HIGH TEMPERATURE UNDERGROUND THERMAL ENERGY STORAGE

SYSTEM FOR SOLAR ENERGY

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PROJECT OUTLINE

Project Title: High Temperature Underground Thermal Storage of Solar
                  Energy

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Project Goals: The objective of this project is to establish the
                  feasibility of high temperature underground thermal
                  storage of energy and arrive at a practical system design.

Project Status: Results to date indicate that salt cavern storage of hot
                  oil is both technically and economically feasible as a
                  method of storing huge quantities of heat at relatively
                  low cost. One particular system identified in this study
                  utilizes a gravel filled cavern leached within a salt
                  dome. Thermal losses are shown to be less than
                  one-percent of cyclicly-transferred heat. A system like
                  this having a 40 MW_t transfer rate capability and over
                  eight hours of storage capacity is shown to cost about
                  $13.50 per KWh_t.

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High Temperature Underground Thermal Storage of Solar Energy

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Objectives: This report documents the second year of a feasibility study of underground storage of solar energy as sensible heat. This effort addresses storage temperatures high enough to utilize conventional steam-electric power generation on the recovery cycle. The method of storage now under evaluation utilizes cavern storage of heat transfer oil at temperatures up to 650°F in leached caverns within salt domes. A study of aquifer storage of hot water at these temperatures was discontinued when it became apparent that such storage would encounter major problems from mineral (silica) solution and requirements for down-hole pumps for the recovery cycle. Research and development efforts have been focused on the following technical problems:

a) Thermal losses

b) Cavern stability

c) Cavern construction

d) Well designs

e) heat exchanger interfacing

f) economics for cavern storage systems:

Conclusions. Studies indicate that salt cavern storage of hot oil will be both technically and economically practical as a method of solar energy storage for electric power generation. The best system identified in this study is a gravel filled cavern using at least one input and one output well, operated in a thermocline mode with injection and retrieval on a diurnal cycle. Thermal losses should be less than one percent of cyclicly-transferred heat. The gravel filling would act as a heat storage medium and as a stabilizer against cavern deformation due to plastic flow of salt. (See Figure 1.).

During the second contract year it has been shown that such a system can be built using existing technology and available materials. In particular, the design and operation of such a system for interfacing to a 10 MW_e central receiver like the one being built at Barstow, California has been evaluated. A cavern storage system could be built for about $4 million having a 10 MW_e

