Preliminary Survey and Evaluation of Nonaquifer Thermal Energy Storage Concepts for Seasonal Storage

November 1980

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PRELIMINARY SURVEY AND EVALUATION OF
NONAQUIFER THERMAL ENERGY STORAGE
CONCEPTS FOR SEASONAL STORAGE

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SUMMARY

Literature was scanned up to September 1979 to review nonaquifer thermal energy storage (TES) methods that might be used on a seasonal basis. Since the oil embargo in 1973, many studies, much laboratory work, and engineering tests have researched TES. Most of the research supported energy conservation and solar energy programs and applied to hourly and daily (short-term) storage, rather than seasonal storage.

The most developed TES methods are also for short-term storage. The only large-scale applied development for seasonal thermal energy storage (STES) has been in the use of aquifers. Nonaquifer STES applied development has been mostly limited to small-scale solar ponds and earth storage.

For a coarse evaluation, this study divided the TES methods into categories of sensible, latent, and thermochemical thermal energy storage. Each category was further subdivided and analyzed with reference to the primary components of a TES system: storage medium, containment, insulation, and heat exchanger.

SENSIBLE TES

Sensible thermal energy is the energy associated with changes in the temperature of a material without a phase change, for example, the heat in hot water. Sensible TES is the most advanced technology because of its simplicity and relatively low cost. The most developed sensible TES methods are used mainly for short-term storage. In Europe, daily storage with off-peak electrically powered alumina, magnesia, and cast iron TES furnaces is a well-developed method. Hot water heater tank TES is an old and well-developed method that applies only to daily or weekly storage. Short-term storage with high-temperature, pressurized water ($>100^{\circ}\text{C}$) is also well developed, but the high cost of pressure vessels makes longer storage unlikely. This concept is used mainly to supply peaking steam and to heat boiler feedwater.

Daily and weekly storage systems using water and/or rocks are used extensively in solar home heating applications. Masonry walls are used for passive

solar heating. Earth and wet earth (mud) storage have been used in agriculture and home heating; wet earth TES, which has promise for these and other small-scale STES systems, should be studied further.

Large insulated-pond TES with water appears to be one of the most promising methods for STES. Large volumes of low-temperature heat can be stored at a relatively low cost. This would be attractive for district water heating and agricultural uses. Coupled with heat pumps in buildings, this method can be used for both heating and cooling when two ponds are used. This method provides an alternative to aquifer TES where aquifer storage is not practical. Ponds can also be covered with solar heat collectors to provide a heat source for the ponds.

Other storage concepts that may be used for sensible STES include natural lakes and ponds, solar ponds, mine open pits, caverns, and rock. Abandoned underground mines or natural caverns that can be easily sealed and are not too deep would be good candidates as containment for sensible heat storage materials. However, these concepts are very site specific; the lack of a nearby energy source or delayed use for the heat can be a problem.

The use of large insulated tanks should also be explored because tanks are the least site specific. The apparently higher cost of tanks may be offset by better storage efficiencies.

LATENT TES

Latent thermal energy is the energy associated with a phase change in a material, for example, with melting or freezing of ice. Overall, latent TES is not a well-developed method and is usually more complex and costly than sensible heat concepts. Researchers are experimenting with Glauber's salt, calcium chloride hexahydrate, and paraffin for daily, low-temperature TES. Salts and eutectics are being developed for daily, high-temperature TES applications such as power generation, boiler feedwater preheating, and industrial process heating.

Near-term use of latent heat in seasonal applications will probably be limited to ice cooling of buildings and of refrigeration facilities. Compacted winter snow and ice can be harvested and placed in an insulated reservoir for summer air conditioning or refrigeration of crops. Sites for use of this concept are limited, however, and ice harvesting methods and economics must be studied further.

Practically all other latent heat TES concepts will be limited to short-term storage, perhaps up to a week. This is due to the high cost of materials, heat exchangers, and containment. A hybrid concept of sensible heat water storage and encapsulated phase change material may provide a daily fixed-temperature buffer storage for a STES system.

THERMOCHEMICAL TES

Thermochemical energy is the thermal energy associated with a chemical reaction and the change in chemical composition of materials, for example, burning wood. For application to energy storage, however, the chemical reactions must be controlled and reversible. Thermochemical TES is even less developed and more complex than latent TES. The development work in this area has been primarily limited to paper studies and laboratory-scale tests. The only concept advanced enough to be considered for seasonal use is the sulphuric acid/water heat pump.

Reports disagree about the potential of thermochemical TES for STES applications. Engineering and full-scale tests must be performed to determine the actual potential of thermochemical STES.

RECOMMENDATIONS

Based on this quick literature review and preliminary evaluations, the currently most promising nonaquifer STES concepts for more detailed evaluation are:

- Large engineered insulated-pond TES with $<95^{\circ}\text{C}$ water (sensible STES heating)
- Wet earth TES with $<95^{\circ}\text{C}$ water (sensible STES heating)

- Natural lakes and ponds, solar ponds, rocks, and water in mines, caverns, and large tanks (sensible STES heating)
- Ice and compacted snow TES (latent STES cooling)
- Sulphuric acid/water heat pumps at 66 to 200°C (thermochemical STES heating and cooling).

These recommended concepts should be considered for use in conjunction with heat pump systems, for use with each other, and perhaps, except for thermochemical STES, for coupling with aquifers. With heat pumps, the sensible STES heating methods could also be used for cooling. Sensible heat and cold storage concepts currently have the most promise because they are the most developed concepts. In general the promising STES concepts use low temperatures (<95°C), low-cost storage media (water and rock), construction with earth, good insulation and leak tightness, and economies of large scale.

A more in-depth review might reveal that some concepts were overlooked or underevaluated in this broad but shallow overview of thermal energy storage concepts possibly applicable to seasonal storage. Research and development may improve other concepts enough that they should be considered for STES. Because of the need to store large thermal inventories over relatively long periods, the principal criteria for successful STES will be low costs of construction, storage media, and operation.

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1.0 INTRODUCTION

Thermal energy storage enables the capture and retention of heat energy (or cold) during one time period for use during another. Seasonal thermal energy storage (STES) involves a period of months between the input and recovery of energy. The purpose of this study was to make a preliminary investigation and evaluation of potential nonaquifer STES systems. Current literature was surveyed to determine the state of the art of thermal energy storage (TES) systems such as hot water pond storage, hot rock storage, cool ice storage, and other more sophisticated concepts which might have potential for future STES programs.

The study was made as part of the nonaquifer STES task for the Seasonal Thermal Energy Storage Program managed by the Pacific Northwest Laboratory. The work is sponsored by the U.S. Department of Energy, Office of Advanced Conservation Technologies, Thermal Energy Storage Program.

