Title

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Author

Tsang, Chin Fu

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Chin Fu Tsang, Fred J. Molz, and A. David Parr

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EXPERIMENTAL AND THEORETICAL STUDIES OF THERMAL ENERGY STORAGE IN AQUIFERS

Chin Fu Tsang*, Fred J. Molz**, and A. David Parr**

*Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

**Civil Engineering Department
Auburn University
Auburn, Alabama 36830

Abstract

A coupled experimental and theoretical study of thermal energy storage in an aquifer is described. Water at an average temperature of 55°C is stored in a confined aquifer near Mobile, Alabama. Approximately 55,000 m^3 of water was injected, stored, and then produced for two consecutive cycles. Data obtained were used to validate a numerical model, "CCC." This model, developed at Lawrence Berkeley Laboratory, is able to calculate heat and fluid flow in a three-dimensional, liquid-saturated system. Without adjusting any parameters, the calculated results reproduce closely the observed data. The energy recovery factor of 66% for the first cycle and 76% for the second cycle indicate that the aquifer may be a very promising thermal energy storage medium. Furthermore, the thermohydrological processes involved appear to be properly accounted for by the numerical model, thus giving us some confidence in the current state-of-the-art in the performance forecast of future aquifer energy storage projects.

Introduction

The need for energy storage is readily recognized when one considers the disparity in supply and demand periods of a solar energy system. Also, the desirability of conservng industrial waste heat for later use and of smoothing load demand fluctuations from a power production system both require energy storage. One of the most promising methods suggested for large-scale seasonal sensible heat storage is to store hot (or chilled) water in aquifers. Aquifers are underground porous rock formations saturated with water, bounded below, and frequently also bounded above by impermeable layers. They are considered promising candidates for long-term storage because of their large size (10^7 m^3 or more) and the low thermal conductivity of geological materials.

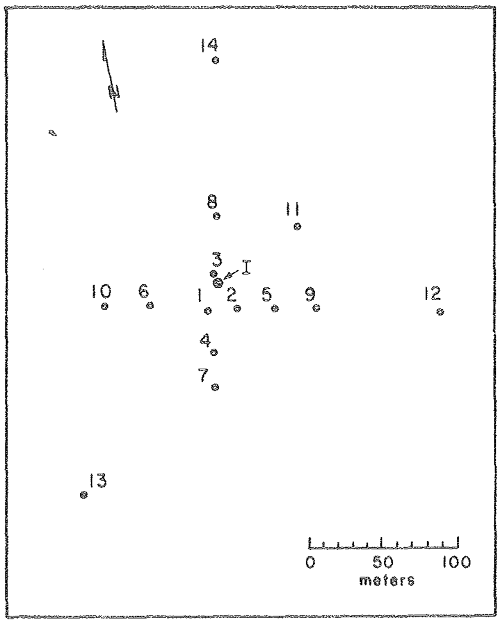
For many years confined aquifers have been used for storing fresh water, oil products and gas, as well as for the disposal of liquid waste. However, the concept of storing hot water in aquifers for later use was suggested only about ten years ago. Various generic and feasibility studies have since been made[1-8]. These mostly considered storage of low or moderate temperature water and several focused on economic and institutional considerations as well. The year 1978 also saw the first International Aquifer Thermal Energy Storage Workshop held at the Lawrence Berkeley Laboratory.[9] Current aquifer thermal storage projects are summarized in a periodic newsletter[10] and two recent review articles.[11,12]

Most of our previous experiences, such as those gained in the storage of fresh water or oil products, are based on isothermal conditions. The nonisothermal character of the Aquifer Thermal Energy Storage (ATES) concept introduces a number of thermal-related problems that have to be investigated. A successful study of the viability of the ATES concept depends on developing an adequate picture of the heat, mass, and momentum transport processes in the porous medium within the aquifer/aquitard systems during the injection/storage/production cycles. An understanding of such coupled processes can best be obtained through simultaneous experimental and theoretical studies of an ATES field project.

The present paper describes a set of field experiments carried out by Auburn University near Mobile, Alabama, involving two injection/storage/production cycles and the interpretation and simulation of these experiments through numerical modeling performed at LBL.

Field Experiment

The project site is located in a soil borrow area at the Barry Steam Plant of the Alabama Power Company, about 20 miles north of Mobile, Alabama (see Molz, Warman, and Jones, 1978, for details). Figure 1 shows a top view of the well field.



XBL 795-7445A

Fig. 1. Top view of the existing well field at the Mobile site drawn to scale.

