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AQUIFER THERMAL ENERGY STORAGE--RECENT PARAMETER AND SITE-SPECIFIC STUDIES

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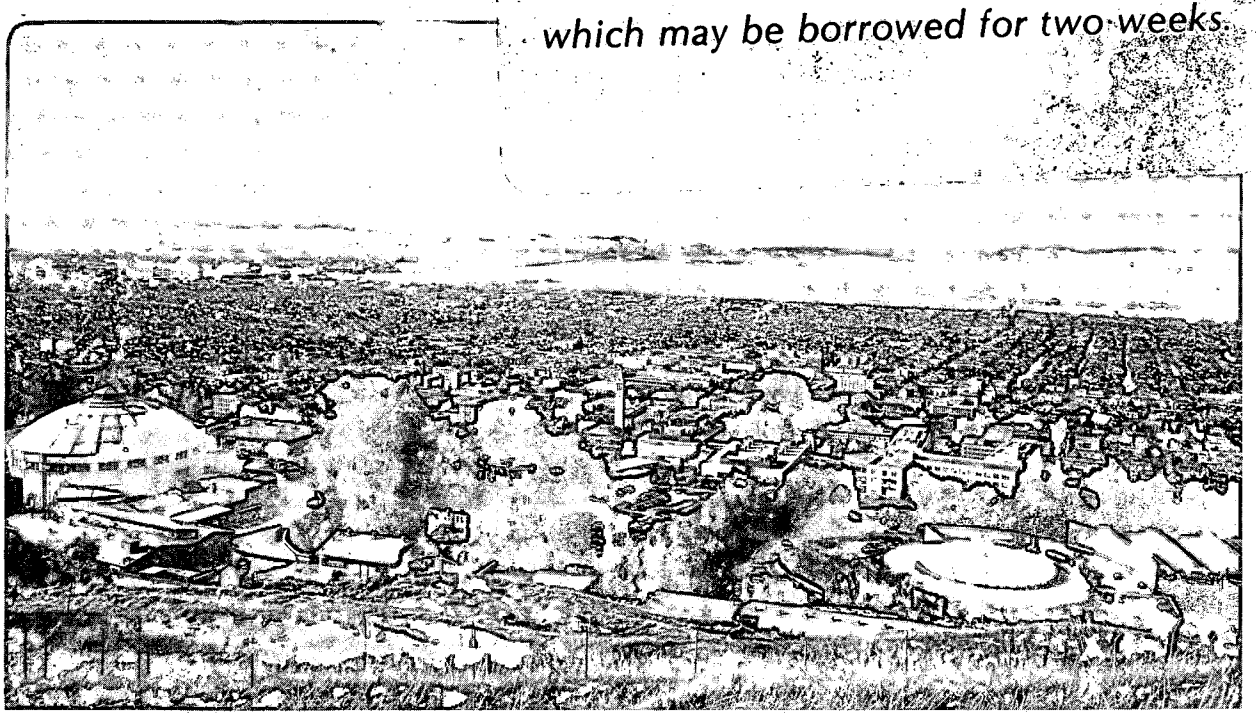

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AQUIFER THERMAL ENERGY STORAGE--RECENT PARAMETER AND SITE-SPECIFIC STUDIES

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ABSTRACT

The concept of Aquifer Thermal Energy Storage (ATES) has been studied extensively for the past six years at the Lawrence Berkeley Laboratory (LBL). In particular, parameter and site-specific studies have been emphasized. In our parameter studies, characterization techniques have been developed for the hydrothermal behavior of ATES systems. These characterization schemes allow production temperatures and energy recovery factors for a range of cases to be read from graphs showing these variables in terms of a few dimensionless parameters. For site-specific studies, a detailed numerical simulation of the Auburn University three-cycle doublet well heat storage experiment has been done in order to demonstrate the predictive ability of the numerical model CCC, as well as to provide guidance in carrying out the second and third cycles of the experiment. The experimental injection temperatures and flowrates were used. Recovery factors and production temperatures were predicted prior to receiving the temperature data from the field. Subsequently, a series of parameter sensitivity studies were done to examine the differences between the predicted and observed results.