Figure 1 indicates the main energy sources for TES and the uses for which the stored energy could be employed. These main sources provide energy that would be wasted or poorly utilized if the energy could not be used on a delayed basis. The main uses of the stored thermal energy are heating, cooling, and steam generation. Approximately one-third of the energy consumed in the U.S. is employed at less than 95°C. Space heating alone requires about 20 percent of the energy.

Thermal energy can be stored in three ways: 1) as sensible heat by raising or lowering the temperature of the storage medium, 2) as latent heat by freezing or melting the medium, and 3) as thermochemical heat by causing a chemical change in the composition of the storage medium.

Sensible heat is the energy associated with changes in the temperature of a material without a phase change. Sensible heat is stored in water, rocks, earth, metals, ceramics, and other materials.

Latent heat is the energy associated with a change in the phase of a material, such as melting or freezing of ice. Latent heat is released or absorbed at the melting point of materials such as ice, paraffin wax, salts,

and metals. A phase change material (PCM) is a material used to store thermal energy as latent heat.

Thermochemical heat is the thermal energy associated with a change in the chemical composition of a mixture of materials. The heat released during combustion of a fuel is one example of thermochemical heat. For application to energy storage, however, the chemical reactions must be controlled and reversible. Heat reactions are endothermic one way and exothermic in the reverse. Often a catalyst is required to speed up the reverse reaction.

FIGURE 1. Thermal Energy Storage Sources and Uses

Section 2 of this report reviews the development of sensible, latent, and thermochemical TES technologies. Section 3 is a preliminary evaluation of the TES methods most applicable to seasonal storage uses. Section 4 outlines preliminary conclusions drawn from the review of current TES literature and recommends further research based on these conclusions. Section 5 is a bibliography of the nonaquifer STES literature review. An appendix gives examples of 53 different TES concepts drawn from the literature.

2.0 THERMAL ENERGY STORAGE TECHNOLOGIES

Of the three basic TES technologies, sensible heat storage is the simplest and most developed technology. Latent heat storage is more complex and is in an intermediate stage of development. Thermochemical heat storage is the most complex and least developed technology. Design concepts and schematics of the three technologies are illustrated in the appendix.

A very general comparison of the three technologies is given in Table 1. This comparison is likely to change as development improves the latent and thermochemical TES concepts. Also, more will be learned about seasonal applications for TES during demonstration projects.

The thermal energy storage system is usually composed of an energy source, a delayed use for the energy, and the following primary components:

- heat or cold storage medium (water, salt, chemical, etc.)
- a container for the storage medium (pond, tank, etc.)
- insulation to minimize heat or cold storage losses (cover, foam, batting, etc.)
- heat exchanger for transferring energy from the energy source to the storage medium to the delayed use (tubes, resistance heater, etc.).

Sensible, latent, and thermochemical TES are reviewed here with reference to each of the primary components of a TES system. For a final design, an entire TES system must work as a single unit.

2.1 SENSIBLE TES TECHNOLOGY

Sensible heat has been stored in water and brick on an hourly and daily basis for many years. In recent years Europe has heated buildings using resistance-heated thermal energy storage furnaces powered by off-peak electricity. The furnaces use alumina, magnesia, cast iron, and water as storage media. The use of heating and cooling with off-peak power is spreading throughout the world.

Solar thermal energy is being stored in water tanks and rock beds on hourly, daily, and multiple-day bases.

TABLE 1. Generalized Relative Comparison of TES Technologies

Subject of Comparison	Sensible TES ^(a)	Latent TES ^(a)	Thermochemical TES ^(a)
• State of Technology Development	1	2	3
• Simplicity	1	2	3
• Reliability	1	2	3
• Economy	1	?	?
• Near-Term Implementation (<5 yrs)	1	2	3
• Safety and Environmental Considerations	1	2	3
• Potential TES Time Applications			
Hourly Storage	1	2	3
Daily Storage	1	2	3
Weekly Storage	1	3	3
Seasonal or Annual Storage	2	X	3
Multi-Year Storage	X	X	3
• Advantages	<ol style="list-style-type: none"> 1. Most well developed and used TES technology 2. Simplest and most reliable 3. Low cost material and container 4. No phase change to contend with 5. Materials are readily available 6. Simple heat exchangers used 	<ol style="list-style-type: none"> 1. Energy stored and recovered at a nearly constant temperature 2. Continued development may verify lower cost and higher performance of PCM for energy storage 3. Smaller volume required if temperature swing is small 4. Usually less site specific than the other technologies 5. Some sensible heat is also stored 	<ol style="list-style-type: none"> 1. Permits indefinite storage at ambient temperature with essentially no time-dependent heat losses; has potential for multi-year storage if inventory cost is justified 2. Energy storage density is high (7-15 times sensible heat storage) 3. Energy can be released to meet variable demands 4. Has potentially large internal heat fluxes 5. Stores high temperature heat for the longest time period.
• Disadvantages	<ol style="list-style-type: none"> 1. Energy returned at an ever-decreasing temperature; May require booster heat. 2. Must be well insulated. 	<ol style="list-style-type: none"> 1. Technology not well developed 2. Volume increases 5-40% during melting 3. Corrosion uncertainties. 4. Must be well insulated. 5. Material breakdown due to cycling and leaks. 6. Temperature governs material selection. 	<ol style="list-style-type: none"> 1. Technology not developed; many technical problems; complex. 2. Safety problems due to reactions and leaks. 3. Material handling problems. 4. Uncertain reliability and lifetimes. 5. High cost until breakthroughs are made. 6. For the high temperature reactions more sophisticated materials, catalysts, and safety designs are required. 7. High temperature reaction material will also react with water and carbon dioxide. Therefore system must be well sealed.

(a) Ratings: 1 = Predictable, good, or developed
 2 = Moderately predictable, fair, or partially developed
 3 = Unpredictable, poor, or undeveloped
 X = Not feasible

Note: Development advancements can change the ratings.
 There are two specific exceptions; ice in latent TES
 and sulfuric acid/water reactions in thermochemical TES.

High-temperature pressurized water has been stored and used for steam generation and boiler feedwater heating for many years on an hourly basis.

Until recently no sensible TES method has been used on a seasonal basis. Some experiments are now under way using aquifers to store heated and cooled water. Solar ponds and moist earth are also being tested for seasonal storage on a small scale.

2.1.1 Sensible TES Media (Materials)

The most common sensible heat materials being considered for TES are listed in Table 2. Some of the data that apply to the materials are also listed in the table.

