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INTRODUCTION

Recently there has been renewed interest[1-5] in the possibility of using underground aquifers for the storage of hot or chilled water. This concept has been seen as a way of remedying the time mismatch between supply and demand periods - one of the major problems facing the design of total energy systems and the development of solar energy. The present paper reviews current studies in this area, with emphasis on the work being performed at the Lawrence Berkeley Laboratory.

The physical basis of the concept lies in: a) the low thermal conductivities of caprock and bedrock materials, b) the large volume of the aquifer (of the order of $10^7 m^3$), and c) the capability of storing water under high pressures. Earlier studies[6-7] involved the general formulation of the idea and various calculations. Recent work includes numerical modeling and practical field tests.

STUDIES AT LAWRENCE BERKELEY LABORATORY

The goal of the LBL project is to apply numerical models and other techniques (1) to study and understand the hydrodynamic, thermal and chemical behavior of an aquifer when used for hot or chilled water storage; (2) to estimate the percentage of stored energy that can later be recovered; and, (3) to suggest optimal arrangements for implementation.

We use a numerical model developed at LBL, called "CCC", which stands for "Conduction, Convection, and Compaction." It is based on the so-called Integrated-Finite-Difference Method. The model computes heat and mass flow in three-dimensional water-saturated porous systems. Concurrent with the mass and energy flow, the vertical deformation of the aquifer system is simulated using the one-dimensional consolidation theory of Terzaghi. Thus in the same calculations we can simultaneously include the effects of temperature on rock and fluid properties (e.g., heat capacity, viscosity and density); heat convection and conduction in the aquifer, caprock and bedrock; effects of gravity; as well as the aquifer properties, and possible compaction and the associated land subsidence due to pressure changes during the injection-withdrawal history are also adequately described by the numerical model.

Five different cases have thus far been studied:

1. Hot water daily storage: hot water is injected for 12 hours during daytime and produced for 12 hours during

nighttime.

2. Hot water seasonal storage, semi-annual cycle: hot water is stored in spring for 90 days, then pumped out for use in air-conditioning in summer for 90 days. In autumn hot water is again stored for 90 days, then pumped out for 90 days for use in winter heating.
3. Hot water seasonal storage, annual cycle: hot water is stored in summer for 90 days, then used for 90 days for winter heating. There is no injection or production during spring or fall.
4. Chilled water seasonal storage: chilled water (at 4°C) is stored in winter for 90 days and produced for 90 days in summer for use in air-conditioning. There is no injection or production during spring or fall.
5. A two-well (doublet) system: during storage period, water is produced from one well, heated, then injected into the other one; during utilization period, hot water is retrieved from the latter, used and then injected back into the former.

The rates of injection and production are kept the same, at 10^6 kg/day (181 gpm). The initial temperature of the aquifer in all cases is assumed to be 20°C. For cases (1) - (3) we have performed calculations with injection temperature T_i, assumed to be 120°C, 220°C and 320°C respectively. It appears that the temperature of the produced water for different injection temperatures approximately scales according to the factor (T_i-T_o). For case (4) only one injection temperature, 4°C, has been used. Some typical results are shown below.*

For case (2), seasonal storage, semi-annual cycle, we have performed calculations not only for a well fully penetrating the aquifer (thickness 100m), but also for a well partially penetrating it for 50m. Figure 1 displays the temperature coutours within the aquifer for the fully penetrating case (a) at the end of the injection period of the first cycle and (b) at the end of the production period of the same cycle. The thermal front is not sharp due to heat conduction within the aquifer and heat loss to the confining beds.

Figure 2 represents the corresponding production temperature at the well during the production period for successive cycles. The recovery temperature is increased for each successive cycle as the aquifer is heated, making it a more efficient hot water storage system. The process will reach quasi-equilibrium when later cycles do not change the temperature appreciably.

These results are summarized in Table 1. It can be seen that the energy recovered (which may be calculated from the integral of temperature over time in Figure 2) improves with each successive cycle. The heat loss is also shown and is two orders of magnitude

*Rock and fluid property parameters are given in reference 3.

smaller than the energy recovered. The difference between energy injected and recovered is the energy diffused to heat the aquifer, making it a better storage system for the following cycle. The last line gives the niminum recovery temperature during production which corresponds to the lowest temperature found at the end of each production period, as shown in Figure 2.