INTRODUCTION

Lawrence Berkeley Laboratory (LBL) began working on seasonal thermal energy storage in aquifers in 1976. Initial studies included comprehensive generic calculations based on a numerical model to calculate the coupled heat and fluid flow in a three-dimensional, complex geometry aquifer system. Proof-of-concept calculations were made for a number of hypothetical situations, the results of which have been published in a series of papers [for example, 1-3].

In 1978 LBL organized and hosted the First International Workshop on Aquifer Thermal Energy Storage (ATES). Active workers from nine countries participated in this workshop and their contributions were published in the workshop proceedings [4]. Since the workshop, a quarterly newsletter [5] has kept researchers abreast of the current status of various projects worldwide. Many of these projects are reviewed in two survey papers published in 1979 [6,7] and an update survey to be published in 1981 [8].

This paper concentrates on our site-related studies during 1981: Parameter studies leading to site characterization techniques to determine optimal storage conditions, and prediction and simulation of the Mobile field experiments.

PARAMETER STUDIES--SITE CHARACTERIZATION

The purpose of our ATES site-characterization studies is to develop some general parameters or procedures whereby, for a given site, the energy recovery factor may be predicted readily for a wide range of operating conditions. This provides the basic results needed for technical or economic optimization of the ATES system. Here, the energy recovery factor is defined as the energy recovered divided by energy stored for the same amount of water injected into and produced from the aquifer. Energy is measured with reference to ambient aquifer temperature energy.

Two ATES site characterization schemes have been developed at LBL during the past year, the first neglecting buoyancy flow, the second including it.

The first study [9] considers the thermal behavior of an ATES system with steady radial fluid flow around a single injection/production well. Buoyancy flow is neglected and the aquifer is confined above and below by impermeable confining layers. Neglecting buoyancy flow may be a reasonable assumption for cases with low aquifer permeability, short storage cycle length, or small temperature difference between injected and ambient water. A criterion [10] exists which may be used to determine if buoyancy flow is negligible for a given case. However, conclusions from this study may still be applicable in a relative sense for cases in which buoyancy flow is significant.

With the above assumptions, the thermal behavior of the system can be described in terms of the following four dimensionless parameter groups:

$$Pe = \frac{QC_w}{2\pi\lambda_a H}; \qquad \Lambda = \frac{C_a^2 H^2}{C_c \lambda_c t_i}; \qquad Bi = \frac{\lambda_a C_a}{\lambda_c C_c}; \qquad \frac{C_a}{C_c}$$

where Q is the flowrate; H is the aquifer thickness; λ_a and λ_c are the aquifer and confining layer thermal conductivities; C_w, C_a, and C_c are the water, aquifer, and confining layer volumetric heat capacities, and t_i is the injection time period.

A simple, numerical steady-flow model has been used to calculate recovery factors and temperatures as a function of these parameters. This numerical model uses a fully explicit, finite-difference scheme to calculate conductive heat transfer. Convection is simulated by translating the temperature field in the aquifer in accordance with a steady radial fluid flow. Some of the results are shown in Figures 1 and 2.

Figure 1 shows the calculated energy recovery factor as a function of Pe and Λ numbers for the first cycle. Results for subsequent cycles have also been calculated. Note that the large initial increase in recovery factor is followed by a more gradual increase as Pe and Λ are increased.

Figure 2 displays the temperature of water extracted during the production period of the first and fifth cycles for different values of Pe and Λ. For values of Pe larger than 200, production temperature shows little dependence on Pe.

Other factors have also been considered through the introduction of several additional parameters. Thermal dispersion has been modeled by creating an effective aquifer thermal conductivity, $\tilde{\lambda}_a$, which adds a dispersion term to the usual aquifer thermal conductivity. This additional term may be constant, proportional to fluid velocity, or proportional to fluid velocity squared. Unequal length periods within a cycle are dealt with by introducing a parameter, τ, defined as the average time a fluid particle spends in the aquifer. Both $\tilde{\lambda}_a$ and τ can be incorporated into the basic four parameter groups. A finite thickness caprock, overlain by a constant temperature boundary representing the ground surface or another aquifer, can be included in the analysis by introducing a parameter d, the ratio of the caprock thickness to the aquifer thickness. Figure 3 shows the effect of the caprock thickness on the recovery factor as a function of Λ for a range of values of d. This variation is independent of Pe.

