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NUMERICAL ANALYSIS OF THE MOBILE, ALABAMA AQUIFER TEST FACILITY

C.F. Tsang and C. Doughty

August 1983

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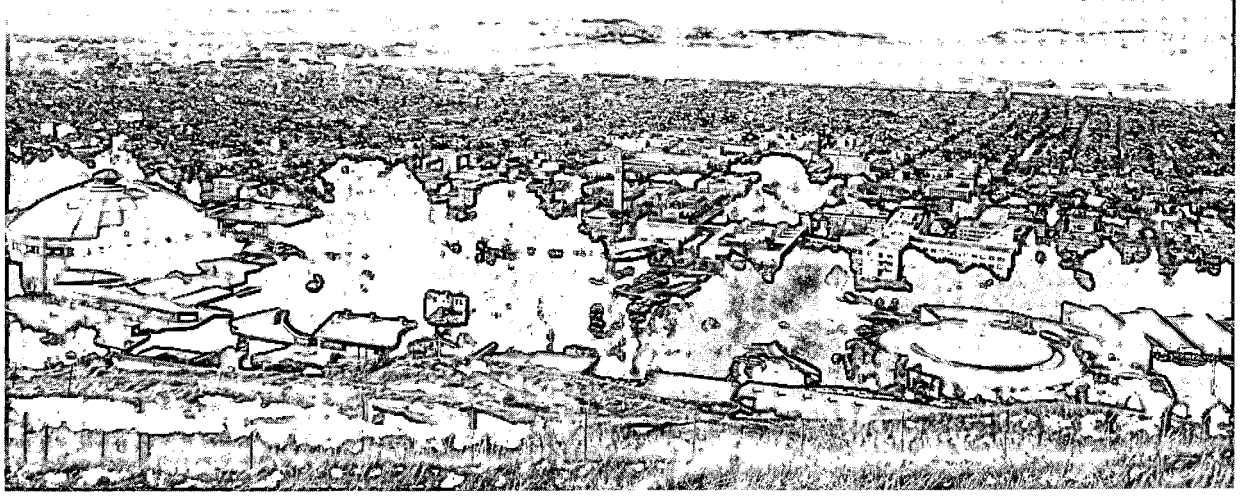

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Numerical Analysis of the Mobile, Alabama Aquifer Test Facility

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Numerical Analysis of the Mobile, Alabama Aquifer Test Facility

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Introduction

For the past several years, Lawrence Berkeley Laboratory (LBL) has been doing numerical modeling studies using the numerical simulator PT, developed at LBL, to simulate and study the ATES field experiments conducted by Auburn University at a site near Mobile, Alabama (Tsang et al., 1981, Buscheck et al.,1983). Last year's report (Tsang et al., 1982) described the prediction of the outcome of each of the first two cycles of the most recent Mobile experiment before its conclusion, as well as a series of design studies for the third cycle. An important result of the first-cycle prediction was the discovery of the heterogeneous nature of the aquifer. An axisymmetric three-layer aquifer model was developed and used for the calculations. Table 1 summarizes the results of these studies.

For the current year, the main task for LBL has been to perform (1) detailed comparisons between first- and second-cycle experimental and calculated temperature distributions, (2) a parameter study to examine the relative magnitudes and dependences of layering effects and buoyancy flow, and (3) the simulation of the third-cycle experiment.

Comparison of First- and Second-Cycle Experimental and Calculated Temperature Distributions

Subsequent to the prediction of the outcome of each of the first and second cycles, the experimental data was released to us. These temperature data were obtained with thermisters located at six depths in each of twelve observation wells. The observation wells were distributed along four lines extending north, south, east, and west from the central injection/production well, at distances of 15, 30, and 45 m from the center.

A variety of comparisons between experimental and calculated temperatures were made. These are described below.

1. T versus r. Temperature versus radial distance profiles are plotted for several depths at various times during the experiment. These plots show the shape of the thermal front as it evolves and allow a comparison between experimental data from different directions. However, because experimental data from only three r values is available,the experimental curves cannot be drawn with certainty, thus providing only limited comparison with calculated results. Figure 1 shows a T versus r plot at the end of the first-cycle injection period for three depths. The variability of the experimental data with direction from the injection/production well is apparent, but the axisymmetric calculated temperature matches the mean experimental data well.

2. T(r,z). Temperature contours in vertical sections of the aquifer are drawn at various times during the experiments. These plots provide an overall picture of the evolution of the shape of the thermal region, thus indicating what the dominant forces in the aquifer are. As for the

Table 1. LBL numerical modeling of recent ATES field experiments at the Mobile site reported last year.

