1. Heat capacity is combined value of rock matrix, fluid, and (in unsaturated zone) air.
2. Several properties are not given in (1), so typical values for shallow aquifer systems are used: porosity, $\phi = 0.30$, and compressibility, $\beta = 10^{-8}$ $Pa^{-1}$.
3. The areal model treats heat loss through the unsaturated zone to the ground surface as a radiation heat flow with an effective heat transfer coefficient $h$. A value of $h = 0.092$ W/$m^2$ °C is determined by matching the experimental and calculated recovery factors.




2. Single-layer areal mesh used in the modeling studies.

To avoid the short time-steps necessary for calculating sharp temperature gradients, the six radial storage drains are approximated by a uniform disk. There is symmetry with respect to a line passing through the center of the disk parallel to the direction of regional flow, so only one-half of the problem need be modeled. The short-term closure of the two most upstream drains during the production period is modeled by producing from only the downstream two-thirds of the injection disk for that time.

Radial Model

The radial model assumes that the effect of regional flow is negligible and that the flow is radially symmetric. Heat and fluid flow are calculated in the upper aquifer, clay layer, and lower aquifer. The radial arrays of storage drains and supply drains are both approximated by uniform disks. Heat flow, but not fluid flow, is considered in the unsaturated zone, so air-water-heat interactions are not calculated and the water table remains at a constant depth of 3 m.

The central portion of the calculational mesh for the radial model is shown in Figure 3. Thermal effects are expected to be limited to this portion of the mesh. The mesh extends to a radial distance of 2500 m, with steadily increasing width elements, to calculate pressure responses to injection and pumping. The horizontal boundary of the mesh below the lower aquifer is insulated, since little temperature change is expected there.

## 4. HISTORY MATCH OF THE FIRST CYCLE

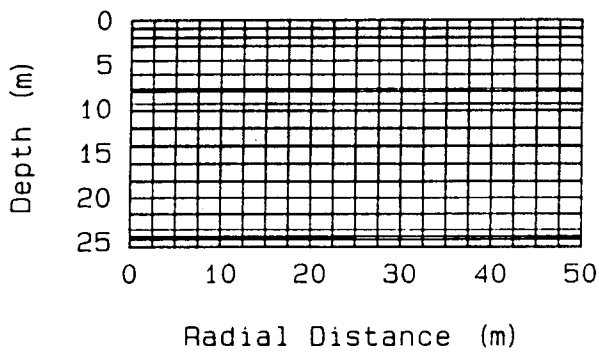
The first cycle consists of 137 days of injection, 42 days of storage, and 77 days of production. The experimental injection and production flow rates and injection temperatures are averaged to a series of 15 constant steps for the numerical model, conserving mass and energy.

