JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION

Professional Papers

AMERICAN SOCIETY OF CIVIL ENGINEERS

PNL-SA-8834

GEOHYDROLOGIC ASPECTS OF AQUIFER THERMAL ENERGY STORAGE

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Presented at a meeting on September 9, 1980
of the Geophysical Group and the Energy
Committee of the Boston Society of Civil
Engineers Section, American Society of
Civil Engineers

Work Supported by
The U.S. Department of Energy
Under Contract DE-AC06-76RLO 1830

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ACKNOWLEDGMENT

Information contained in two reports was freely used in preparing this paper: Reilly, R. W., A Descriptive Analysis of Aquifer Thermal Energy Storage Systems, PNL-3298, Battelle, Pacific Northwest Laboratory, Richland, Washington, June 1980; and, Meyer, C. F. and Walter Hausz, Guidelines for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage Systems, (Draft Report) TEMPO-General Electric Co., Santa Barbara, California, August 1980.

The data provided by these publications are greatly appreciated.

INTRODUCTION

During the last decade, the storage of thermal energy in aquifers has received considerable attention. The motivations for storing large quantities of thermal energy on a long-term basis have been numerous, including: a) the need to store solar heat that is collected in the summer for use in the winter months, b) the cost effectiveness of utilizing heat now wasted in electrical generation plants, c) the need to profitably use industrial waste heat, and d) the need to more economically provide summer cooling for buildings. The end objective, of course, is the conservation or displacement of costly and scarce petroleum fuels. Seasonal aquifer storage should contribute significantly to satisfy the above needs. Most geologists and ground-water hydrologists agree that heated and chilled water can be injected, stored, and recovered from aquifers. Geologic materials are good thermal insulators; and potentially suitable aquifers are distributed throughout the United States. Recent studies and small-scale field experiments have reported energy recovery rates above 70% for seasonal storage. The U.S. Department of Energy predicts that, by the year 2000, seasonal aquifer storage could replace or conserve up to 350 million barrels of oil per year. However, successful demonstration of large-scale aquifer thermal energy storage has not yet been attempted and the concept's economic feasibility and institutional acceptability have yet to be established.

Many potential energy sources exist for use in an aquifer thermal energy storage system. These include solar heat, power plant cogeneration, winter chill, and industrial waste heat sources such as aluminum plants, paper and pulp mills, food processing plants, garbage incineration units, cement plants, and iron and steel mills. For heating, energy sources ranging from 50 to over 250°C are available. Potential energy uses include space heating on an individual or district scale, heating for industrial or institutional plants and heat for processing/manufacturing.

Investigation of Aquifer Thermal Energy Storage (ATES) is a major part of the Seasonal Thermal Energy Storage (STES) Program, managed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy, Office of Advanced Conservation Technologies (OACT). The STES Program is one element of OACT's Thermal Energy Storage Program.

AQUIFER THERMAL ENERGY STORAGE DESCRIPTION

An ATES installation in its simplest form is composed of a pair (doublet) of fairly conventional water supply wells drilled into an aquifer. During operation, the ground water is withdrawn from one well, heated (or chilled) in a heat exchanger, and then returned to the same aquifer through the second well (Figure 1). The thermal energy is stored in the aquifer until needed. At recovery, the second well is pumped, and the hot (or chilled) water circulated through a heat exchanger to recapture the stored energy and then returned to the aquifer through the first well (Figure 2). The thermal energy can then be employed for space or process heating (or cooling), thus reducing the need for generation of primary energy. The cycle is repeated on a seasonal or other temporal basis (Figure 3). The concept is simple, inexpensive, and relatively efficient.

Aquifers are good heat capacitors. Consequently, under favorable conditions, a large amount of heat (or chill) can be stored in a relatively small aquifer volume. At a typical aquifer thermal capacity of 0.2 cal/g/^{o}C, a ground-water system has capability of storing up to 30 Btu's per degree (F) temperature change per cubic foot of aquifer volume. As a practical example, an aquifer volume of 1.73×10^{7} ft^{3} (a cylinder with a radius of 235 ft and height of 100 ft--assuming "plug" flow and negligible thermal loss) could store 3.1×10^{10} Btu of heat (9070 MW-hr) assuming a water injection rate of 200 gpm at a temperature rise of 144^{o}F (4.2 MW) over a 90 day period.

When heated water is injected into the receiving well of an ATES doublet system which fully penetrates an idealized porous media aquifer (uniform permeability, porosity, thickness, thermal properties and no regional ground-water flow), the water moves away from the injection well in cylindrical form (radial symmetry) with a temperature gradient (thermocline) that separates the heated water from the ambient-temperature ground water. The injection process (because of the fluid pressure increase) establishes a higher than ambient potentiometric surface and resultant streamlines adjacent to the injection well. In the idealized case, the lines of equipotential inscribe circles around the injection well, with potential gradient and flow velocity being greatest near the well and decreasing inversely with distance from the well.

Evaluation of the thermal interface between the injected hot water and the colder aquifer solely by classical molecular and thermal diffusion analysis would show that the thermocline in the idealized case is extremely sharp (high heat gradient) and essentially vertical in attitude. Analsyis by the same methods also would show that heat recovery (pumping from the heat injection well) would be very high (more than 95%). However, in the "real world" there are a number of other factors that greatly modify the gradient and form of the thermocline and generally combine to reduce recovery efficiency.