transfer rate capability and 8^+ hours of storage capacity. Storage would be at about 650°F and cost about $13.50.per kWh_t. This compares favorably with DOE objectives, but larger cavern storage systems would be more cost effective with costs estimated at a low $7.50 per kWh_t. Thus, cavern storage would be preferred to above-ground storage where it is geologically feasible. A review and summary of the various studies carried out during the past year isolate and explain primary conclusions.
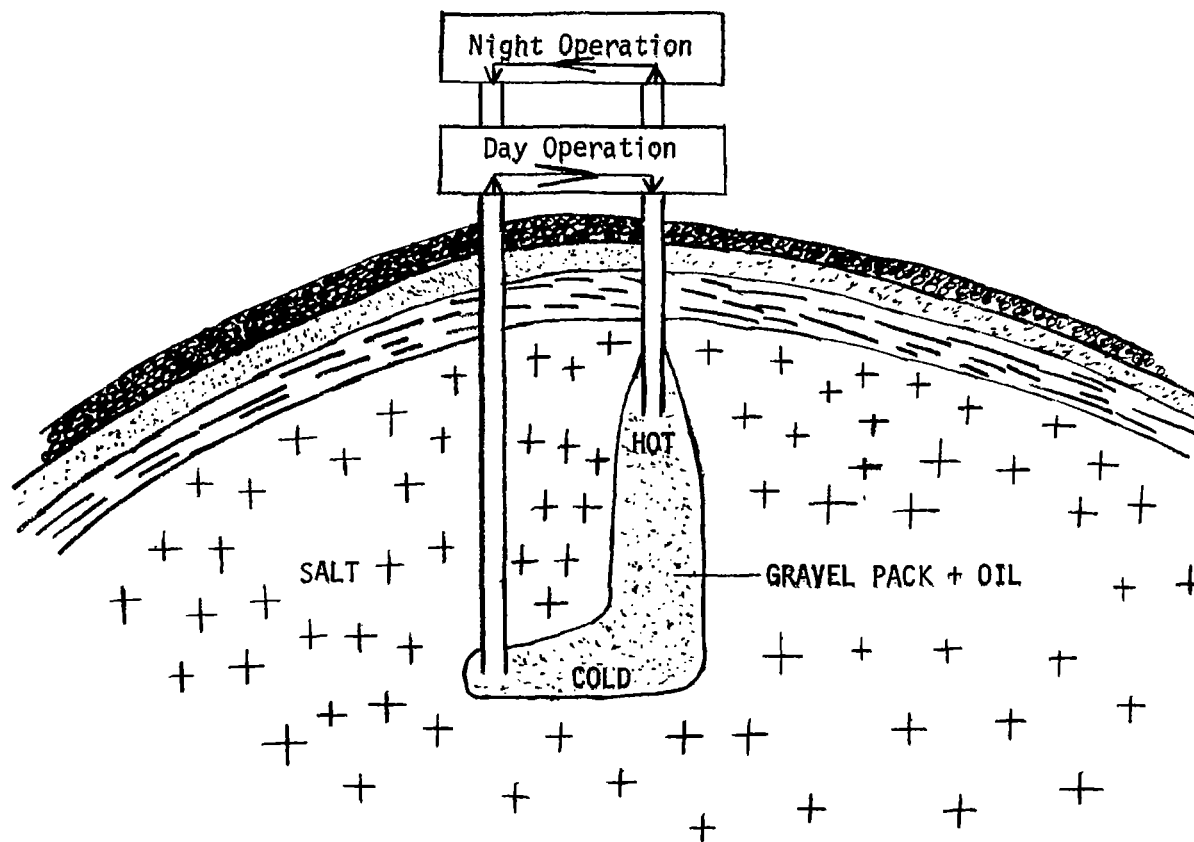

Figure 1. Schematic of gravel filled salt cavern for thermocline storage of heat using heat transfer oil.

Thermal Losses from Cavern Storage Systems. In the first year of the five-year study, we have reported results on thermal losses, calculated with a computer simulator assuming a cavern with perfect mixing (homogeneous temperature inside), for cyclic operating conditions. Those studies showed that for daily cycles of a hot oil storage cavern--8 hours injection and 16 hours retrieval--thermal losses would decline rapidly from a moderately high

value to less than one percent of the transferred energy by the end of one year of operation. This model has also been used to study effects of non-cyclic operation that would result with shut-down of the solar collector in cloudy weather. These studies indicated that losses would not be prohibitive for shut-down periods up to several days if the cavern were sufficiently large.

The simulator under study is an oversimplified model, for it assumes perfect mixing of oil within a spherical cavern. The model also describes a storage system consisting of two caverns, a hot cavern and a cold cavern with a nitrogen gas cap in each cavern. The nitrogen gas cap is compressed during fluid injeftion and the expansion of the gas produces back-flow in the retrieval cycle, thus negating the requirement of a downhole pump. However this system requires caverns at significant depth to sustain required internal pressures and poses problems of mechanical stability.

It now appears that the preferred cavern storage system will be a single gravel filled cavern with two wells operated in a thermocline mode using oil and rocks essentially like the above ground tanks; one well connects to the top of the cavern (the hot well) and one to the lower end of the cavern (the cold well). (See Figure 1.).

Gravel filling in a thermal storage cavern serves three purposes: 1) the gravel is a storage medium for sensible heat and reduces the required oil volume, 2) the gravel restricts thermal convection and stabilizes the thermocline, and 3) the gravel provides mechanical support and rigidity to the cavern to prevent cavern deformation due to creep of the salt, or plastic flow, provided that internal fluid pressure is less than external geostatic pressure.

The perfect mixing model has therefore been put aside and attention devoted to the formulation of computer simulators for the study of fluid move-ment, heat transfer, and thermal losses in a gravel filled cavern operated as a thermocline with oil. Preliminary results from these models show that the order of magnitude of the thermal loss in this system is not radically different from that in the homogeneous cavern.

