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Aquifer Thermal Energy Storage: An Attempt to Counter Free Thermal Convection

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In previous Aquifer Thermal Energy Storage (ATES) experiments, appreciable free thermal convection was observed. In an attempt to counter the detrimental effects of convection, a dual recovery well system was constructed at the Mobile site and a third injection-storage-recovery cycle performed. Using a partially penetrating well, cycle 3-3 injection began on April 7, 1982. A total of 56,680 m^3 of 79°C water were injected. After 57 days of storage, production began with a dual recovery well system. Due to the dominating effect of nonhomogeneities, the dual well system did not work particularly well, and a recovery factor of 0.42 was achieved. The degree of aquifer heterogeneity at the location of the present experiments was not apparent during previous experiments at a location only 109 m away, although pumping tests indicated similar values of transmissivity. Therefore aquifers with the same transmissivity can behave quite differently in a thermal sense. Heat conduction to the upper aquitard was a major energy loss mechanism. Water sample analyses indicated that there were no important changes in the chemical constituents during the third set of experiments. There was a 19% increase in total dissolved solids. At the end of injection, the land surface near the injection well had risen 1.39 cm with respect to bench marks located 70 m away.

INTRODUCTION

Beginning in 1975, Auburn University conducted a series of aquifer thermal energy storage (ATES) experiments in a confined aquifer near Mobile, Alabama [*Molz et al.*, 1978, 1979, 1981]. The objectives of these experiments were to demonstrate the technical feasibility of the ATES concept, to identify and resolve inherent operational problems, and to acquire a data base for developing and testing mathematical models. For the most part, these objectives have been met. ATES is technically feasible at the Mobile site, and inherent operational problems that were encountered have been largely resolved [*Molz et al.*, 1983; *Parr et al.*, 1983]. The collected data have served as a partial basis for testing several mathematical models of varying degrees of complexity, and the resulting studies have proved to be illuminating [*Papadopulos and Larson*, 1978; *Tsang et al.*, 1981; *Sauty et al.*, 1982; *Doughty et al.*, 1982; *Sykes et al.*, 1982; *Buscheck et al.*, 1983].

The most recent field experiments (third set) were based on the geometry shown in Figure 1 and consisted of three injection-storage-recovery cycles of 3 months, 7.3 months, and 8 months duration respectively. During cycle 3-1, 25,402 m^3 of water were injected at an average temperature of 58.5°C. After storage and recovery, this was followed by cycle 3-2 injection of 58,063 m^3 at an average temperature of 81°C. Both of these cycles are described in detail by *Molz et al.* [1983] and simulated by *Buscheck et al.* [1983] using a computer model called PT. A summary of all three sets of experiments performed at the Mobile site is presented in Table 1.

During the storage phase of cycle 3-1, it became apparent that a relatively large amount of free thermal convection was occurring in the confined aquifer. Such a phenomenon was not observed to a significant extent during cycles 2-1 and 2-2, which took place in a different storage zone [*Molz et al.*, 1979, 1981; *Sykes et al.*, 1982]. Convection leads to thermal stratification in the storage aquifer (relatively hot on top and cold on the bottom) which causes mixing of hot and cold water during recovery. Thermal losses by conduction into the upper aquitard are maximized also. Both effects act to lower the recovery factor.

At the higher injection temperature (81°C) of cycle 3-2, free thermal convection was more pronounced and the initial recovery temperature was only 55.1°C. By 2 weeks into the production period, water above 45°C had migrated to the top half of the storage aquifer. At this time it was decided to modify the recovery well in an attempt to improve energy recovery. The bottom half of the well was filled with sand and a figure *k* packer was placed above the sand. After this modification was complete, pumping resumed, and ultimately the recovery factor was 0.45. If the modification had not been made, it is estimated that the recovery factor would have been 0.40 [*Molz et al.*, 1983].

After consideration of the free thermal convection problem and its negative effect on recovery temperature, it was concluded that a dual recovery well system might result in improved energy recovery. The two wells would be located as close together as possible, with one well screened in the upper half of the storage aquifer and the other screened in the lower half. Upon initiation of recovery pumping, both wells would be pumped simultaneously. In a thermally stratified and homogeneous storage aquifer this would maintain radial flow approximately, with colder water entering the lower screen and warmer water entering the upper screen. The colder water could then be reinjected or wasted at an appropriate location. The effect of nonhomogeneities, which we know exist at the Mobile site, cannot be predicted in detail but would probably act to reduce the effectiveness of a dual well system.

At the Mobile site, construction of a dual recovery well system was completed on April 1, 1982, and cycle 3-3 injection began on April 7. The two major objectives of this paper are to report the resulting cycle 3-3 data and to discuss the effectiveness of the dual recovery well system. A third

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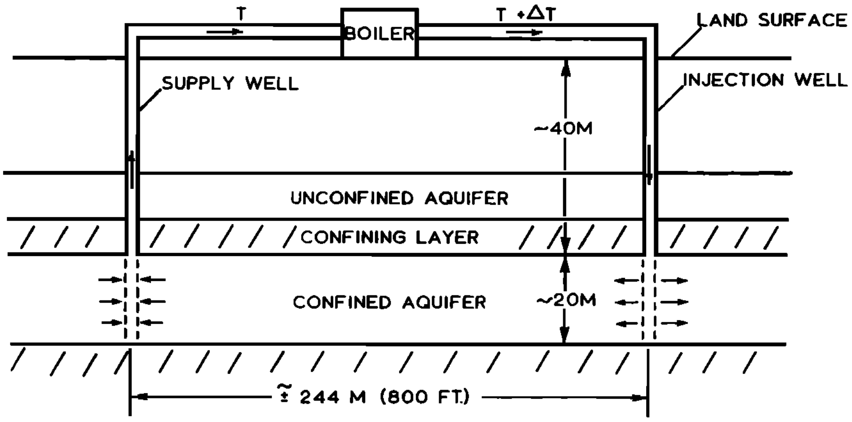

Fig. 1. Diagram of the subsurface geometry and doublet well system at the Mobile field site.

objective is to compare some of the results with those of previous cycles and previous experiments.