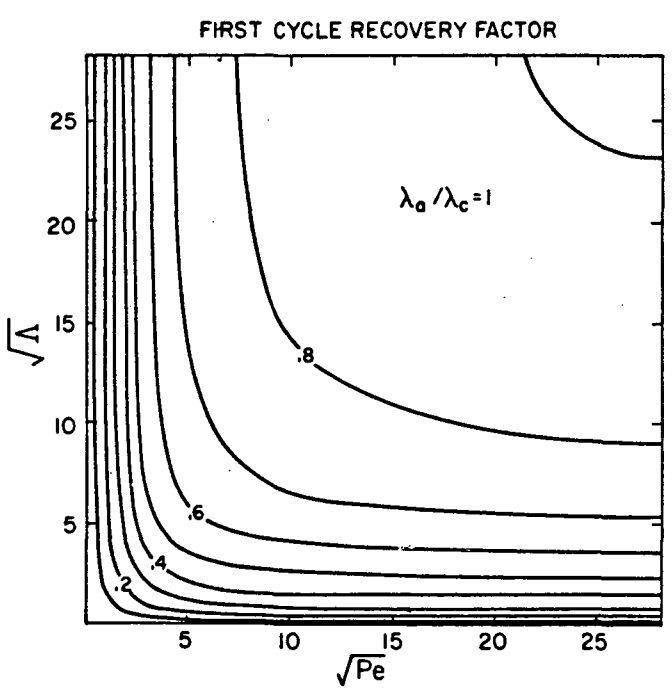


Figure 1. Recovery factor as a function of $\sqrt{Pe}$ and $\sqrt{\Lambda}$ for the first cycle, when $\lambda_a/\lambda_c = 1$. [XBL 8012-6516]

