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Vol. IV, No. 3 June 1982

A NOTE FROM THE EDITOR

In this issue you will notice an announcement concerning the upcoming international conference on Subsurface Heat Storage in Theory and Practice, to be held in Stockholm in June 1983. We wish to encourage our readers to submit abstracts for papers they may wish to present, or at least consider attending what should prove to be a very stimulating conference.

As you know, the primary purpose of this newsletter is to promote the exchange of information among countries and institutions. In the past, such exchanges of information have led to very fruitful international cooperative efforts, and I would hope that such efforts will continue to thrive in the form of the transfer of new information, scientific staff exchanges, and cooperative projects.

Finally, I would like to say a few words about the articles our contributors so generously submit to us for publication. We are most appreciative of them all, and they are generally of fine quality. We would like to request, however, that the articles be as clear and concise as possible and of a reasonable length (about 300-600 words is usually sufficient). Illustrations are welcome but should be kept to the minimum number necessary to provide a clear explanation of your work and results. The illustrations should be submitted in camera-ready condition. We want to express our appreciation for past and continued support of this newsletter by all our readers.

The STES Newsletter is a compilation of written contributions from researchers working in the field of seasonal thermal energy storage. Articles and reviews of current events, and new developments in this field are welcome.

Contributions for the next issue, as well as suggestions and changes of address should reach us by August 6, 1982.
Send to:

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INTERNATIONAL CONFERENCE ON SUBSURFACE HEAT STORAGE IN THEORY AND PRACTICE

The second "International Conference on Subsurface Heat Storage in Theory and Practice" will be held in Stockholm, Sweden, June 6-8, 1983. This conference follows the first International Conference on Energy Storage held in Seattle, Washington, U.S.A., October 19-21, 1981. The conference is sponsored by the National Swedish Council for Building Research. Abstracts for papers and poster sessions will be accepted until September 15, 1982. The North American contact for the conference is Dr. Imre Gyuk, U. S. Department of Energy, 1000 Independence Avenue, Room 5E052, Washington, D. C. 20585, U.S.A.; telephone: (202) 252-1508. The European contact is Reso Congress Service, S-105 24 Stockholm, Sweden.

EXPERIMENTAL INVESTIGATIONS INTO AQUIFER THERMAL ENERGY STORAGE IN THE UNITED KINGDOM

Contact: R. Kitching and B. Adams, Institute of Geological Sciences, Hydrogeological Unit, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, United Kingdom.

As reported in Vol. III, No. 4 of the STES Newsletter, an experiment to study the problems and potential of aquifer thermal energy storage has been set up in the Cambridge area. The Lower Greensand aquifer is the target aquifer. The geologic sequence at the research site is as follows: Chalk (4 m), Gault Clay (31 m), Lower Greensand (13 m), Clay. A 15 cm-diameter injection borehole and three smaller observation boreholes, all lined with thermoplastic screen and casing, have been drilled to penetrate the target aquifer. The observation holes are 5 m, 10 m, and 13 m from the injection hole, in different radial directions. Each well is instrumented with thermistors at one-meter intervals in the screened section, and with pressure transducers to monitor changes in groundwater potential.

Water from the Chalk aquifer is heated on site and injected at a rate of approximately 20 m^3/day at a temperature of about 60°C. Following 60 days injection, a temperature of 49.5°C was reached in

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the nearest observation borehole (natural groundwater temperature being 11.3°C), a temperature of 18.7°C in the next nearest, and 11.7°C in the remaining borehole.

A storage phase of a few months will follow the end of injection, which will then be followed by a recovery phase. The thermal anomaly will be monitored throughout.

It was interesting to note the thermistor problems encountered in the Auburn University field experiment and reported in Vol. III, No. 4 of the Newsletter. In the Cambridge experiment some of the thermistors in the injection borehole have apparently failed, and it is assumed that this is due to a combination of injection turbulence and temperature. No thermistor failures subsequent to the start of injection have been noted in any of the observation boreholes where temperatures are below 60°C.