For cases (1) - (3) the percentage of energy recovered (i.e., recovered energy divided by total injected energy) during each cycle is plotted against the cycle number in Figure 3 which displays surprisingly high values (>80%).

For case (4), where chilled water is stored, the temperature of production during the summer is shown in Figure 4, and the highest temperature during production (at the end of the production period) versus the cycle number is shown in Figure 5. Thus, after three cycles the temperature during production is expected to stay below 10°C during the whole production period.

Further calculations are being conducted, and modeling of field experiments will also be attempted.

OTHER STUDIES IN U.S. AND EUROPE

In this section we will first summarize the current U.S. projects before mentioning briefly the European efforts. The U.S. projects are supported by the U.S. Department of Energy, Division of Energy Storage Systems. Four of them, including the LBL efforts, are managed by Oak Ridge National Laboratory; one is managed by the National Astronautical and Space Administration Center at Lewis, Ohio. The LBL project, involving numerical modeling and technical feasibility studies, is described in some detail above. The others are described as follows:

1. Experimental Study of Subsurface Waste Heat Storage — Auburn University. Field work will be carried out in a shallow confined aquifer to test the hot water storage concept and provide data for the calibration of mathematical models. One injection well and 14 observation wells have been drilled. Injection of heated water at about 40°C has recently begun and measurements at the observation wells will soon be carried out.
2. Storage of Cold Water in Groundwater Aquifers for Cooling Purposes — Texas A and M University. This project involves storing chilled water to be used for air-conditioning in summer. In winter a production well provides water at about 70°F, to be chilled in cooling ponds to about 50°F when it will then be injected for storage in an unconfined aquifer about 60 feet deep. Resulting water movement and temperature will be monitored by a system of 11 observation wells.
3. Aquifer Storage at J.F. Kennedy International Airport to Capture Winter Cold for Summer Air-Conditioning — Desert

Reclamation Industries. This demonstration project involves carrying out a technical and economic study of an application of aquifer storage of cold thermal energy. In winter, water from a confined aquifer (about 500 feet deep) will be produced and chilled by cooling towers and heat exchangers. The chilled water will then be stored in the aquifer until used later for summer air-conditioning of the airport buildings. Economic and engineering feasibility studies will be made during FY 1978. It is also proposed that by the end of FY 1978, five test wells should be drilled to make an evaluation of the aquifer properties.

4. High Temperature Underground Storage — University of Houston. This project considers the feasibility of (a) storage of superheated water at about 650°F and 3000 psi in deep aquifers; (b) storage of high temperature oil in caverns dissolved in salt domes. Preliminary review of potential sites will be carried out, and computer simulators developed.

The European efforts[8] include two field experiments in France, one at Bonnaud, performed by the Bureau of Geologic and Mining Research at Orlean; the other at Nimes, performed by the National School of Mines in Paris. The former represents a series of careful experiments yielding detailed temperature, pressure and tracer migration data. Experiments there were completed in 1977, and data will be analyzed and used to validate numerical models. Other European work are being conducted at the University of Lund, Sweden; the University of Neuchatel, Switzerland; and an energetic research program has also been started in West Germany.

CONCLUSIONS

Currently there is active interest both in the U.S. and Europe to develop hot or cold water storage systems in aquifers. Most studies are experimental investigations. Only the project J.F. Kennedy Airport represents the beginning of a demonstration project.

From the numerical modeling studies at LBL, the concept of aquifer thermal energy storage appears to be very promising, with a high estimated storage-recovery ratio (>85%). For a successful implementation of such a concept, several engineering problems are yet to be solved, such as injectibility of the storage well, chemical reaction and precipitation, and coupling with solar power or total energy systems. We believe the active research now going on will successfully answer many of these problems.

