STES NEWSLETTER
A Quarterly Review of Seasonal Thermal Energy Storage

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A NOTE FROM THE EDITOR

Of particular interest in this issue is the article by Ausseur, Récan and Sauty on hot water storage in a flowing aquifer. They make two suggestions: (1) the implementation of a circular impervious, slurry wall around the storage volume to minimize the effects of the regional flow; and (2) the creation of a horizontal thermal front with vertical movement within the storage volume by means of 6 horizontal drains at the top of the storage volume and 6 wells opened at the lower level. The former suggestion demands an economic analysis as well as chemical study of the slurry wall at different temperature conditions. The latter is an interesting variation of the SPEOS concept carried out at Dorigny in Switzerland, which involves the use of horizontal drains at both the upper and lower levels of the storage volume.

We continue to encourage all readers to submit articles to us. Articles on new ideas in energy storage, project plans and descriptions, as well as recent progress and significant findings are most welcome. Through this Newsletter, we hope to encourage informal discussions, and international collaboration.

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, as well as new developments in this field are welcome. Please keep us informed of research plans, significant results, and accomplishments.

Contributions for the next issue, as well as suggestions and changes of address should reach us by May 24, 1985.

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CENTRAL SOLAR HEATING PLANTS WITH SEASONAL STORAGE: EVALUATION OF SYSTEMS CONCEPTS BASED ON HEAT STORAGE IN AQUIFERS

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One of the tasks of the International Energy Agency's Solar Heating and Cooling Program is to evaluate central solar heating plants using seasonal storage. This task is further divided into various subtasks, one of which is the evaluation of systems concepts. The systems concepts examined in this effort are limited to those that can be modeled with the analytic tool MINSUN, which is a system simulation and economic analysis program for central solar heating plants with seasonal storage. The program calculates thermal output from large solar collector arrays using an hourly time step, and then performs system simulation with a daily time step. From results of energy loads, subsystem capacities and requirements for auxiliary energy are calculated. Based on the thermal results, system costs are calculated.

The systems reported here have the following major characteristics:

- typical residential space and water heating loads (but with wide variation in the relative amounts of space heating and domestic hot water requirements); varied in size by a factor of 100;

- aquifer seasonal thermal storage at a central location;

- large collector array at the central location; both low performance (glazed and unglazed flat plate) and high performance (stationary CPC) collector types;

- supply temperatures characteristic of low temperature (solar-oriented) design and high temperature (retro-fit) design;

- energy conditioning with a heat pump compared to no heat pump;

- continental climate represented by Madison, Wisconsin, USA and maritime climate represented by Copenhagen, Denmark. *(continued)*

The important limitations resulting from using the MINSUN analytic tool are:

- the aquifer model represents only one well (the "hot" well) of at least a two-well system;
- the buoyancy effect, often significant in an aquifer, is not modeled;
- the aquifer model does not 'preheat' the aquifer to simulate steady state conditions; multi-year computer runs were made but are expensive;
- the increased costs associated with increasing aquifer capacity are not accounted for;
- daily buffering storage is not modeled;
- direct supply of load from collector sub-system without using aquifer storage is not modeled;
- pumping energy requirements, more significant for aquifer operation than or other storage methods, are not included;
- the trade-off between distribution system cost and delivery temperature is not modeled.

Economic analysis of various systems concepts was performed on a present value basis. The most useful summary statistic of system cost performance was defined as annualized solar system cost divided by (useful) annual solar system heat output. The solar system cost included collectors, storage, associated pipes, controls, etc., and heat pumps (if any). Solar system cost does not include distribution, capital costs or pumping costs. The useful heat output was defined as heat extracted from storage (recall that there is a no collector-to-load connection) delivered directly to the distribution network or to the heat pump evaporator. A marginal cost analysis was performed on the optimum system envelope for each of the water/supply temperature combinations.

Optimal system design was based on minimum per unit solar cost ($/MWH). Many system designs were simulated and analyzed. Results were examined in terms of solar unit cost for a range of solar fractions (useful solar output divided by load). These results were plotted and essentially represented expansion paths - i.e., represented how solar system costs (and key parameters) would change as the design was modified to progressively meet more and more of the load from solar (increasing solar fraction). These curves provide very useful information about each case and also provide a common basis for comparing one case with another.

For a few selected reference cases, sensitivity analyses were performed to determine the cost impact of:

- relative amount of domestic hot water and space heating;
- load size (varied by a factor of 100);
- a key aquifer parameter (reservoir height).