Hydrodynamic dispersion acts to modify the thermocline gradient to a much greater extent than thermal diffusion. Hydrodynamic dispersion is a complex function (in porous media) of media grain size, shape and porosity and results from stream line "tortuosity." Ground water flows through irregular pore spaces and paths of different length in the media which result in varying local water velocities. The paths are interconnected, and as they diverge and rejoin, waters of different temperature are comingled. This results in a spreading or blurring (reduced gradient) in the thermocline.

The heated water within the thermocline is less dense and less viscous than the ground water outside of the thermocline. The pressure gradient within the thermocline will be less than the gradient in the surrounding aquifer, resulting in a greater horizontal pressure gradient at the top of the aquifer than at the bottom. Therefore, the thermocline will advance more rapidly at the top than at the bottom, producing a tilted interface. In other words, the body of heated water within the thermocline has the shape of an inverted truncated cone rather than a cylinder. The tilting is aided by the buoyancy of the less dense hot water which tends to float to the top of the aquifer. The viscosity/density effects are amplified by hydrodynamic dispersion. During the thermal energy recovery cycle, the viscosity effect will cause the thermocline to move inward more rapidly at the top of the aquifer than at the bottom; thus partially reducing the thermocline tilt. However, the buoyancy effect will continue to act in increasing tilt during the heat recovery cycle.

Figures 4a and 4b are sections through a confined aquifer (one-half of a storage zone) which shows an analytical synthesis of an ATES system which incorporates the factors discussed above.[1]

Shown in Figure 4a is the situation after 90 days of injection of 1 MGD of 350^{O}F water into an aquifer 100 ft thick. Each of the effects was analyzed in closed form separately, to better understand the nature and importance of the effect. They were then combined by superposition, with suitable approximations in non-linear overlap areas. Isotherms are shown at 80^{O}, 200^{O}, and 320^{O}F. Hydrodynamic and thermal dispersion dominates the thermocline spread. Also shown are the isotherm contours in the confining cap and confining bottom showing more penetration near the well where exposure to heat has been longest. The dashed line shows the location of the thermocline if no loss had occurred from hydrodynamic/thermal dispersion.

Figure 4b shows the approximate location of the isotherms after a period of withdrawal of less than 90 days. Withdrawal was stopped when the temperature of water withdrawn dropped to 320^{o}F, a mixture of 350^{o}F water over most of the well depth with colder water near the bottom of the well. During withdrawal the radial separation between isotherms expands greatly as expected from the preceding discussion. The retreating hot water leads to the confining cap and bottom being hotter than the adjacent aquifer, so some heat lost to these layers is returned to the aquifer as indicated by the isotherms. The continuing buoyancy of the hot water leads to first the 320^{o}F contour, then the 200^{o}F contour reaching the bottom of the well, so the average well temperature, with mixing, decreases. Again, the dashed line shows the thermocline location had no loss occurred from dispersion.

Numerical integration of the volume within each isotherm contour indicates that about 31% (recovery of 69^{o}) of the injected energy remains in the aquifer and confining layer after one cycle. More heat could be withdrawn if the application is not penalized by temperatures below 320^{o}F.

Each cycle leaves energy behind, as an increasing buffer reducing the thermal gradients outside of the stored energy zone, hence reducing the rate of heat loss and increasing the recovery efficiency in succeeding cycles.

The doublet configuration averts many potential operational and environmental problems. Since the in-situ ground water is used as the storage medium (rather than a newly introduced, chemically different water), the potential for chemical or physical reactions of the water with the aquifer matrix is reduced, and thus a major cause of clogging of the aquifer can be minimized. The doublet concept also precludes any problems with ground-water depletion, since virtually all of the water withdrawn is immediately returned to the aquifer. There are numerous possible ATES well configurations in addition to the basic doublet. For larger sized systems, either a number of separate doublets, rows of doublets, concentric rings of injection and withdrawal wells, or other multiwell patterns probably will be required.

The key to ATES's effectiveness is that the recovered energy is energy that would have been wasted without seasonal storage, generally because no demand existed at the time of availability. This mismatch of energy supply and demand over time is the common occurrence that makes ATES attractive.

Available energy in this category includes cogeneration, climate-related energy, and industrial waste heat.

Aquifer Thermal Energy Storage Projects

Storage of thermal energy in aquifers has received widespread attention only within the last decade since the onset of the "energy crisis." This new interest in ATES is international in scope, with considerable effort being made in the United States and Scandanavian countries to implement demonstration projects.

The United States' effort in ATES is centered in the Seasonal Thermal Energy Storage (STES) Program, managed by the Pacific Northwest Laboratory (operated by Battelle Memorial Institute) for the U.S. Department of Energy (DOE), Office of Advanced Conservation Technologies (OACT).

Under the STES Program, three projects are presently being implemented under DOE funding to demonstrate the commercialization potential of ATES technology. These projects are in aquifer characterization/conceptual design status (Phase I). Project Phase I is scheduled for completion in mid-1982. If these demonstrations are determined to be feasible, some or all of the projects will proceed to final design, construction and operation (Phase II) under cost sharing between the DOE and the operating entity. Phase II will be completed in 1985. Table 1 gives information on the contractor, location, type, energy source and energy use for the three demonstration projects.