A USAF-DOE RESEARCH SOLAR POND FOR SEASONAL SPACE HEATING

Contact: Kenneth A. Meyer, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, U.S.A.

A cooperative effort between the Los Alamos National Laboratory, Solar Energy Research Institute, Ohio State University, and Mound Laboratory is under way to design a one-acre salt-gradient solar pond for the United States Air Force Academy. This pond will be a joint USAF-DOE research facility designed for the collection and seasonal storage of solar energy. The principal aim of the project is to provide a research tool to advance the understanding of pond behavior. Energy collected and stored during the course of a year will be used for winter space heating.

Salt-gradient solar ponds are large-area, low-cost devices for the collection and storage of solar energy. Typically, a pond consists of three fluid regions: an upper convecting region of relatively low salinity and temperature, a stagnant insulating region where salinity and temperature increase with depth, and a lower convecting thermal storage region of high salinity and temperature. Sunlight penetrating the pond warms the bottom region of water. Upward heat loss is minimized because of the insulation provided by the nonconvecting middle region. Side and downward heat loss are governed by the soil conditions. Fluid containment is provided by an impermeable liner.

The effectiveness of a solar pond is determined to a large extent by the thickness of the various fluid regions. The upper convecting region absorbs radiation but provides no insulation, therefore it is desirable to minimize its thickness. The gradient region provides the pond's insulation and its reduction below optimum design thickness will result in increased heat loss. The thickness of the lower convecting region determines the amount of thermal storage available.

In operating ponds, both unplanned growth of the upper convection region and upward migration of the lower boundary of the gradient region have been observed. These effects reduce the pond's thermal efficiency. The Air Force Academy pond will be used to study all aspects of design and operation, including methods of layer control. The data will also be used to aid in the development and verification of numerical pond models currently under study at Los Alamos, SERI, and other institutions.

Higher than anticipated ground losses have been observed in a number of small experimental ponds. The Air Force Academy pond will be instrumented to obtain information on ground loss and its variation over the pond's lifetime. Current plans call for the design to be completed and construction to begin this summer. Completion of the pond is scheduled for the summer of 1983.

ATES DEMONSTRATION - CANADA

Contact: Glynn Williams and Stuart Angus, Hooper and Angus Associates Ltd., 950 Yonge St., Suite 502, Toronto, Ontario, CANADA, M4W-2J7.

As reported in a previous issue of the Newsletter (Vol. III, No. 2), the consulting team of Hooper and Angus Associates Ltd. and Hydrology Consultants have been engaged in an ATES Demonstration Project at the Atmospheric Environment Service (AES) building in metropolitan Toronto, Ontario. The program was initiated by Public Works Canada in 1980 and is managed through the Energy Secretariat. The project objective is to demonstrate the feasibility of chilling an existing, large commercial building with winter cold stored in the confined aquifer beneath the building.

The current Phase II follows a preliminary assessment of the aquifer and building. Results of the assessment were reported at the International Conference on STES/CAES in Seattle in October, 1981. Under Phase II, detailed design drawings are to be prepared for the construction (Phase III) of a full-scale ATES cooling system for the 30,000 m^2 (gross floor area) AES building. A number of key technical issues must be settled before the final design can be developed. These issues relate principally to understanding the behavior of the aquifer under storage cycles. Field testing of the formation is now underway. A network of observation wells have been drilled, logged, and developed in the northern half of the property. The well logs confirm that the confined aquifer consists of fine to medium-grained sand extending to a sequence of fine gravel at the bottom of the formation. The aquifer thickness is approximately 10 m, with the top of the aquifer being 38 m below grade level. Static water-level measurements in the piezometers indicate that the local flow velocity is only about 0.03 m/day in a southeasterly direction. Water

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samples have been taken for analysis. High concentrations of iron and nitrate pose potential difficulties as both scaling and clogging of buildingside equipment and the aquifer may occur.