The option of a ground source heat supply, i.e., using the ambient temperature of the aquifer to supply heat through a heat pump without the collection of solar energy, was investigated as a limiting case. The principal results of the analysis of the aquifer-based systems indicate that heat pump systems are generally more cost-effective than systems without heat pump. Figure 1 is a graph of costs for low temperature systems in continental (Madison, WI) climates.

(continued)

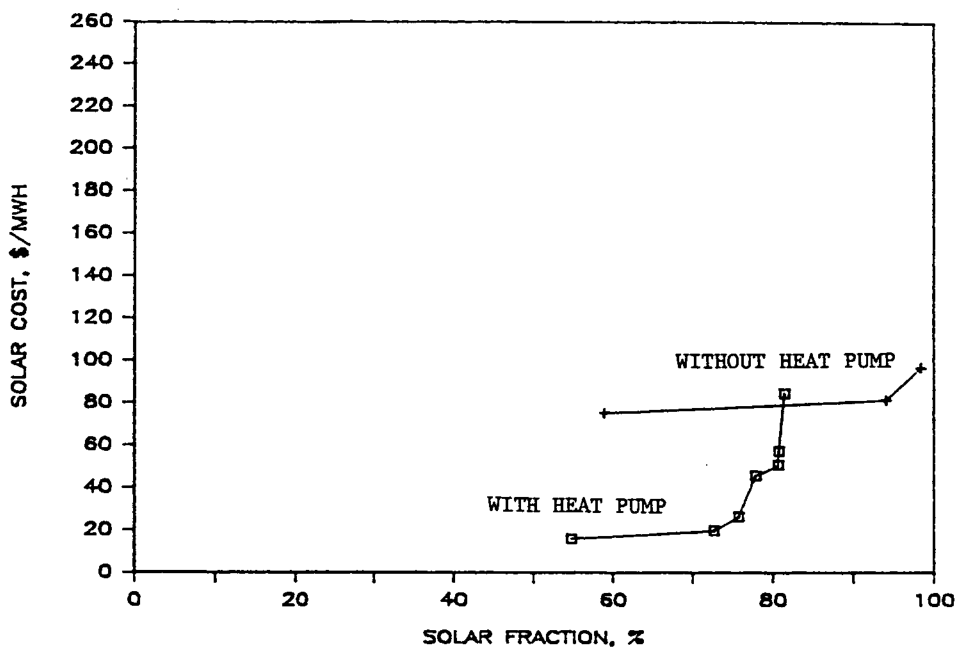

Figure 1. Plot of minimum unit solar cost for low temperature systems in continental (Madison, WI) climates.

For low temperature supply cases, the solar unit cost with a heat pump is in the range 30-40 \$US per MWh (or 3-4¢ /kWh) for solar fractions in the range from 50% to approximately 80% (the remaining load is supplied by heat pump input energy plus auxiliary heat, if necessary). This heat supply cost range is comparable with conventional energy sources in many countries and in certain regions of the USA (New England States) and Canada (Maritime Provinces). For the limited cases analyzed so far, which include distribution costs and auxiliary energy costs, these system unit costs compare favorably with single-dwelling solar space heating systems.

For the high temperature supply cases (probably retro-fit design cases), the solar unit cost with a heat pump is in the range of 50-60 \$/MWh. These cases could be cost competitive with conventional supply in specific applications.

The no heat pump supply case would be cost effective when the alternative energy supply is more than \$100/MWh or when very high solar fractions are desirable.

SEASONAL HOT WATER STORAGE IN A FLOWING AQUIFER: LATERAL CONFINEMENT BY SLURRY WALL

Contact: J. Y. Ausseur, M. Récan and J.P. Sauty, B.R.G.M., BP 6009, 45018 Orleans Cedex, France

Underground seasonal storage of hot water by injection into an aquifer through a typical vertical well can only be performed in areas of low velocity groundwater; otherwise, advection would bring the injected heat out of reach of the well. The use of this method is also limited by temperature. The Auburn experiment has shown very good heat recovery when storing at 55°C, while storage above 80°C yielded much lower efficiency due to buoyancy effects with front tilting. Thus, pumping back produced a mixing of warm water from the top with cold water from the lower levels of the aquifer.

Hot water storage inside a cylindrical portion of aquifer, confined by means of a circular impervious wall, prevents rapid loss of the stored heat, which would have to first diffuse across the wall before being carried away by advection. These principles have been applied to a project to be implemented in the Rhone Valley aquifer. The project is intended to provide heat to a school (Ecole Normale) in Lyon-Gerland; the first buildings are intended to be occupied by September 1986. At this location during summer, heat can be obtained at a very low cost (about 10 times below the winter sale price), and then stored and used for winter heating.

