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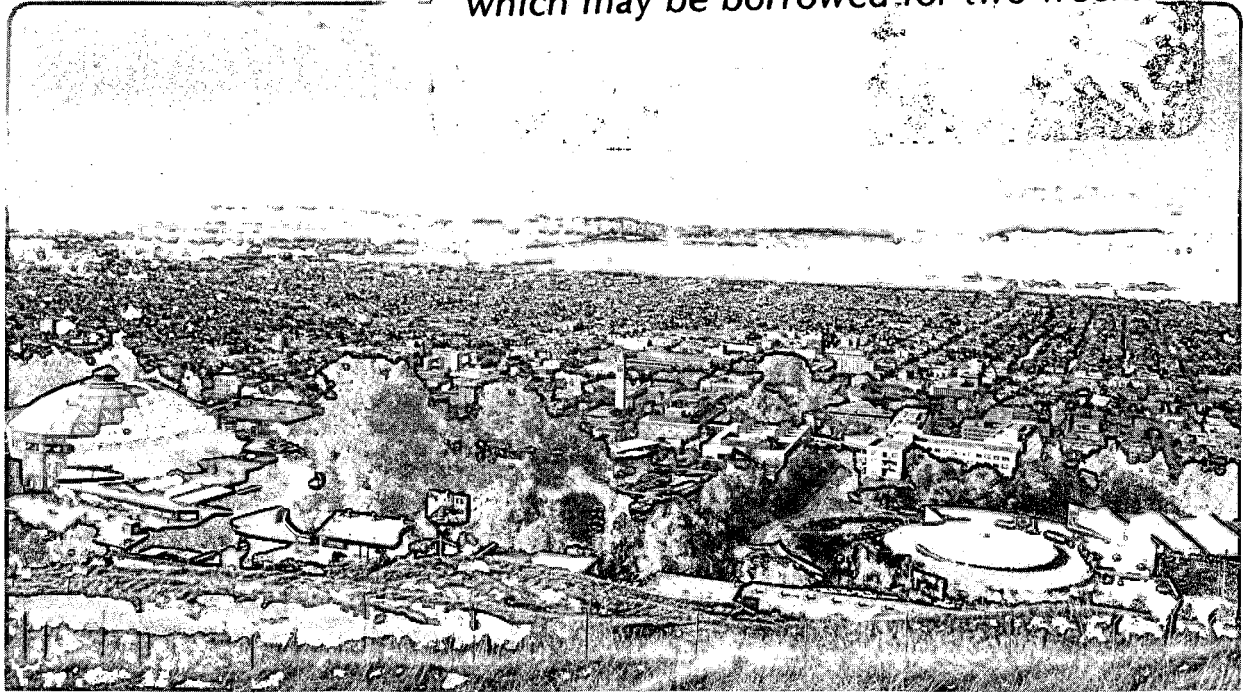
To be presented at the 21st Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 25-29, 1986

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July 1986

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Seasonal Heat Storage in Unsaturated Soils: Example of Design Study

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ABSTRACT

Unsaturated soils are proposed as a preferred storage medium for low temperature heat storage applications. Their use is justified in warmer climates, in areas where shallow aquifers are not available or are needed for water supply. The use of unsaturated soils for heat storage presents a different set of problems than does the use of aquifers.

The theory and proposed practice of unsaturated soil heat storage is discussed and a proposed storage-system design is presented. One of the key elements of the design is the maintenance of soil moisture conditions, which allows an approximate description of the storage system in terms of constant thermal parameters. The engineering aspects of this design are described and a mathematical model of the storage system is developed. The model is first verified against analytical solutions for simplified cases. Then several years of transient storage-system behavior are simulated under differing charge and load conditions. The results indicate the range of operating conditions possible for this unsaturated soil heat storage system. Field experiments are proposed for the validation of the critical features of this model.

1. BACKGROUND

1.1 MOTIVATION – Seasonal heat storage is considered to be an essential element in the utilization of alternative energies with low-temperature heat supplies, as it helps in solving some of the inherent problems arising from the stochastic nature of the supply-demand pattern. The main alternative sources considered here are solar energy, natural thermal waters, and industrial waste heat. A prospective future source of heat is associated with the use of large-scale electrical energy storage in batteries, fuel cells, and compressed air.

Significant advances have been reported, demonstrating the feasibility of the operation of seasonal heat storage in various soil formations – by far the least expensive and most widely available storage medium (1*, 2, 3). However, these applications refer mainly to colder or moderate climatic zones, while only limited progress on the application of this concept is reported for warm climatic zones (WCZ). While seasonal heat storage in WCZ may be expected to benefit from lower heat losses to the environment and higher solar inputs, the lower specific demand for domestic heat and shorter heating periods make the need for heat storage seem less urgent and the investment less attractive. Cursory analysis indicates that this need not be the right conclusion. These zones, which include the southwest United States, parts of Australia, and the Mediterranean countries, are subject to intensive growth in population and in industrial and agricultural development. They should be expected to develop and benefit from suitable methods of heat storage.

1.2 METHOD OF APPROACH – This report analyzes the characteristic features of WCZ which determine the preferred methods of seasonal heat (or cold) storage, including climatic factors, sources and demand of heat (or cold), hydrogeological factors, technological developments, and accumulated experience from other climatic zones. Unsaturated soils are indicated as the most suitable medium for seasonal heat storage under these conditions. A preliminary description and mathematical model of a seasonal unsaturated soil heat storage (USHS) system for a specific configuration have been presented (4). The present report describes the further analysis of this model, through several stages of optimization and sensitivity analysis.