The best materials for STES appear to be water, rock, and mud (wet earth). They function at low temperatures where STES systems can be designed at low cost with a minimum of surprises. As temperatures increase, more insulation, more expensive seals, more corrosion, and more unknowns are encountered. The higher-temperature materials are more suitable for short-period TES up to a week.

2.1.2 Sensible TES Containers

The sensible heat storage materials are the easiest to contain and control because they operate without any phase or chemical changes. The TES material can be contained in earth, caverns, mine excavations, tanks, or some combination. The earth and mine pits can be used to contain ponds, lakes, mud, rock beds, and earth itself. Caverns which are adequately sealed and insulated can be used to hold water, oil, rock, or some combination of the materials. Tanks can be used to contain liquids and solids.

Use of earth and caverns as TES containers is highly site specific. It is necessary to seal, insulate, and cover the container, especially for STES applications. Liners are needed to prevent fluid leaks that lose energy. Insulation is required to reduce thermal losses through the top, sides, and bottom. A cover is needed to prevent ingress of rain and snow because such ingress will reduce the storage efficiency. The cover also provides an insulating air barrier and reduces thermal losses from convection and evaporation. Soil surrounding the container must be kept dry.

TABLE 2. Sensible TES Media Data

Material	Rough Temperature Range, °C	Relative Stage of Development	Cost	Storage Duration(a)	Storage Container(b)
Water	0 to 95	Excellent	Low	H,D,W,S	E,C,T
Wet Earth (Mud)	-50 to 95	Fair	Low	W,S	E,C
Concrete	0 to 200	Fair	Medium	D	E
Earth	-50 to 300	Fair	Low	W,S	E
Oil	95 to 400	Good	High	H,D	C,T
Sulfur (Liquid)	130 to 430	Poor	Medium	H,D	T
Pressurized Water (HTW)	100 to 700	Good	Low	H,D	C,T
Rocks and Gravel	-50 to 1000	Good	Low	D,W	E,C
Salt (Molten)	150 to 1000	Fair	Medium	H,D	T
Metal	-50 to 1000	Excellent	High	H,D	T
Sand	-50 to 1300	Fair	Low	D,W	E,C
Ceramics	-50 to 1800	Excellent	Medium	H,D	T

(a)H - Hourly

D - Daily

W - Weekly

S - Seasonal

(b)E - Earth

C - Cavern

T - Tank

Tanks are usually fabricated out of reinforced concrete, fiberglass, or steel, depending on temperature and corrosion requirements. Some tanks are lined or coated with plastic, rubber, or another appropriate material. Tanks can be made in section modules to reduce costs, but their lifetimes are hard to predict. The main limitation of using tanks for STES is the high cost.

The use of tanks or insulated ponds are the least site-specific STES methods. They, along with wet earth storage, will probably be the best alternatives to aquifer STES. Sites that have natural valleys for constructing ponds, natural caverns, and abandoned mines might be attractive because of reduced excavation costs.

2.1.3 Sensible TES Insulation

A STES system is basically charged and discharged only once per year. The storage unit is sized to match the energy source and user demands in an optimal fashion. In a system where source energy is available for one month and demand is primarily spread over the remaining eleven months, the storage would be of maximum size. In a system where the source is a steady 365 days per year, such as an aluminum plant, the storage size would be about 5 to 25 percent as large. A typical annual-storage solar space-heating system has a storage capacity equal to 35 to 60 percent of the annual heat load for the buildings. By the same token, the solar collector system can be smaller than that required on daily basis and yet meet 100 percent of the heating requirements.

In any case, the energy must be stored in inventory for long periods of time in large quantities; therefore the prevention of heat loss is crucial to the system.

A model of heat flow from a thermal storage unit is shown in Figure 2. The greatest rate of heat loss is at the top and in the shortest path to the water table. Insulation must be heaviest in those regions to protect the natural thermocline stratification. Wet soil should not be allowed to come in contact with the container because the thermal conductivity of wet soil can be ten or more times that of dry soil.

Tanks above ground will require a substantial amount of insulation, and commercial insulation is available to do the job. Commercial insulation is

FIGURE 2. Boundaries for The Thermal Storage Heat Loss Model
(56a; Hooper 1979, p. 13)

probably available for the other methods of storage also, but some testing will be required. Foam insulation, such as isocyanurate foam used for swimming pools, may find application in ponds. Urethane foam can be used for floating covers and to help stratify temperatures. Foam concrete can be used in the structures.

Additional research should be done to determine or develop insulation for the various applications. Insulation will be the most important factor to justify STES projects at many sites.

2.1.4 Sensible TES Heat Exchangers

Heat exchangers for STES are incorporated in the design of the system. For solid sensible heat media, such as rocks and gravel, the fluid (air, water, etc.) should be passed in direct contact through the media to add or retrieve heat. For fluid media, such as water, tube-type heat exchangers can be used or the water can interact directly with the source and use without heat exchangers internal to the storage system.

The heat exchangers can be located in the medium or remote from the medium. Except for heat exchanger fouling and corrosion, not many problems are anticipated at the low temperatures ($<95^{\circ}\text{C}$).

Some of the heat exchanger concepts are shown in the appendix.

2.2 LATENT TES TECHNOLOGY

The latent heat of fusion is the thermal energy associated with a change in the physical condition (phase change) of a material by melting or freezing. The harvest of natural ice during the winter for use in summer refrigeration is a historical example of latent thermal energy storage. It probably still has the best near-term potential for latent TES. Use of Glauber's salt, calcium chloride hexahydrate, and paraffin has been under development for several years for low-temperature heat ($<90^{\circ}\text{C}$).

Use of the latent heat of vaporization or sublimation does not appear to be practical, except perhaps for extremely short-term energy storage (up to an hour), because of the large storage volumes required for vapor (e.g., steam occupies $26\text{ ft}^3/\text{lb}$ at 100°C and atmospheric pressure). The latent heat of transformation may have potential for daily storage, but very little literature was available, and the concept is not discussed in this report.

Storage as latent heat has the advantage that energy is stored and recovered at nearly constant temperature. This temperature is a unique property of the storage material and will govern the selection of a storage material for a specific application. Solid-liquid processes are the most practical for near-term applications and include both melting of salt mixtures and crystallization of salt solutions.

Latent heat storage technologies are significantly less advanced than those for sensible heat. Continued development is expected to verify the lower cost and higher performance potential of phase change materials (PCMs) for energy storage. The use of phase change for seasonal applications is probably unlikely because of the higher material cost. The main use will be for the short-term energy storage perhaps up to several days. Use of the PCMs on a daily basis coupled with seasonal storage or incorporated with a sensible system to stabilize temperature (e.g., paraffin stored in containers in water) has some potential. Some commercial TES equipment is available to couple latent and sensible heat on a daily basis.