Single-Layer Areal Model

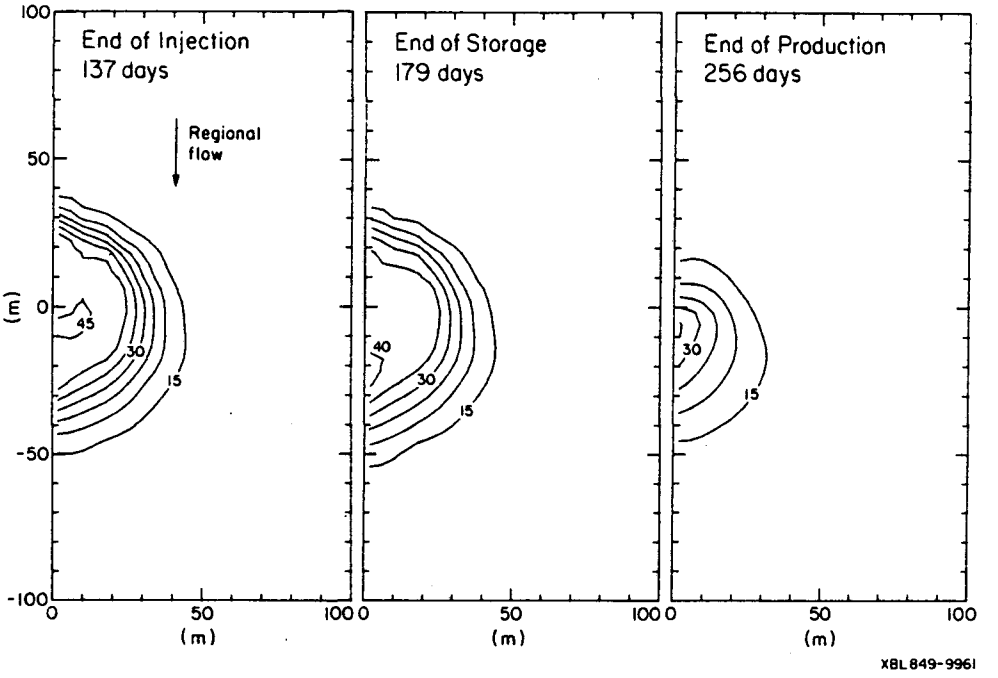
The temperature distributions at the end of the injection, storage, and production periods calculated using the areal model are shown in Figure 4. Due to the irregular mesh, simple interpolation of the calculated temperatures is not possible, so a computerized interpolation program is used to generate the contour plots. The interpolation program introduces the small oscillations in the temperature distributions seen in the figure. The contour plots illustrate the shift of the injected plume downstream due to the regional flow. Vertical heat loss is evidenced by the decrease in the temperature levels between the end of the injection and storage periods.

The calculated and experimental production temperatures versus time are shown in Figure 5. The time-averaged production temperature is proportional to the recovery factor of the system, which is calculated to be 0.42. The effective heat transfer coefficient, $h$, has been chosen so that the calculated recovery factor agrees with the experimental value (0.41).

The production temperature increase between days 198 and 219 corresponds to the closure of the most upstream drains, D5 and D6. These drains extract lower temperature water than do the other drains, due to the regional flow. Overall, the calculated temperatures match the experimental values quite well. The early-time underprediction and late-time overprediction are probably due to the single layer model used, which averages temperatures vertically over the aquifer. In reality, the drains are only about 30 cm thick, compared to the thickness of the upper aquifer of 6.5 m, so that after injection the temperature at the drain level should be higher




3. Central portion of the radial mesh used in the modeling studies. XBL 855-10500




4. Temperature distributions calculated with the areal model.

than the depth-averaged temperature in the aquifer. Thus for early times, when water at the drain level is extracted, production temperatures will be higher than those calculated; conversely, the late-time production temperatures will be lower than those calculated.

The good match between the experimental and calculated production temperatures indicates that even with a simple one-layer model, many essential features of the Dorigny experiment can be studied. Several additional calculations have been made using the areal model, to study the relative importance of various heat-loss mechanisms. These are discussed in Section 5 below.

Radial Model

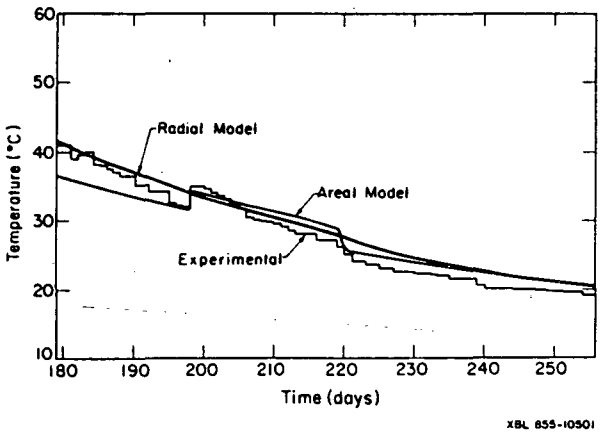
The temperature distributions at the end of the injection, storage, and production periods calculated using the radial model are shown in Figure 6. The calculated production temperature versus time is shown in Figure 5. Because regional flow and the upstream drain closure are not included in the radial model calculation, there is no corresponding jump in production temperature as there is for the areal model calculation. The steeper slope of the radial model production temperature is due to the discretization of the upper aquifer, as described above. The recovery factor calculated by the radial model is 0.45. This overpredicts the experimental value of 0.41, probably because of the neglect of the heat dissipation effects of regional groundwater flow.

