

SEASONAL THERMAL ENERGY STORAGE IN AQUIFERS - MATHEMATICAL
MODELING STUDIES IN 1979

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PROJECT OUTLINE

Project Title: Mathematical Modeling of Thermal Energy Storage in
Aquifers and Support for Seasonal Thermal Energy Storage
Projects

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Project Goals: Develop methods for evaluating hydrodynamic and thermal
factors for aquifer thermal energy storage (ATES).
Disseminate information on aquifer thermal energy storage
and provide technical support for the Seasonal Thermal
Energy Storage (STES) Program.

Develop numerical models to simulate water and heat flow
in geologic media, and use these models to predict and
evaluate performance of aquifer thermal energy storage
tests. Compile, publish, and distribute a bimonthly ATES
Newsletter.

Project Status: A numerical model was developed, verified, and tested to
simulate and predict ATES performance.

Issuance of the ATES Newsletter, initiated in FY-1978,
continued in FY-1979.

Modeling of the Auburn field test was completed with
evaluation of the first and second heat
injection/recovery cycles.

Work planned for FY-1980 includes continuation of the
ATES Newsletter, modeling of the Texas A&M University
1978-1979 field experiment, completion of ATES generic
sensitivity and parametric studies, and STES technical
support as required.

Contract Number: W7405-ENG26

Contract Period:

Funding Level: \$96,700 (FY 1979)

Funding Source: Energy Storage Systems Division
U.S. Department of Energy

Seasonal Thermal Energy Storage in Aquifers -
Mathematical Modeling Studies in 1979

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Introduction

Lawrence Berkeley Laboratory (LBL) first began working on seasonal thermal energy storage in aquifers in 1976. Initial studies have included comprehensive generic calculations based on a numerical model to calculate the coupled heat and fluid flows in a three-dimensional, complex-geometry aquifer system. Various situations have been considered, including hot or cold water storage, storage for different periods of time, inhomogeneity of the storage aquifer, the presence of barriers, regional flow, and the situation of a storage well partially or fully penetrating the aquifer. Many of the results have been published in a series of papers (for example, References 1-3).

In 1978, LBL organized and hosted the First International Workshop on Aquifer Thermal Energy Storage. Active workers from nine countries participated in this workshop and their contributions were published in The Workshop Proceedings (Reference 4). Since the Workshop, a periodic Newsletter (Reference 5) has kept researchers abreast of the current status of various projects worldwide. Many of these projects are reviewed in invited conference review papers published in 1979 (References 6 and 7).

During fiscal year 1979 (October 1978 - September 1979) major LBL work involved the numerical modeling of the recently-completed hot water storage field experiments at Auburn University. This work was funded by the U.S. Department of Energy, Energy Storage Division, through Battelle Pacific Northwest Laboratory and Oak Ridge National Laboratory. Work was also done, under separate funding, on the basic understanding of thermal stratification, dispersion, and buoyancy flow in an aquifer used for hot or cold water storage. These questions are crucial in determining the efficiency of aquifer energy storage and will be discussed elsewhere (References 8 and 9).

The remainder of this paper will summarize the results of the simulation of Auburn field experiments. Details of the simulation will be published in a paper under preparation.

Simulation of Auburn Field Experiments

The recent experiments by Auburn University involved two injection-storage-recovery cycles. Details may be found in a companion paper (Reference 10). The first six month injection-storage-production cycle involved the storage of 55000 m³ of water at about 55°C. The injection took 79.2 days, at the end of which the hot water was stored for 52.5 days. Production was then started at an average rate of 245.6 gpm until the recovered water temperature fell to 32.8°C. At that point 66% of the injected energy was recovered. The second injection-storage-production cycle was carried out in essentially the same manner, using 58,000 m³ of water at an average temperature of 55.4°C. When the production temperature had dropped to 33°C, a recovery of 76% of the injected energy was realized.

The first stage of the simulation involved the determination of the hydraulic parameters of the aquifer (the transmissivity and storativity), and the location of a linear hydrologic barrier through well test analysis. Conventional well test type curve analysis techniques require a constant or carefully controlled flow rate. To get around this limitation, LBL has developed a computer-assisted analysis method, program ANALYZE (References 11 and 12) that can handle a system of several production and injection wells, each flowing at an arbitrarily varying flow rate. This program was applied to the Auburn case, treating the injection period also as a part of the well test data (Reference 13).

With parameters thus obtained, the LBL three-dimensional, complex geometry, single-phase model, CCC, was used to make detailed modeling studies. A radially symmetric mesh was assumed. There is one major hydrologic parameter that was not determined by well test analysis. This parameter, the ratio of vertical to horizontal permeability, has to be inferred from field experience and parameter studies. After making a preliminary parameter study, we decided to use a value of 0.10 for this ratio. The same ratio was suggested by the USGS (Reference 14).