DESCRIPTION OF EXPERIMENTS

The project site is located in a soil borrow area at the Barry Steam Plant of the Alabama Power Company, about 32 km north of Mobile, Alabama (see *Molz et al.* [1978, 1983] for details). The storage aquifer is composed of a medium sand of Quaternary age containing interstitial silts and clays [*Molz et al.*, 1978]. In order to conduct cycles 3-1, 3-2, and 3-3, the well field shown in Figure 2 was constructed. For cycle 3-3, well I2 was used for injection of heated water and for production. Groundwater temperatures were only recorded at 6 elevations in wells I2, I1, 4, 5, and 6. There was no tracer injected during cycle 3-3, but heads were recorded in each head observation well. Land elevation changes and groundwater chemistry data were recorded also.

Wells I2 and R1 constitute the dual recovery well system shown schematically in Figure 3. During recovery I2 is called the production well and R1 is called the rejection well. The wells are separated horizontally by 1.8 m, with I2 screened in the top 9.1 m of the storage aquifer. The rejection well screen is 9.1 m in length also and begins 1.5 m below the bottom of the upper screen.

Cycle 3-3 injection began on April 7, 1982 and continued intermittently until July 14, 1982 when a total of 56,680 m^3 of water had been injected. The average injection temperature was 79°C. Shown in Figures 4 and 5 are the cumulative injection volume and the injection temperature as functions of time, respectively. Injection proceeded smoothly except for failure of a fuel pump (large horizontal segment in Figure 4) at about 1000 hours into the experiment. A 52-day storage period ended on September 9, 1982, and production pumping with the dual recovery system began. Plots of cumulative production and rejection volumes versus time are shown in Figures 6 and 7, respectively. Recovery pumping was officially ended on November 16, 1982. At this time 64,140 m^3 of water had been produced and 19,300 m^3 rejected.

At regular intervals during cycle 3-3, careful level measurements were made so that data could continue to be obtained on land surface elevation changes caused by ATES [*Molz et al.*, 1981]. As described in *Molz* [1983], two reference pads, two measurement pads, and one observation pad were constructed of reinforced concrete with surveying markers embedded in the center of each. A level was placed on the observation pad, and from this location relative elevations of the markers on the reference and measurement pads were recorded.

RESULTS AND DISCUSSION OF CYCLE 3-3

The temperature history of the production and rejection wells during recovery pumping is shown in Figure 8. After a few minutes of pumping the production temperature stabilized at 51.5°C, which is well below the average injection temperature of 79°C. It was soon discovered that variations in the rejection pumping rate had very little effect on the production temperature. Evidently, the nonhomogeneity in the storage aquifer was exerting a dominant influence on the velocity distribution. Further evidence for the significant effect of heterogeneous and temperature-dependent hydraulic conductivity in the storage aquifer can be obtained by examining the vertical temperature distribution curve ob-

TABLE 1. Summary of Six Injection-Storage-Recovery Experiments Performed at the Mobile Site Over the Past Seven Years

Cycle	Injection Duration, days	Injection Volume, m^3	Injection Temperature, °C	Storage Duration, days	Recovery Duration, days	Recovery Factor
1–1	17	7,570	37	37	31	0.53
2–1	79	54,800	55	51	41	0.66
2–2	64	58,010	55	63	48	0.68
3–1	33	25,402	58.5	30	26	0.56
3–2	110*	58,063	81	34	54	0.45
3–3	98	56,680	79	57	68	0.42

The recovery duration indicated resulted in recovery volume equaling injection volume.
*27 days of early down time were removed to facilitate comparison.

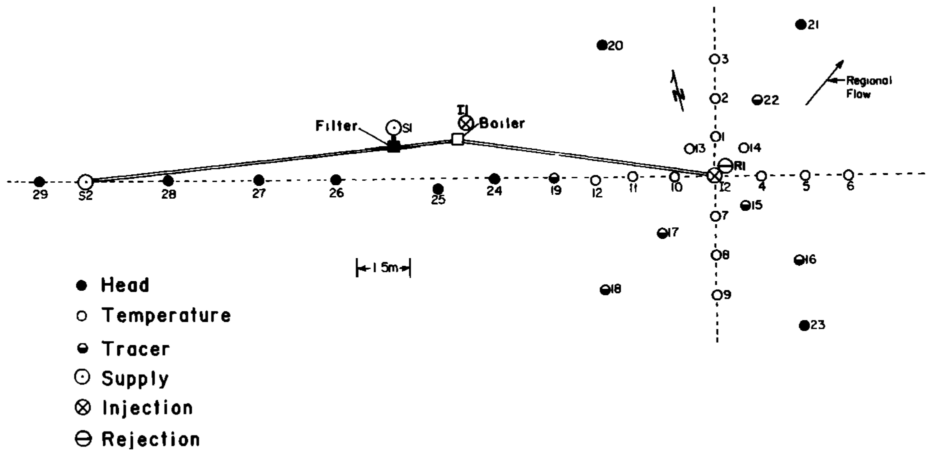

Fig. 2. Plan view of the wellfield at the Mobile site showing the different types of wells.

tained from the 15-m observation well (well 4) and shown in Figure 9. At various times during production the average temperature in the upper 50% to 60% of the aquifer is within a degree or two of the production temperature. However, the average temperature in the bottom half of the aquifer is 10°C to 12°C below the observed rejection temperature. This data implies a preferential flow in the upper half of the aquifer, at least within a 15-m radius of the production well. Such a flow would be induced by the high intrinsic permeability zone somewhere near the center of the aquifer and a temperature-induced permeability increase (kinematic viscosity of water decreases by 50% between 30°C and 70°C) due to hotter water in the upper part of the aquifer, some of which remained after cycle 3-2. The magnitude of a temperature-induced permeability change is comparable to the intrinsic permeability differences selected by *Buscheck et al.* [1983] in their simulations of cycles 3-1 and 3-2.