	Cycle Duration* (days)	Injection Volume (m^3)	Injection Temperature (°C)	Energy Recovery Factor Experimental	Energy Recovery Factor Calculated
First Cycle	33-30-26	25,000	59	0.55	0.58
Second Cycle	130-34-54	58,000	82	0.45	0.42
Third Cycle Design Studies	30-30-30	18,300	82	--	.40-.52
	60-0-30	36,600	82	--	.61-.66

*Each cycle is made up of injection, storage, and production periods. The duration of each period is given in days.

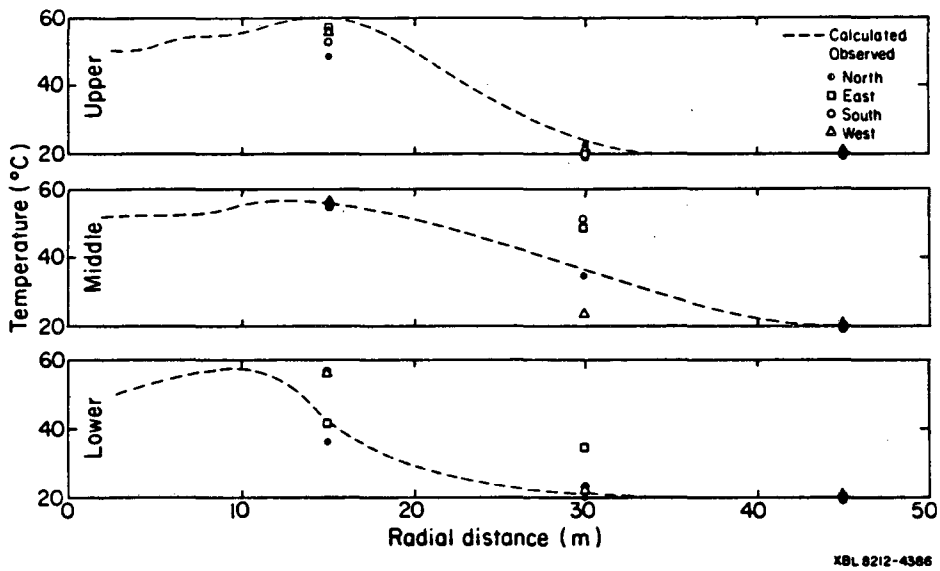

Figure 1. Temperature versus radial distance at the end of the first-cycle injection period.

T versus r plots, the small number of observation wells in each direction makes drawing contours uncertain. In addition, a quantitative comparison between experimental and calculated contour plots is difficult due to the complexity of the plots. Figure 2 shows contour plots of temperature distributions at the end of the first-cycle injection period. The experimental data, shown for north-south and east-west vertical sections of the aquifer, indicates that in most of the aquifer there is a preferential flow into the middle of the aquifer. The axisymmetric calculated temperature distributions for a homogeneous, one-layer aquifer and for a three-layer aquifer in which the middle layer is 2.5 times as permeable as the upper and lower layers indicate that the three-layer model matches the experimental data better. This is type of comparison used to formulate the three-layer aquifer model.

3. T versus t. Temperature versus time is plotted for a given radial distance at several depths. As opposed to the T versus r plots, T versus t plots allow a detailed comparison between experimental and calculated results because there are many experimental data points available. Variation between experimental data from different directions can also be examined. Figure 3 shows a T versus t plot for a radial distance of 15 m at three depths for the first cycle. Again some variation between temperatures measured at wells located in different directions from the injection/production well is seen. The calculated temperatures agree reasonably with the experimental data in the middle and lower aquifer layers, but slightly overpredict it in the upper layer.

4. T(z,t). Temperature contours are plotted as a function of depth and time for a given radial distance. As for conventional T(r,z) contour plots, these provide an overview of forces acting in the aquifer. However, in this case, there is