REFERENCES

1. Proceedings of Second Annual Thermal Energy Storage Contractor's Information Exchange Meeting, Gatlinburg, Tennessee, September 29-30, 1977 (pp. 91, 24, 152, 253).
2. C. F. Tsang, C. B. Goranson, M. J. Lippmann, and P. A. Witherspoon, *Numerical Modeling of Cyclic Storage of Hot Water in Aquifers*, American Geophysical Union Fall Annual Meeting, December 6-10, 1976, San Francisco, California, USA. Lawrence Berkeley Laboratory, LBL-5929.
3. C. F. Tsang, C. B. Goranson, M. J. Lippmann, and P. A. Witherspoon, "Modeling Underground Storage in Aquifers of Hot Water from Solar Power Systems," paper presented at the International Solar Energy Society Solar World Conference, Orlando, Florida, June 6-9, 1977.
4. C. F. Tsang, M. J. Lippmann, and P. A. Witherspoon, "Underground Aquifer Storage of Hot Water from Solar Energy Collectors", presented at the International Solar Energy Congress at New Delhi, India, January 16-21, 1978.
5. F. J. Molz, J. C. Warman, T. E. Jones, "Transport of Water and Heat in an Aquifer Used for Hot Water Storage-Experimental Study," Am. Geophy. Union Fall Ann. Meeting, Dec. 6-10, 1976, San Francisco, CA.
6. R. T. Robbimov, G. Ya. Umarov, and R. A. Zakhidov, *Storage of Solar Energy in a Sandy-Gravel Ground,* Gebiotckhnika, V. 7, No. 5, p. 57-64, 1971. English translation in "Applied Solar Energy (USSR)".
7. C. F. Meyer, D. K. Todd, Environmental Science Technology, V. 7, No. 6, p. 512-516, 1973.
8. These efforts, as well as those in U.S., will be discussed at the "Workshop on Thermal Energy Storage in Aquifers" to be held at Lawrence Berkeley Laboratory May 10-12, 1978. Proceeding will be published. (Contact: C. F. Tsang, Chairman of Workshop.)

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	CYCLE				
	1	2	3	4	5
Energy Injected (Joules)	5.71×10^{13}	5.71×10^{13}	5.71×10^{13}	5.71×10^{13}	5.71×10^{13}
Energy Recovered (Joules)	4.96×10^{13}	5.092×10^{13}	5.144×10^{13}	5.18×10^{13}	5.2×10^{13}
Energy Lost From Aquifer (Joules)	5.34×10^{11}	6.81×10^{11}	7.7×10^{11}	8.41×10^{11}	9.1×10^{11}
Energy Left in Aquifer at End of Cycle (Joules)	7.10×10^{12}	5.5×10^{12}	4.9×10^{12}	4.46×10^{12}	4.2×10^{12}
Percentage of Energy Recovered	86.8%	89.2%	90.0%	90.7%	91.1%
Production Temperature at End of Cycle	124°C	139°C	147°C	151°C	155°C

Table 1. Energy Balance for each cycle for the case of seasonal storage with semi-annual cycle (full penetration): $T_i = 220°C$; $T_o = 20°C$; $Q = 1 \times 10^6$ kg/day; $H = 100$ m.