## 5. INVESTIGATION OF HEAT-LOSS MECHANISMS

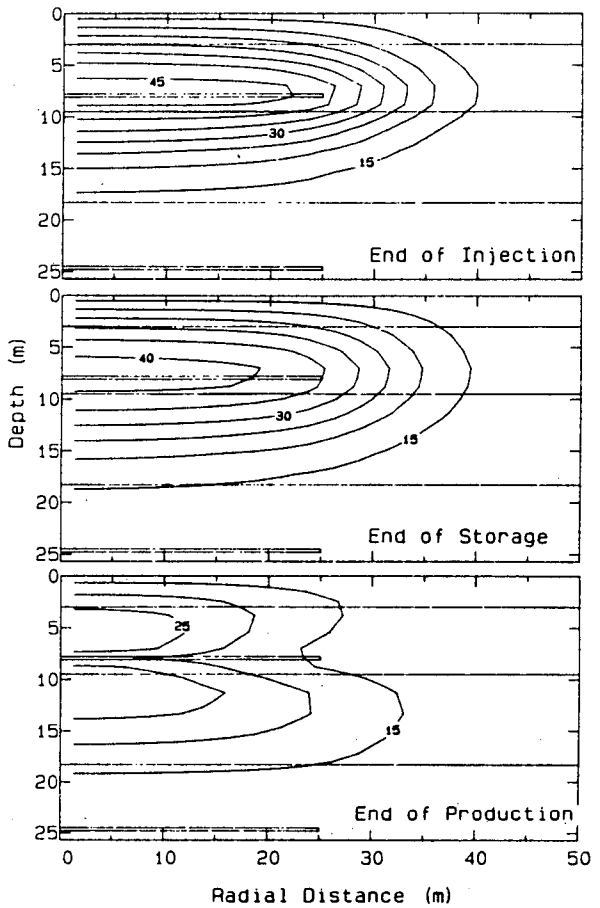
In the following calculations using the areal model, various heat-loss mechanisms have been isolated in order to study their relative importance for the Dorigny experiment. Unless otherwise noted, the material properties given in Table 1 are used. Table 2 summarizes the calculation results, and Figure 7 shows selected production temperature curves.

Case 1 considers an insulated upper aquifer (no vertical heat losses), with no regional flow. The closure of the upstream drains during the production period is not modeled. The only heat-loss mechanism is lateral diffusion, so the calculated recovery factor, 0.71, is quite high.

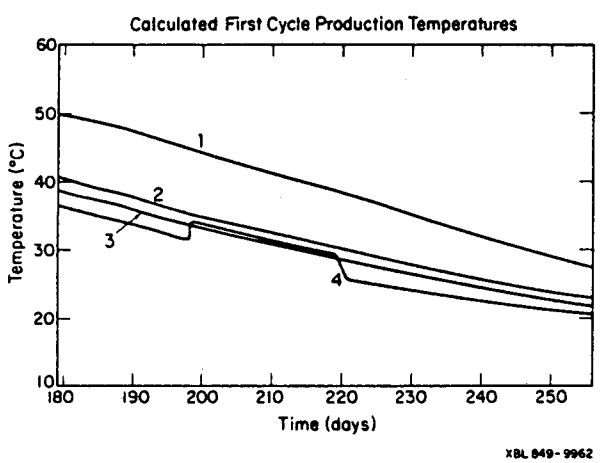
For Case 2 the conductive losses to the clay layer underlying the upper aquifer are added to Case 1. The recovery factor, 0.50, is substantially decreased, indicating that vertical heat losses have a major effect on the overall thermal behavior of the system. The importance of vertical heat loss is due to the large aspect ratio of the injected plume (the ratio of the plume's lateral to vertical dimension). An aspect ratio of 0.5 creates a minimal plume surface to volume ratio, minimizing heat loss. For the Dorigny experiment, the aspect ratio is 4.8.