The injection/production well is labeled I, while wells 1 through 14 are observation wells. Temperatures and hydraulic heads were recorded in the inner array of 11 observation wells which are located within the thermal radius of influence. Wells 12, 13, and 14 were used to observe the hydraulic conditions at what is arbitrarily called the boundary of the system.

The system for supplying, heating, and injecting water is shown schematically in Fig. 2. Supply water is pumped from a sandy-gravel aquifer located between 24 m and 34 m below the surface. The water is then metered and passed through an oil-fired boiler which raises its temperature from approximately 20°C to 55°C. Injection was into a storage formation which is composed of a medium sand containing approximately 15% silt and clay by weight. Aquitards above and below are composed of several different types of clay.

With the exception of well 10, each of the inner observation wells are equipped with thermistors to measure groundwater temperatures at six depths. Shown in Fig. 3 is a diagram of a typical observation well. Plastic materials were used for well construction, and the thermistors were spaced uniformly in the vertical dimension of the storage aquifer.

Beginning on March 18, 1978, approximately 54,784 m^3 of water were pumped from a shallow supply aquifer, heated to an average temperature of 55°C, and injected into a deeper confined aquifer where the ambient temperature was 20°C. After a storage period of 51 days, 55,345 m^3 of water were produced from the confined aquifer. During the 41-day production period the temperature of the produced water dropped from 55°C to 33°C, and 65% of the injected thermal energy was recovered. This injection/storage/recovery cycle, which lasted approximately six months, was the first of a planned two-cycle experiment. The second cycle began on September 23, 1978, 18 days after the first cycle was terminated.

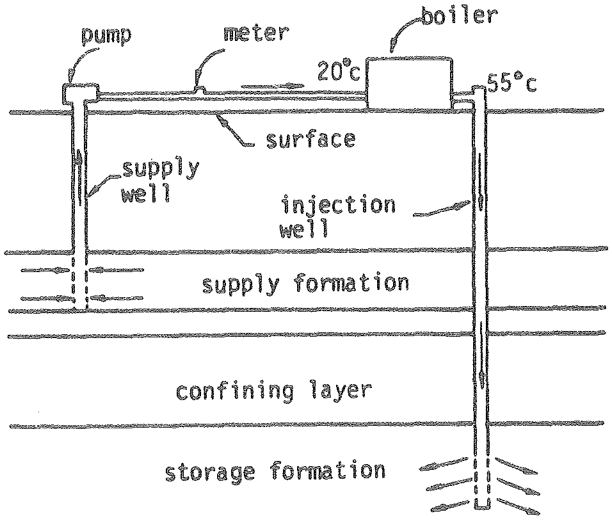


Fig. 2. Diagram of the system for supplying, heating, and injecting water into the storage aquifer. (XBL 805-9678)

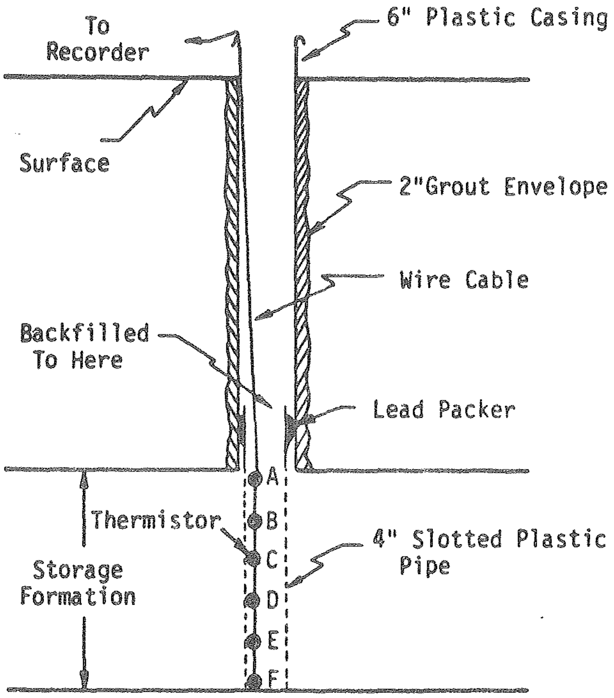


Fig. 3. Side view of a typical observation well showing details of the well construction and the position of the six thermistors used to record groundwater temperatures. (XBL 805-9679)

The second injection/storage/recovery cycle was very similar to the first except that production continued for a longer period. Injection began on September 23, 1978, and continued until November 25, 1978, a total of 64 days. An injection rate varying from 845 m^3day^{-1} (155 gpm) to 1172 m^3day^{-1} (215 gpm) resulted in an injection volume of 58,010 m^3 at an average temperature of 55°C. A 63-day storage period began on November 25, 1978, and was terminated on January 27, 1979, when production began and continued for approximately 84 additional days. The production pumping rate averaged 1205 m^3day^{-1} (221 gpm) and ultimately resulted in a production volume of 100,100 m^3. Pumping was stopped when the production temperature reached 27.5°C which was 7.5°C above the ambient groundwater temperature.