Two new simulators are being evaluated; the first is designed to describe in detail the mass and heat flow within the cavern as well as the heat flow within the salt, while the second simulator is designed for accurate description of the heat flow across the cavern boundaries and within the salt

while the mass and heat flow within the cavern are treated by more approximate means. This program is operational and is being used to generate systematic data on cavern operations.

The model has already been used to show that a thermocline cavern storage system for a small scale system (10 MW$_e$) with eight hours storage would lose about 2.6% of the useful stored heat during one daily cycle after about three months of continuous operation. The loss rate at the end of one year of continuous operation is approximately 1.5%. For systems of larger size (100 MW$_e$ or more) the long term loss rate would be 1%, or less, of the cyclicly transferred heat.

Cavern Stability Studies. The major problem anticipated for the cavern storage system was cavern deformation due to creep of the salt at high temperatures, or plastic flow. Published experimental data for a wide range of strains, rates of strain and temperatures have been curve-fitted to provide an adequate description of the viscoelastic/plastic properties of halite. This rheological model for halite is given as a general equation of strain rate as a function of strain, differential stress and temperature for uni-axial conditions. For particular constant stress and temperature values it can be integrated numerically to give the total strain as a function of time. For a temperature of 599°F and an expected differential pressure of 300 psi, the integration yields a total strain on an element of halite of 1.8% in 20 years or 2.2% in 50 years. The same element of halite, when subjected to a differential pressure of 600 psi at the same temperature would suffer a total deformation of 8.4% in 20 years or 14% in 50 years. Note that these results do not take into account the rigidity of the gravel pack which would function to reduce these deformations.

Gravel filling will be a greater deterrent to cavern deformation than initially anticipated. It is well known that a container filled with rigid granules in firm contact cannot undergo a shear deformation without expansion of the container volume. Thus, since the pressure of the overburden must be overcome, in order for the cavern to expand, the gravel should give great rigidity to the cavern. A simulator is currently being developed to determine the deformation and rates of deformation experienced by a spherical cavity filled with saturated gravel, the boundary of which is subjected to hydrostatic loading. This simulator is now in the debugging stage. A survey of the literature is also underway to find sufficient data to determine the elastic/creep constants of saturated sands to be used as input to the simulator.

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The critical factor for the stabilizing role of the gravel on the cavern appears to be maintenance of fluid pressure within the pore space less than the confining geostatic pressure of the salt. An analytical solution for the pressure distribution within the cavern has been obtained, valid within some simplifying assumptions, which shows that fluid pressure increases required to maintain fluid flow will generally be on the order of a few hundred psi. Such pressures could be tolerated in caverns at reasonable depths. Further study of these flow effects is underway, using both analytical and numerical methods.

Thermal Storage Fluids. The optimum fluid to be used in the cavern storage system would minimize replacement costs for a given power from the system. Replacement costs are directly proportional to fluid loss rate due to thermal degradation. Published experimental data for fluid loss rates of some commercially available heat transfer fluids have been examined from this viewpoint. Caloria HT43, SUN 21 and Therminol 66 were considered. Of these it appears that Caloria HT 43 would be most suitable with a loss rate of about 6.25% per year at 600°F. However, more information is required on effects of contact with metals, air, water and salt on rate of degradation.

Well Designs and Cavern Construction. A comprehensive review of the literature indicated that existing equipment, materials, and procedures for oil wells can be adopted for construction of wells for the cavern storage system. The main body of the second-year report on this project provides a detailed description of the process of drilling, completing the wells, leaching the caverns, and placing gravel in the caverns.

The major consideration in the well designs is the requirement of adequate cement bond in the installation of the well casing pipe to constrain the pipe against thermal expansion. The thermal expansion of the injection tubing can be accommodated by thermal expansion joints. A rigid, porous silica foam coating on the exterior of this tubing can provide good thermal insulation.

Other major considerations in the design of cavern systems are brine disposal while leaching and the technique of gravel placement.

Detailed casing designs have been formulated for wells of three flow rates, 1500 gpm, 2000 gpm, and 2500 gpm, and two depths, 3000 ft and 5000 ft. Detailed cost estimates account for materials, installation, and supervision. Costs have also been estimated for cavern leaching and gravel filling.