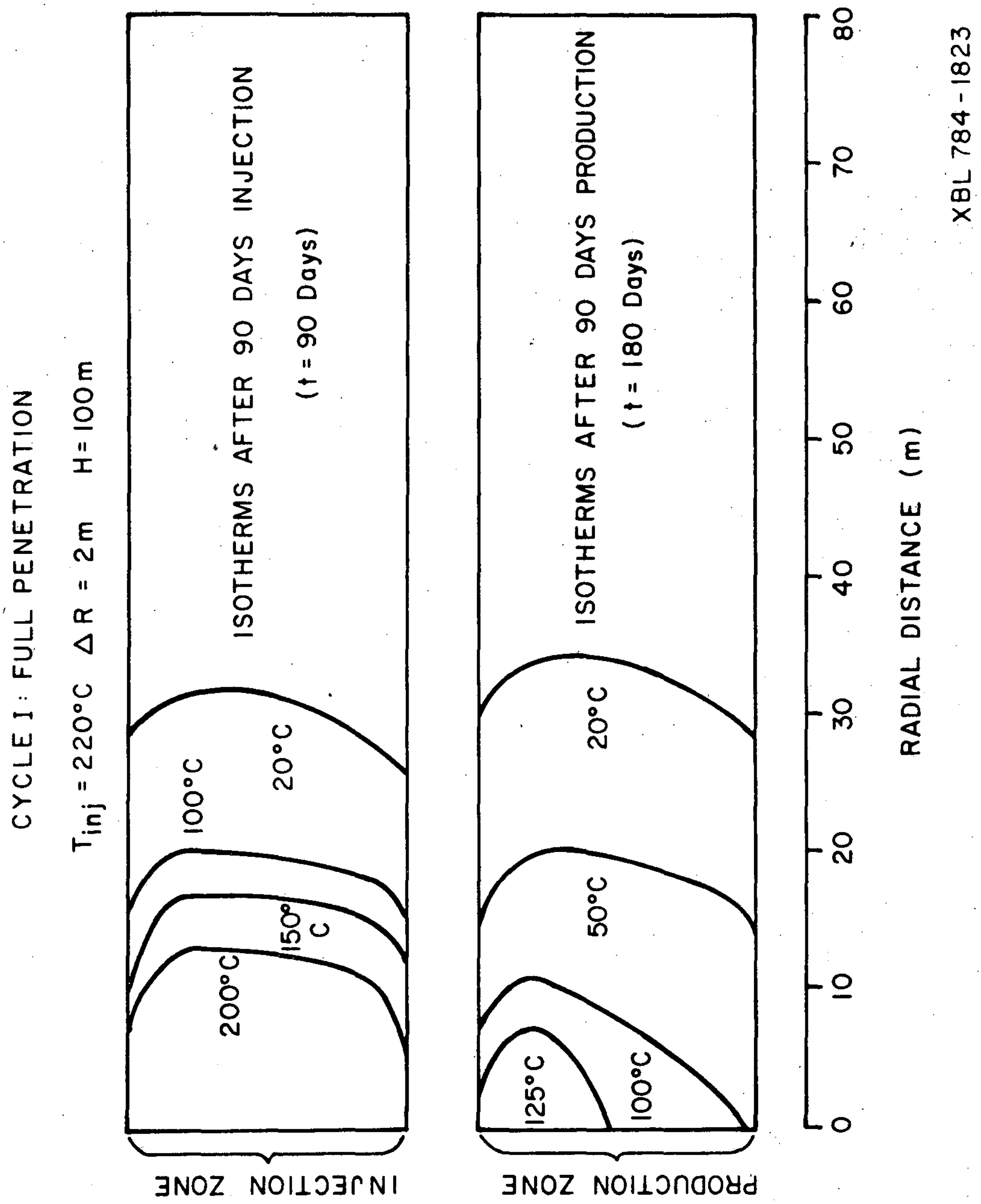
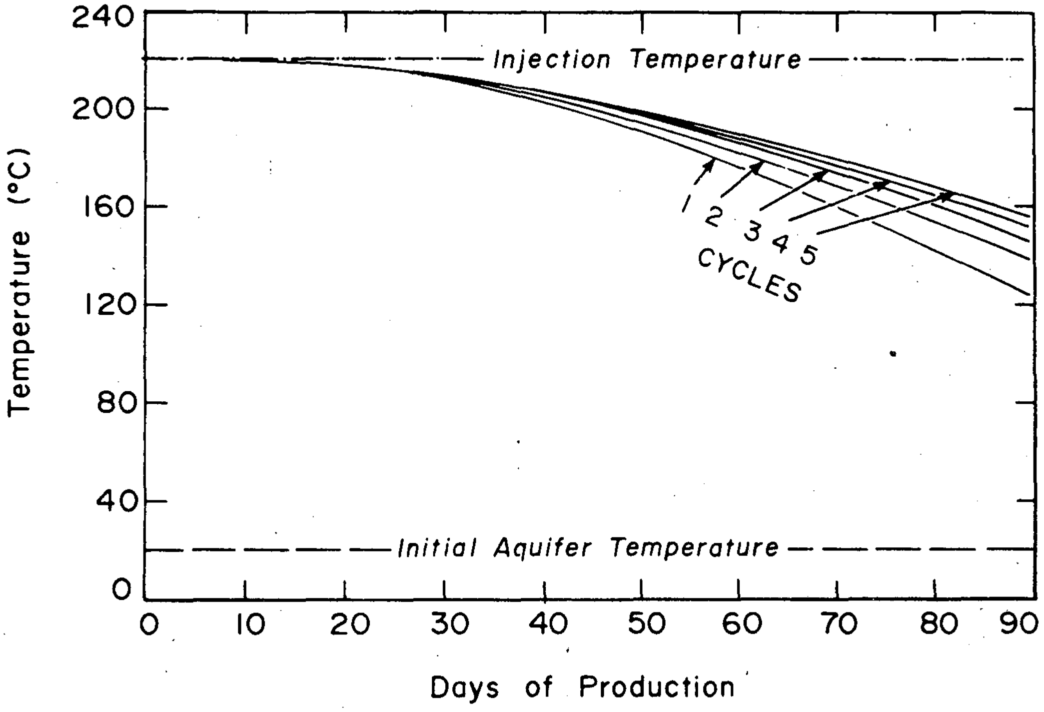