The previously mentioned relationship between average aquifer temperature, production temperature, and rejection temperature held even when the production pumping rate was five times greater than the rejection rate. Pumping the rejection well at a higher rate relative to the production well resulted in simply raising the rejection temperature with little or no effect on the production temperature. It appears, therefore, that both wells are pulling water from the middle to upper portion of the storage aquifer where a high intrinsic permeability zone exists and where the hottest water resides. Relatively little water is moving horizontally through the bottom third of the aquifer in the vicinity of the rejection well where the intrinsic permeability is lower and the water viscosity is higher due to lower temperatures.

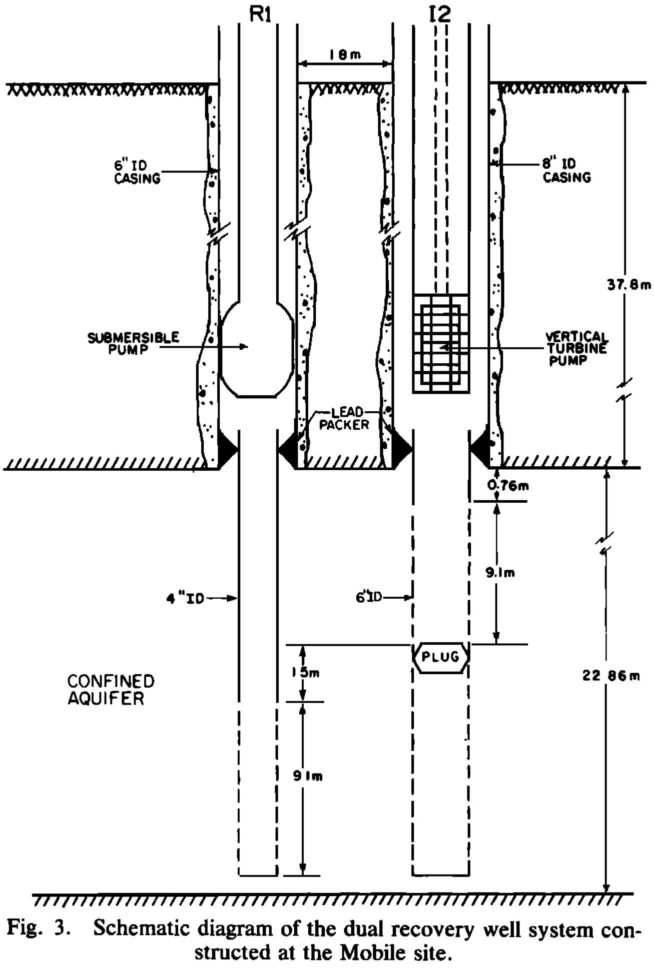

Fig. 3. Schematic diagram of the dual recovery well system constructed at the Mobile site.

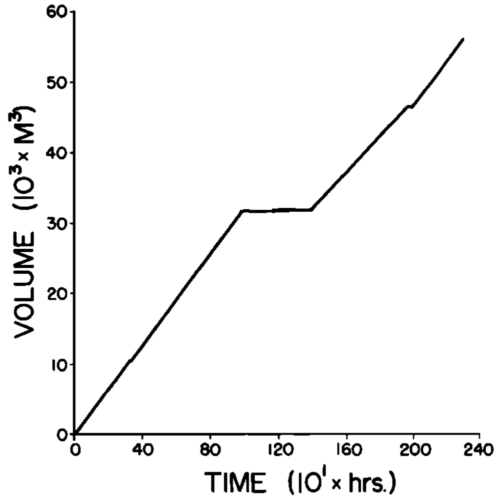

Fig. 4. Cumulative injection volume versus time for cycle 3-3. The large horizontal segment was due to the unexpected failure of the boiler fuel pump.

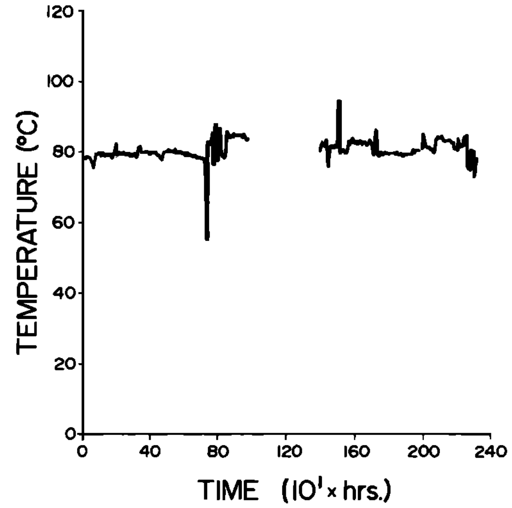

Fig. 5. Injection temperature versus time for cycle 3-3.