TABLE 1. ATES Demonstration Projects (Phase I)

Contractor	TRW Incorporated	Dames & Moore	Univ. of Minnesota
Location	Bethel, Alaska	Stony Brook, New York	Minneapolis, Minnesota
Type	Heat 95°C	Chill	Heat 150°C
Energy of Source	Diesel Exhaust and Cooling Water	Cooling Tower	Cogeneration Steam
Energy Use	District Heating	Building Air Conditioning	Campus Heating

In addition, institutional environmental and technical issues affecting commercialization of ATES are being evaluated in the STES Program, and field tests are in progress to provide technical information, and operational experience in support of the demonstration projects.

Aquifer Thermal Energy Storage Evaluation Factors

In addition to surface facility engineering (heat exchangers, piping, pumps and valves), which seems to be straightforward, there are a number of factors that must be considered in development of ATES Systems. These factors are: 1) legal/institutional, 2) environmental, 3) economic, 4) chemical, 5) biologic, and 6) geologic/hydrologic. Each of these factors are extremely important in analysis and design of ATES systems; and failing to consider and evaluate any one of the areas could prevent or complicate system implementation. However, the purpose of this paper is to discuss, in some detail, the various geohydrologic factors that are important to ATES and some of their interrelationships.

Geohydrologic Factors

Table 2 shows the geologic factors or parameters that are important and require measurement and evaluation for implementation of ATES systems.

TABLE 2. Geohydrologic Parameters Important to ATES

Aquifer Factors

- Permeability (Vertical and Horizontal)
- Porosity
- Thickness
- Gradient
- Regional Flow
- Thermal Conductivity
- Specific Heat (Thermal Capacity)
- Boundaries

Aquiclude/Aquitard Factors

- Permeability
- Boundaries
- Thermal Conductivity

Permeability, a measure of the relative ability of a porous medium to transmit water, is of first-order importance in design and evaluation of ATES systems. Permeability is a property of the porous medium that is dependent upon the size and shape of the pores. Media permeability (k) multiplied by aquifer thickness (m) equals aquifer transmissivity, which is a measure of the rate at which water moves through a unit width of the aquifer under a unit hydraulic gradient.

A high permeability (and transmissivity) is desired to produce the largest volume of water from a well with the least drawdown. As an example, Figure 5 shows well drawdown (s) plotted against permeability (k) from solution of the steady-state Thiem equation (an approximation of maximum well drawdown) for a 33 meter (100 ft) thick aquifer at a pumping rate of 45 m^3/hr (200 gpm). Forty-five m^3/hr probably is a lower water injection/withdrawal rate at reasonable temperature differentials for pratical commercial ATES heat or chill storage systems. Permeability is in "darcys." The darcy is defined by the volume of water in cubic centimeters flowing in 1 sec through a 1 cm^2 area of porous medium under a pressure gradient of 1 atm/cm. The darcy is equal (at 60^{o}C) to 18.2 gal/day/ft^2 (gal/day/ft^2 is the "Meinzer" unit coefficient of permeability formerly widely used to define permeability). Figure 5 shows, for the given conditions, that a well water level decrease (drawdown) of about 30 meters occurs if the permeability is approximately 2 darcys. A drawdown of 30$\pm$ meters would be unacceptable for the given system under water table (unconfined) conditions, but may be marginally acceptable for some artesian aquifer systems. In any case, it would be preferable to limit the drawdown to a few meters. In this situation, a well drawdown of about 10 meters would result at a permeability of 5 darcys and a drawdown of 3.5 meters at 15 darcys.

Conversely, particularly for higher temperature ATES systems, low permeability is desirable to prevent excessive tilting of the thermocline from viscosity/buoyancy effects. Figure 6 shows upper limit permeability values required to prevent excessive tilting plotted against aquifer thickness for three injection temperatures. Combinations of permeability and aquifer thickness that would fall above the respective injection temperature curves would result in inefficient heat recovery. Thus, for a reference case aquifer thickness of 33 meters, permeability should be less than 2.7 darcys for an injection temperature of 120^{o}C. The resultant well drawdown in this case at a water injection/withdrawal rate of 45 m^3/hr would probably be unacceptable, and the injection temperature would have to be reduced; or multiple injection/recovery wells would be required. As shown in Figure 6, upper limit permeabilities (for a 33 meter thick aquifer) are 4 darcys for a 90^{o}C injection temperature and 10.3 darcys for a 60^{o}C injection temperature. The data shown in Figure 6 were derived by Hellstrom, Tsang and Claesson(2) from operation of a numerical model(3) which computes heat and mass flow in water-saturated porous media.

Isotropic media (the same permeability in all directions) is desirable to obtain maximum water supply from a well with minimum drawdown. Conversely, anisotropic conditions with vertical permeability being much less than horizontal permeability is desirable for ATES systems to resist tilting of the thermocline. Sedimentary earth materials generally have horizontal permeabilities from 5 to 10 times greater than the vertical permeability--a definite benefit for high-temperature ATES systems.

Porosity of a rock or soil is its property of containing interstices or voids (pores). Porosity is expressed as the ratio of the pore volume to the total volume of the rock (a decimal fraction or percentage). With regard to the storage and movement of water in a porous medium, only the system of interconnected interstices (effective porosity) is significant. It is obvious that the porosity of the aquifer matrix is an important consideration in ATES systems, because it determines the amount of water (and the heat or chill) that can be stored per unit volume of the aquifer. Most aquifers suitable for ATES will be in clastic sediments with effective porosities of 10% to 20%. Most aquifers that occur in consolidated igneous and metamorphic rocks which have secondary (fracture) porosities of less than 5% will not be satisfactory for ATES. Applicability of aquifers in carbonates and evaporites for ATES is also limited.