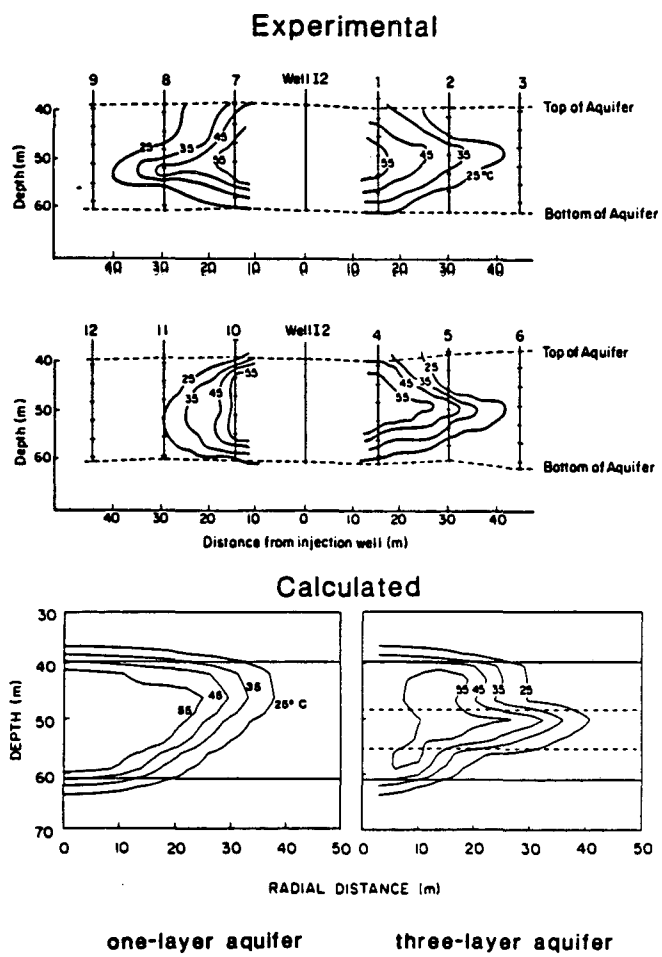

Figure 2. Temperature contour plots, T(r,z), at the end of the first-cycle injection period.

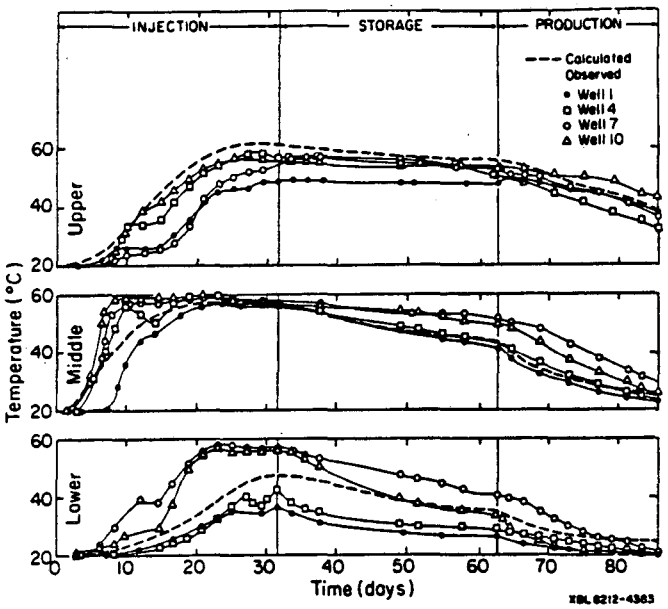

Figure 3. **Temperature versus time during the first cycle at a radial distance of 15 m for three depths in the aquifer.**

much more experimental data to compare, thus allowing more definite conclusions to be drawn. Figure 4 shows T(z,t) plots for three wells located 30 m from the injection/production well for part of the first-cycle injection period, and calculated results using three different axisymmetric three-layer aquifer models in which the permeability of the middle layer layer varies from 2 to 3 times that of the upper and lower layers. By comparing the experimental and calculated results it is apparent that the relative permeabilities of the layers vary throughout the aquifer, and that 2.5:1 matches the average experimental data best.

Parameter Study to Examine Layering Effects and Buoyancy Flow

The aquifer layering and the large buoyancy flow present in this experiment are important considerations in the understanding of hot water flow in an aquifer. The following comparison of calculated first-and second-cycle recovery factors illustrates the relative importance and dependencies of these effects. A simplified graphical technique (Doughty et al., 1982) that does not include buoyancy flow or layering predicts similar values for first- and second-cycle recovery factors, assuming a production