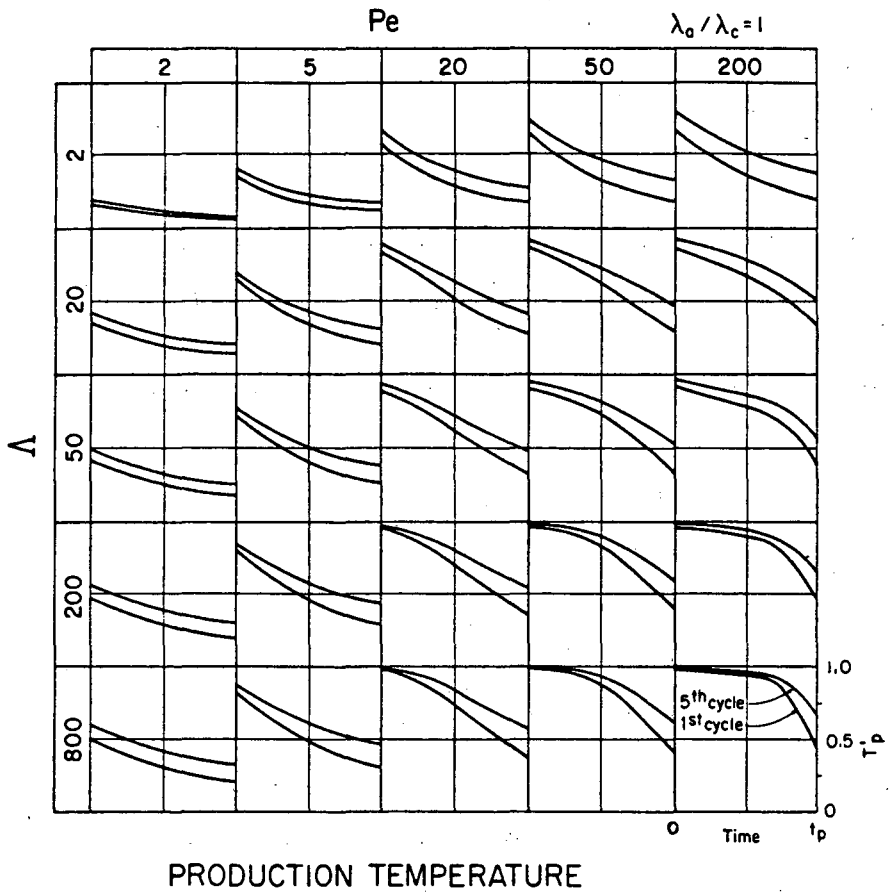


Figure 2. First and fifth cycle production temperatures versus time for a range of Pe and Λ when $\lambda_a/\lambda_c = 1$. [XBL 8012-6582C]

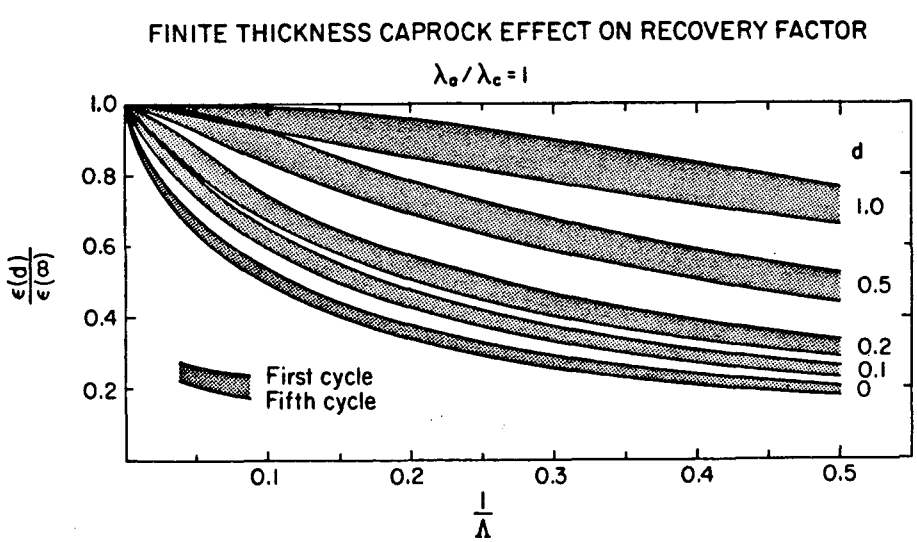


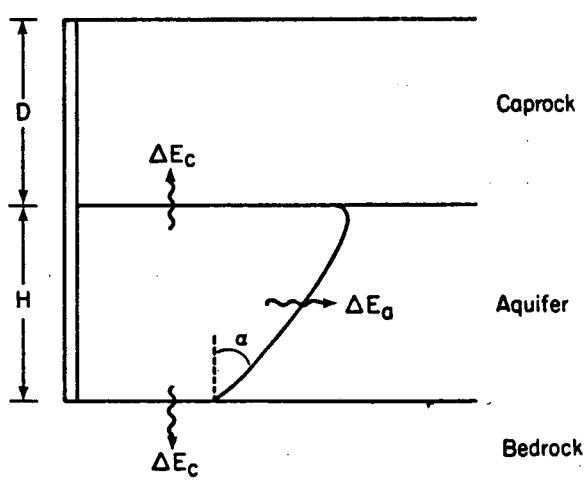
Figure 3. Finite thickness caprock effect for the first and fifth cycle recovery factors as a function of Λ when $\lambda_a/\lambda_c = 1$. [XBL 8012-6591]

Table 1 displays the application of this characterization technique to the Mobile [11,12] and Bonnaud [13] experiments. In this table, ε is the calculated energy recovery factor and ε_{exp} is the experimentally observed value. For the Auburn case, two calculations were made: (a) assuming that the well penetrates the full thickness of the aquifer, and (b) correcting for the fact that experimentally the well was open to only 9 m out of the 21 m thickness of the aquifer. The comparisons are very encouraging.