During summer, hot water (between 80 and 90°C) will be injected at the top of the reservoir through a series of 6 horizontal drains, while water at the same flow rate will be pumped from the lower level through 6 wells. The total amount of water in the system is conserved; the water flows through an exchanger, picks up heat and is drawn back through the upper level. The reservoir is therefore progressively filled with hot water from top to bottom; hence density (buoyancy) effects are avoided. Fingering might occur during the injection phase, but with the recirculation of water, this would not mean significant losses. During the cold season, the flow is reversed; depression in the drain and pressure in the bottom wells allows the water to be extracted from the upper section (between 80 and 50°C) and returned at about 25°C through the lower part.

A study was carried out during the first half of 1984 that included the following features:

1) A hydrological investigation of the site in order to determine the flow conditions inside the reservoir and in the aquifer. Mathematical models were used to predict heat losses into the aquifer and into the ground, using different options for insulation of the reservoir.

2) A thermal study of the buildings with 3 heating devices at different temperatures:

   - radiators with a water temperature of up to 65°C during the colder days;

   - pulsed air at 35°C;

   - preheating of water in the hot water distribution.

3) A hydrothermal study of the whole system, including storage, distribution, and usage in buildings as a function of energy needs, storage operation and different heat sources.

4) A study of the characteristics of materials used for heat and flow insulation (impervious walls and surface insulation).

5) An economic study, including an energy balance and a financial balance of the project as well as the final dimensions and mode of operation.

The main conclusions of the study are as follows:

1) The aquifer is homogeneous within the scale of the project, with high horizontal permeabilities and low vertical permeabilities; due to the high anisotropy factor (20), six wells are sufficient to ensure a practically horizontal interface.

2) The final storage volume will be 15 m thick, and 75 m in diameter.

3) Simulation of storage shows a reasonably high efficiency (66% during the second year).

4) Storage at 90°C will enable one to satisfy 78% of the needs, which amount to 2.3 GWh/year.

5) Various possibilities of impervious walls have been investigated. The slurry wall was found to be more economical. An experimental study of thermal conductivity for different slurry compositions showed a linear dependency of

conductivity on density. A light mixture was chosen because of its lower cost and better insulation.

6) Chemical aspects need more periodic investigation, with monitoring and eventually periodic treatment of water.

7) Total investment amounts to 5.4 million francs, of which 4.7 are capital costs.

8) Better economics would be achieved with a larger storage volume; heat losses and wall costs are proportional to the surface area, while stored heat is proportional to the volume.

EXPERIMENTAL TESTING OF COOLING BY LOW PRESSURE ADSORPTION IN A ZEOLITE

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The New Mexico Solar Energy Institute, under contract to Pacific Northwest Laboratory (operated for the U.S. Department of Energy by Battelle Memorial Institute) designed, constructed, and utilized a small scale facility to test the use of zeolite adsorption of water vapor to augment chill storage in ice for conventional space cooling. The facility uses solar-derived energy for the heat source and evaporatively chilled water for the heat sump. However, to speed up the overall test schedule, an electric water heater was added to the test apparatus. The product cooling uses sublimation of ice instead of melting. The specific tasks of this project were to: (1) develop and design a detailed specification for a solar zeolite chill-augmented storage system, which includes a zeolite tank, ice tank, and heat exchanger; (2) construct the system as approved by PNL; (3) instrument and test the system; (4) perform a study of adsorbers; and (5) analyze and report the findings.

The Zeolite Chill-Augmented Test (ZCAT) Facility utilizes a heat pumping technique in which a water vapor adsorbent functions as the compressor and condenser. The design was based on the use of 13X zeolite as the adsorber because of its high adsorbence at low pressures. However, as a result of the work done on this project it has been determined that other materials such as silica gel would give superior performance. Table 1 below shows that while zeolite 13X holds more water in the pressure and temperature ranges of interest, silica gel cycles more water and has less residual water. Both points are very important in the design of an efficient and cost effective system.

The ZCAT facility consists of three primary subsystems: (1) the central part of the facility is the evacuated system consisting of 64 zeolite tubes, 64 condenser tubes, manifold, ice tank, and a daily cooling storage tank; (2) the thermal drive is a solar water heating system; and (3) the heat sump is an evaporative water chiller. The solar panel and evaporative water chiller were available from previous projects and were not optimized for this project.

The facility utilizes zeolites in a heat-pumping model, which reduces the pressure below 0.0887 psia. Heat from stored ice is transferred via water vapor to the zeolite. The sublimated vapor releases its heat to the zeolite upon adsorption. The heat of adsorption varies inversely with zeolite temperature, but in the temperature range of most interest it is typically betweeen 1200 and 1400 Btu per pound. Circulating water carries the heat from the zeolite to the heat sump. The 1218.7 Btu removed from the ice for each pound of ice sublimated can be used to freeze an additional 8.5 pounds of water, cool ice, or cool a heat load.