2.2.1 Latent TES Media (Materials)

Numerous materials are available for latent heating and cooling from the melt/freeze phase changes. The general categories of materials (listed in approximate order of increasing melting temperatures) are as follows:

- clathrates
- water
- clathrate hydrates
- hydrate eutectics
- paraffin wax
- organics
- inorganic salts
- metals

The most promising PCMs according to the literature are listed in Table 3 along with some of their properties. Numerous studies have reviewed and evaluated thousands of materials according to several selection criteria. The evaluations have reduced the quantity of PCMs to just a few which provide optimum performance in various temperature ranges.

Typical PCM selection criteria include the following:

1. The material should have a melting point within the temperature range of the heating or cooling requirements. Although this seems to be quite obvious, many materials tend to supercool when cooling, such that their effective solidification temperature falls below the temperature range of cycling. This makes them useless as TES materials.
2. The material should have a large heat of fusion. A larger heat of fusion allows storage of larger amounts of energy. All of the materials considered for low-temperature heating and cooling applications have lower heats of fusion than water.

Table 3. Most Promising Phase Change Materials

Material	~ Melting Point, °C	~ Heat of Fusion (Btu/lb)	~ Density, lb/ft ³	~ Cost, \$/lb
Water	0	144	62.4	0.00-0.02
Clathrate Hydrate, C ₄ H ₈ O·17·2H ₂ O	4	109	--	--
1 - Decanol	6	88	--	0.38
Paraffins				
C ₁₄ -C ₁₆ Paraffin	5	65	--	0.16
C ₁₆ Paraffin	16	86	--	0.40
PI16	47	90	49	0.15
Salt Hydrates (Inorganic)				
K ₂ HPO ₄ · 6H ₂ O	13	--	--	--
ZnCl ₂ · 3H ₂ O	10	--	--	--
Na(OH) · 3-1/2 H ₂ O	15	96	--	--
CaCl ₂ · 6H ₂ O	29-39	75	102	0.02
Na ₂ CO ₃ · 10H ₂ O	32-36	106	90	--
Na ₂ HPO ₄ · 12 H ₂ O	36	114	95	--
Na ₂ SO ₄ · 10 H ₂ O	32	108	91	--
Na ₂ S ₂ O ₃ · 5H ₂ O	48	90	104	0.14
Mg Cl ₂ · 6H ₂ O	117	72	--	0.07
Mg(NO ₃) ₂ · 6H ₂ O	90	73	--	--
Mg(NO ₃) ₂ · 2H ₂ O	130	--	--	--
Organics				
Phthalic Anhydride	131	65	--	0.27
Polyethelene (High Density)	125-135	81	60	0.32
Polypropylene (Isotactic)	155-165	79	57	0.32
Salts				
KNO ₃ · CaNO ₃ (66/34)	146	--	--	--
NaNO ₃ · KNO ₃ (50/50)	222	43	--	0.09
NaNO ₃ · CaNO ₃ (71/29)	232	--	--	--
Na(OH) · Na ₂ CO ₃ (93/7)	283	--	--	--
Na(OH) · NaNO ₃ · MnO ₂ (91.8/8/0.2)	234-293	--	--	--
NaNO ₃	310	75	141	0.08
K(OH)	360	58	127	--
KCl·NaCl·MgCl ₂ (15/22/63)	385	126	140	--
LiCO ₃ · K ₂ CO ₃ (35/65)	505	148	--	--
KNO ₃ ·NaNO ₃ ·NaNO ₂ (40/7/53)	538	--	--	--
NaF · ZnF ₂ (63/37)	640	231	146	0.31
CaF ₂ · KF · NaF (7/54/39)	682	240	124	0.21
Metals				
Mg - Zn (71/29)	343	77	--	--
Al - Mg (67.5/37.5)	451	131	--	--
Al - Si (88/12)	579	217	--	--
Al	660	169	--	0.65
Si-Mg (53/47)	946	344	--	--

3. The material should have a congruent melting/freezing points. The material should melt completely at a fixed temperature or within a very narrow range of temperature (at most 5°C or 9°F). Otherwise, the difference in densities between solid and liquid will cause segregation, resulting in changes in the chemical composition of the material. This introduces complications in the cooling behavior. Also a low change of volume upon fusion is desirable.
4. The material should not supercool. When the TES material is cooled while in the liquid phase, the melt should solidify at the thermodynamic melting point. This requires a large rate of nucleation and growth. Otherwise, the liquid will supercool and the stored energy will not be released. Some materials require addition of nucleating agents to prevent super-cooling and to promote a uniform crystallization of the medium. Larger storage systems are less likely to experience supercooling. Thermal conductivity and specific heat should also be adequate.
5. The material should be stable. All applications to be considered in this report are long-term uses of thermal energy storage materials. The envisaged lifetime of such a system is about twenty years or more. Hence, the materials to be used should be very stable and not tend to decompose into other materials. This is particularly critical for TES materials at high temperatures in the liquid state, since the diffusion of atoms is enhanced, and the rates of chemical reactions generally increase in these conditions. The possible reactions should be investigated from the thermodynamic and the kinetic points of view to determine whether they should be considered or whether they can be safely ignored. Material breakdown will occur more slowly in a seasonal system because of less frequent thermocycling across the melting point. The material vaporization pressure characteristics must also be reviewed closely.
6. The material should not interact with the container or heat exchanger. This is an extension of point 4 above, but it relates to material-container interaction rather than internal reactions of the

material. The material should not corrode or react with the container and heat exchanger.

7. The material should not be dangerous. Since the possibility of accidental leakage is always present, it is preferable to choose a material that is nonexplosive, nonflammable, and nontoxic and that does not have a bad smell. A low vapor pressure must be avoided.
8. The material should be cheap and available. This point is not very well defined. The cost of a material that is presently available may be much higher than the cost of the same material if a large demand were generated for that material or if a more economic way of producing it were found. The ultimate cost is related to the availability of the material or of its primary elements. We should attempt to confine our choices to common materials which are available in large quantities at low cost.

It will be difficult to find a material that simultaneously satisfies all these requirements. It is possible to find some materials that are acceptable, if the disadvantages are factored into the system design.

2.2.2 Latent TES Containers

Tanks will be the primary method of storing PCMs. However, if desirable, PCMs can be encapsulated in small capsules or containers and placed within a larger container; for instance, PCM capsules could be placed in tanks, ponds, caverns, etc., to form a hybrid system.