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Heat Exchangers and Power Generation. Since a specific solar collector has not yet been identified to interface with a cavern heat storage system, the 10 MW_e system being built at Barstow, California, was used for evaluation purposes. Using data provided in the McDonnell Douglas report on this system, design studies were carried out to determine the type of modifications of the heat exchangers and power generation equipment that might be required in order to interface the solar collector with a cavern storage system. Though some modifications would be necessary, none are considered to be of major significance.

Larger systems—100 MW_e to 1000 MW_e— would require a much more complex interfacing of the solar collector, cavern storage, and steam-electric turbines. One proposed design for such larger systems is a cross-compound system using steam-electric conversion at two different temperature levels, one direct from the collector and one direct from the cavern, with cross coupling. This would be desirable since output from the solar tower would be at 900-1000°F while cavern storage is limited to about 650°F by the oil storage fluid.

Detailed cost estimates were prepared for the 10 MW_e system and some preliminary estimates of costs for larger systems were made; these are shown below.

Economics. The total cost, C, of a cavern storage system is given by

$$C = c_c \cdot V + C_W + C_D + C_a$$

where

c_c = unit volume cost of cavern and contents (gravel, oil)
V = cavern volume
C_W = costs of hot and cold wells
C_D = cost of brine disposal well
C_a = cost of above ground equipment.

For systems of the size envisioned in this study, one brine disposal well (C_D = \$620,000) would be adequate for the cavern leaching operation. The unit volume cost of the cavern and its contents is approximately \$2.85/ft^3. This includes costs of leaching, gravel placement, and oil. The cavern volume is dependent upon the desired storage capacity while C_W and C_a depend upon the desired transfer rate.

Cost estimates for the components of a cavern system with a transfer rate of 33 MW_t and 8-hour storage period, given in various sections of the complete second year report, are summarized below:

Total storage system costs for 33 MW_t
transfer rate and 8-hour storage period.

	million $
Cavern Contents (139,000 ft^3 @ c_c = $2.85)	0.396
C_w (1 hot well, 1 cold well)	1.638
C_D (1 brine disposal well)	.620
C_a (heat exchangers, pumps)	.733
TOTAL	$3.387

The total cost of this system is approximately $3.4 million. This sum corresponds to total storage system costs of $103/$kW_t$ and $13/$kWh_t$. These figures compare favorably with Department of Energy cost goals for near term sensible heat storage. Cost goals (C_t) can be compared to power related costs (C_p) and capacity related costs (C_s). Power related cost (C_p) depends upon the capability of the storage system to accept and deliver thermal energy at a given rate (heat exchangers, wells, pumps, etc.). Capacity related cost (C_s) is related to the maximum amount of energy that can be contained within storage (oil, gravel, construction costs of cavern capacity). These relations are shown below:

Storage System Costs

	C_t		h hours of storage	C_p power cost	C_s Capacity cost
	$/$kW_t$	$/$kWh_t$		$/$kW_t$	$/$kWh_t$
DOE Goals	90	15	6	45	7.50
DOE Goals*	105	13.3	8	45	7.50
This study (small system)	103	13	8	91	1.50

Here: $C_t($/kW_t) = C_p + h \cdot C_s$

$C_t($/kWh_t) = (C_p + h \cdot C_s)/h$

*DOE 6 hour costs converted to 8 hour costs for direct comparison with this study.

The underground storage value for the power cost is about twice the DOE goal, but the capacity cost is much less. This difference exists because the underground system has very low containment costs which reduce capacity related costs (C_s), but the power related costs (C_p) are increased primarily due to the well costs.

Cost figures quoted are for a minimum underground system, costs for larger commercial scale systems would be less. Minor modifications in well design would conceivably allow doubling the flow rates used in this study. With this change, the cost of a large storage system (100 MW_e or larger) would be approximately $60/kW_t$ or $7.50 kWh_t$. Therefore, cavern storage appears to be an attractive option for near term sensible heat storage for solar power systems of large size. Cavern storage may also be economically favorable for storage periods long enough (16 hours) to provide baseline electric power.