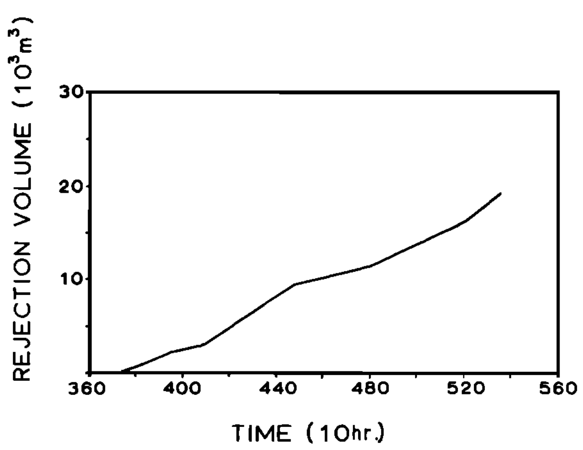

Fig. 7. Cumulative rejection pumping volume as a function of time.

An indication of the geometry of the high intrinsic permeability zone detected at the present storage location may be obtained by examining Figures 10 and 11. Shown in these figures are first arrival times of the thermal front recorded in the temperature observation wells during cycle 3-1. For each aquifer cross section the locations of the two smallest arrival times in each observation well are connected to those of neighboring wells by straight lines. The line segments indicate approximate boundaries of a high permeability zone near the middle of the aquifer. This approximation correlates well with the temperature distributions shown in Figures 13 and 14 of *Molz et al.* [1983]. It supports also the three layer aquifer permeability model used by *Buscheck et al.* [1983] in their computer simulations of cycles 3-1 and 3-2.

It is important to note that the degree of aquifer nonhomogeneity indicated by the present experiments was not observed in experiment set 2 (cycles 2-1 and 2-2) which utilized a zone of the aquifer approximately 109 m from the present storage zone. Examination of Figures 7, 8, and 9 of *Molz et al.* [1979] indicates a relatively symmetric temperature distribution. For comparison an average radial section of the isotherms at the end of cycle 2-1 injection is shown in Figure 12 along with an isothermal plot for a vertical aquifer cross section at the end of cycle 3-1 injection. The central fingering apparent at the new location during cycle 3-1 was not observed during cycle 2-1 at the old location. While still playing an important role, the effects of the nonhomogeneity on the temperature isotherms was not as apparent during cycles 3-2 [*Molz et al.*, 1983] and 3-3 (Figure 13) because the relatively strong buoyancy flow at the higher injection temperatures smears out the obvious effect of the nonhomogeneity [*Buscheck et al.*, 1983].

The inferred differences in storage aquifer hydraulic properties at two locations only 109 m apart have important implications for testing programs whose purpose is to select aquifers suitable for ATES. Often it may not be sufficient to simply measure average horizontal hydraulic conductivity, which is what results (we hope!) from standard pumping tests. It is not easy to detect layering in unconsolidated media without variable screen length pumping tests or tracer

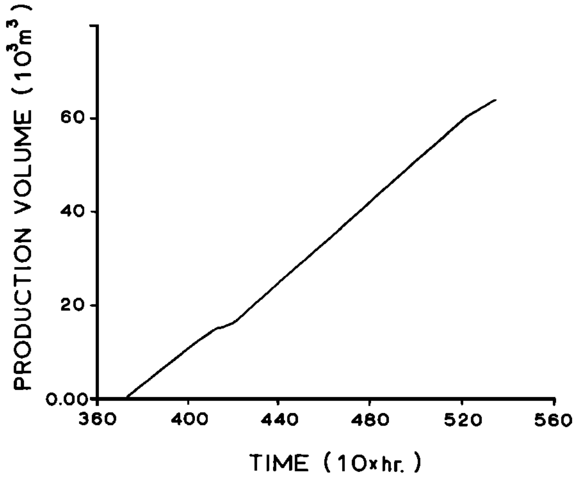

Fig. 6. Cycle 3-3 cumulative production pumping volume as a function of time.

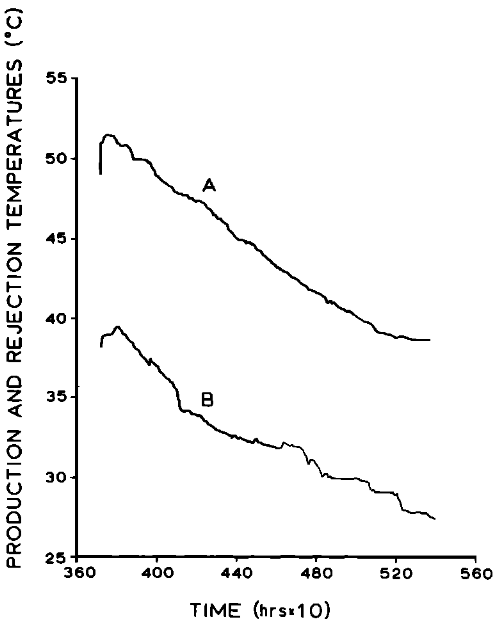

Fig. 8. Production temperature (curve A) and rejection temperature (curve B) versus time for cycle 3-3.

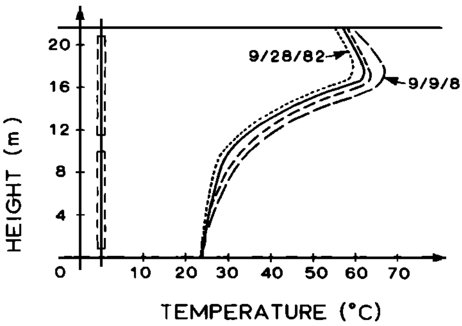

Fig. 9. Vertical temperature profiles at the 15-m observation well during the first 3 weeks of recovery pumping.

tests, and these procedures can be quite tedious. Simulation models are useful but only after good data have been obtained. It may be that moderate-scale hot water injection testing will be an economical procedure for making an overall and final evaluation of an aquifer's suitability for ATES.