Tanks or capsules for storing PCM heat require development for the higher temperatures ($>95^{\circ}\text{C}$) because of corrosion, PCM expansion during melting (5 to 40 percent), and incorporation of heat exchangers. Even low-temperature experience ($<95^{\circ}\text{C}$) with Glauber's salt indicates that it is difficult to incorporate effective heat exchange due to supercooling and selective crystallization of salts which will deteriorate the storage and heat exchange efficiency.

2.2.3 Latent TES Insulation

Insulation is very important for latent TES, as it is for sensible TES. Adequate insulation must surround the storage tank to minimize heat losses. Standard commercial insulation should be available for most latent TES systems because PCMs are contained in tanks or in capsules within vessels.

2.2.4 Latent TES Heat Exchangers

TES materials which are placed in containers can be designed to exchange heat directly with the cooling and heating media. Conventional designs such as the tube/shell concept can be used, but special materials and designs are likely to be required. Materials, especially for the higher temperatures, will have to be carefully selected.

Some of the heat exchanger concepts which have been reviewed for salt media TES include: 1) direct contact open system, 2) shell and tube, 3) reflux boilers, 4) jet impingement, 5) tumbling abrasive, 6) external and internal scrapers, and 7) passive tube intensive.

Some heat exchanger concepts are illustrated in the figures of the appendix. Much development work remains in this area.

2.3 THERMOCHEMICAL TES TECHNOLOGY

Thermochemical energy storage uses reversible chemical reactions to store thermal energy as chemical-bond energy by changing the chemical composition of the storage medium. The concept of advanced thermochemical energy storage is to employ controllable chemical reactions in a closed cycle with a net exchange of thermal energy and no net gain or loss of material.

The concept is a long way from being developed for commercial applications. Most of the research has been done for solar electric power generation and building heating and cooling. A few high-temperature systems and one low-temperature system are described in the next two sections.

2.3.1 High-Temperature TES (>250°C)

Development of thermochemical methods for daily storage of thermal energy in solar-thermal power plants involves identifying a chemically reacting system which is rapid and controllable and which accepts and returns thermal energy in the temperature range of 400° to 800°C (750° to 1475°F). The three systems shown below are promising candidates:

Thermal energy from the receiver causes decomposition of the starting material to form a series of high-energy products, such as CaO (lime) and H₂O (water) in system (3). Separation and containment of the high-energy products at ambient temperatures result in energy storage with no time-dependent loss. The products are recombined on demand to recover the stored energy and to retrieve the starting material. While the equipment for reacting, treating, and storing the chemical products is complex, thermochemical storage is suited to seasonal storage because of the increased storage density (2 to 15 times that of sensible or latent technologies) and the absence of a time-dependent energy loss.

More than five hundred chemical reactions were evaluated for use in TES applications. Most of those investigated involve solid or entirely gaseous constituents which are difficult to manipulate and difficult to store.

Although a purely liquid system is highly desirable, no purely liquid system with high-temperature capabilities has been identified. The best compromise in terms of energy storage density and high-temperature capability is the sulfur dioxide/oxygen system, even though one of the reactants has to be stored as a gas.

While there is considerable experience in carrying out these chemical reactions in industry, no experience has been obtained using the reactions for actual energy storage. Most of the research done thus far has been in the form of paper studies. The most extensive systems analysis was done on the sulfur trioxide reaction listed as system (2).

During the course of the sulfur trioxide analyses, the following areas had uncertainties that must be addressed in subsequent research:

- materials selection
- system lifetime
- oxygen versus air (effluents)
- catalysts
- complexity
- reliability
- cost analysis
- safety – leaks cause sulfuric acid; flammable; hot O_2 could burn metal pipes, etc.; mechanical strength up to $800^\circ C$

2.3.2 Low-Temperature TES (<250°C)

A lower-temperature reaction concept, which would apply primarily to low-temperature steam and the heating and cooling of buildings, is being developed with engineering-scale tests using an all-liquid reversible chemical reaction between sulfuric acid and water. This reaction operates from 66 to $200^\circ C$. It looks promising based upon studies and tests done to date. It is also sometimes referred to as a chemical heat pump. Other chemical heat pump concepts under study, but not as far progressed, include metal hydrides, ammoniated salts, magnesium chloride/water, and methanol-based salts.

The chemical heat pump/thermal energy storage device using the reversible reaction $\text{H}_2\text{SO}_4 \cdot \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{SO}_4 + \text{H}_2\text{O}$ operates by storing energy at a low temperature when the chemicals are separated and returning the energy at the user-designated temperature during the recombination reaction. The device can be used for heat pumping, space cooling, and extended-duration thermal energy storage capabilities. In addition, the unique properties of the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ system include:

- high energy density (60,000 Btu/ft³ and greater)
- long duration storage potential (energy not stored in high-temperature gradients)
- relatively available and inexpensive thermal energy storage capacity (media cost less than \$0.02/lb)

Recent analyses indicate that the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ system also operates favorably with solar energy, off-peak electric heating and cooling, waste heat coupled absorption chillers, and heat pumping of industrial fluid streams to higher useful temperatures.

Except for the work on the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ system, thermochemical TES systems are in the infancy stage. It is an emerging technology, currently at the bench-scale level of development, and is seen as a long-term prospect .

2.3.3 Thermochemical TES Media (Materials)

Hundreds of common materials have been investigated for use in this concept. The materials mentioned earlier in this section appear to be the closest to implementation. The $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ reaction is probably the only reaction that should now be studied further for STES.

2.3.4 Thermochemical TES Containers

More containers are employed in thermochemical TES systems than in the sensible and latent TES systems. Illustrations of the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ system and the SO_3 system (Figures A.49 and A.50 in the appendix) show the additional complexity. Considerable additional development is needed before the systems can be scaled up for demonstration projects.

2.3.5 Thermochemical TES Insulation

Insulation is not as important for this method of storage as it is for sensible and latent heat storage; however, insulation is still important for short-term storage applications. For monthly and seasonal storage the need is not as critical because the material will be stored in ambient conditions anyway. Reaction vessels and pipelines can be insulated with commercially available insulations.

2.3.6 Thermochemical TES Heat Exchangers

Commercially available reactors, tanks, and piping can be used for the lower-temperature reactions by careful selection of materials. More research is needed for selection of the best materials for the higher-temperature reactions. Development of low-cost heat transfer systems is needed.

3.0 PRELIMINARY EVALUATION OF STES METHODS

Based on the review of literature it appears that the best STES methods will utilize sensible heat using low-cost storage media (water, rock), construction with earth, good insulation and leak tightness, and economies of large scale. The best application is in the $<95^{\circ}\text{C}$ temperature range for district or large building heating and cooling and agriculture industry heating and drying. Cooling can also be done effectively where ice and snow can be harvested efficiently.