An injection test has been planned to determine whether plugging will occur during recharge cycles. The injection period will be simulated using the test rig schematically represented in Figure 1. Aquifer water will be withdrawn from the formation, heated by a portable boiler/heat exchanger unit, and injected into the aquifer some 50 m from the withdrawal well at a temperature rise of 16.6°C above the resident fluid temperature. These observation wells are being instrumented with temperature sensors.

Predictions of the movement of the thermal front are being made using the USGS model. These predictions are based upon data obtained in the feasibility study, from the new well logs, and on assumed values of formation parameters. Results of the injection test will be used to fine-tune the model so that an assessment of the thermal storage potential of the formation can be made for the full-scale modeling and design activity.

With the test lasting 20 days, valuable hydraulic information will be obtained. The piezometric surface can be expected to have stabilized at this point and a measure of the natural recharge to the aquifer can be made. Additionally, by monitoring the head levels in the observation well network, aquifer boundaries can be deduced. The effect of temperature changes on water chemistry, which is of importance as far as well plugging and equipment fouling are concerned, is to be assessed by monitoring the chemistry of the water both before it enters and after it leaves the boiler unit. Detailed test procedures, particularly with respect to injection start-up, are being developed, with operational experience obtained in other ATES projects being drawn upon.

Following interpretation of the results of the injection test, system modeling and design is planned. If all goes well, final design documents will be completed by the end of this summer, with construction scheduled to start in the spring of 1983.

DESIGN STUDIES FOR THE THIRD CYCLE OF THE MOBILE EXPERIMENT

Contact: Chin Fu Tsang and Christine Doughty, Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

The successful numerical simulation of the first (58°C) and second (82°C) cycles of the current Mobile ATES field experiment conducted by Auburn University, have been described in STES Newsletter, Vol. III, No. 4 and Vol. IV, No. 2, where the field experiments are also described. Currently a third cycle is under way (described elsewhere in this issue). The goal of the third-cycle experiment is to maximize the recovery factor for a three-month cycle with an injection temperature of 82°C. A series of injection/production schemes have been simulated to aid in the design of the experiments. Each assumes a constant injection flow rate of 112 gpm at 82°C and the ambient aquifer temperature is taken to be 20°C. Making use of the knowledge gained from the first- and second-cycle simulations, that buoyancy flow is strong, three approaches have been taken:

1. Simply inject into, and produce from, the upper portion of the aquifer where most of the hot water would naturally flow (labeled U).

2. Attempt to maintain a compact shape for the injected fluid. Buoyancy flow is counteracted by pumping from the bottom of the aquifer as hot water is injected into the top (labeled S).

3. Inject into the upper half of the aquifer; then, while producing from the upper half, produce (and discard) colder water from the lower portion of the aquifer. In this way the colder water in the lower portion of the aquifer will not be pulled into the upper portion where it would lower production temperature (labeled M).

Table 1 summarizes the results of the numerical simulations. For a cycle consisting of one month each of injection, storage, and production, the maximum recovery factor is about 0.52, representing an improvement of about 0.12 over the reference case. However, if the three-month cycle is altered

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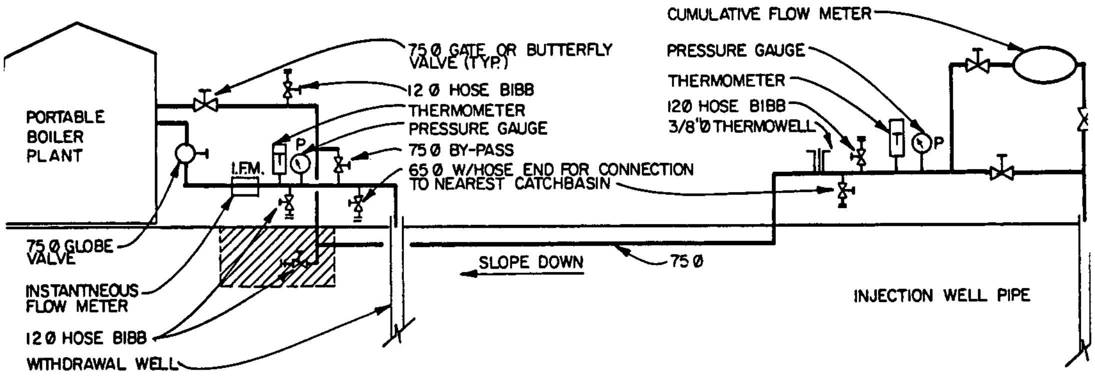