Table 1. Comparison of no buoyancy flow characterization scheme recovery factors with field experiments.

	$\sqrt{Pe}$	$\sqrt{\Lambda}$	ε	ε_{exp}
Mobile (first cycle)				
(a)	8.8	9.0	0.71	0.66
(b)	10.1	6.8	0.68	
Bonnaud (fourth cycle)	3.9	5.0	0.63	0.677

To investigate the effect of thermal front tilting caused by buoyancy flow, a second study [14] has been carried out. Calculations have been conducted over a wide range of aquifer permeabilities and injection temperatures using the numerical model CCC, which takes into account temperature-dependent parameters and the buoyancy flow process. In each case, an energy balance was kept for various times, separating radial diffusive losses in the aquifer and the vertical losses to the confining layers. A study of these results shows that over a wide range of conditions, the radial and vertical heat losses can be decoupled. Thus the energy recovery factor ε may be expressed as the product of two factors, $\varepsilon = (1 - \Delta E_a)(1 - \Delta E_c)$ where ΔE_a is the normalized energy lost radially when the aquifer is insulated from the confining layers above and below, and ΔE_c is the normalized energy loss due to vertical conduction into the upper and lower confining layers. A schematic drawing showing ΔE_a and ΔE_c is shown in Figure 4.



$$\epsilon = (1-\Delta E_c)(1-\Delta E_a)$$

Figure 4. A schematic drawing of the energy losses associated with the characterization scheme including buoyancy flow. [XBL 818-3395]

The decoupling of radial and vertical heat losses reduces the number of parameter groups required to describe the system to three: Pe, Λ, and Bi. However, the thermal front tilting influences both the radial and vertical losses, since the tilting modifies the area over which heat conduction occurs. An empirical shape factor based on the thermal front angle of tilt, α, is introduced to modify the parameter groups. Thus ΔE_a depends on the modified Pe number, Pe*, while ΔE_c depends on Λ^* and Bi*.

ΔE_c as a function of Λ^* and Bi*, shown in Figure 5, is calculated from a one-dimensional heat conduction problem in which heat diffuses from aquifer to aquitard. The effect of a constant temperature boundary overlying a finite thickness caprock is also included. ΔE_a as a function of Pe*, shown in Figure 6, is calculated from vertically insulated cases of ATES cycles. Hence, using values of Pe*, Λ^* and Bi* obtained from field input data, ΔE_c and ΔE_a may be determined and combined to form ε. Although not mathematically rigorous, the method has been shown to yield accurate predictions for a wide range of conditions when compared with CCC-simulated results.

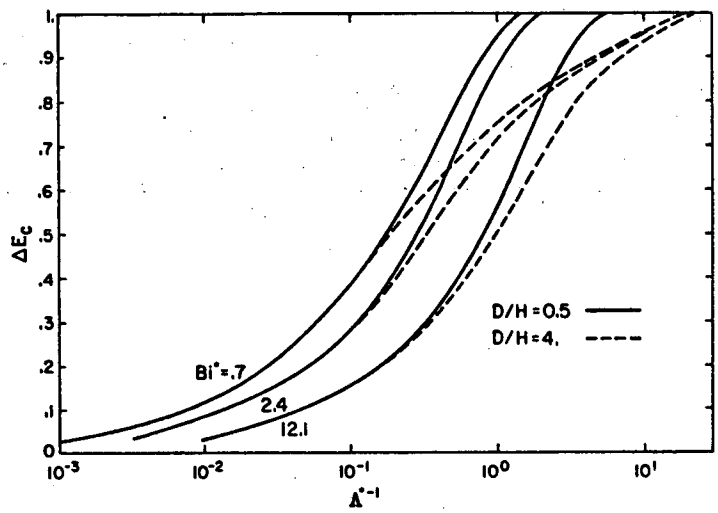


Figure 5. Vertical heat loss, ΔE_c, as a function of $\Lambda^{-1}*$, Bi*, and D/H - the ratio of caprock to aquifer thickness. For D/H > 4 the system behaves as though D/H = ∞. [XBL 813-2757A]