Details of the thermal results will be shown in the next section together with calculated simulation results.

The major technical problem encountered during the first and second cycles was clogging of the injection/production well during injection. This was controlled to a large extent by a regular well backwashing program. Whenever the injection pressure at the wellhead reached approximately 1.45 x 10^5 Nm^{-2} (21 psi), the pumps were surged and water was pumped out of the injection well for a short period of time. After this procedure was completed, the injection pressure would drop and the flow rate would increase. Actually during the second cycle injection, the average specific capacity between backwashings remained nearly constant with time and the injection rate was increased by 24%.

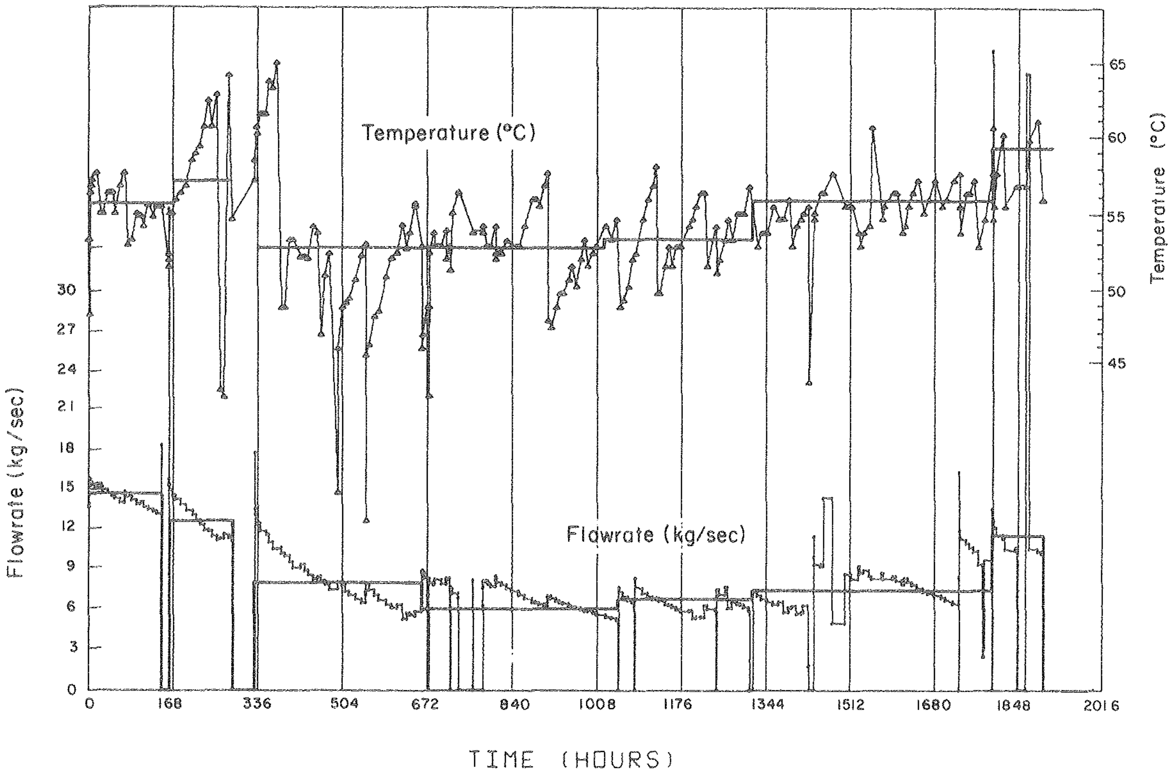


Fig. 4. Auburn Injection Flowrate and Temperature, First Cycle. (XBL 795-7460)

Numerical Modeling

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, 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 data, treating the injection period as a part of the well test data.