Because neither the injection flow rate nor temperature was held constant, it was necessary in our simulations to break up both the injection (and production) periods into segments having average flow rate and temperature values, conserving injected mass and energy (Figure 1). Results of the simulation include the recovery factor, plots of production temperatures versus time, as well as temperature contour plots and temperature profiles at various times during the injection, storage, and production periods. Both the first and second cycles have been successfully simulated.

For the first cycle, the simulated recovery factor of 0.68 agrees well with the observed value of 0.66. For the second cycle the simulated value is 0.78, and the observed value is 0.76. The details of the comparison between simulated and observed energy recovery can be studied in production temperature versus time plots (Figures 2 and 3). For both cycles, the initial simulated and observed temperatures agree (55°C). During the early part of the production period, the observed temperatures decrease slightly faster than the simulated temperature. During the latter part, the simulated temperatures decrease faster than the observed temperature so that by the end of the production period the simulated and observed temperatures again agree (33°C). The discrepancy over the whole range is, at most, 1-2 degrees.

Temperature contour maps of vertical cross-sections of the aquifer at given times (e.g., Figure 4) show the details of buoyancy flow, heat loss through the upper and lower confining layers, and the radial extent of the hot water in the aquifer. Buoyancy flow is important in this rather permeable system. Comparison with temperatures recorded in observation wells throughout the aquifer show that the simulated temperature distribution agrees generally with observed temperatures. However, these discrepancies are much larger than the differences between calculated and observed production temperatures. Apparently there are local variations in the aquifer which tend to average out. Temperatures versus radial distance at given depths and times are also plotted (e.g. Figures 5 and 6) and, from these profiles, the effects of thermal conductivity and dispersion on the shape of the thermal front can be studied.

In order to prove the mesh-independence of these results, the first cycle has been modeled again, using first a coarser mesh (doubling the radial step) and then a finer mesh (half the radial step). The coarse mesh recovery factor is 0.65, to be compared with a value of 0.66 using our first mesh. Interestingly, the coarse mesh simulation yields a recovery factor slightly closer to the observed value than does the original simulation, so the increased numerical dispersion may be more closely simulating thermal dispersion due to local heterogeneities in the aquifer. Temperature as a function of radial distance (Figure 7) and the production temperature as a function of time (Figure 8) show the insensitivity of the results to the mesh chosen.

Plans for Next Year

In the coming year we have been asked by the Department of Energy through Battelle Pacific Northwest Laboratory to model the Texas A and M University chilled water storage experiment that was recently completed. Further generic and parameter studies will be made, including calculations of effects of varying the ratio of vertical and horizontal permeabilities, the storativity parameter, the storage temperatures and effects of the well partially or fully penetrating the aquifer. The Aquifer Thermal Energy Storage Newsletter edited and published by Lawrence Berkeley Laboratory will also be continued.

References

1. Chin Fu Tsang, Marcelo J. Lippmann and Paul A. Witherspoon, "Numerical Modeling of Cyclic Storage of Hot Water in Aquifers," talk presented at the Symposium on "Use of Aquifer Systems for Cyclic Storage of Water," of the Fall Annual Meeting of the American Geophysical Union, San Francisco, December 9, 1976.
2. Chin Fu Tsang, Marcelo J. Lippmann and Paul A. Witherspoon, "Underground Aquifer Storage of Hot Water from Solar Energy Collectors," proceedings of International Solar Energy Congress, New Delhi, India, January 16-21, 1978.
3. Chin Fu Tsang, Tom Buscheck, Donald Mangold, Marcelo J. Lippmann, "Mathematical Modeling of Thermal Energy Storage in Aquifers," proceedings of Aquifer Thermal Energy Storage Workshop, Lawrence Berkeley Laboratory, Berkeley, California, May 10-12, 1978.

4. Proceedings of Aquifer Thermal Energy Storage Workshop, Lawrence Berkeley Laboratory, Berkeley, California, May 10-12, 1978. Lawrence Berkeley Laboratory Report LBL 8431.
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14. S.S. Papadapulos and S.P. Larson, 1978, Aquifer Storage of Heated Water: Part II: Numerical simulation of field results; Groundwater, v. 16, no. 4.