1.3 SCOPE OF INVESTIGATION – For the numerical modeling studies, a solar heat-supply pattern typical of WCZ and a heat demand with interyear variability are imposed, and the USHS system is modeled through several years of transient response. A specific case of greenhouse heat demand with root zone heating is considered. This should not be considered as a limitation of the applicability of USHS, as these conditions present rather severe design demands, which can be readily relaxed for alternative types of supply and demand. The model is based on an axial 2-D configuration, deemed to provide an efficient heat transfer area and storage volume. System dimensions are improved in several stages of sensitivity analysis. Analytical models of simpler configurations are investigated, and used for verification of the computations.

The model uses linear and nonlinear approximations of the heat transfer equations, but does not consider coupled heat and fluid flows in the unsaturated-soil storage medium. This is shown not to be necessary under the assumed storage conditions in which fluid flow in the unsaturated soil is small. There is no attempt to include details of engineering design, but the available new technological options are indicated. This information may allow a preliminary economic estimate of the proposed storage system.

2. METHODS OF SEASONAL HEAT STORAGE

2.1 PRINCIPLES OF DESIGN – A number of approaches to the design of seasonal heat storage have been extensively described in the literature of the last decade (1, 2, 3). Several reports deal with guidelines and principles of design (5, 6, 7). Generally, the storage method adopted depends on the local availability of storage media, on environmental conditions, on operational temperatures of sources and demand, and on the type of back-up system required. For example, the storage temperature, which can be above, below, or intermediate to the mean ambient temperature, is determined by environmental conditions and source temperatures. Storage temperature in turn influences the physical design of the storage system and the operational procedure of heat supply and extraction. Another classification is made with regard to the source of stored energy: active replacement, passive replacement, or recharge from a semi-infinite reservoir (earth). Again, each option requires a different technical approach in order to optimize its potential.

Not all design needs can be satisfactorily fulfilled at present, which is not surprising for a recently developed technology. The research and development needs in this area (8) are mainly on the topics of heat transfer, heat losses to the surroundings, entropy losses, drilling, and installation methods. Every adopted design has to account for these (possibly temporary) deficiences by a certain amount of over-design.

* Numbers in parentheses designate References at end of paper.

2.2 STORAGE MEDIA – There are a number of proposed storage media. Several have been analyzed theoretically or tested experimentally (9, 10). Choice of a storage medium is guided by the principles of design discussed above. These guidelines, when applied to WCZ, indicate that unsaturated soil is likely to be the only available storage medium. Artificial or excavated storage is excluded for seasonal storage on technological and economic grounds. Rock formations are rare and likely to be too expensive for storage installation. Aquifers are likely to be used or destined for use as sources of water supply, which makes them incompatible with heat storage use. Aquifers with poor water quality, unusable for water supply, are available in more arid zones, but tend to be found at greater depth, thus increasing installation and operation costs. The analysis of the capabilities of unsaturated soils to act as seasonal storage media is therefore seen as a primary goal in the introduction of this technology into WCZ.

2.3 ENVIRONMENTAL CONSIDERATIONS – The effects of environmental conditions in WCZ may be considered under the following headings.

Climate – Climate determines the length of the charge and demand periods, typically 8 months (for solar input) and 4 months, respectively. If cold storage is planned, the cooling demand may last 5-7 months. The insolation intensity and high ambient temperatures allow high collection temperature with simple solar collector design and cost. In some cases, solar input is available during the demand period, typically 20-25% of the yearly total. There are low heat losses from storage and transport between storage and users, due to high ambient soil and air temperatures and high thermal resistance of dry surface soil. Average ambient temperatures for ground surface, deep soil, and groundwaters are 17-19 °C, compared to 4-8 °C for cold zones and 10-13 °C for intermediate climatic zones. In the more arid areas, rainfall tends to be limited to winter months, with little ground infiltration, eliminating a common cause of convective heat loss in rainy areas.

Types of Soil – Soil properties (heat capacity, thermal conductivity) determine drying out of soils due to high heat gradients, and physicochemical changes at the heat transfer surfaces. These processes have to be accounted for in the design procedure, or modified, as discussed in Section 3.

Hydrogeological Conditions – The relevant condition is the distance to areas of saturated water transport. The proximity of aquifers or of seasonal interflow and infiltration increases the heat losses of the storage system to the environment.

COMPARISON WITH OTHER STORAGE MEDIA – This comparison is limited to natural storage media. A more general comparison was made by (11), while several points of comparison with aquifer thermal energy storage (ATES) were discussed by (12). This discussion is again directed mainly to comparison with ATES, which is, except for dry rock, closest in design considerations to USHS and for which there exists a large amount of data. The points of comparison are: (a) Availability – more widely available at middle latitudes than other options; siting limitations are due to nearby underlying aquifers and interflow zones. (b) Control of heat deposition – better than in aquifers, which are influenced by natural and induced flow regime of groundwaters and exhibit high thermal dispersion. (c) Heat transfer rates – low, limited by the heat diffusion mechanism. (d) Geochemical problems – minimal, due to closed water system. (e) Heat recovery – high if positioned under user area. (f) Access for geophysical survey – easy. (g) Modeling – more complex than for alternatives but simplifications may be possible. (h) Minimum size – small, with possibility of modular expansion due to factors mentioned in (b). (i) Construction cost – relatively low, as system is positioned close to the surface and has no insulation. There are no additional space requirements if placed under user area.