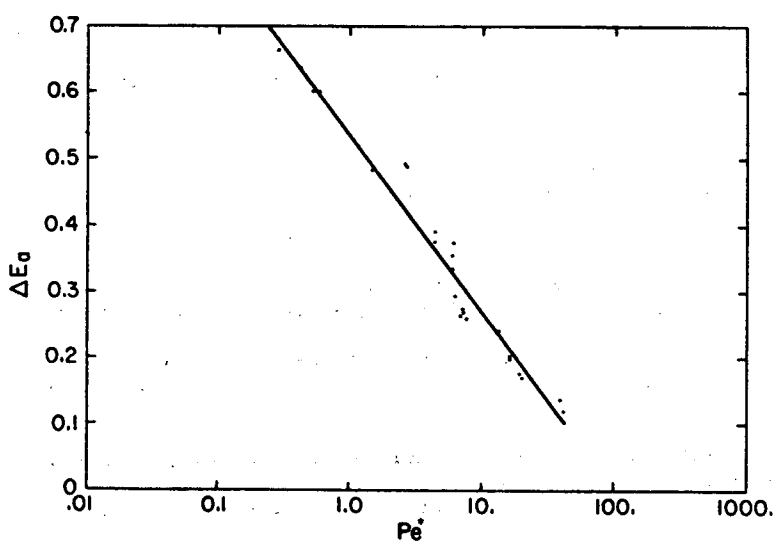


Figure 6. Radial heat loss, ΔE_a, as a function of Pe*. [XBL813-2756]

SIMULATION OF THE MOBILE EXPERIMENTS

While the first cycle of the 1981 series of experiments was being carried out by Auburn University at Mobile, Alabama, LBL performed a numerical simulation based on the field operating conditions to predict the outcome of the experiment before its conclusion. The goal was to test our understanding of the aquifer storage problem and to verify our numerical model CCC.

Details of the Mobile experiment are described elsewhere in this volume. The basic idea is that water at approximately 55 to 60°C is injected over a period of one month into an aquifer approximately 21 m thick and with a permeability of about 63 darcys. It is then stored for one month and subsequently produced. The injected water is obtained from a supply well perforated in the same aquifer 240 m away from the injection/production well. LBL was provided with the basic geological, well test, injection flowrate, and injection temperature data.

The simulation method was similar to that used by LBL to model the 1979-1980 Auburn experiment [15]. The well test data and geological information were studied and analyzed to obtain reservoir parameters and their range of uncertainty. Our results generally confirmed the analyses done by Auburn University. The parameters used in our numerical simulation are listed in Table 2. Since the supply well is 240 m from the injection/storage well and the thermal radius is only about 25 m, it was decided that a radial calculation mesh would be adequate. Based on the injection flowrates and temperatures provided, we employed the numerical model CCC to calculate production temperature and energy recovery factor for a given production flow rate schedule. The result is presented as curve A in Figure 7, where the experimental result is also plotted. The experimental results were made known to us after we completed and presented our results. The predicted energy recovery factor is 0.62 compared to the experimental value of 0.56. This agreement is satisfactory.

Table 2. Parameters used in numerical simulation.

Thermal conductivity:	Aquifer	2.29 J/m.s.°C
	Aquitard	2.56 J/m.s.°C
Heat capacity of rock		1.81×10^6 J/m^3.°C
Aquifer horizontal permeability		63 darcys
Aquifer vertical to horizontal permeability ratio		1:7
Aquitard to aquifer permeability ratio		10^{-5}
Porosity:	Aquifer	0.25
	Aquitard	0.35
Storativity:	Aquifer	6×10^{-4}
	Aquitard	9×10^{-2}

Subsequent to comparing our predictions with the experimental results, we made a series of parameter sensitivity studies. Several sets of calculations were made, including:

(1) Mesh variation. Results are found to be nearly mesh-independent.

(2) An arbitrary increase of aquifer permeability from 63 darcys to 94 darcys. The calculated recovery factor is reduced from 0.62 to 0.55. The production temperature is shown as curve B in Figure 7.