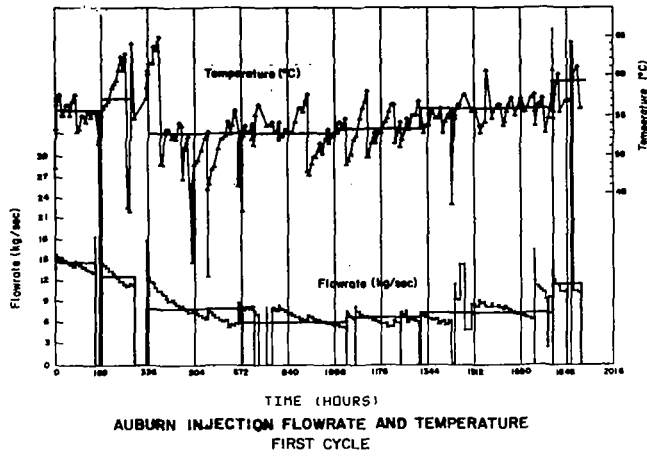


Figure 1. Injection flowrate and temperature versus time, and the average segments used in the simulation.

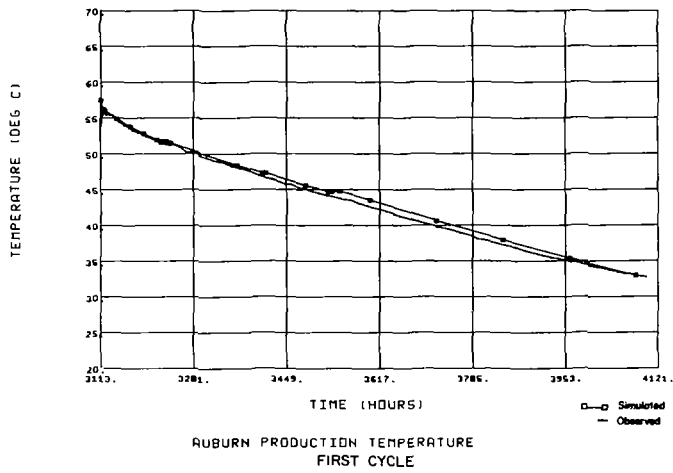


Figure 2. Observed and simulated production temperature as a function of time for the first cycle.

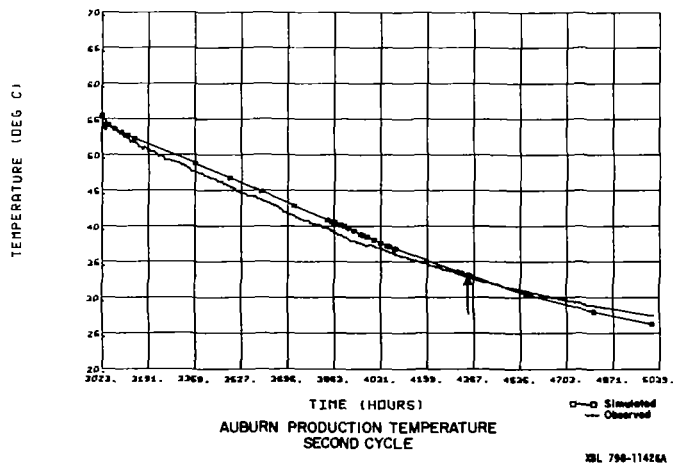


Figure 3. Observed and simulated production temperature as a function of time for the second cycle.

AUBRNO2
 Calculated temperature
 t = 1900 hrs.

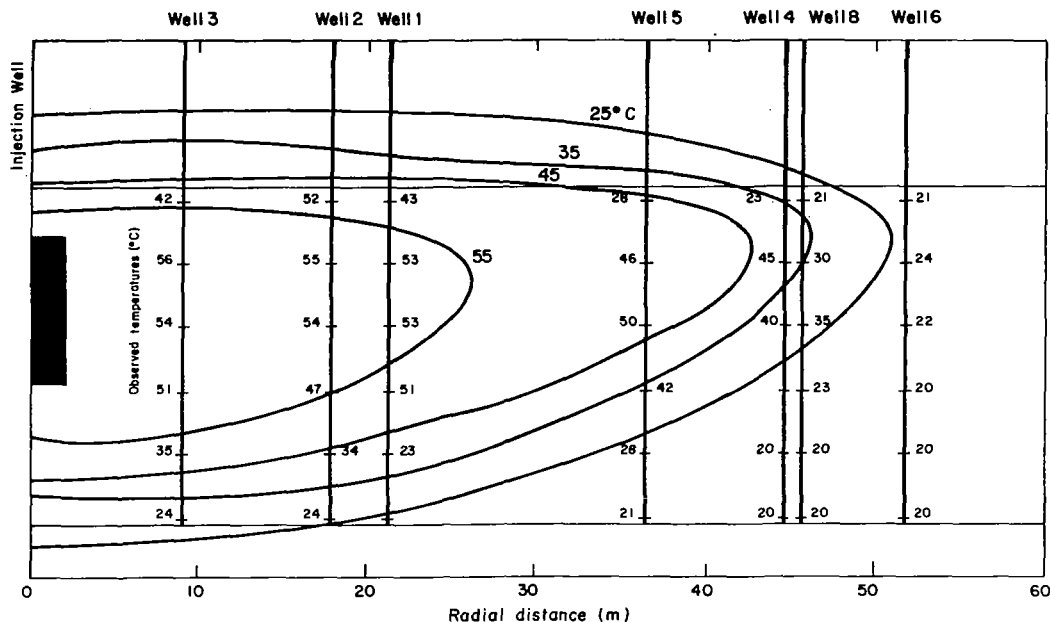


Figure 4. Simulated temperature contours in a vertical cross section of the aquifer at the end of the injection period of the first cycle, observed temperatures are also indicated.