5. First-cycle experimental and calculated production temperatures.




6. Temperature distributions calculated with the radial model. XBL 855-2484




7. First-cycle calculated (areal model) production temperatures for Cases 1-4.

Table 2. Areal model calculations isolating various heat-loss mechanisms.

| Case | Description | Recovery Factor |
|---|---|---|
| 1* | No vertical heat loss<br>No regional flow | 0.71 |
| 2* | No surface heat loss<br>No regional flow | 0.50 |
| 3* | No regional flow | 0.46 |
| 4* | Basic Case | 0.42 |
| 5 | Larger surface heat loss<br>$h$ =0.185 W/m$^2$ · C | 0.40 |
| 6 | Smaller surface heat loss<br>$h$ =0.046 W/m$^2$ · C | 0.44 |
| 7 | Larger surface heat loss<br>$h$ =0.40 W/m$^2$ · C<br>Smaller clay layer heat loss<br>$\lambda$=0.5 W/m · C | 0.42 |
| 8 | Constant surface temperature | 0.42 |

A * indicates that the production temperature curve is shown in Figure 7.

If the clay layer were not present and the fluid flow vertical, the aspect ratio would be 2.5, a much more favorable value. For larger injected volumes, the aspect ratio would further decrease to 1.5 (drain length 25 m/vertical interval 17 m).

The production temperature curve for Case 2 is markedly less steep than that for Case 1 (see Figure 7). This is because the conductive heat losses included in Case 2 are somewhat reversible. Heat that is conducted to the cooler clay layers during the injection period is conducted back into the aquifer during the production period, leading to the more gradual decrease in production temperature than in Case 1.

Case 3 adds the heat transfer through the unsaturated zone to the ground surface to Case 2, and yields a recovery factor of 0.46. The production temperature curve essentially parallels that for Case 2 because surface heat losses are irreversible.

Results of the radial model, which considers vertical heat loss in detail, can be compared to results of Case 3, which simplifies vertical heat loss, because regional flow is not included in Case 3. The good agreement between the respective recovery factors (0.45 and 0.46), indicates that the simplifications made for the areal model are valid.

Case 4 adds regional flow and the upstream drain closure during the production period to Case 3, and yields a recovery factor of 0.42, a modest decrease from Case 3. Thus the regional flow appears not to be a dominant heat-loss mechanism, indicating that the radial model may be useful. Case 4 is the basic areal model case presented in the last section with results shown in Figures 4 and 5.

Cases 5 and 6 consider doubled and halved values for the surface heat transfer coefficient $h$ relative to Case 4, and yield recovery factors of 0.40 and 0.44, respectively. Together

Cases 4, 5, and 6 show that the Dorigny experiment is only moderately sensitive to $h$, a parameter which combines several physical effects.

Case 7 considers larger surface heat loss ($h$ =0.40 W/m$^2$ • C) and smaller clay layer heat loss ($\lambda$=0.5 W/m • C) than Case 4. The values of $h$ and $\lambda$ are chosen so that the recovery factor, 0.42, is the same as that for Case 4. The shape of the production temperature curve is quite similar to that for Case 4, with a maximum deviation of about 1 • C. The small deviation indicates the insensitivity of the system to the relative value of these parameters, and further increases our confidence in the use of this simple model.

Case 8 assumes a constant surface temperature of 11.7 • C, the average of the measured annual variation between 5 and 15.5 • C used in the other cases. The recovery factor is essentially the same as in the basic case, indicating that surface temperature variation has a negligible effect.

## 6. GENERAL VERTICAL-FLOW STORAGE CONCEPT STUDIES

Two topics relevant to the vertical-flow ATES concept in general are studied in the following calculations. The first examines the effect of regional flow, the second considers the influence of permeability variations. The calculations are summarized in Table 3. Unless otherwise noted, the material properties and scheduling assumed are those of the Dorigny first-cycle experiment.