3. DESIGN APPROACH

This section deals with more specific and quantitative details of design of a seasonal heat storage system in the unsaturated zone of the soil. It should be regarded as an attempt to apply the guidelines and principles of Section 2. Alternative solutions may be suitable under given local conditions, and no generalization of the validity of this approach is implied.

3.1 CONSIDERATION OF SOIL PROPERTIES – An estimate of thermal, hydraulic, and geochemical properties of the soil in the storage area and its environment is required for the planning stage of the storage system. This estimate can be deduced from published data, accumulated experience with local soils, or from in situ tests. However, detailed local tests are expensive and time consuming, and may still leave many unexplored details within the storage area. The proposed approach is to gain an estimate of the expected values of soil properties and their variability; the design should then be robust enough to allow effective operation of the storage for possible departures from the expected values.

The information on thermal properties required for the design of a USHS system is discussed in (13). The thermal processes are shown to be coupled to hydraulic processes, which in turn depend on the physicochemical structure of the soil. The theory of these processes is presented in a multitude of references (e.g. 14, 15). There are still certain discrepancies between theory and experimentally determined values of effective thermal conductivity, which is composed of a pure conductive component, for transport in rock and liquid water, and a component representing latent heat transport by vapor diffusion.

Temperature- and moisture-dependent values of thermal conductivity for common soil types have been measured (16, 17). An extensive summary of experimental data (18) shows a high correlation between thermal conductivity and both quartz content and dry density. A comprehensive summary of thermal and hydraulic properties of soils is given in (19). Up to 70 °C, the conductivity is a monotonic function of temperature, with a broad plateau above ~20% water content. Unfortunately, the common classification of soil types by grain size does not lead to consistent values of thermal conductivity; the results of (16) are lower by ~30% than those of (17) for similar soil designation, water content, and temperature.

Heat capacity, being an extensive property of the medium, can be readily evaluated from known basic data. It is strongly dependent on the variable water content, but weakly dependent on temperature, within the range of conditions found in the storage system. Matric potential has been widely studied for various soil types, primarily in the agricultural domain (19), however its temperature dependence is still controversial (20).

Soils with high clay content are subject to chemical and structural changes at high temperatures and high temperature gradients. Drying and chemical modification are expected at the heat exchanger surface. Effects of drying at the bottom boundary of solar ponds have been analyzed (21). A field scale experimental model has been used (22, 23) to measure all the above mentioned phenomena in an unsaturated zone above a saturated heat storage area. The kinetics of the drying process under high thermal gradients has been investigated (24) as a function of initial moisture content.

The cumulative experience and theoretical analysis seem to indicate that at a water content of more than ~15% and temperatures below ~70 °C, there is a high probability of stable heat transfer, and only limited moisture transfer. The heat transfer process can be then be described by a heat transfer equation which is not coupled to the moisture transfer equation, although it is still nonlinear and depends on local moisture content. This uncoupling allows the application of numerical methods with reasonable effort, while the application of the fully coupled equations in 2 or 3 dimensions with variable boundary conditions is beyond the capabilities of the available computational methods.

The initial parameter values adopted for this model are intermediate with respect to the published values, and the calculations include sensitivity tests to parameter variations.

3.2 SPATIAL VARIABILITY OF SOIL PROPERTIES – Thermal and hydraulic properties of soils may vary significantly over the storage area. Vertical variability is relatively easy to determine from existing wells or test logs. Thermal logs are not commonly available but are easily performed in test logs. The thermal profile reflects the thermal properties of stratified soils through the attenuation of surface temperature amplitudes and the phase shift, for approximately constant thermal coefficients (25, 26). The storage area may also have large horizontal variability, even in areas of generally horizontal stratification. Variations can be determined with reasonable effort using the recently developed methods

of computerized geophysical tomography (27) and the application of ground penetrating radar to map natural soil and rock conditions in the unsaturated zone (28). Commonly found variability of soil composition is not expected to have significant effects on heat storage and transfer. Rock outcrops may however increase drilling expenses.

3.3 SITING CONSIDERATIONS – The main factors affecting site selection are: a) soil properties, b) hydrogeological conditions, c) distance to source and users of heat (or cold), and d) economics of excavation, installation, and operation of the storage site. Factors a) and b) are discussed in Sections 2 and 3.1 above. Distances to source and users are minimized in order to reduce heat losses in transit, circulation energy, and investment in piping. The WCZ benefit by having lower heat losses in transit. Heat pipes buried in dry surface soil during the summer charge period have lower conductive losses, due to higher thermal resistance and higher ambient temperatures. Anti-freeze protection is unnecessary in most cases.

Vertical siting has two opposing constraints: shallow sites have high conductive heat losses to the surface, while deeper sites are more expensive to construct and have lower distance to the saturated zone – a virtual sink for conductive heat flow. The dimensions selected for this model place the heat exchanger top 4 m below the ground surface. The heat exchange process is of the regenerative type, with the heat-wave advancing upwards from 16 m below the ground surface. The heat flux to the surface is therefore delayed with respect to the charging period. A specific siting option (29) that offers several operational and economic advantages, considers a greenhouse overlying the storage area, thus offering both protection from direct infiltration and lower heat losses. An added feature of this design is direct root zone heating, which benefits certain plants more than conventional space heating. This siting option is readily available for agricultural applications, but is not suitable for retrofit of existing structures; it is best installed in advance of their construction as underfloor heating.