Shown in Figure 13 are radial isothermal plots of the aquifer temperature distribution at the end of injection and storage respectively. There is clear visual evidence of free thermal convection during the storage period. Based on a more detailed version of Figure 13 and a simple numerical integration scheme, it is possible to estimate the percentage of stored heat that was lost due to convection and conduction from various zones of the aquifer during the storage period. The result indicated that 45% of the thermal energy stored in a cylinder of aquifer concentric with the injection well and of 15.25-m radius was lost from that zone during storage. An estimate based on average injection temperature and initial production temperature alone would have been 47% [[(79 − 20) − (51.5 − 20)]/(79 − 20)]. This energy loss is quite large and little or nothing can be done during storage to counteract it. Heat losses in similar aquifer volumes of 30.5-m radius and 45.7-m radius were estimated to be 32% and 22%, respectively.

Obviously, free thermal convection occurred during cycle 3-3 just as it did during cycle 3-2. The dual well recovery system was beneficial but not highly effective in counteracting negative convection effects. Shown in Figure 14 are plots of recovery fraction versus cumulative recovery volume with (curve A) and without (curve B) the dual well system. (To get curve B we simply combined the heat flows and pumping volumes from the production and rejection wells as if they were a single well.) With the dual well system operating, we obtained a recovery factor of 0.42. A single production well would have yielded a recovery factor of about 0.40.

Further understanding of the thermo-hydrodynamics at the Mobile site may be obtained by examining the radial isotherm plots at the end of the various recovery periods (defined as time when water volumes pumped in and out are equal) displayed in Figure 15. These plots show the progressive effects of free thermal convection and emphasize the role played by the high intrinsic permeability zone near the center of the aquifer.

At the end of cycle 3-1 recovery, there is a large difference in temperature between the bottom and top of the storage aquifer. For the homogeneous case without buoyancy flow, the hottest water would be located symmetrically along the upper and lower aquitards. Even cycle 3-1 with a 58.5°C injection temperature deviates dramatically from this pattern, with 40°C water located at the very top of the aquifer and 22°C water at the bottom. Cycle 3-2 recovery ended with a production temperature of 39.5°C. At this time the temperature in the upper third of the aquifer varied from 50°C to about 62°C at the top. The temperature near the aquifer bottom was only 2 or 3 degrees above ambient (20°C). Due to the high-permeability zone near the aquifer center, a relatively steep temperature gradient of about 9°C/m is created at the top of the middle third of the storage aquifer. Presumably, this is due to a relatively high discharge of cooler water carrying away heat from the upper third of the aquifer. By the end of cycle 3-3 recovery, the aquifer is almost perfectly stratified thermally within a 45-m radius of the injection well.

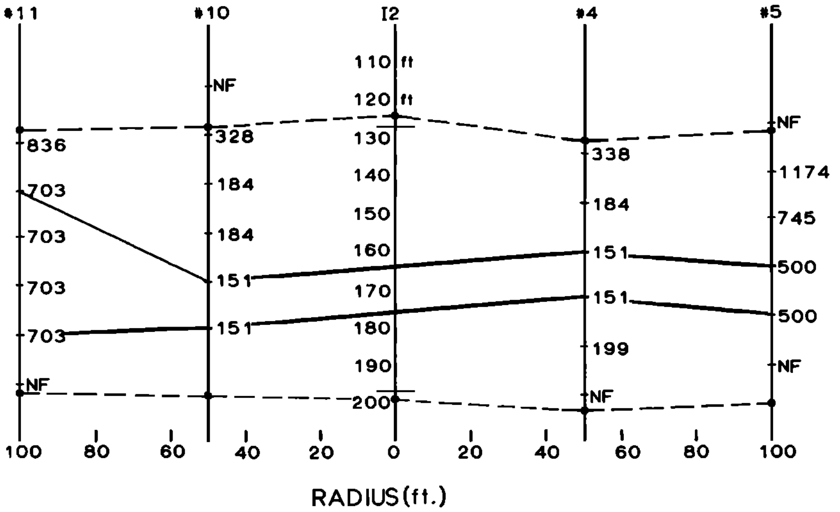

Fig. 10. Scale diagram of a west to east vertical aquifer profile showing first thermal arrival times (in hours) at the various thermistors during cycle 3-1 injection. The early arrival times, mostly near the aquifer center, indicate a high intrinsic permeability zone. The notation 'NF' means that a definite thermal front did not arrive. The dashed lines indicate the upper and lower aquifer boundaries.