Zeolite is a good compessor-condenser only when it is sufficiently dry. The major complexity of this heat-pumping technique is the process for drying the zeolite. The "dryness" increases with increasing temperature and decreasing pressure in the zeolite. The ZCAT facility utilizes hot water from a solar heating system and condensing water from an evaporative water chiller to dry the zeolite.

Table 1. Adsorber Comparison.

Temperature (°F)	Pressure (psia/torr)	Silica Gel	Zeolite
		(lbs water/100 lbs adsorber)	
167	0.256/13.2	3.1	20.2
77	0.087/4.5	10.2	23.6
Water cycled		7.1	3.4
Residual water		3.1	20.2

Systems testing of the zeolite heat pumping system was inititated on January 30, 1984. In the next 7 weeks, 17 test runs were made, critical temperatures were plotted, adsorption and desorption end points were plotted on zeolite isobars, and desorption versus time plots were drawn. Performance analysis was done and estimates of system effectiveness were made.

Table 2 summarizes the performance of 14 test runs. These test runs averaged 141% in performance when comparing actual water processed (cooling furnished) to the theoretical water processed. The average time to 90% of desorption was 70 minutes. Since the ZCAT facility did not have a vapor flow meter, adsorption time was not determined. The table also shows that performance increased significantly after long vacuum pumping (typically 6 to 10 hours) and then decreased with time if significant vacuum pumping was not done.

In conclusion, the zeolite chill-augmented test facility was designed, constructed, and tested and found to conform to the theory based on the zeolite manufacturer's data. Other noteworthy factors are listed below.

1) Testing results indicate that the ZCAT facility performance is dependent on the duration of vacuum pumping done prior to initiation of testing. No method of measuring the "cleanness" of the zeolite was available but indications of "gas poisoning" are implied by some test data.

2) Indications are that both adsorption and desorption flow rates were higher than projected.

3) The speeds of adsorption and desorption seem to be limited by the rate of heat flow out of and into the zeolite and out of the vapor during condensation.

4) The zeolite used for this test was not optimum. Other materials have been found to process more water (furnish project cooling) and leave less residual water.

The general design of the system was suitable for this project. However, the tanks housing the zeolites, condenser and manifold sections did not allow differential pressurization, and operational problems resulted. Thermal insulation of the system was marginal, allowing some ambient air and solar derived heating. Also a bidirectional low pressure vapor flowmeter should be used to more thoroughly analyze system performance.

Table 2. Summary of Performance.

Date of Test	Desorbed Water[1] (lbs)	Percent of Theoretical[2]	Desorption Time (min)	Time to 90% of Desorption (min)
1/30	10.40	179[3]	140	82
1/31	6.85	134	168	132
2/2	5.64	115	183	140
2/7	4.30	88	47	28
2/10	6.40	121[3]	81	47
2/14	6.80	155[3]	119	36
2/18	5.15	123	79	52
2/24	6.00	140	120	55
3/1	6.15	154[4]	87	56
3/6	5.50	131	100	80
3/11	1.64	51	120	59
3/12	4.74	296[4]	123	80
3/13	4.75	151	120	76
3/14	5.06	144	130	63
	Average	141	116	70

[1]Measured with a graded cylinder.

[2]Percent of measured water to that determined by pressure and temperature measurements and zeolite manufacturer's data.

[3]Long vacuum pumping the day before the test.

[4]Long vacuum pumping the night before the test.

HEAT TRANSMISSION STUDY OF DUAL FLOW BOREHOLE

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A study has been conducted at BRGM to investigate heat extraction from the ground through a dual-flow borehole with a central tube annulus. Water in a closed circuit flows down through the annulus, and is warmed by conductive exchange with the rock. It then flows back up through the central tube, and through the heat exchanger of the heat pump (this device is commonly used in Scandinavia and Germany, for example).

To simulate heat conduction between a well and the surrounding rock, a numerical model has been developed, along with simplified analytical solutions, using two different operating hypotheses: (i) specified recycle temperature at the heat exchanger; and (ii) specified energy output. Heat storage by a single borehole or many densely arranged boreholes also has been investigated, and type curves involving dimensionless variables have been developed.

These methods can be applied to a simple evaluation of relatively complex cyclic heat production operations (superposition of seasonal, weekly and daily cycles). They were applied to the evaluation of a project which is to be implemented in 1985. There will be a detailed moitoring program for the first operation cycle.

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