(3) Two-layered-permeability aquifer, in which the upper layer is two times as permeable as the lower but with an average of 63 darcys corresponding to the field value. The recovery factor is calculated to be 0.60.

(4) Three-layered-permeability aquifer, in which the middle layer is two times as permeable as the upper and lower layers while keeping the average at the field value of 63 darcys. The recovery factor is calculated to be 0.62; production temperature is displayed as curve C in Figure 7.

(5) Simulation of a large thermal dispersion effect. We followed Sauty [16] who approximated this effect by using an effective thermal conductivity value. A value ten times the normal value was used. Based on an approximate relationship developed by Doughty et al. [9], this corresponds to a dispersion length of 3 m. The energy recovery factor is calculated to be 0.57; production temperature is shown as curve D in Figure 7.

Several additional parameter-sensitivity calculations were made. It was found that although the recovery factor can be made to reproduce the experimental data, the time rate of decrease of calculated production temperature for many alternative cases is always faster than the experimental value. After these studies, we came to the preliminary conclusion that this production-temperature discrepancy may be due to either thermal dispersion or aquifer heterogeneity. Efforts have been initiated to study both processes. Understanding the cause of this discrepancy is important for further prediction calculations. Although the comparison of experiment and calculation may be considered satisfactory, we want to be sure that the discrepancy will not increase with changes in storage temperature or other conditions.

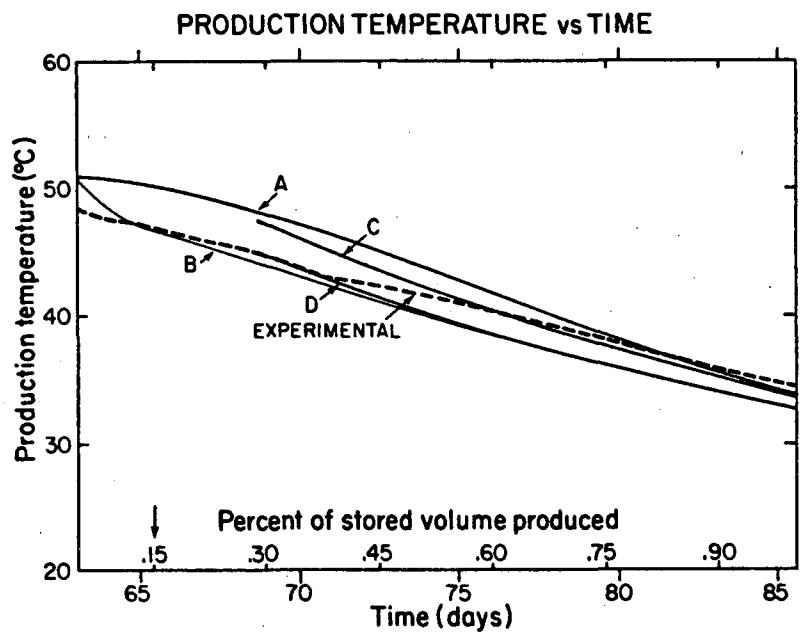


Figure 7. 1981 Mobile Experiment first cycle production temperature as a function of time. Curve A shows the basic numerical simulation result, while curves B, C, and D show parameter study results described in the text. [XBL 817-3266]

SUMMARY AND CONCLUSIONS

Considerable progress has been made in site characterization for optimization. In sites where buoyancy flow may be neglected, dimensionless parameter groups have been derived and type curves have been plotted to quickly obtain energy recovery factors and production temperatures for different conditions. In sites where buoyancy flow cannot be neglected, a semi-empirical method has been developed which reproduces the results of a realistic numerical model (CCC) over a wide range of parameters.

Much progress has also been made in predicting the results of field experiments by Auburn University at Mobile, Alabama. Calculations were able to predict, to within about 5%, the experimental value of the energy recovery factor and the production temperature. Studies of these results disclosed a discrepancy between calculated and observed rate of decrease of production temperatures which may be due to thermal dispersion or aquifer heterogeneity. Work has been initiated to study these, since an understanding of the discrepancy is important in ensuring a satisfactory prediction for further field cases.

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