3.4 TECHNOLOGICAL CONSIDERATIONS – This report does not include detailed engineering designs and cost estimates. However, the feasibility of the proposed concepts, storage configurations, and operational procedures depends on the availability of proven technologies and materials, both at reasonable cost; these include the indirect sensing discussed above, techniques of large diameter drilling, and durable components for underground heat exchangers. The configuration of the storage medium and heat exchangers considered here requires the capability of drilling 1-m-diameter wells. This has been reported to be available at moderate expense, following the developments and experience of the Scarborough Project (30). Buried heat exchange pipes are now used routinely for a multitude of heat transport applications, and PVC pipes have a record of 20 years of continuous use in underground irrigation systems.

Detailed specifications of components, materials, and techniques are available for vertical or horizontal closed loops for ground-coupled heat pump use (31). The design proposed here is a 1-m-diameter helical coil constructed from 3.2 cm diameter tube of PVC or polybutylene. Thus the small diameter tubing is made 'to look' like a large diameter heat exchange surface with interior and exterior storage volumes. The effects of helically coiled pipes on heat transfer has been investigated (32). Using that derivation and the design values planned here, there is no need to consider modifications from linear-pipe heat transfer calculations.

Heat transfer benefits from high water content at the heat exchange surfaces. A circular drip irrigation pipe is included in our design, and positioned at the top of the heat exchanger. There is considerable experience to date with subsurface irrigation for agricultural purposes.

The storage volume interior to the heat exchanger provides the option for placing PCM (Phase Change Material) in an effective location without additional excavation. This is expected to enhance the operational capabilities of the storage system in terms of heat transfer and stored enthalpy. There is no known PCM material which would justify the economics of this arrangement under the proposed conditions, therefore its inclusion is not planned in the first stage of the proposed experiments, but it certainly is an interesting future option.

4. MATHEMATICAL MODELING OF AN UNSATURATED SOIL HEAT STORAGE SYSTEM

4.1 MODEL DESCRIPTION – The numerical code PT (33) developed at Lawrence Berkeley Laboratory, is used for the present calculations. PT calculates coupled liquid and heat flows in a porous or fractured-porous medium. PT has been verified against a number of analytical solutions and validated against several field experiments (34) as well as being applied to a great number of energy-storage and geothermal-reservoir simulation problems.

The heat storage system being modeled consists of a square array of vertical helical storage ducts placed in unsaturated soil initially at 24 °C. The top of the helix is 4 m below the ground surface and its length is 12 m. The helix has a diameter of 1 m and the spacing between adjacent ducts is 6 m. Between 0.5 and 1 m below the ground surface there is a shallow charge zone consisting of horizontal ducts. Figure 1 shows a schematic diagram of the storage system.

During summer (deep charge period), water warmed by solar collectors to 65 °C is pumped into the bottom of the vertical helix and cools as it flows to the top, depositing heat in the surrounding soil. During winter (deep discharge period), cool water at 20 °C is pumped into the top of the helix and warms as it flows to the bottom, extracting heat from the soil. The shallow heat storage zone is used during winter to provide short-term storage between daily peak periods of energy supply (daytime) and demand (night-time). Heat is transferred by diffusion from the soil to the ground surface, then into the overlying air.

The ground surface temperature has an annual sinusoidal variation with a mean value of 24 °C and an amplitude of ±4 °C. In addition, unusually warm or cold winters are considered in which short-term (5-10 days) changes of ± 5 °C are added to the sinusoidal pattern.

As described in Section 3.1, no fluid flow is considered in the unsaturated soil, so heat transfer there is purely by conduction. Uniform temperature- and saturation-independent thermal properties for a medium consisting of 60% soil, 20% water, and 20% air are used. In the duct, heat transfer is by convection and conduction.

From symmetry considerations, a duct in the interior of the array can be represented by an isolated duct enclosed in a square insulated boundary. For modeling purposes, the square boundary is approximated by a circular boundary, and the helix is approximated by a cylindrical conduit, yielding an axisymmetric model. A discretized mesh composed of 500 nodes is used for the calculation. The mesh extends vertically from the ground surface to a depth of 50 m, and radially from 0 to 3 m. The mesh spacing is finest close to the

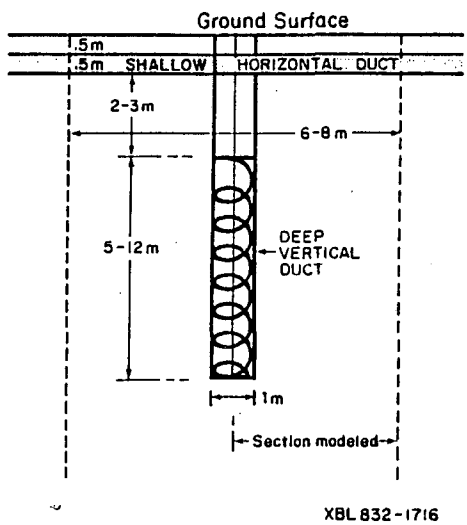


Fig. 1 – Vertical cross section of one duct of the storage system

duct ($-16<z<-4$, $r=0.5$ m). The contribution of ducts on the edge of the array is studied by modeling a single duct surrounded by a radially infinite storage medium.