Where suitable aquifers are available, it is unlikely that nonaquifer methods can compete economically. Where suitable aquifers are not available, the use of engineered, insulated ponds is probably the most attractive alternative. Two ponds, one for heating and the other for cooling, can be coupled with district home heat pumps to provide low cost heating and cooling. A favorable climate is also necessary, however.

If open pit mine excavations or natural valleys can be adequately sealed and insulated, they might provide a lower-cost pond alternative. Also natural caverns, salt domes, or underground mine caverns might be considered. Engineered caverns might be justified if high-temperature water ($250\text{--}350^{\circ}\text{C}$) is used.

Natural ponds and lakes with very favorable site characteristics might be considered. Site-specific problems such as spring water inflow, seepage, wet soil thermal conduction, air convection and evaporation losses, ingress of snow-rain/runoff, wind and storm protection, etc. must be countered to reduce heat loss from the storage media. Costs to reduce these losses may end up being higher than the cost of a man-made pond.

Wet earth surrounded by vapor barriers and dry earth can provide seasonal storage on a smaller scale for agricultural uses (e.g., animal shelters, crop drying, greenhouses). Development of low-cost installation techniques may make wet earth or dry earth STES possible for individual homes also.

Huge insulated water tanks may be considered if costs can be reduced sufficiently.

The most promising latent heat STES application is for cooling with the use of natural harvested ice and highly compacted snow. This restricts use to the northern or mountainous regions where ice and cold is available. Use of ice manufactured with off-peak power is a consideration where favorable power rates are available.

Other latent heat materials do not appear attractive on an annual or seasonal basis because of higher material cost and greater complexity in storage and heat exchanger systems. Seasonal storage using latent heat does not appear to be practical except in special applications where requirements for a higher density and steady output temperature justify the added cost (e.g., space exploration, factory ships, marine laboratories). Latent heat concepts will compete primarily in the hourly, daily, and perhaps weekly storage ranges. In some instances latent heat might be coupled with water STES systems to provide more stable output temperatures or daily buffering.

Thermochemical STES may be practical in the long term for storage of high-temperature ($>250^{\circ}\text{C}$) heat. The only near-term exception might be all-liquid reactions like the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ reaction ($<250^{\circ}\text{C}$). The $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ reaction could be used for both heating and cooling applications. Some safety concerns will have to be resolved first, however.

The next four subsections evaluate the 1) operating characteristics, 2) possible applications, 3) potential thermal effectiveness, and 4) potential cost effectiveness of the most promising STES concepts.

3.1 OPERATING CHARACTERISTICS EVALUATION

A preliminary evaluation of the operating characteristics of the most promising STES concepts is provided in Table 4. Because of simplicity, demonstrated reliability, and good safety, the sensible TES concepts have the best potential for STES in the near term. Latent heat STES requires more development and some large breakthroughs before it can be considered (an exception is ice storage). Thermochemical TES has potential for seasonal storage and even multiyear storage. It also has potential for transporting the energy between sites by pipeline or rail. However, much more development and experience is required before thermochemical STES can be seriously considered (except for the $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ reaction).

TABLE 4. Preliminary Evaluation of Operating Characteristics of STES Methods

Method	Temperature Range, °C	General State of Technology	Advantages and Disadvantages
<u>Sensible STES (Heat or Cold)</u>			
Insulated Pond w/water and cover. (Pond can be engineered or in mine pit or in natural valley)	<95	Artificial ponds well developed. Liners and insulation may need additional development. Some experience with small solar ponds. Water is well understood.	Adv. - less site specific. Low cost for large ponds. Can be coupled with solar energy. Simple, safe. Disadv. - Land is required.
Wet Earth (Mud)	<95	Small greenhouse successful. Plain earth used to heat animal shelters. Development of low-cost installation techniques will help.	Adv. - Water improves heat conductivity and capacity in soil. Simple and safe. Land can be used for some other purposes. Can be used in smaller applications. Disadv. - Land may not be as stable for supporting structures. Need deep soil.
Natural Pond or Lake	<95	No experience except paper studies. Studies indicate this type of storage is feasible. Water is well understood, but currents and thermal stratification require more study.	Adv. - Construction costs may be reduced. Simple. Disadv. - Hard to stop thermal losses. Very site specific. Weather can cause damage.
Cavern w/water	<95	No experience. Some work done on compressed air storage. Water is well understood.	Adv. - Natural salt domes or mine caverns would be low cost. Excavated caverns might be okay for pressurized water. Attractive where land is unavailable (cities). Disadv. - Sealing is crucial to prevent leaks. Very site specific. Pumping costs.
Insulated Water Tanks	<95	Well developed.	Adv. - Not site specific. High storage efficiency. Simple. Safe. Disadv. - High cost.
Rock Bed	<500	Experience with solar heating and cooling. Also crop drying. No STES experience. Air flow is not completely understood.	Adv. - Leak problems not as severe. Higher temperature than water. Disadv. - Rock costs more and requires materials handling. Site specific. Heat exchangers may be difficult. Stratification may be problem to control.
<u>Latent STES</u>			
Ice Storage (Cooling)	-40 to 12	Many years experience. Harvesting and handling costs must be reduced by improved equipment. Well understood. Heat exchanger may need slight development. Ice making w/off-peak power might be economical in some locations.	Adv. - Requires 1/3 or less the volume of water storage. Nature can provide the cold. Cools at steady temperature. Simple and safe. Disposal of city snow. Disadv. - Considerable material handling required. Insulation.
Paraffin and Salt Hydrates, Various temp.	0 to 100	Experience with small quantities in heating and cooling of buildings. Could be used to stabilize water temperatures.	Adv. - Releases heat (or cool) at steady temperature. May be encapsulated to work with water storage. Disadv. - Slow heat transfer. Expensive. Paraffin is combustible.
<u>Thermochemical STES</u>			
H ₂ SO ₄ /H ₂ O heat pump	66 to 200	Engineering-scale test in progress. Safety problems need research. Appears economically feasible. Heat exchangers and materials need research. Thermal efficiency also needs more study.	Adv. - Can be used to heat or cool. Has large heat storage capacity. Acid readily available at low cost. Disadv. - Safety problems with acid handling and leaks. Complex system. Equipment costs.

3.2 EVALUATION OF POSSIBLE STES APPLICATIONS

The best possible applications for the STES methods listed in Table 4 are primarily for low-temperature heating and cooling. Building heating and cooling will probably be the best application. The useful temperatures are:

5-15°C	Air Conditioning
45-55°C	Heating
65-80°C	Hydronic Heating
100-140°C	Absorption Air Conditioning
>100°C	Steam
200-220°C	Thermosorb

Ponds, lakes, caverns, and tanks can be used for district heating of buildings. When coupled with heat pumps they can provide cooling as well. Covered ponds in some areas of the country can be utilized with solar collectors, providing the energy source as well as thermal energy storage. A hybrid solar pond layer over a conventional pond may be the most economical.