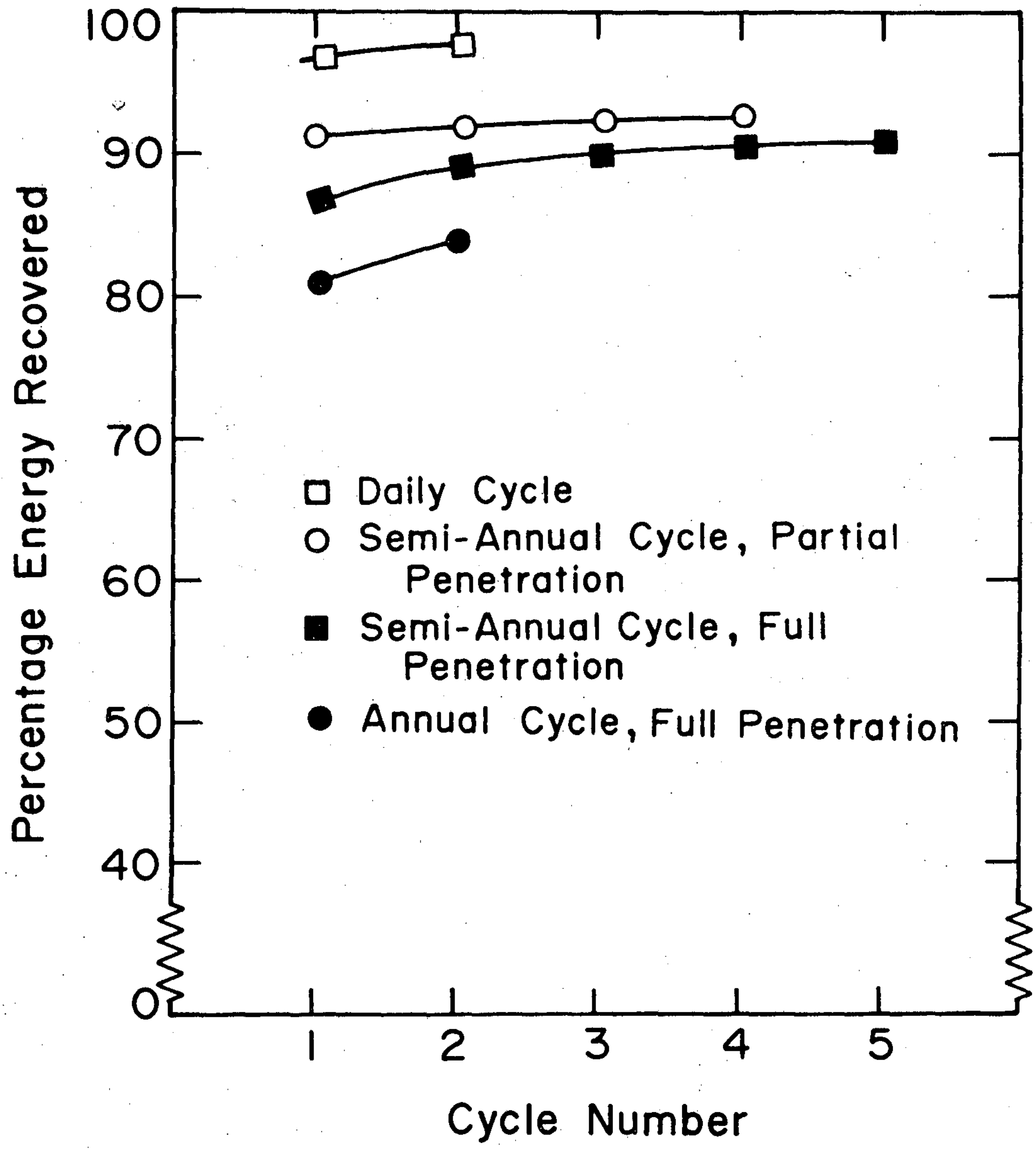