For the calculation, the seasonally variable supply and demand of energy is averaged to a series of constant segments ranging from five days to one month in length. To determine the average daily pumping rate, the daily supply or demand of energy for each duct is equated to the energy deposited or extracted for each duct in one day:

$$E = 24 C_w (T_{in} - T_{out}) \overline{Q} \quad (1)$$

where E is the supply or demand of energy per duct (MJ/day); C_w is the specific heat of water (MJ/kg°C); T_{in} is the duct inlet temperature, 65°C during deep charge, 20°C during deep discharge; T_{out} is the variable duct outlet temperature (°C); and $\overline{Q}$ is the average fluid flow rate through the duct (kg/hr). Thus $\overline{Q}$ is given by

$$\overline{Q} = \frac{E}{24 C_w (T_{in} - T_{out})} \quad (2)$$

The parameters E, C_w, and T_{in} are given constants, while T_{out} is a variable calculated by PT. To calculate $\overline{Q}$ for the first day of operation, T_{out} is assumed to be 24°C. To calculate $\overline{Q}$ for subsequent days, T_{out} is determined by linear extrapolation from the T_{out} values for the two previous days. Clearly as T_{out} approaches T_{in}, $\overline{Q}$ approaches ∞. This indicates that heat conduction through the soil cannot keep up with energy supply or demand, or that the storage volume is fully charged or fully depleted.

4.2 ANALYTICAL MODELS - Analytical solutions for the behavior of the heat exchanger and the storage configuration proposed here are not available. A single well storage volume, in the interior of the storage area, is modeled with the following simplifying assumptions: (a) the square pattern of the wells is approximated by circular geometry for each well; (b) the helical coils are approximated by a cylinder of hollow walls of equal volumes as the coils, and equal surface area; and (c) longitudinal and radial dispersion is neglected in the convective flow in the pipe conduit. This leaves the model with axial convective mass and heat transport, and conductive radial heat transport into the inner and outer soil volumes. Axial conductivity in the soil, the existence of the pipe wall, and the moisture- and temperature-dependence of thermal conductivity (drying out regions), are included whenever necessary. For multi-year simulations, the initial temperature distribution in the storage area presents added complexity.

The closest analytical models known to us include several further simplifying assumptions: neglect of vertical conduction in the soil and the interior storage volume. The earliest models originate from the literature on solute transport in porous media with axial convection and radial dispersion (35, 36, 37, 38). A similar model applied to heat storage (39) includes sensitivity analysis to several parameter values. This is therefore a suitable candidate for verification of the numerical programs modified according to the above simplifications. Several results of transient heat transfer from heat exchangers are given (40, 41), including some theoretical estimates of heat losses from storage for a variety of subsurface configurations and dimensions. It is not yet clear whether the boundary wells of our design, having a 3-dimensional heat distribution, are adequately approximated by these models.

An analytical solution (42) for a simplified heat-transfer problem that includes some of the features of the present model is compared to PT-calculated results to verify that the code works properly. The problem considers radial flow from a constant-temperature cylinder. An infinitely long cylinder with radius a is surrounded by an infinite medium with thermal diffusivity $\alpha = \lambda / C$. Both are initially at temperature T_0. For times $t > t_0$, the temperature of the cylinder is held fixed at T_1. The temperature distribution in the medium for $t > t_0$ is given by

$$T(r,t) = T_0 + (T_1 - T_0)\left\{1 - \frac{2}{\pi}\int_0^\infty \frac{e^{-\tau u^2} C_0(u, Ru)\, du}{u\left[J_0^2(u) + Y_0^2(u)\right]}\right\} \quad (3)$$

where

$$\tau = \frac{\alpha t}{a^2} \qquad R = \frac{r}{a}$$

$$C_0(u, Ru) = J_0(u) Y_0(Ru) - Y_0(u) J_0(Ru)$$

and J_0 and Y_0 are first-order Bessel functions of the first and second kinds, respectively.

Three cases are calculated with the numerical model, using the following boundary conditions:

1) Constant temperature $T_1 = 70$°C at $r = a = 0.5$ m
2) Very high fluid flow rate at $T_1 = 70$°C through the duct
3) Typical summer flow rate ($\overline{Q} = 25$ kg/hr) at $T_1 = 70$°C

In each case there is a uniform initial temperature of $T_0 = 20$°C.

The calculated temperature variation with radial distance at mid-duct depth is given in Figure 2, along with the analytical solution, for a series of times. Cases 1) and 2) give identical results, and match the analytical solution very well. Case 3), which represents the actual USHS system better, shows a rather different behavior, confirming that use of a numerical model is in fact necessary for analysis of the current USHS problem.

4.3 MULTI-YEAR CALCULATION - A number of multi-year energy supply-demand sequences have been modeled using an insulated-boundary model to represent an interior duct. (Edge effects are discussed at the end of the section.) Table 1 shows the sequence of seasons considered. In general, summers (energy charge), labeled S, are all similar, while winters (energy discharge) vary. Some winter segments are a response to climatic variations; these segments are labeled C (cold), A (average), or W (warm). Other winter segments are special operational procedures, designed to optimize system performance; these segments are labeled L (low-demand), H (high-demand), or B (bleed, an especially high demand designed to exhaust the stored heat supply). The key measurement of the system's response to varying energy demands is $\overline{Q}$, the average daily flow rate. A value of $\overline{Q}$ greater than 180 kg/hr indicates that the system cannot meet the imposed demands. For earlier versions of the model, $\overline{Q} > 180$ during the first winter discharge, leading to the inclusion of the low-demand winter to provide a gradual start-up period for the system.