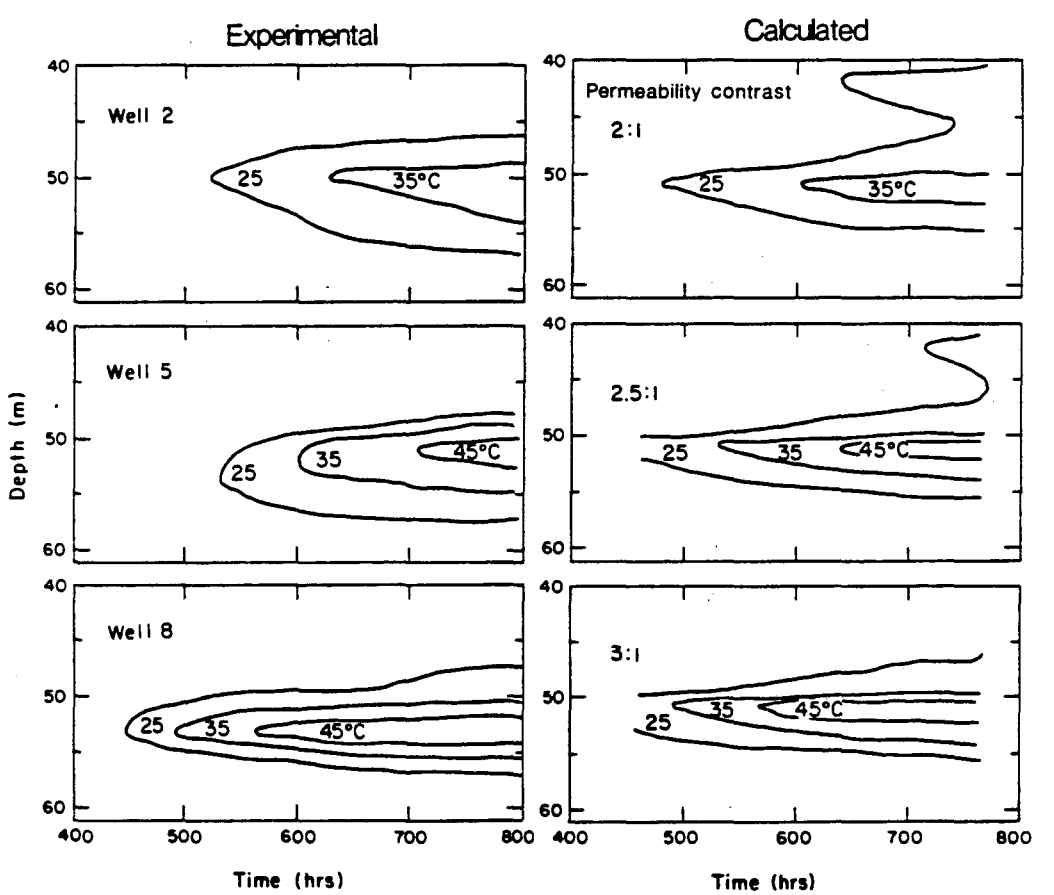

Figure 4. **Temperature contour plots T(z,t), at a radial distance of 30 m during the first-cycle injection period. The permeability contrast measures the ratio of permeability in the middle aquifer layer to that in the upper and lower layers of the numerical model.**

Table 2. Comparison of layering and buoyancy effects on calculated recovery factor.

	One-layer Aquifer	Three-Layer Aquifer	Difference
First Cycle Low Injection Temperature Little Buoyancy Flow	0.61	0.58	5%
Second Cycle High Injection Temperature Much Buoyancy Flow	0.41	0.40	3%
Difference	39%	38%	

well open to the entire aquifer thickness is used for both cycles. To study the addition of buoyancy and layering, various calculations using the numerical model PT are examined. Table 2 summarizes the recovery factors calculated by PT for case assuming either a homogeneous or layered aquifer and either little or substantial buoyancy flow. By reading across the table, we see that the effect of layering on recovery factor is small. Furthermore it is quite similar for the two cycles, thus is temperature-independent. By reading down the table, we see that the increased injection temperature of the second cycle, which increases buoyancy flow, greatly decreases the recovery factor. The decrease is independent of layering in this case, when the average transmissivity of the three-layer aquifer is the same as that of the one-layer aquifer. Although buoyancy flow is very sensitive to overall permeability values, the present results indicate that the detailed spatial distribution of permeabilities does not have a major influence on buoyancy flow for this particular system.

The successful prediction of the first and second cycles, with different injection temperatures, thus different relative magnitudes of layering and buoyancy effects, demonstrates that we have properly accounted for both effects in our calculations.

Third-Cycle Simulation

A preliminary calculation based on the third cycle has been done using the axisymmetric three-layer aquifer model developed during the first-cycle simulation. The material properties and geometry of the numerical model are given in Table 3.

Table 3. Parameters used in the third-cycle calculation.