Wet earth TES can be used for both heating and cooling in the agricultural industry. Low-temperature heat is needed for greenhouses, aquaculture, animal shelters, and others. Cooling can be used in summer for similar applications.

Rock beds can also be used for heating and cooling of buildings. Because of their higher temperature capability, it may be possible for hot rocks to generate steam for industrial or peaking power generation.

Latent energy from ice can provide cooling for buildings and agricultural refrigeration applications.

Thermochemical STES with the sulfuric acid and water system can also be used for heating and cooling of buildings. The system operates favorably for off-peak electric heating and cooling, waste heat coupled absorption chillers, industrial steam generation, and heat pumping of industrial fluid streams to higher useful temperatures.

All of the methods listed in Table 4 can be coupled with heat pumps for heating and cooling. Heat pumps are being developed which can increase temperatures to above 160°C. Heat in the 60 to 200°C range is used extensively in the chemical, paper, food, and forest product industries.

3.3 POTENTIAL STES THERMAL EFFECTIVENESS

No good comparisons of the different systems were found in the literature. The ones which were found are probably optimistic and biased and probably use different bases and definitions. It would be helpful if standard terminology, definitions, and measurements would be established so systems can be compared on a common basis.

It is important to design the storage system so it takes advantage of proper thermal stratification. Stratification leads to better overall system performance for 2 reasons:

- (1) It improves storage discharge efficiency by taking heat out at the higher temperature.
- (2) It improves storage charge efficiency and hence source collector efficiency.

Current experiments on all concepts have shown that it is important to have adequate insulation. The performance of test ponds has been poor because they have been insufficiently insulated and too small.

Seasonal storage would therefore require very good insulation and larger medium masses when sensible heat or ice storage is used. For thermochemical STES there are disputes about how much insulation is needed. Some reports claim little heat is lost when storing at ambient temperatures and others claim a large amount of energy is lost in tanks, pipes, catalysts, and reaction tanks.

Some heat recovery efficiency data based upon small-scale tests and computer studies are given in Table 5. Thermal studies need to be made on the STES methods like ponds, lakes, tanks, rockbeds, caverns, icebeds, and sulfuric acid/water reactions.

It has been found that moisture in the earth greatly accelerates heat losses. In most soils the thermal conductivity varies by an order of magnitude or more over the full range from dry to saturated soil. In underground tanks 10 to 60 % of the heat delivered can be lost through the surrounding soil medium.

TABLE 5. Thermal Recovery Efficiency Estimates

Method	Operating Temperature, °C	Storage Round Trip Efficiency	Storage Cycle Time
Sensible TES			
Hot Water Storage in Insulated Tank	30 to 70	40 to 90	Seasonal
Moist Soil Insulated by Dry Soil and Vapor Barriers	30 to 80	50 to 80	Seasonal
Granite Pebble Bed	49 to 65	57	Daily
MgO Storage in Insulated Tank	533 to 752	77	Daily
Latent TES			
Na ₂ S ₂ O ₃ · 5H ₂ O/Varso1	47	95	Daily
Na ₂ HPO ₄ · 12 H ₂ O/Varso1	34	77	Daily
7CaF ₂ - 54KF - 39 NaF	550 to 800	64.8	Daily
Thermochemical TES			
H ₂ SO ₄ /H ₂ O Heat Pump	66 to 200	74 to 80	Daily
SO ₂ /O ₂	430 to 875	68.5	Daily

Soil moisture mechanisms such as water percolation during rainfall, spring runoff, and evaporation and condensation of the soil moisture involve a mass transfer of either liquid or vapor, and hence transfer of the internal energy of the migrating water. Soil properties and the heat flow regime are also influenced by the freezing and thawing cycle.

To minimize heat losses it is essential to be concerned about the type of backfill, soil layering, surface grading, moisture barriers, type of drainage system, and type of insulation. It is probably necessary to add good foam insulation around tanks, pond bottoms, etc. to reduce heat losses, especially on a seasonal basis. The container surface area with the storage medium should be minimized (e.g., a large shallow pond has higher heat loss than a small deep one).

As the size of the storage reservoir increases, it becomes more cost effective because of the lower cost-per-unit capacity and the lower unit heat losses resulting from decreasing the surface-to-volume ratio.

Storage demonstrations with large volumes must be made to better assess the effectiveness of the STES concepts. Things that have been learned in small-scale tests to date should be incorporated in the large-scale designs. More heat transfer and thermal analysis is needed for all of the nonaquifer STES concepts.

3.4 POTENTIAL STES COST EFFECTIVENESS

The potential cost effectiveness of nonaquifer seasonal storage is dependent upon many site-specific variables and the energy source/use requirements. A specific concept will vary in cost between sites. Not enough data is available to accurately compare the costs of STES systems.

The STES system for an energy source that provides a steady uniform supply of thermal energy (e.g., aluminum plant) can be substantially smaller and less costly than a system that uses an energy source that supplies the bulk of heat in summer (solar) and does not use the energy until winter when insolation is low.

Lower-temperature storage means that insulation requirements are not as great as for high-temperature storage. A lower-temperature gradient means less insulation and lower cost. Lower temperatures also mean that a larger variety of materials and lower-cost materials can be considered in the construction of the containers and heat exchangers.

If complex special heat exchangers are required to minimize corrosion and fouling, to maintain cleanliness, etc., the cost will be much higher than for simple units where storage media are directly interfaced with heating and cooling fluids.

Probably the most important cost element to consider in seasonal or annual storage systems is the cost of the storage medium. A rough comparison of costs for a 56°C storage temperature swing is:

<u>Material</u>	<u>Btu/\$</u>
Water	625,000
Rock	10,000
Oil	400

The STES systems become more economic as the capacity increases because of economies of scale. Large systems have lower costs and smaller heat loss percentages.

The only common basis for costs of the three basic systems (sensible, latent, and thermochemical) was found in a study for power plants. The three systems were compared using the Solar-Brayton power cycle operating at 400-800°C. The cost analysis is summarized in Tables 6 and 7. The analysis is like comparing apples and oranges because only the sensible heat concept is now close to being technically and economically viable.

A cost analysis comparing various sensible STES concepts for storing waste heat from an aluminum plant is shown in Figure 3. The initial storage cost is estimated as a function of storage capacity. Table 8 gives some order-of-magnitude costs based upon review of the literature and some of my own estimates. More cost work needs to be done on nonaquifer STES systems, especially on a life-cycle basis.