Cases 1, 2, and 3 consider three alternative second winters: warm, average, and cool. The energy demand is met in all cases, with successively higher values of $\overline{Q}$ required in each case. Figure 3 shows the time variation of ground-surface temperature, energy

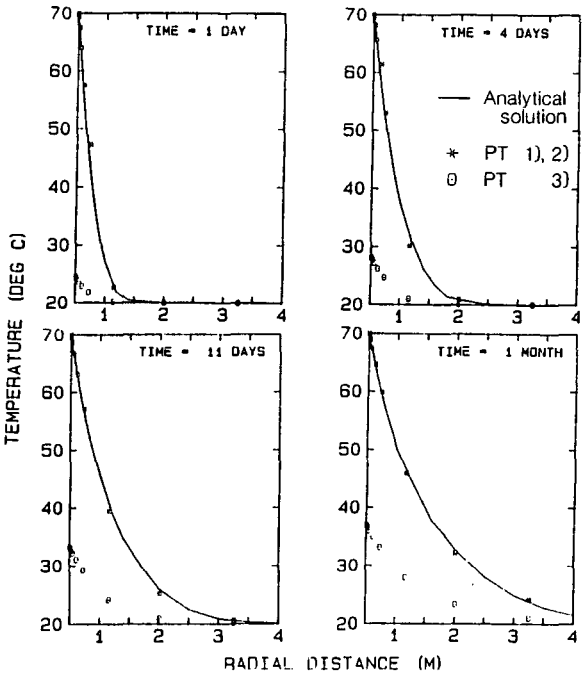


Fig. 2 - Analytical and calculated temperature distributions for a simplified problem involving radial heat flow from a cylinder; the curves labeled 1), 2), and 3) represent different boundary conditions for the numerical model, as explained in the text

supply and demand, $\overline{Q}$, T_{out}, heat flux through the ground surface, and cumulative stored energy for Case 2.

To further explore system capacity, Case 4 considers an especially high-demand situation with no shallow charge. Again the demand is met with an increase in $\overline{Q}$. Case 5 continues Case 2 for a third summer. Near the end of the charge period, $\overline{Q} > 180$, indicating that the heat storage volume is full, and cannot accommodate the remainder of the energy supply. Case 6 continues Case 3 for a third summer. Again $\overline{Q} > 180$ near the end of the charge period, despite the lower level of energy in the system at the start of the third year due to the higher demand during the second winter for Case 3 (cold winter) relative to Case 2 (average winter). Case 7 considers a 'bleed' second winter, designed to exhaust the system in preparation for the third year. Too much heat is required, however, and $\overline{Q} > 180$ during the bleed winter. Case 8 considers a more moderate bleed winter, and the system can meet the demand. The third summer's charge can be accepted as well. The moderate bleed winter is repeated for the third and fourth years, successfully. By the end of the fourth year transient effects have greatly diminished. This indicates that there is an operational range of ~66% energy recovery after an initial transient period of 3 years. This is associated however with considerable exergy loss.

Averaged Pumping Schedule – As described in Section 4.1, the USHS system responds to seasonal variations in energy supply and demand by varying the average daily pumping rate $\overline{Q}$. In general, each day really consists of a pumping period and a resting period. Summer charge occurs during the daytime at a variable rate with a maximum at about 1 pm. Winter discharge occurs during the night-time at a constant rate. Modeling this discontinuous pumping schedule is rather inefficient, as PT takes very small time steps during the transient periods that occur whenever pumping begins or ceases. Because sequences of several years must be calculated, such small time steps are quite impractical. To allow larger time steps, instead of the real system pumping part of the day at a flow rate Q, we model a system pumping continuously at an average flow rate $\overline{Q}$. Because the change in $\overline{Q}$ from day to day is gradual, PT can take much larger time steps than when the discontinuous pumping schedule is used. Selected short time intervals (one to two weeks) from various portions of the yearly charge-discharge cycle have been calculated with both the discontinuous and averaged pumping schedules, confirming that the averaged schedule gives proper results. Figure 4 compares averaged and discontinuous T_{out} values for Case 2 for part of the second year. All the calculations listed in Table 1 are made with the averaged pumping schedule.

Table 1 – Calculations Made Using the Insulated-Boundary Model to Represent an Interior Duct

Case	Sequence of Seasons	Comments
1	1S–1L–2S–2W	7-m-duct also meets demand
2	1S–1L–2S–2A	7-m-duct cannot meet demand
3	1S–1L–2S–2C	
4	1S–1L–2S–2H	
5	1S–1L–2S–2A–3S	$\overline{Q} > 180$ kg/hr during 3S
6	1S–1L–2S–2C–3S	$\overline{Q} > 180$ during 3S
7	1S–1L–2S–2B	$\overline{Q} > 180$ during 2B
8	1S–1L–2S–2B′–3S–3B′ –4S–4B′	

	Season	Heat Transfer Mode	Total Deep Charge (+) or Discharge (–)
S	Average Summer	Deep charge	+18,650 MJ
W	Warm Winter	Deep charge, deep discharge, and shallow charge	–2,000
A	Average Winter	Deep discharge and shallow charge	–6,600
C	Cold Winter	Deep discharge and shallow charge	–8,050
L	Low-demand Winter	Deep discharge and shallow charge	–2,400
H	High-demand Winter	Deep discharge, no shallow charge	–12,000
B	Bleed Winter	Deep discharge and shallow charge	–15,375
B′	Moderate-bleed Winter	Deep discharge and shallow charge	–12,075