Porosity is also important because it is one factor which controls groundwater velocity. Fluid flow velocity in a porous medium is proportional to the permeability and gradient and inversely proportional to the porosity: $v = kI/p$ where v is the interstitial fluid velocity, k is the media permeability and I is the hydraulic gradient. For ATES considerations in this aspect also, a high porosity is desirable to reduce the fluid velocity and hydrodynamic dispersion.

Figure 7 shows the results of a computer model study[4,5] to evaluate regional ground-water flow considerations in thermal front breakthrough for an ATES doublet well system. Location of the thermal fronts are shown for several time invervals. Figure 7a shows that under the assumed conditions (well spacing of 500 meters, steady-state water injection/withdrawal rate of 7 m^3/min, and a porosity of 20%), thermal breakthrough occurs after 2.1 years of operation with no regional ground-water flow. Figure 7b shows that breakthrough occurs in 1.8 years if a required ground-water flow velocity of 100 m/yr is imposed on the system (flow is from left to right, as indicated by the arrow). It is evident that ground-water velocities in this order will not materially effect ATES systems. Regional velocities in confined (artesian) hydrologic systems are usually very low. Ground-water movement in unconfined aquifers can be much greater (up to tens of meters per day) and would have to be considered in ATES system selection and design.

Aquifer gradient was considered in the discussion of porosity and permeability as one element that controls velocity, and this is the main interest in gradient. Gradients in natural aquifers are in the order of 0.1% or less, and thus are unlikely to directly influence the stored thermal water from upgradient movement due to buoyancy of the heated water.

The thermal characteristics of the aquifer are important in determining the heat capacity of the system and conduction of heat out of the storage volume. Thermal conductivity is the quantity of heat conducted in unit time across an element of surface under a given thermal gradient--units of cal/cm sec ^{o}C. Porous geologic materials, saturated with water, do not vary widely in thermal conductivity values.[6] Sands, silts and clays (saturated) have thermal conductivities on the order of 1×10^{-2} cal/cm sec ^{o}C. Thermal conductivity of these materials drops to about 30 to 50% of the saturated value under unsaturated conditions. Compressing the rock increases thermal conductivity slightly, and thermal conductivity decreases slightly with increased temperature. Water has a thermal conductivity of 1.5×10^{-3} cal/cm sec ^{o}C at 30^{o}C. Basically, earth materials are good insulators as considered for ATES conditions, and differences in their thermal conductivities are relatively small; their changes in thermal conductivity are of second-order importance.

Thermal capacity (specific heat) of a material is the quantity of heat required to produce unit change of temperature in unit mass (units of cal/g/^{o}C). Thermal capacity of sandstone is about 0.2 cal/g/^{o}C. Variation in thermal capacity of earth materials, as with thermal conductivity, is expected to be small, thus changes in thermal capacity will be of second-order importance. Earth materials and the contained water are basically good heat capacitors.

Areal aquifer boundaries (together with aquifer thickness) will determine the volume available for storage of heat or chill. Aquifer volume generally will be much greater than the required storage volume, but boundary location may be of interest if the proposed ATES storage site is near zones of recharge or discharge, or on the periphery of a ground-water system.

Characteristics of aquicludes/aquitards are of interest and importance in evaluating heat storage in confined aquifers. It is important that permeability of the confining bed is low and that the bed has areal continuity to prevent convective loss of water and heat. It is desirable that the confining bed have a low thermal conductivity, but this will be of second-order importance since the geologic units involved probably will vary by only a factor of two or three in thermal conductivity.

Characteristics of the unsaturated zone overlying the thermal storage area in an unconfined aquifer is of interest for the same reason. The thermal conductivity value of the unsaturated earth material probably will be satisfactory. However, it is important that the overburden be thick enough to prevent heat loss to the atmosphere and also that it isolates the storage zone from direct access by precipitation and surface water.

Geohydrologic Parameter Measurement

Methods of measuring geohydrologic parameters have been derived from water supply, petroleum production and agricultural technologies. Most of the measurement methods are directly applicable to ATES systems, and provide adequate parameter values for design and engineering purposes. Many of the measurement techniques require access to the subsurface aquifer or formation under investigation. This access is usually provided by wells, which makes extensive field investigations a costly procedure. There is a continuing search for more cost-effective, methods for in situ measurement of geohydrologic characteristics.

Aquifer permeability/transmissivity is generally determined by well pumping tests and application of various graphical, analytical or numerical techniques for analysis of the resultant water level drawdown data. Aquifer transmissivity is the characteristic actually determined from the test, and an average permeability derived by dividing the transmissivity value by aquifer thickness. The derived permeability/transmissivity is generally the horizontal value (or in some cases a composite horizontal-vertical value). Pumping tests can be designed to skew the measurement toward vertical components. Field determination of aquifer permeability/transmissivity has generally been adequate for analysis of ground-water supply, and probably provides the best means of obtaining permeability/transmissivity data for ATES.

Permeability can also be determined in the laboratory by measuring fluid flow-through and pressure drop across a core sample of geologic media. The test is more applicable to consolidated porous media than unconsolidated material or rock with secondary (fracture porosity). Both horizontal and vertical permeability can be determined by proper orientation of the core. Laboratory permeability tests are generally less reliable than the field tests due to the small core size and possible disturbance of the sample, although the tests may provide information on comparative permeability and may provide the only available information on vertical (or other oriented) permeability.