### Single-Layer Areal Model

For some cases, it may be desirable to neutralize the effect of regional groundwater flow. One possibility being considered for the Dorigny site is the creation of a by-pass around the storage system that will pump water out of the aquifer upstream from the drains and reinject it downstream. As an alternative, we consider several selective injection/production procedures to counteract the effect of regional flow, similar to the closure of drains D5 and D6.

Case A assumes the same total injection rate as the basic areal model case, but injects only into the upstream two-thirds of the disk and produces only from the downstream two-thirds. Case A yields a recovery factor of 0.48, an increase over the basic case (0.42) even larger than the decrease due to the addition of regional flow (Case 3 to Case 4; 0.46 to 0.42). Thus another effect besides the counteraction of regional flow is coming into play: the plume created from the smaller injection area has a more favorable aspect ratio than the basic case plume, so recovery factor increases.

Case B further concentrates the injection and production to the upstream one-third and downstream one-third of the disk, respectively, and yields a recovery factor of 0.49.

Table 3. Calculations for general vertical-flow ATES systems.

| Model | Case | Description | Recovery Factor |
|---|---|---|---|
| Areal Model | A | Upstream 2/3 injection<br>Downstream 2/3 production | 0.48 |
| | B | Upstream 1/3 injection<br>Downstream 1/3 production | 0.49 |
| Radial Model | C | Clay layer replaced by extension of upper aquifer | 0.49 |
| | D | Clay layer replaced by extension of lower aquifer | 0.53 |
| | E | Upper aquifer, lower aquifer, clay layer all isotropic with equal permeabilities | 0.55 |

### Radial Model

The low permeability clay layer discovered after the start of the Dorigny experiment plays a major role in determining the shape of the hot water plume. This in turn has a large effect on the recovery factor. In order to predict the behavior of the vertical-flow ATES concept at other sites, several variations in the permeability distribution at the Dorigny site are considered.

Case C assumes that the clay layer has the same horizontal and vertical permeability as the upper aquifer. Because the upper aquifer has a large permeability anisotropy value, the aspect ratio of the plume remains rather large, and the recovery factor increases only a modest amount, from 0.45 to 0.49.

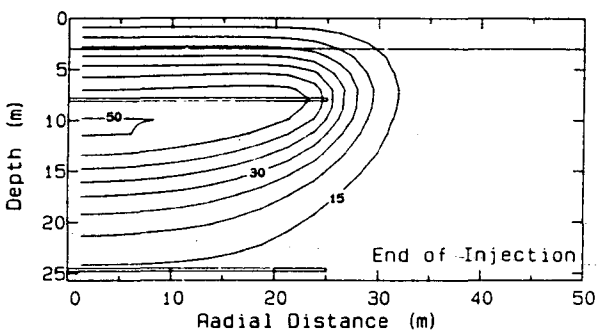
Case D assumes that the clay layer has the same vertical permeability as the lower aquifer, a factor of ten higher than that of the upper aquifer. The aspect ratio of the plume decreases as more fluid flows downward toward the supply drains, and the recovery factor improves to 0.53.

Case E assumes that the upper aquifer, the clay layer, and the lower aquifer are all isotropic with equal horizontal and vertical permeabilities. The plume moves downward readily, as shown in Figure 8, and the recovery factor is 0.55, a significant improvement over the basic case (0.45).

The present results indicate the importance of vertical permeability value for the efficiency of an ATES system. Extra effort should be made to estimate its value for any field ATES system.

## 7. CONCLUSIONS

Although the simple areal and radial models used in these mathematical modeling studies are highly idealized, they provide much useful information for the analysis of the Dorigny field experiment, and the vertical flow ATES concept in general. The largest single factor influencing the recovery factor




8. Temperature distribution at the end of the injection period, calculated with the radial model assuming no clay layer (Case E).

at the Dorigny site is the large aspect ratio of the injected plume. The radial model has been used to show that without the clay layer, a smaller aspect ratio would result, yielding an improvement in recovery factor from 0.45 to 0.55. The regional flow has a less pronounced effect, but measures to minimize its influence, such as the proposed by-pass or selective injection-production strategies, will also improve recovery factor.

## ACKNOWLEDGMENTS

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