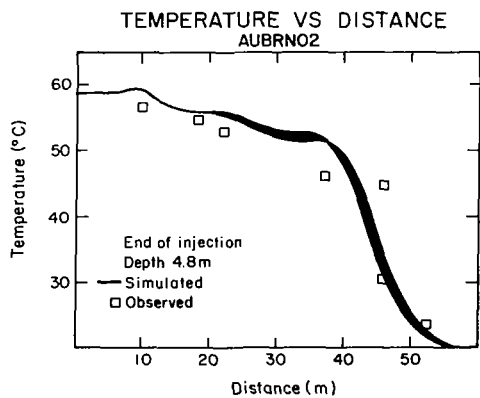


Figure 5. Temperature versus radial distance at the end of injection period for the first cycle. Shaded curve indicates simulated values, boxes show observed values.

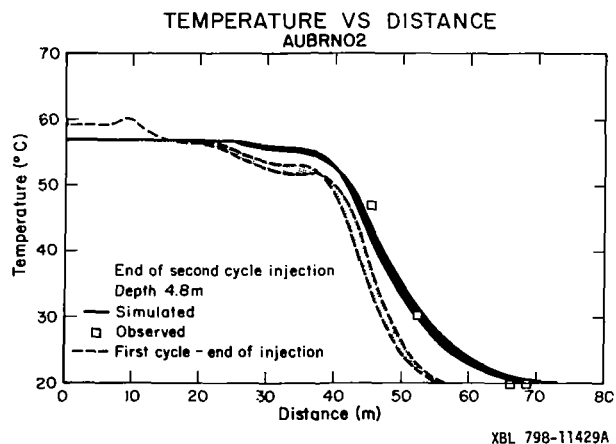
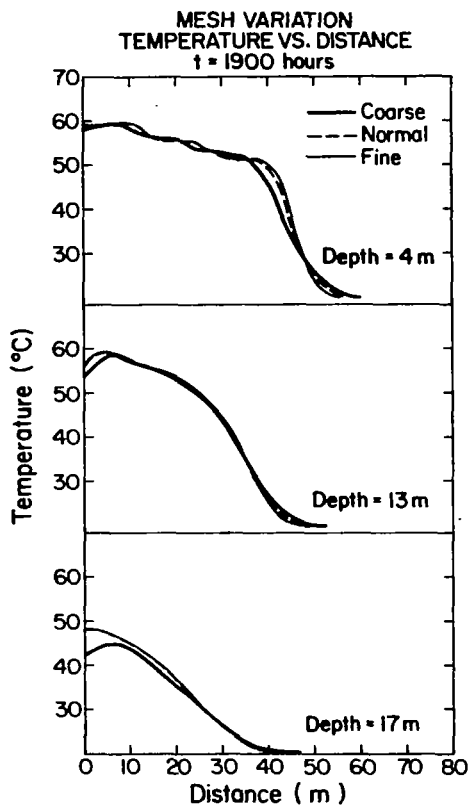


Figure 6. Temperature versus radial distance at the end of injection period for the second cycle. The broken curves shows the simulated values for the first cycle, for comparison.



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Figure 7. Simulated temperature versus radial distance at the end of the injection period for the coarse, normal, and fine meshes.

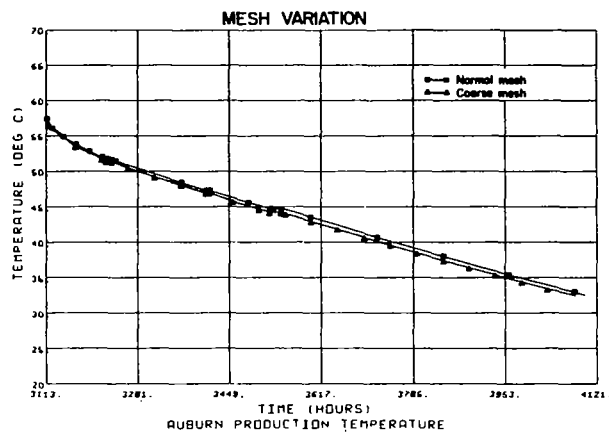


Figure 8. Production temperature versus time for the coarse and normal meshes.