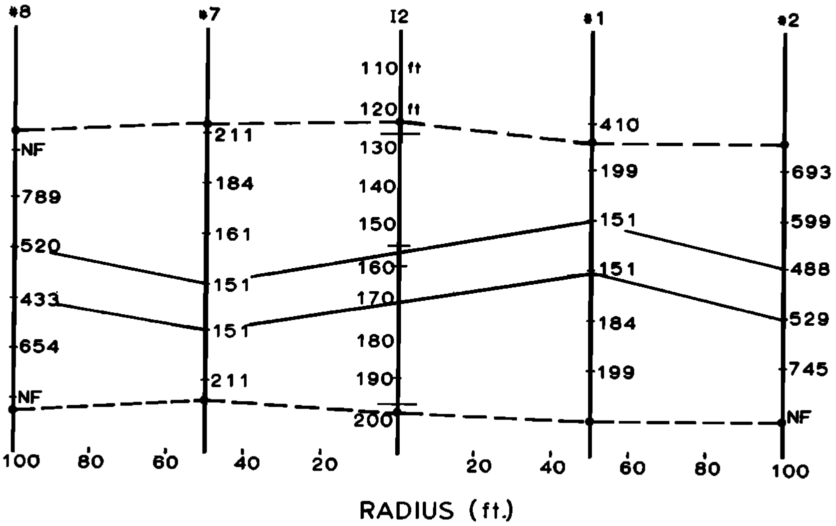

Fig. 11. Scale diagram of a south to north vertical aquifer profile showing first thermal arrival times (in hours) at the various thermistors during cycle 3-1 injection. The early arrival times, mostly near the aquifer center, indicate a high intrinsic permeability zone. The notation NF means that a definite thermal front did not arrive. The dashed lines indicate the upper and lower aquifer boundaries.

The upper portion of the aquifer is cooler compared to cycle 3-2 because of the longer storage period and lower injection temperature. However, the steep temperature gradient zone is still evident.

Based on the temperature distributions shown in Figure 15 and the measured injection and recovery energies, it is possible to develop an energy budget for the third set of experiments. This budget, which is listed in Table 2, reflects the gross energy distribution and heat storage changes throughout the third set of experiments. The most interesting figures relate to heat storage in the aquitards. Probably 95% or more of this energy resides in the upper aquitard, and by the end of cycle 3-3 recovery (i.e., when the production plus rejection volumes were equal to the injection volume) the cumulative heat content increase of the caprock was nearly equal to the total energy injected during the cycle. Due to the interaction of buoyancy flow and nonhomogeneities, heat conduction into the caprock thus emerges as a major energy loss mechanism at the Mobile site.

Use of a partially penetrating injection well during cycle 3-3 did not have a significant effect on the overall aquifer temperature distribution when compared to cycle 3-2, in which a fully penetrating well was employed. Shown in Figure 13 are radial isothermal plots at the end of injection for cycles 3-2 and 3-3. A complete comparison cannot be made because of thermistor failures at higher temperatures during cycle 3-2. [*Molz et al.*, 1983]. However, the 25°C and 35°C isotherms are quite similar, indicating no gross differences within 50 m of the injection well. This observation is also consistent with the proposed high intrinsic permeability

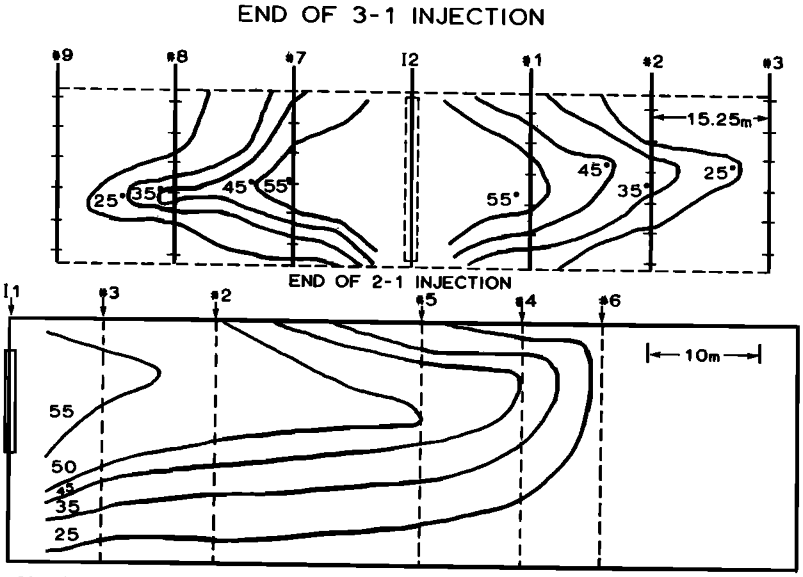

Fig. 12. Plot of isotherms in degrees Celsius on a vertical aquifer cross section at the end of injection for cycles 2-1 and 3-1, respectively. Isotherm 'fingering' during cycle 3-1 injection suggests the existence of a high permeability zone. Little fingering was observed during cycle 2-1 which was conducted at a different location in the same aquifer.

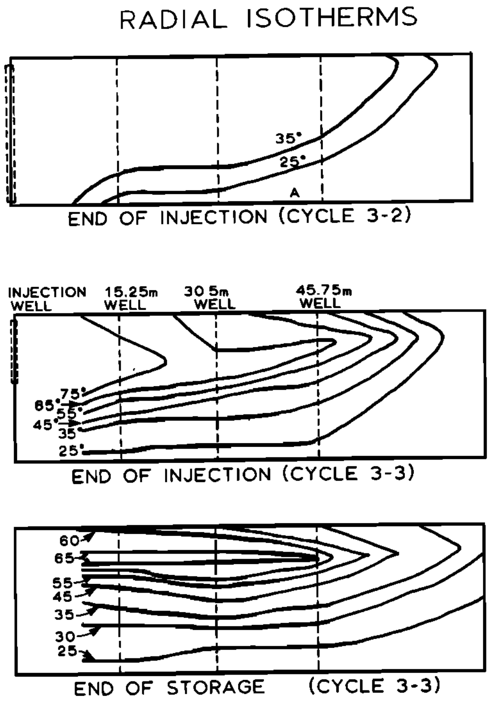

Fig. 13. Plot of isotherms in degrees Celsius on a vertical aquifer cross section at the end of injection for cycles 3-2 and 3-3. A similar plot is given for the end of cycle 3-3 storage.