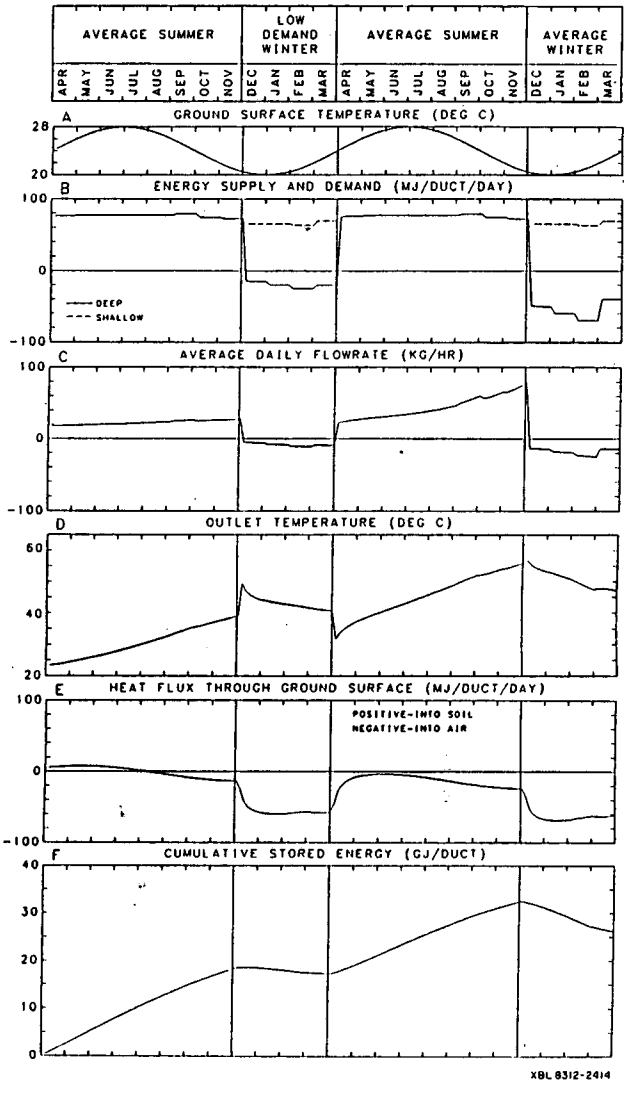


Fig. 3 – Boundary conditions (A and B) and calculated results (C, D, E, and F) for Case 2

Edge Effects – The axisymmetric single-duct model with an insulated outer boundary approximates the behavior of inner ducts of the storage array well. It is also applicable to outer (edge or corner) ducts at late times, after lateral heat losses from early cycles have created a buffer around the storage array. For early-time edge effects, the infinite-radius model is used to provide a lower limit for system behavior. For Case 2 temperature distributions in the storage volume and variations in T_{out} and $\overline{Q}$ (Figure 5) are very different than the corresponding insulated-boundary results (Figure 3). In fact, the 2A (average winter) demand cannot be met by the infinite-radius model. When both interior and edge ducts are considered together, the problem of not accepting summer charge (Cases 5 and 6) will be eliminated; even if interior storage volumes are full, outer ones will not be and $\overline{Q}$ can be varied between ducts to achieve as constant a T_{out} as possible.

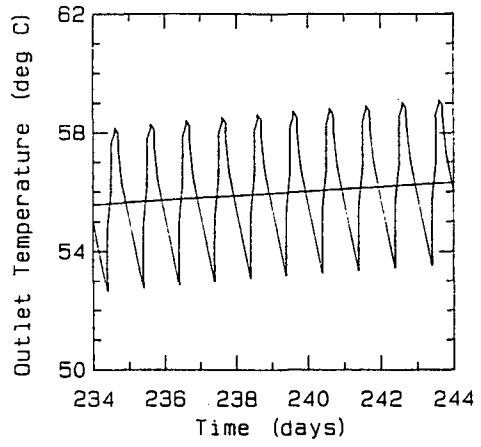


Fig. 4 – T_{out} calculated with averaged and discontinuous pumping schedules for the final ten days of the 1S-1L-2S sequence

4.4 SENSITIVITY ANALYSIS – A number of parameter-variation calculations were made during the development of the model described in Section 4.1.

Storage Volume Geometry – The original model included a 5-m-long duct located at a depth of 3 m, a 6.8-m horizontal spacing between ducts, and an inlet temperature of 60 ° C during deep charge. Initial calculations indicated that the volume of soil around each duct was not big enough to store the duct's energy supply for a typical summer, so the soil storage volume was enlarged by lengthening the duct from 5 to 7 m, and increasing the distance between ducts from 6.8 to 8 m. The larger volume was big enough to accommodate an entire summer heat supply, however the winter demand could not be met because the thermal conductivity of the unsaturated soil was too low for stored heat to travel from the edge of the storage volume to the duct within the short winter period. To remedy this, the dimensions of the storage volume were varied to allow more effective heat transfer to the duct, by lengthening the duct from 7 to 12 m, while decreasing the spacing between ducts from 8 to 6 m. Excessive heat losses to the ground surface during summer were decreased by increasing the depth of the duct from 3 to 4 m below the ground surface.