Figure 1. Temperature contours in the aquifer after 90 days of injection; and after 90 days of production in Cycle 1, for the case of semi-annual cycle, seasonal storage. Number labeling the contours are in degrees Centigrade.



XBL 7712-11223

Figure 2. Temperature at the well versus production time for each cycle. The case shown is for seasonal storage with semi-annual cycle, well fully penetrating the aquifer.



XBL 7712-11225

Figure 3. Percentage of energy recovered over energy injected versus cycle number.

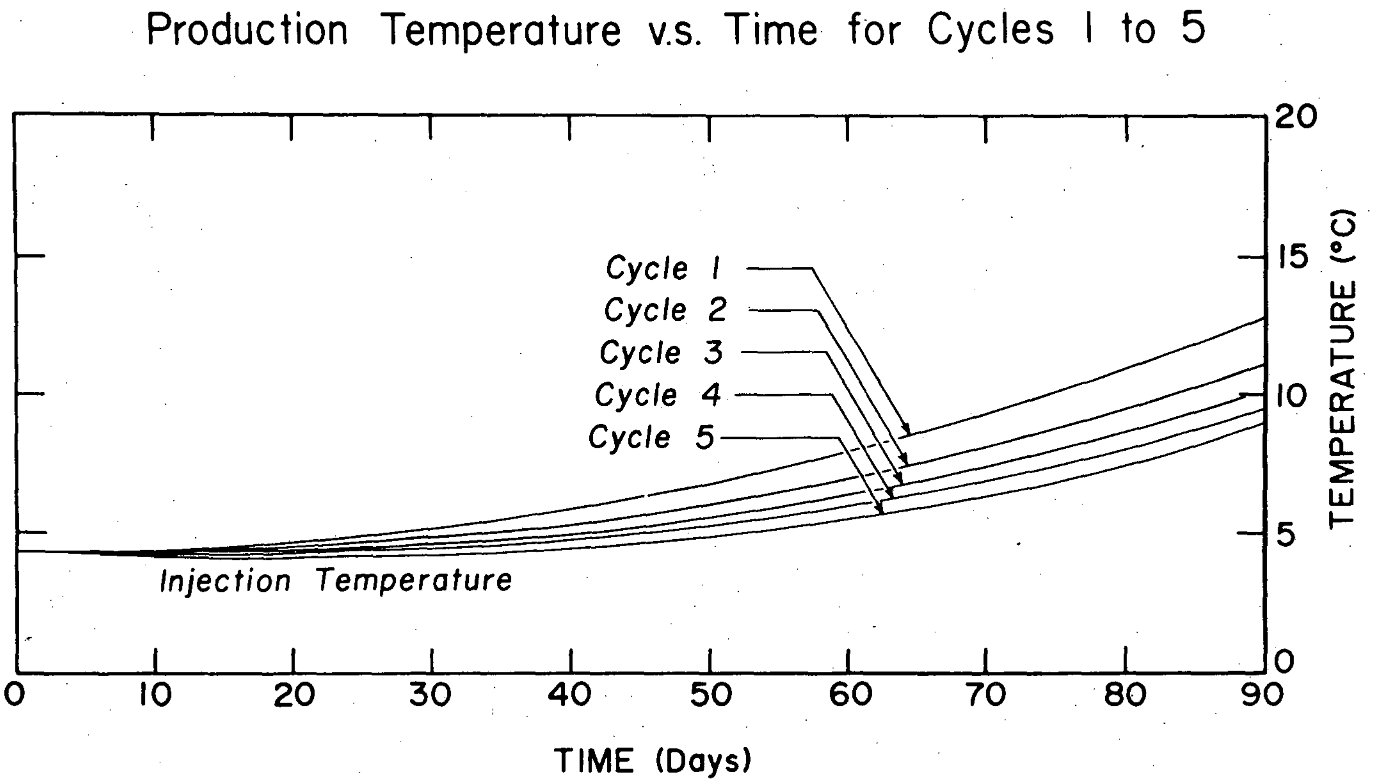
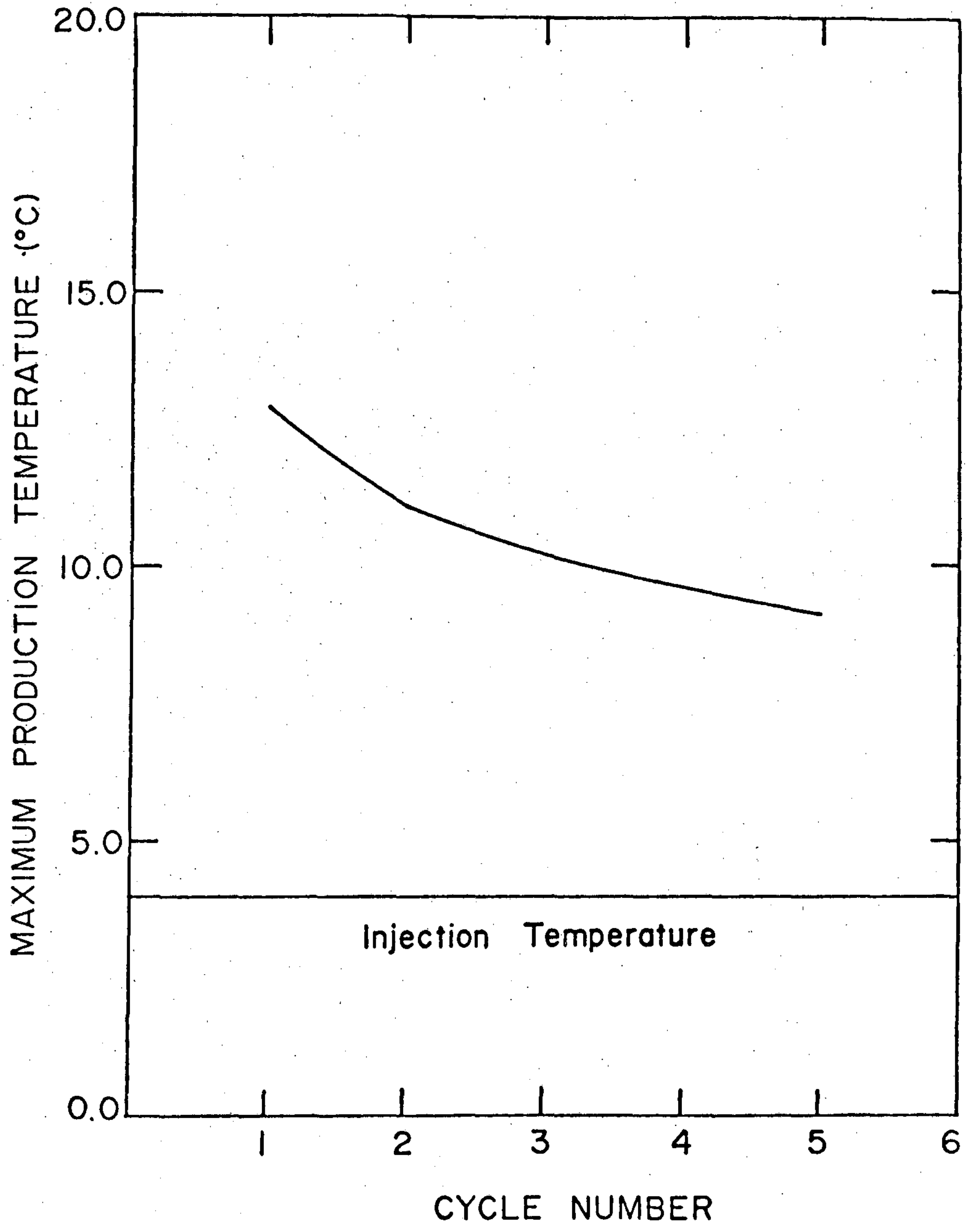


Figure 1. Chilled water storage: Temperature at the well versus production time for each of the Cycles 1 to 5.

XBL 783-7508



XBL 783-75

Figure 5. Chilled water storage: Temperature at the end of each production period (maximum production temperature) versus cycle number.

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