Figure 1. Injection test rig.

so that two months of injection are followed immediately by one month of production (at twice the injection flow rate), hence doubling the storage volume, a recovery factor of about 0.66 is possible. Therefore for this system, the volume of fluid injected is as important as the manner in which it is injected and produced.

Table 1. Third-Cycle Design Studies.
T_1 = 82°C, Q = 112 gpm

I. 1 month each, injection, storage, production
$V = 18{,}300 m^3$

	Well Screen Interval		
Case	Injection	Production	ε
Ref.	Full	Full	0.404
U1	Upper 40%	Upper 40%	0.448
U2	Upper 40%	Upper 20%	0.501
S1	Upper 20% Lower 20%	Upper 20%	0.516
S2	Upper 20% Lower 20%	Upper 20% Lower 20%	0.487
M1	Upper 40%	Upper 40% Lower 55%	0.500
M2	Upper 40%	Upper 20% Lower 55%	0.521

II. 2 months injection, 1 month production.
$V = 36{,}600 m^3$, $Q_p = 2Q_i$.

U1-2	Upper 40%	Upper 40%	0.609
M1-2	Upper 40%	Upper 40% Lower 55%	0.629
M3-2	Upper 40%	Upper 40% Lower 20%	0.631
M4-2	Upper 40%	Upper 20% Lower 20%	0.661

AUBURN UNIVERSITY FIELD STUDIES OF THE AQUIFER THERMAL ENERGY STORAGE CONCEPT

Contact: Fred Molz or Joel Melville, Principal Investigators, Department of Civil Engineering, Auburn University, Auburn, Alabama 36849, U.S.A., and David Myers, Field Test Facilities Coordinator, Pacific Northwest Laboratory, Richland, Washington 99352, U.S.A.

The third injection phase of three injection-storage-recovery cycles in the third series of such experiments is nearly complete at the Mobile, Alabama, field test site. (See ATES/STES Newsletters, Vol I, No 4; Vol II, Nos. 1 and 2; Vol III, No 1, 2, and 3; Vol. IV, Nos. 1 and 2.) Third-cycle injection was initiated on April 7, 1982 and has continued at a nearly constant rate (140 gpm) since that time. As of May 10, 1982 (791 hours into the third cycle), the injection volume was 25,000 m^3 at an average temperature of 79.5°C.

As reported in Vol. IV, No. 1 of this Newsletter, second-cycle energy recovery was significantly reduced due to the occurrence of free thermal convection in the storage aquifer. In an attempt to improve second-cycle recovery, production pumping was halted on December 14, 1981 so that the recovery well could be modified. The bottom half of the well was filled with sand and a figure-k packer was placed above the sand. It was reasoned that pumping only from the upper half of the production well would pull relatively more water from the upper and hotter portion of the storage aquifer. Recovery was resumed on December 16.

Upon resumption of pumping, the recovery temperature jumped from 49.5°C to 52.5°C. Ultimately, the energy recovered in a volume of water equal to the injection volume was 45.2% of the injected energy, the reference energy being that of 20°C water. Based on linear extrapolations of the temperature curve segments before and after modification, it was estimated that the energy recovery would have been 40% if modifications had not been made and 46-47% if modifications had been made prior to initiation of the production period. Thus an energy recovery improvement of approximately 6% would have been possible with the type of modifications that were made. It would have been possible to recover additional energy if the effective penetration of the recovery well had been reduced significantly below 50%. In all practical cases, however, recovery factors less than 0.51 are projected based on computer simulations (Lawrence Berkeley Laboratory, personal communication).