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 U. S. Geological Survey.[5]

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 (Fig. 4). Results of the simulation include the recovery ratio, 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 (Figs. 5 and 6). For both cycles, the initial simulated and observed

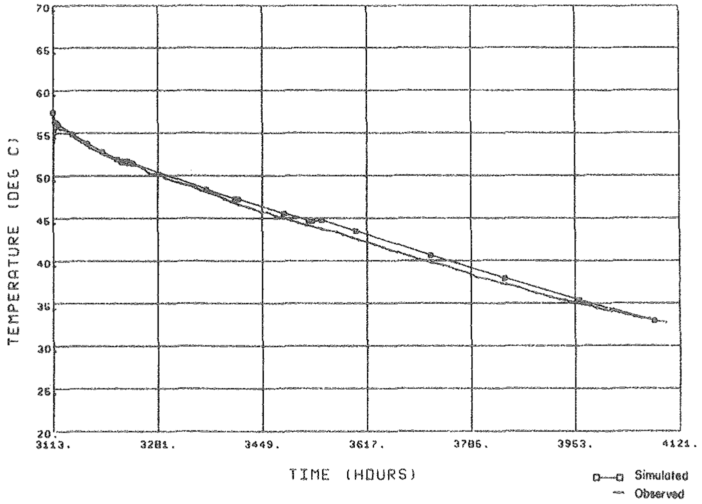


Fig. 5. Auburn production temperature, first cycle. (XBL 798-11428)

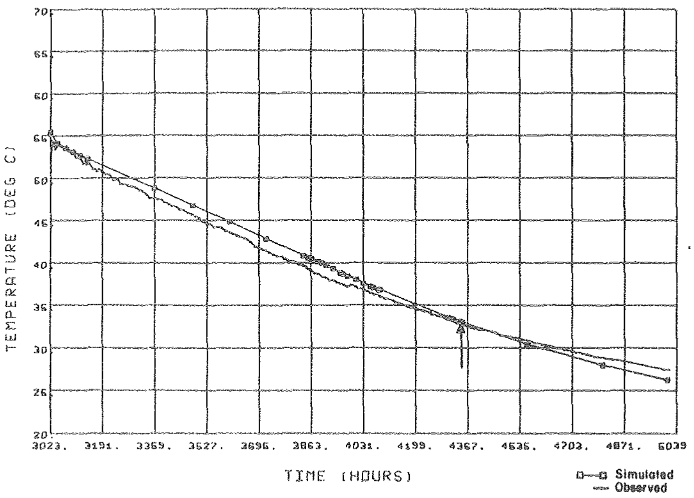


Fig. 6. Auburn production temperature, second cycle. (XBL 798-11426)

temperatures agree (55°C). During the early part of the production period, the observed temperature decreases slightly faster than the simulated temperature. During the latter part, the simulated temperature increases 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 or 2 degrees.

Temperature contour maps of vertical cross sections of the aquifer at given times (e.g., Fig. 7) 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 (Fig. 7) show that the simulated temperature distribution agrees generally with observed temperatures. However, the 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., Figs. 8 and 9) 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 (double 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 and the production temperature as a function of time show that the results are insensitive to the mesh chosen.

Conclusions

A coupled experimental and theoretical study of an aquifer thermal energy storage project was successfully carried out for two injection/storage/