Porosity of geologic material can be determined by either field or laboratory tests. Well pumping test analysis yield "effective" porosity data for unconfined aquifers. Geophysical well logging (neutron-neutron) can measure the "total" porosity of geologic formations adjacent to the well bore. Porosity can be determined from fluid displacement tests on core samples in the laboratory. Both the field and laboratory methods of determining porosity seem adequate for ATES analysis.

Vertical and horizontal boundaries and stratigraphy of earth materials are determined from field studies. Well evaluation, geologic mapping, geophysical logging and surface geophysics, individually or in concert can be applied to resolve these parameters. If there are adequate time and funds available, these methods are fully adequate for ATES analysis.

Measurement of ground-water gradient can only be determined from well measurements (and from surface geophysics in some special cases). Thus, adequate definition of the ground-water surface is dependent on the number and location of wells. Again, if time and funds are available for test/observation wells, the gradient measurement method is adequate.

Ground-water velocity can be measured from field tracer tests, well dilution tests and calculated from porosity/permeability/gradient relationships. Measurements generally will be average or order-of-magnitude values, but probably adequate for ATES assessment. The related hydrodynamic dispersion can be measured by field tracer tests. The test methods give order-of-magnitude values. Better methods of measuring hydrodynamic dispersion are needed.

Thermal characteristics of earth materials (thermal conductivity and heat capacity) can be determined in the field or laboratory by application of heat across a section of the material and measuring temperature change in the media with time. The field methods (subsurface) are costly and time consuming. Laboratory core or sample analysis for thermal characterization appears adequate.

Aquifer Thermal Energy Storage System Simulation and Optimization

It is obvious that design and operation of complex ATES geohydrologic systems will require simulation of the system to provide predictive and optimization capabilities. The examples of geohydrologic parameter relationships discussed above were derived by simple analytical methods or somewhat more complex numerical models.

Technology development in simulation of complex hydrothermal systems has evolved to numerical computer codes that solve the applicable heat and fluid flow equations. The codes can handle most of the parameters involved in the physical system, thus numerical models of the systems can be developed. The present codes are adequate for prediction of ATES system response, given a specific system design. They also can assist in system design through iterative selection. Their shortcomings, in general, are in areas of optimization and system size. The existing codes do not operate with adequate speed or efficiency to provide true system optimization; and optimization of ATES system design and operation is required for cost-effective development of the technology. Most of the codes can either model a small ATES geohydrologic area/volume in considerable detail or model a large area in broad detail.

Much effort is being made in refining the codes applicable to ATES modeling, and these problems are expected to be resolved in the near term.

CONCLUSIONS

Investigation of ATES technology indicates that it is a cost-effective, fuel-conserving technique for provisions of thermal energy for residential, commercial and industrial uses. Most of the existing methods and techniques for measuring geohydrologic elements important to ATES are satisfactory. Small scale field tests have been successfully demonstrated, and larger scale demonstration projects are in progress.

With a suitable institutional framework, ATES promises to provide a significant portion of the nation's future thermal energy.

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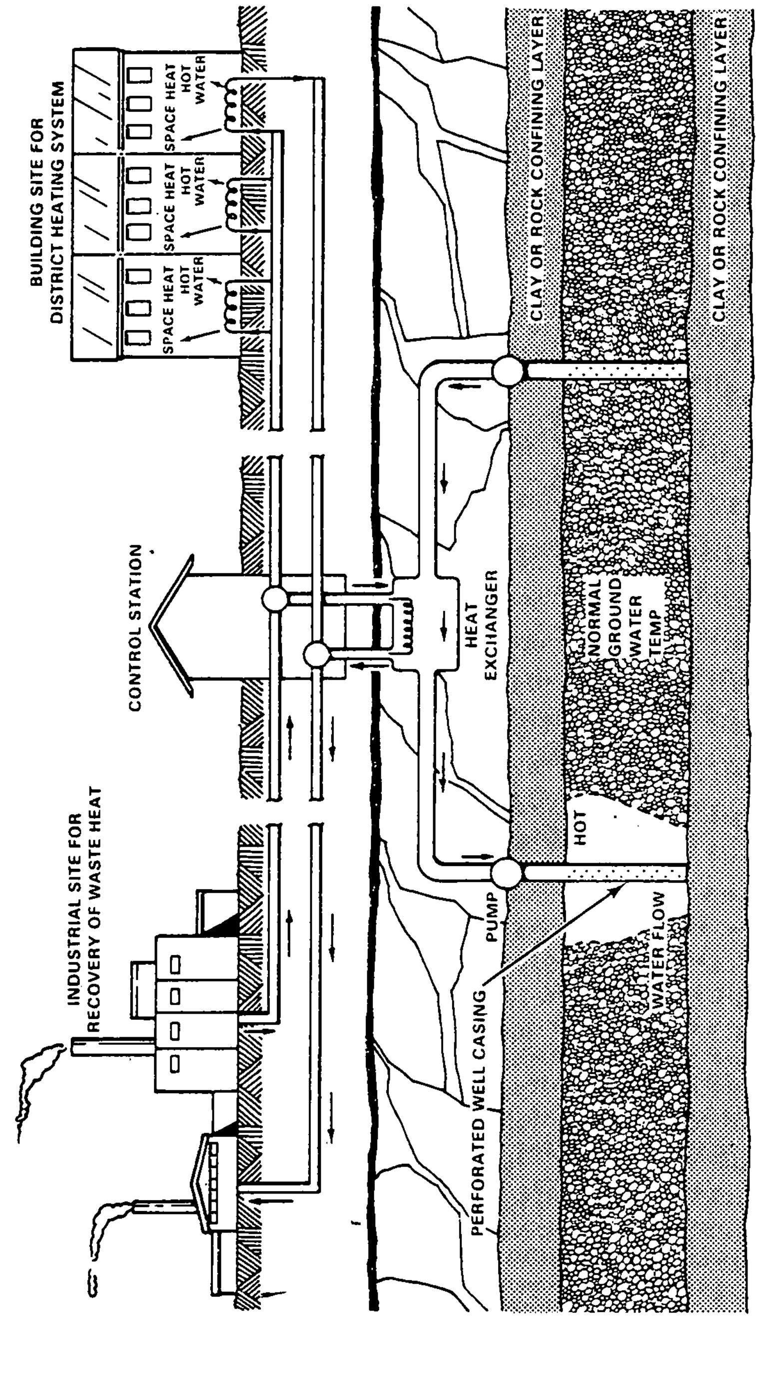
SEASONAL THERMAL ENERGY STORAGE