Inlet Temperature – Initial information on solar collectors indicated the maximum input temperature for charge periods to be 60 ° C. More recent developments suggest that 65 ° C is possible. For otherwise identical conditions, the increase from T_{in}=60 to T_{in}=65 ° C causes only a small decrease in T_{out} during the charge period, but a substantial decrease in required flow rate, due to the form of equation (2).

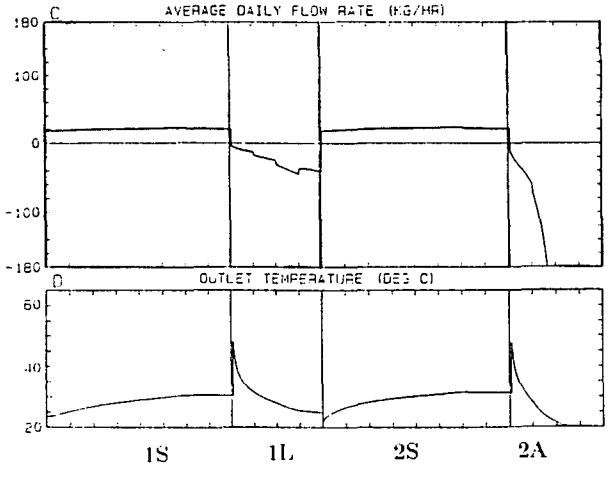


Fig. 5 – T_{out} and $\overline{Q}$ for Case 2, for the infinite-radius model

Duct Geometry – In an attempt to improve heat transfer between the duct and the soil, the thickness of the duct was doubled, and the velocity of water flowing through the duct correspondingly halved. Heat transfer into the soil was nearly unchanged, indicating that heat flow through the soil is the limiting factor determining heat exchange, rather than duct fluid velocity.

Soil Properties – The property controlling heat flow through the soil is the thermal conductivity λ. If λ is decreased from the usual value of 1.6 to 0.65 W/m ° C, corresponding, to a decrease in soil moisture content, then $\overline{Q}$ increases dramatically, from 30 to 150 kg/hr. On the other hand, if λ is increased from 1.6 to 2.4 W/m ° C, $\overline{Q}$ remains nearly unchanged, indicating that the system is less sensitive to thermal conductivity above a value of 1.6 W/m ° C. Moisture content decreases as high temperatures increase the evaporation rate in the soil. If the dry region is limited to a thin layer adjacent to the duct, then $\overline{Q}$ does not increase appreciably.

4.5 FUTURE MODEL DEVELOPMENT – The appreciable difference in behavior between the insulated and infinite storage volume cases indicates that a multi-duct model may be necessary to properly model the early years of the system. Because of the detail necessary for each duct, a fully three-dimensional model would be quite expensive and cumbersome to use. Instead, an alternative approach is being developed, calling for a superposition of local (single well) and global (multi-well) models, and an iteration between models.

The strong dependence of thermal conductivity on moisture content necessitates the control of moisture content in order for the PT calculations, which assume constant λ, to be valid. For situations in which moisture content cannot be held fixed, or when fluid flow through the unsaturated soil is important in its own right, a computer code incorporating the coupled flows of water (liquid and vapor phases), air, and heat must be used.

5. POTENTIAL APPLICATIONS

5.1 RESIDENTIAL AND INDUSTRIAL SPACE HEAT SUPPLY – The application of seasonal heat storage for residential and industrial space heating has been widely discussed, experimentally tested, and proven to be technologically sound and even economically competitive in several locations in the colder climatic zones. Our discussion should therefore center on the evaluation of the specific characteristics of its application in the WCZ. Most factors specific to the WCZ (Section 2) seem to favor such applications: lower heat losses in storage and transport, readily available storage areas, shorter heating periods, higher inputs (for solar source), possibility of direct use, and higher COP with heat pump use. The present design favors application to housing areas or industrial structures requiring a storage system with over 2000 m^2 surface area (~30,000 m^3 volume), with ~1000 GJ energy stored per cycle. Application for single homes is however not efficient.

5.2 AGRICULTURAL USES – Agricultural uses were considered initially to be the preferred candidates for seasonal heat storage applications in WCZ. Several designs were offered for greenhouse space heating with an associated or independent root zone heating (13, 29, 43). In many WCZ, intensive winter crop cultivation is a major component of the overall agricultural production. Winter productivity is shown to be significantly enhanced by additional heat in protected and semi-protected environments. Therefore the availability of the inexpensive, widely distributed, and reliable heat supply at relatively low temperatures offered by the seasonal storage of solar energy is of great interest.

5.3 EFFECTS ON RESOURCE DEVELOPMENT – The feasibility of seasonal heat storage may have significant influence on investment in the development of alternative energy resources. Due to the relatively short heating season, the mismatch between supply and demand of heat is greater in WCZ than in the colder zones, therefore many potential resources, such as solar, low temperature geothermal, and industrial waste heat, may not justify development. The seasonal storage allows year round operation of the facilities, reduction in peak heat transport demand and the associated investment in transport facilities. Detailed discussion of these factors is given in (44).

6. SUMMARY

Seasonal heat storage is shown to be a potentially valuable component in energy conservation and energy management in WCZ. Its introduction lags behind that for colder climatic zones. A design, specifically adapted to WCZ, is proposed, its model is described, and several simulations are performed. Experimental verification and validation of the concepts, models, and simulations is proposed, as an essential step in gaining acceptance of this technology.

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