On February 9, 1982, a meeting was held at the Pacific Northwest Laboratory, Richland, Washington, U.S.A. Second-cycle predictions developed by Lawrence Berkeley Laboratory were compared with data obtained by Auburn University. Agreement was excellent, supporting the conclusion that the overall ATES program has developed a good practical and theoretical understanding of aquifer storage at the Mobile site.

A second subject considered at the February 9 meeting was the manner in which the third injection-storage-recovery cycle should be conducted. After much discussion it was concluded that a dual recovery well system would probably result in significantly 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 storage aquifer this would maintain approximately horizontal radial flow with colder water entering the lower screen and warmer water entering the upper screen. The colder water could then be reinjected at an appropriate location. Through this procedure, gross mixing of cold and hot water may be largely eliminated.

At the Mobile site, construction of a dual recovery well system was completed on April 1, 1982. The two wells are separated horizontally by 1.8 m with the upper production well screened in the top 9.1 m of the storage aquifer. Presently, this well is being used for the third-cycle injection men-

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tioned previously. The screen for the lower production well is also 9.1 m in length. It begins 1.5 m below the bottom of the upper screen.

Initiation of third-cycle storage is tentatively planned to begin in mid-June. Production would then begin in August, which would allow testing of the dual recovery well system.

THE DANISH AQUIFER STORAGE PROJECT: MATHEMATICAL MODELING

Contact: J. Reffstrup, Laboratory for Energetics, Technical University of Denmark, Building 403, 2800 Lyngby, Denmark, and J. Wurtz, Risø National Laboratory, 4000 Roskilde, Denmark.

The Danish Aquifer Storage Project is a joint project between the Laboratory for Energetics of the Technical University of Denmark, the Geological Survey of Denmark, and the Risø National Laboratory, which is funded by the Danish Ministry of Energy. This article describes several of the models developed within the project, and is a continuation of past articles describing the project (see STES Newsletter, Vol. I, No. 4, Vol. III, No. 3, Vol. III, No. 4, and Vol. IV, No. 2).

Flow models have been developed and used to determine the flow patterns in the horizontal x-y plane and the vertical r-z plane. The basis for these calculations was the five-well pattern. The objective of the calculations in the horizontal x-y plane was to determine the time for breakthrough (short circuit) of the thermal front at the four low-temperature stores. The model used for this type of calculation is based on a simple, explicit numerical integration scheme using the potential flow field associated with the five-well pattern. The influence of density and viscosity differences on the flow field is hence neglected. An example of the result of such a calculation is shown in Figure 1, which shows the position of the thermal front every six days during a sixty-day injection period.

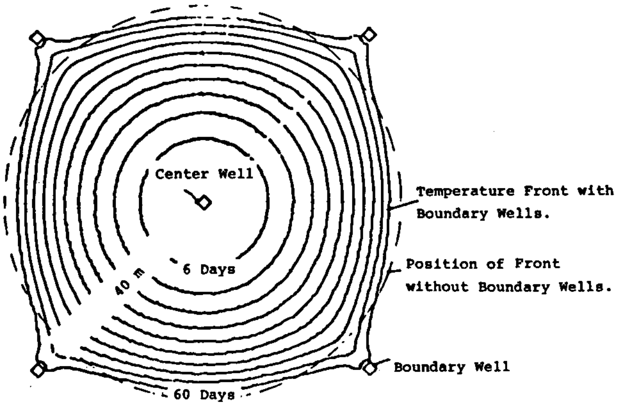

Figure 1. Position of temperature front at different times of a sixty-day injection period.