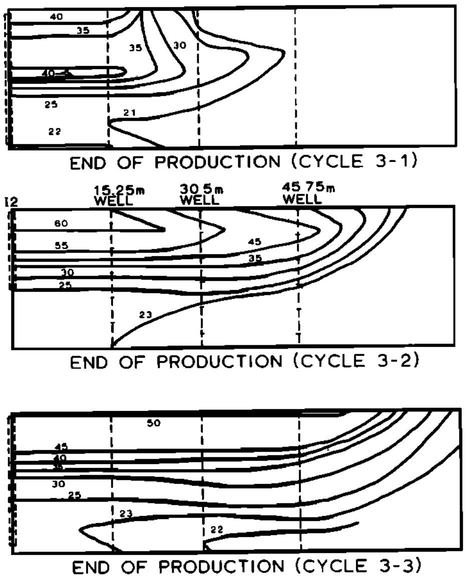

Fig. 15. Plot of isotherms in degrees Celsius on a vertical aquifer cross section at the end of production for cycles 3-1, 3-2, and 3-3, respectively. Numerical integration of these figures enabled us to estimate the quantity of injected energy remaining in the aquifer at the end of the various production periods.

zone. Flow from both the partially and fully penetrating injection wells would tend to follow the high permeability nonhomogeneity.

At the end of cycle 3-3 injection, it was decided to perform additional water chemistry analyses to determine if the flushing of heated water through the storage aquifer had caused changes in the concentrations of various dissolved materials. Accordingly, samples were taken on July 12, 1982 from wells S2 and 22. The water obtained from well 22 was at a temperature of 62°C and had been flushed through the storage zone during cycle 3-2 and 3-3. That obtained from S2 was closer to a sample of the native groundwater but still subject to some flushing. Analyses of both samples along with previous measurements utilizing native groundwater are displayed in Table 3. This data supports the conclusion that there were no major changes in the chemical constituents of the groundwater during the third set of experiments.

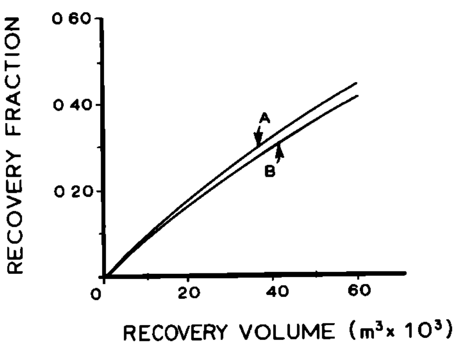

Fig. 14. Cycle 3-3 energy recovery fraction as a function of recovery volume. Curve A represents the dual recovery well system, and curve B is the predicted result for a single equivalent well.

The best overall measure of change is probably the total dissolved solids (TDS), and the data in Table 2 indicate a trend from 274 to 284 to 299 mg/l. Throughout most of the experiment, TDS at the injection/production well was measured on a weekly basis. During cycle 3-1 the TDS averaged 280 mg/l. This average held for 3-2 injection, but during production the average TDS increased to 320 mg/l. During cycle 3-3 injection the average increased again to 333 mg/l. Most likely this increase was due to minor dissolution of the aquifer matrix by the hotter water during cycles 3-2 and 3-3. Also, by cycle 3-2 recovery the hot water had been in contact with the aquifer matrix for an extended period of time.

Land surface elevation measurements were performed during the later part of cycle 3-3, and the results are shown in Figure 16. At the end of injection, the relative elevation increase peaked at 1.39 cm and then began a steady fall during storage and recovery. The maximum elevation gradient between pads A and B occurred at the end of cycle 3-2 injection and was 0.00023. The maximum average gradient between pad A and the reference pads were 0.0002 at the end of cycle 3-3 injection. Such elevation changes are not negligible, and their potential effect on foundations would have to be considered, especially if an ATES system were being designed for an urban environment. Depending on local stratigraphy, injection temperature (assumed <100°C) and injection volume, elevation changes 2 or 3 times greater than those observed at the Mobile site seem possible.

Summary and Conclusions

This paper deals primarily with the third injection-storage-recovery cycle of the third set of aquifer storage experiments (cycle 3-3) to be conducted by Auburn University at the Mobile, Alabama field test facility. Using a partially penetrating well, cycle 3-3 injection began on April 7, 1982. By 98 days later a total of 56,680 m^3 of water at an average

TABLE 2. Summary of the Energy Budget for the Third Set of Experiments

Cycle	Energy Injected, J	Energy Recovered, J	Cumulative Energy Left, J		Energy Added, J	
			Aquifer	Aquitards	Aquifer	Aquitards
3–1	4.02×10^{12}	2.25×10^{12}	8.77×10^{11}	8.93×10^{11}	8.77×10^{11}	8.93×10^{11}
3–2	1.44×10^{13}	6.48×10^{12}	3.90×10^{12}	5.79×10^{12}	3.02×10^{12}	4.90×10^{12}
3–3	1.38×10^{13}	5.51×10^{12}	5.78×10^{12}	1.22×10^{13}	1.88×10^{12}	6.41×10^{12}

The cumulative energy left behind in the aquifer was calculated by numerical integration of the temperature distributions shown in Figure 15.

temperature of 79°C had been injected. After a 57-day storage period, production began with a dual recovery well system. The objective was to pull the hotter water in the upper portion of the storage aquifer into the production well and the colder water in the bottom portion into the rejection well. By varying the pumping rates of the two wells, it was hoped that a near-optimum energy recovery from a thermally stratified aquifer could be achieved.