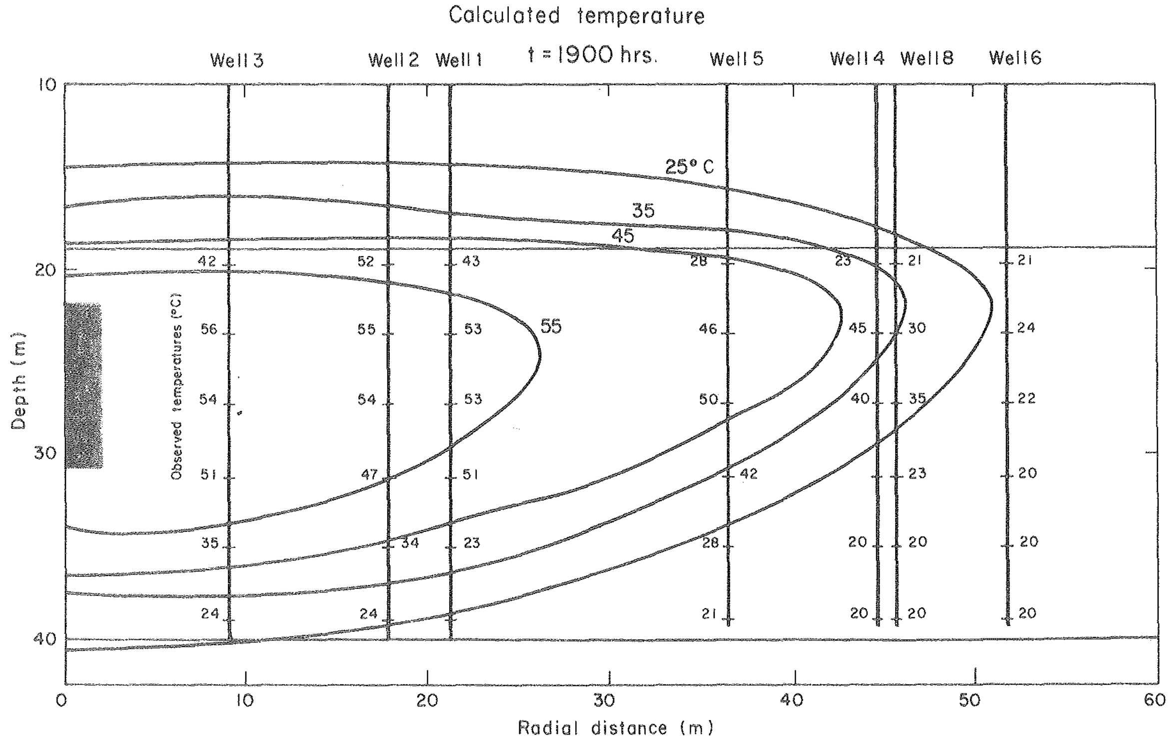


Fig. 7. Buoyancy flow, heat loss through the upper and lower confining layers, and the radial extent of the hot water in the aquifer. (XBL 795-7452)

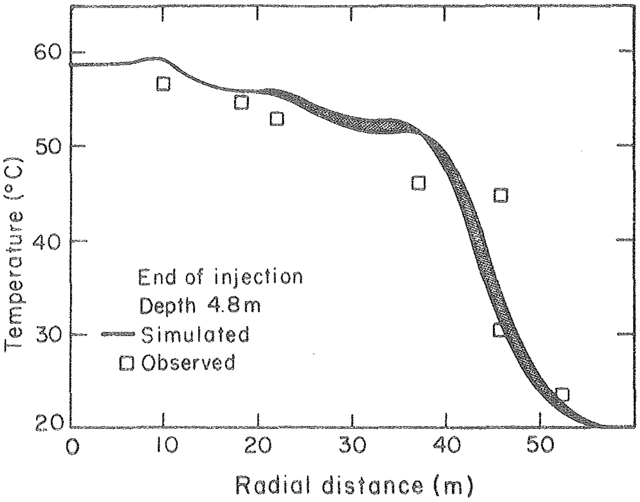


Fig. 8. Temperature versus radial distance at given depths and times. (XBL 795-7463)

production cycles. As predicted by theory, an increase in energy recovery was observed with multiple injection/storage/recovery cycles. At the Mobile site, second-cycle energy recovery was 76% in the temperature range 55°C to 33°C. Recovery at the end of the first cycle in the same temperature range was 66%. The recovery increase was due mainly to residual heat remaining in the aquifer after the first cycle was completed.

The major aquifer thermal energy storage problem identified by these experiments is clogging of the injection well. A regular backwashing program was able to maintain the injection rate and, for the second cycle injection, the average specific injection capacity between backwashings remained nearly constant with time. However much work still remains to be done in this area.

The thermohydrological processes involved in this experiment appear to be properly accounted for by our theoretical studies. The simulated production temperatures and energy ratio agree very well with field data. This strongly indicates the validity of the numerical model and the simulation procedures used, and gives us confidence in predicting performance of future cycles. Larger discrepancies between calculations and experimental data are noticed in detailed temperature distribution comparisons. There appears to be a smoothing and "compensation" effect by which some discrepancies are averaged out and some cancel themselves by the injection-and-production process, so that the final production temperatures are simulated very well.

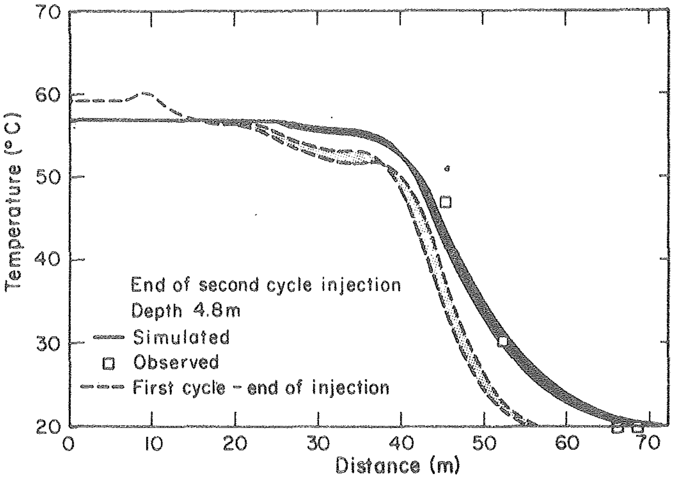


Fig. 9. Temperature versus radial distance at given depths and times (XBL 798-11429B)

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720