The next step in the development of flow models was the development of a two-dimensional numerical simulation model. This model is based on the numerical solution of the partial differential equations describing mass and energy transport in porous structures. The model is based on the finite-element technique. The model has been used to check the validity of simpler flow models, to gain further insight into the mechanisms governing the flow in the store, and to test the impact on the storage efficiency of different designs and operational modes of the store.

The results of these investigations have been used in the design phase of the energy store in Hørsholm. One of the interesting results of these investigations is that it seems possible to some extent to control the flow in the store by using a combination of fully and partially penetrating wells and hence counteract unfavorable warm and cold water mixing caused by buoyancy effects.

Figure 2 gives an example of a calculated temperature distribution at a given time of the production period. In this test run the center well was made partially penetrating during the production period, thus increasing the storage efficiency.

The work with mathematical models is being continued within the framework of the Danish Aquifer Storage Project; however the emphasis will be placed on the improvement of existing models and the use of the models to analyze experimental data concurrent to the full-scale experiment at Hørsholm.

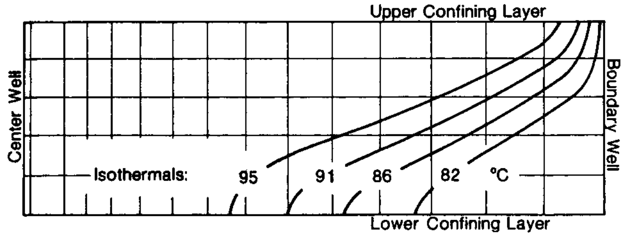

Figure 2. Temperature distribution in the aquifer at an instant during the production period.

REMINDER

Contributions for the next issue of the Newsletter are due August 6, 1982.

THERMAL INTERFACE TILTING

Contact: W. Hausz, Eco-Energy Associates, 4520 Via Vistosa, Santa Barbara, California 93110, U.S.A.

Tilting of the thermal interface caused by the density difference between hot and cold water is a matter of concern in all phases of aquifer thermal energy storage. Because buoyancy makes the hot water tend to rise and the cold water to sink, an extreme case could cause cold-water production from the bottom of the well simultaneous to hot-water production from the top, degrading the quality of the energy withdrawn from storage.

The nature of this tilting is easily demonstrated by a decorative device containing two thin squares of plastic, between which is a small space half-filled with a viscous fluid and half-filled with air. The interface between them is normally horizontal. When the device is suddenly turned 90°, the vertical interface between two fluids of different densities begins to tilt.

To see if this behavior simulates the tilting behavior of ATES in the shut-in mode, a simple analytic model was suggested in "Guidelines for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage" by Meyer and Hausz, PNL-3581, 1980. Around any closed path intersecting the interface, a driving force can be expected toward the denser, cold fluid. Assuming the simplest possible flow channels (a set of concentric circles) the flow velocity in each channel can be found as a function of the driving force (or difference in head) and the viscous resistance of the paths. Initially, the mass of water on the cold-water side will be greater than that on the hot-water side by an amount proportional to the density difference and the diameter of the path. Channel resistance is proportional to viscosity and to the perimeter (also diameter) and inversely to the permeability. The ratio of force to resistance determines flow velocity and is independent of the flow-path radius. This means that the angular rate of tilting is greatest near the center. With a small perimeter, the interface quickly approaches the horizontal. As the interface moves clockwise in each channel, the density difference between right and left, hence the driving force, decreases asymptotically to zero as the horizontal is approached.

The interface shapes achieved are far from linear and resemble the behavior of the air-water interface in the decorative device mentioned earlier. Linearity, or an angular velocity independent of radius, has been assumed by some sources as reasonable (Hellstrom, Tsang and Claesson, LBL-14246, 1979). Modelers tend to use a coarser resolution in the vertical direction than in the horizontal, assuming, perhaps implicitly, roughly linear interfaces.

The shape of the interface was not very sensitive to alternative flow path shapes assumed; ellipses and rectangles of varied length-height ratios were tried. If the thermal interface is assumed to be finite in thickness with density varying linearly through the thickness, the shape of the interface is modified accordingly.

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