Shortly after production began, it became obvious that the dual recovery well system was not going to work as well as had been intended. The inadequate control was due to the following interacting effects.

1. During injection, much of the flow occurred near the center of the aquifer which caused significant lateral spreading of the injected volume.
2. During storage, thermal convection in and above the high permeability zone was dramatic, causing increased lateral spreading of the heat.
3. Hot water in the top of the aquifer having spread over a large area, allowed for maximum conductive heat loss to the upper confining layer.
4. The selective recovery system, although it is estimated to have increased the recovery factor from 0.40 to 0.42, did not have a dramatic effect because the aquifer anisotropy and nonhomogeneity controlled the velocity distribution to a significant extent.

Because of the above phenomena, the initial production temperature was 51.5°C, well below the average injection temperature of 79°C. During storage, approximately 45% of the thermal energy stored in a cylinder of aquifer of 15.25 m radius was lost.

The degree of aquifer nonhomogeneity inferred at the location of the present experiments was not apparent during previous experiments at a location only 109 m away. Therefore aquifers with the same transmissivity can behave quite differently in a thermal energy storage sense. Vertical variations of horizontal hydraulic conductivity are difficult to detect, and moderate-scale hot water injection testing along with computer simulation may be an economical procedure for making an overall and final evaluation of an aquifer's suitability for ATES.

Chemical analyses of water samples over the course of the Mobile experiments indicated that there were no important changes in the chemical constituents during the third set of experiments. However, due to the flushing of heated water through the system the total dissolved solids content increased from 280 mg/l to 333 mg/l.

At the end of 3-3 injection the land surface near the injection well had risen 1.39 cm with respect to bench marks located 70 m away. The average elevation gradient was 0.0002. Depending on local stratigraphy, injection temperature (assumed <100°C), and injection volume, elevation changes 2 or 3 times greater than those observed at the Mobile site seem possible.

It is safe to say that the various experiments at the Mobile site have demonstrated the technical feasibility of low-

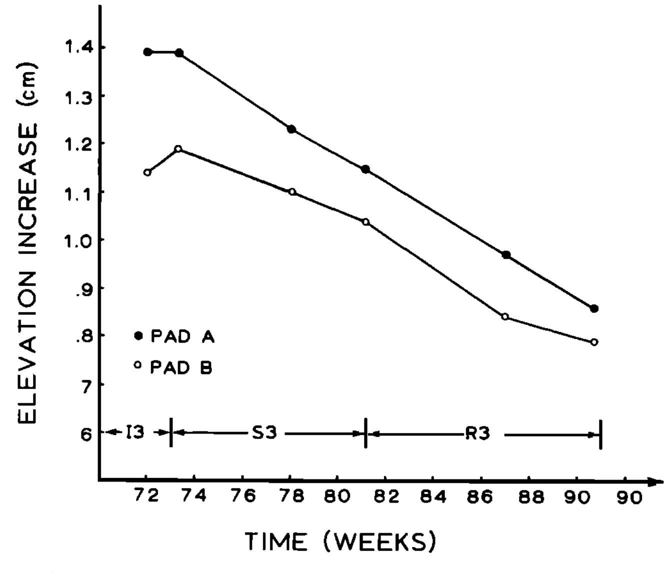

Fig. 16. Increase in land surface elevation near the injection well as a function of time. The elevation was measured relative to a benchmark approximately 70 m away.

TABLE 3. Results of Chemical Analyses Made at Various Times During the ATES Experiments at the Mobile Site

Parameter	Well S-2, July 12, 1982	Well 22, July 12, 1982	Well I-1, June 20, 1978
pH	7.38	7.38	7.38
Dissolved solids, mg/l	284	299	274
Ca^{2+}, mg/l	4	4	2
Mg^{2+}, mg/l	0	0	
Alkalinity, mg/l as $CaCO_3$	170	191	176
Hardness, mg/l as $CaCO_3$	9.6	11.6	
Na^+, mg/l	85 *	85 *	9.4
NH_4^+ N, mg/l	0.2	0.7	
NO_3^- N, mg/l	0.5	0.6	
Fe^{3+}, mg/l	<0.1	<0.1	<0.1
Mn^{2+}, mg/l	<0.05	<0.05	
SO_4^{2-}, mg/l	<1.0	<1.0	
K^+, mg/l	0.6	1.2	
COD, mg/l	12	8	
Cl^-, mg/l	21	18	
Zn^{2+}, mg/l	<0.1	<0.1	
Cu^+, mg/l	<0.1	<0.1	
Si, mg/l	5	8	10
Br, mg/l	10 *	9.5*	<0.4

*Elevated levels due to NaBr tracer injection during cycles 3-1 and 3-2.

temperature ATES but not necessarily the economic feasibility. However, several applications of ATES technology currently underway in Canada, Denmark, Sweden, and other locations in Europe will soon contribute to resolution of the economic question. Some of the more interesting approaches involve the use of heat pump systems to extract heat from warm aquifer water and produce a useful temperature for space heating, water heating, and other applications.

With the combined aid of field tests and computer modeling techniques that have been perfected over the past decade, it is now relatively straightforward to develop the initial design of an ATES system. However, the useful lifetime and long-term maintenance costs are more difficult to define. The most subtle problems are chemical in nature. They result mainly from mixing waters having different temperature and chemical properties (*p*H, ion concentration, etc.) during the injection process. This will occur to some degree even when the supply and injection wells are located in the same aquifer. Deleterious geochemical and/or colloid chemical effects can be immediate and dramatic, seriously imparing injection within a few days, or they can be of a very gradual, long-term nature. For obvious reasons, the latter situation has received the least amount of study.

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