HEAT INJECTION (INITIAL)

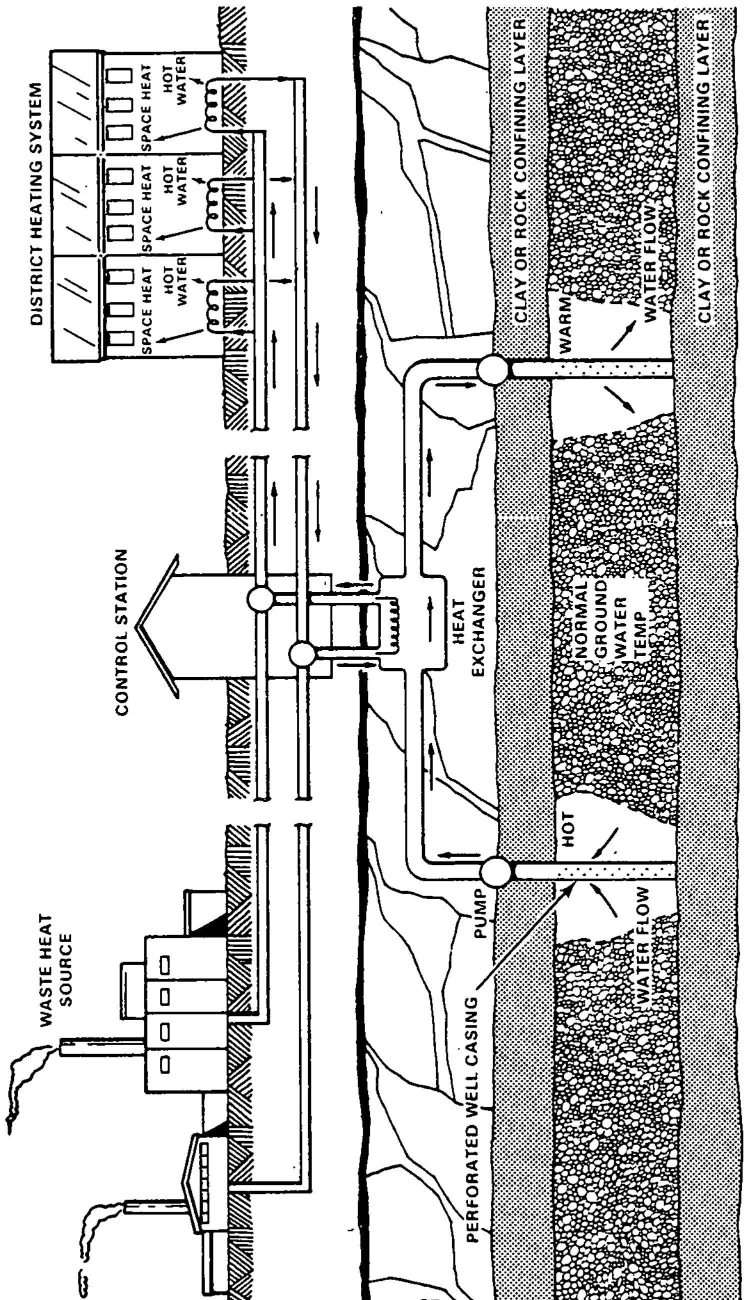


DOUBLET WELL AQUIFER STORAGE SYSTEM

FIGURE 1

SEASONAL THERMAL ENERGY STORAGE

HEAT RECOVERY CYCLE

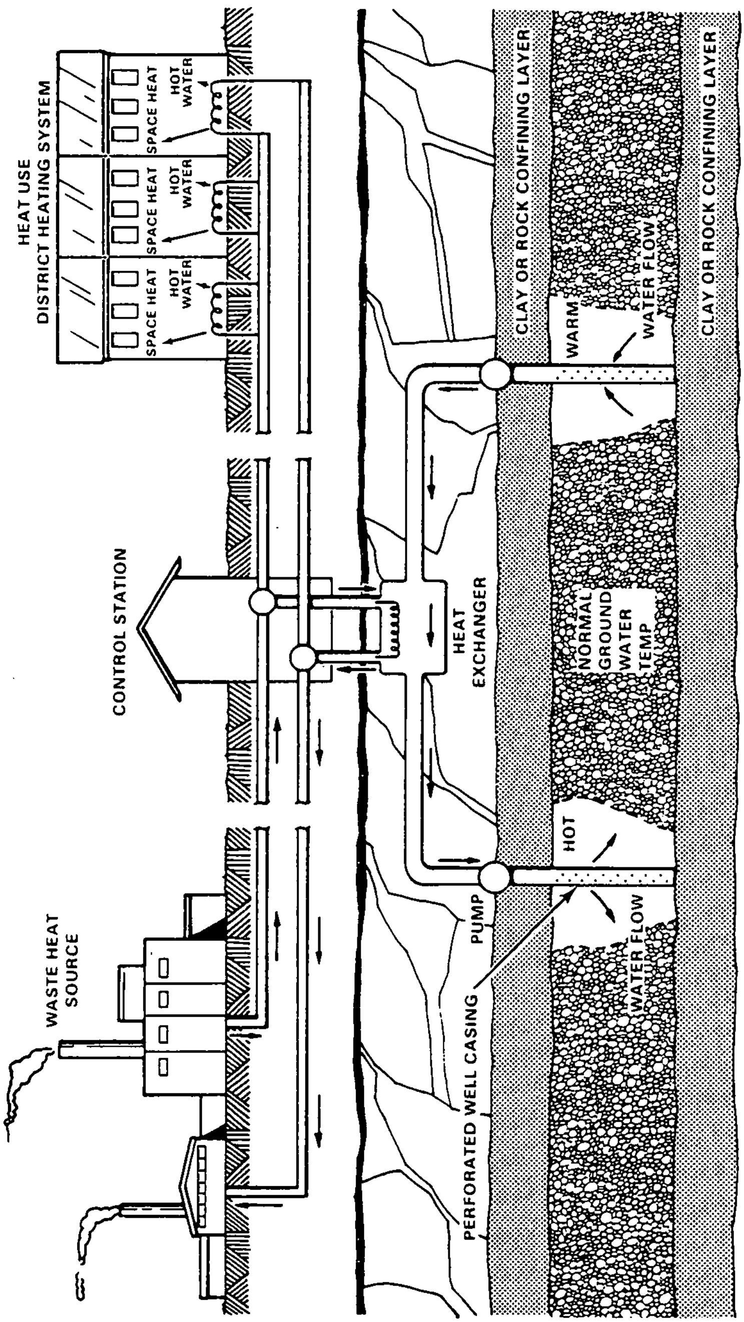


DOUBLET WELL AQUIFER STORAGE SYSTEM

FIGURE 2

SEASONAL THERMAL ENERGY STORAGE