Formation Thickness	Aquifer	21 m
	Aquitard	9 m
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
Density of rock		2600 kg/m^3
Aquifer Horizontal Permeability		
Upper layer	9.6 m thick	0.46×10^{-10} m^2 (46 darcies)
Middle layer	5 m thick	1.16×10^{-10} m^2 (116 darcies)
Lower layer	6.6 m thick	0.46×10^{-10} m^2 (46 darcies)
Average value		0.63×10^{-10} m^2 (63 darcies)
Overall 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}

During the third cycle, 56,700 m^3 of water at an average temperature of 80°C was injected over a period of three months, stored for two months, then produced over a period of two months. The injection/production well open interval was the upper 45% of the aquifer thickness. During the production period a rejection well located just 2 m from the injection/production well, but open over the lower 45% of the aquifer thickness, withdrew and discarded cool water from the lower region of the aquifer at an average flow rate of about 20% of the production flow rate. This rejection well was designed to improve the energy recovery factor by discouraging mixing of cool water from the lower region of the aquifer with warm water being produced from the upper region of the aquifer.

The calculated energy recovery factor of 0.44 agrees very well with the experimental value of 0.42. The experimental and calculated production and rejection temperatures versus time are shown in Figure 5. The calculated production temperature variation shows a pattern typical of recent numerical simulations of experiments at the Mobile site--initial overprediction of the experimental production temperature, followed by a more rapid decline than is found experimentally, leading to a final underprediction. The calculated rejection temperature consistently underpredicts the experimental value by about 5°C. The production temperature provides an integrated picture of the thermal behavior in the upper region of the aquifer while the rejection temperature provides similar information on the lower region. This allows a more stringent test of the numerical model than has been made in previous studies.

While the overall agreement between calculated and experimental temperature distributions in the aquifer at various times throughout the cycle is good, it is apparent that the numerical model is overpredicting buoyancy flow somewhat. This is consistent with the underprediction of rejection temperature seen in Figure 5.

Overall, the simulation of the third cycle shows adequate agreement with the experimental results, but further studies to match both the production and rejection temperatures more closely may lend new insight into the physical processes occurring in this system.

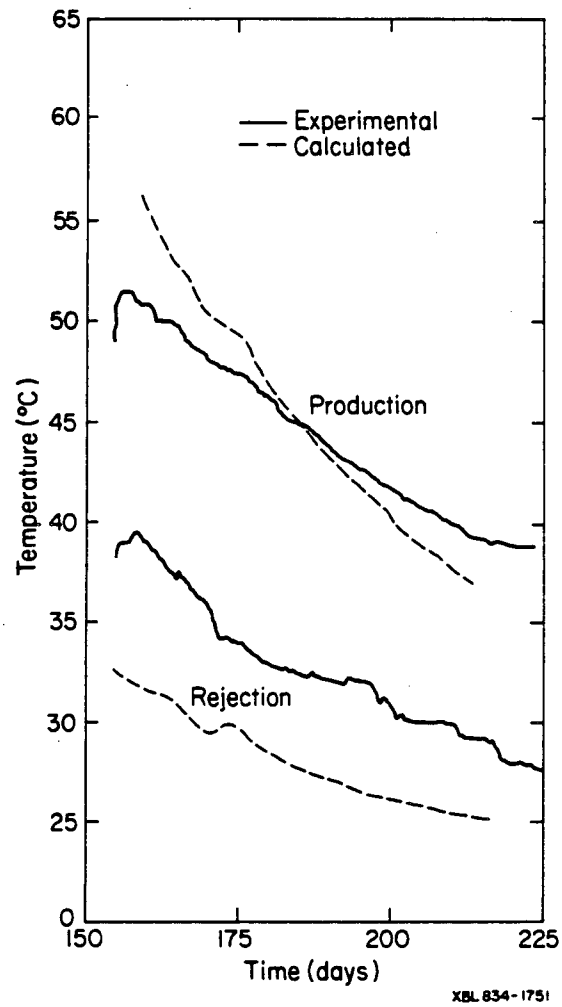

Figure 5. Production and rejection temperatures versus time for the third cycle.

Conclusions

Within the past year substantial work has been done on numerical studies of the Mobile field experiments. The detailed comparison of experimental and calculated temperature distributions has provided insight into the major processes occurring in the aquifer. In general the numerical model does an excellent job of matching the experimental data, but there is some evidence for an overprediction of buoyancy flow. The parameter study on layering and buoyancy has yielded valuable information on the relative importance and interaction of these factors. The third cycle simulation, while yielding a satisfactory match to the experimental results, has provided a stringent test of the numerical model, and indicated further model refinement may be possible.

Acknowledgement

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