HEAT INJECTION CYCLE (CONTINUED)



DOUBLET WELL AQUIFER STORAGE SYSTEM

FIGURE 3

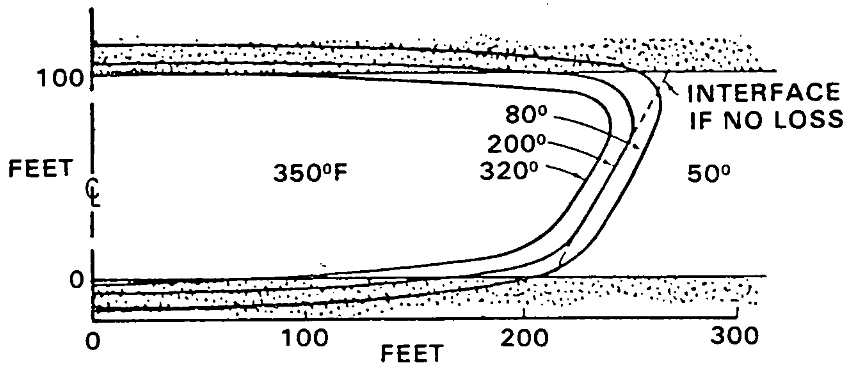


FIGURE 4a. ATES Isotherms-Injection Cycle
(Meyer, 1980)

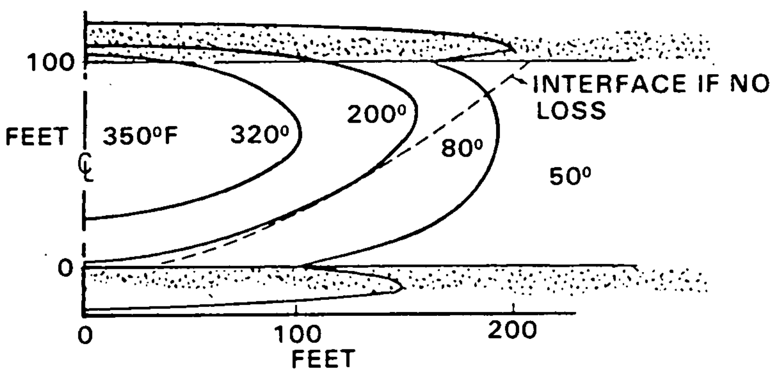


FIGURE 4b. ATES Isotherms-Recovery Cycle
(Meyer, 1980)

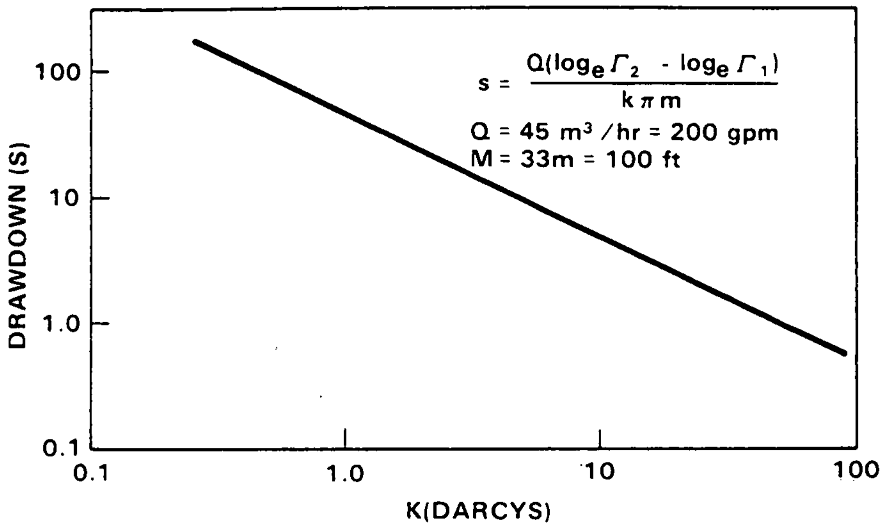


FIGURE 5. Water Levêl Drawdown

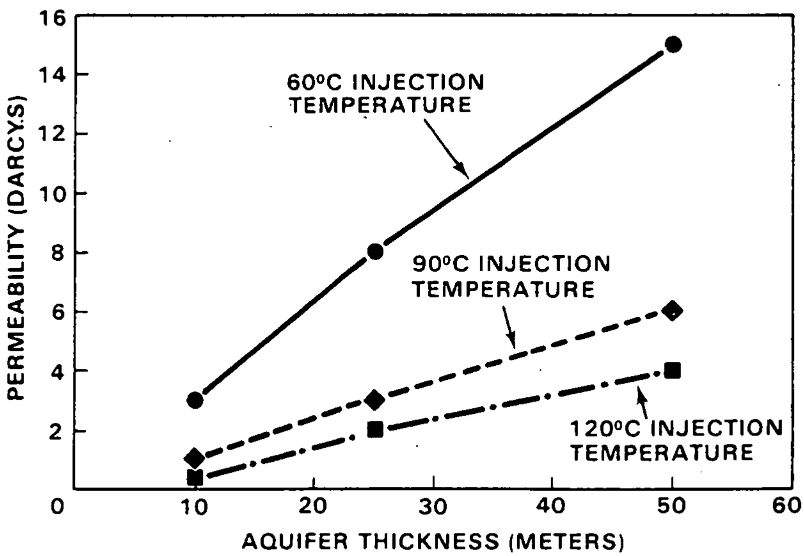


FIGURE 6. Upper Limit Permeability (After Hellstrom, 1979)

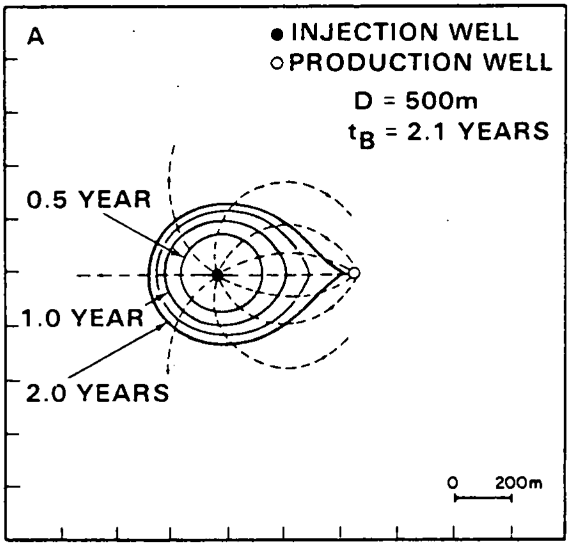


FIGURE 7a. Thermal Breakthrough Without Regional Ground-Water Flow (Lippman, 1978)

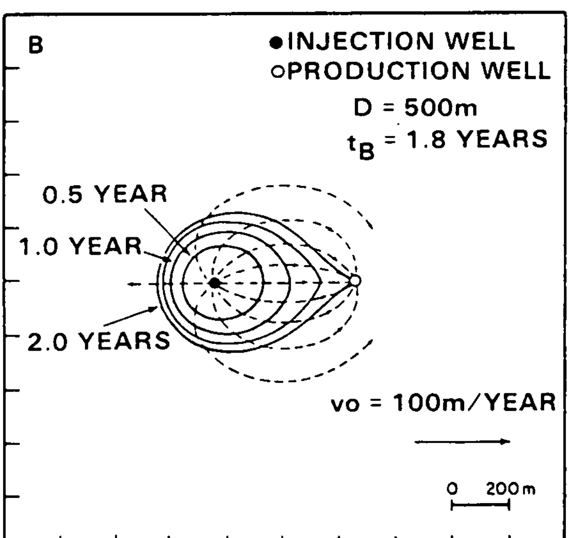


FIGURE 7b. Thermal Breakthrough With Regional Ground-Water Flow (Lippman, 1978)