TABLE 6. Storage System Cost Summary
(Millions of Dollars)

<u>Account</u>	<u>Thermochemical</u>	<u>Phase Change</u>	<u>Sensible Heat</u>
Storage medium	0.5	2.0	3.0
Storage container(s)	1.8	0.3	13.0
Reactor	4.9	--	--
Heat exchanger			
Tubes	--	3.1	--
Construction	--	0.3	0.5
Misc plant equipment	3.4	--	--
He circulating system	1.1	1.4	1.3
Total system	11.7	7.1	17.8

- 50 MWe module
- 6 hours storage

TABLE 7. Energy Cost Comparisons

	<u>Storage Capital Cost*</u>		<u>Plant Cost</u>	<u>Busbar Energy Cost</u>
	<u>(\$/kW)</u>	<u>(\$/kWh)</u>	<u>(\$/kW)</u>	<u>(mills/kWh)</u>
Sensible heat concept	42	52.1	1,841	63.0
Phase change concept	50	15.2	1,558	54.4
Thermochemical concept	217	7.8	1,719	61.0

- Inyokern, California
- Strawman field = 1.0 km²
- Storage = 6 hours
- Plant capacity = 100 MWe (2 modules)
- Seasonal average

*Storage capital cost = \$/kW + \$/kWh

FIGURE 3. Initial Storage System Capital Cost (2; Katter and Hoskins 1978, p. 102)

TABLE 8. Rough Cost Estimates for TES Containers

Method	Temp, °C	Capacity, Btu	Capital Cost, \$	Capital Cost, \$/10 ⁶ Btu	Storage Duration	Application
● Aquifer Storage (H ₂ O)	<95	--	--	2	Seasonal	Heating
● Pond Storage (H ₂ O)	<95	--	--	40	Seasonal	Heating
● Moist Soil	<95	60,000,000	5,000	83	Seasonal	Heating
● Insulated Tanks (H ₂ O)	<95	6.7 x 10 ¹⁰	6,400,000	96	Seasonal	Heating
● Insulated Earth Tank (H ₂ O)	<95	10,000,000	7,700	720	Weekly	Heating
● H ₂ SO ₄ /H ₂ O	66-200	--	--	357	Weekly	Heat and Cool
● Water Tank	<95	--	--	700	Weekly	Heating
● Underground Cavity w/Steel Liner (HTW)	360	--	--	272	Daily	Power Gen.
● Precast Concrete Pressure Vessel (HTW)	360	--	--	1,454	Daily	Power Gen.
● Rock Chamber w/Steel Liner and Insulation		2.13 x 10 ⁹	1,700,000	798	Daily	Heating
● Granite Pebble Bed	<95	18,500,000	28,000	1,513	Daily	Dryer
● Immiscible Fluids						
NaHPO ₄	<95	398,200	996	2,500	Daily	Heating
CaCl ₂	<95	398,200	1,415	3,500	Daily	Heating
NaSO ₄	<95	398,200	1,149	2,900	Daily	Heating
Na ₂ S ₂ O ₃	<95	398,200	1,162	2,900	Daily	Heating
● Liquid Thermal Transfer						
HDPE/EG	<95	250,000	2,350	9,400	Daily	Heating
Rock/EG	<95	250,000	3,040	12,200	Daily	Heating
Water	<95	250,000	2,600	10,400	Daily	Heating

It appears that the most cost effective seasonal storage will be to use the best technology at temperatures suitable for district heating and cooling and agricultural uses. This is in the $<200^{\circ}\text{C}$ range. Use of water and/or rock as a storage medium with earth for the container appears the least costly at the current time: the simpler and less unknown, the better.

Most of the present cost estimates are based upon paper studies, and they should be refined after experience is gained with actual testing.

Many estimates are based on the capacity for one home and a daily or multiday duration. These estimates are hard to compare and use for seasonal storage. Supporting information for costs is often lacking, and estimates may be biased. As stated earlier, there is a need for improved cost estimates, especially for the nonaquifer STES concepts that have near-term applications.

Although the cost of the TES system is one consideration, the overall cost, including the source and use systems, is the most important consideration at a particular site. Sometimes a more expensive TES system is needed to accommodate the energy source or use requirements.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the literature reviewed so far, the use of seasonal nonaquifer thermal energy storage should be limited to the sensible heat methods in the low-temperature ($<95^{\circ}\text{C}$) ranges during the next few years. Use of the high-temperature range with sensible heat methods seems practical for only the daily mode of TES due to the higher costs for material and insulation.

Use of latent heat for TES also appears to be only practical for daily storage applications because of high costs and further development requirements. It is unlikely that use of latent heat for seasonal storage will ever be practical. It may be used for daily buffer storage of an STES system, however. The only exception for latent STES would be in cooling applications with ice.

Thermochemical STES above 250°C requires much more development and may never be feasible, technically and economically. Liquid thermochemical STES below 250°C appears to be marginally feasible if safety concerns with the sulfuric acid/water method can be resolved.

The currently most promising nonaquifer concepts for more detailed evaluation of potential energy savings, thermal effectiveness, and cost effectiveness are:

Sensible STES Heating^(a)

- Large engineered, insulated ponds with $<95^{\circ}\text{C}$ water
- Wet earth storage with $<95^{\circ}\text{C}$ water
- Others that have less potential but still might be considered: deep natural lakes and ponds, solar ponds, mine open pits, caverns, rock storage and water tanks. Rocks can also be used for cooling.

Latent STES Cooling

- Ice and compacted snow storage

(a) May be used for cooling also with heat pumps. Heat pumps should be considered for use in all the concepts.

Thermochemical STES Heating and Cooling

- Sulfuric acid/water storage

The best applications for these seasonal concepts is district heating and cooling and agricultural uses (greenhouses, crop drying, animal shelters, aquaculture, etc.). These concepts, coupled with heat pumps, show good near-term promise. Once the more advanced high-temperature heat pumps are developed, the application of these concepts can be increased to include industrial steam for food, textiles, paper, and chemicals. High-temperature heat pumps can work with temperatures to 160°C and can increase temperatures by up to 100°C.

As a minimum, preliminary studies should be made of the concepts listed above to evaluate the thermal insulation requirements and life-cycle costs before spending large sums of money on the concepts. Costs estimates should be made for systems capable of heating and/or cooling 100, 1000, and 10,000 homes.

Probably one of the most promising concepts would be to cover an engineered pond with solar heat collectors. This would combine the source of the heat as well as storage, make better use of the land, and increase the sites available for STES applications.

5.0 BIBLIOGRAPHY

The references accumulated to date are in the STES Library operated by Midwest Research Institute for the Pacific Northwest Laboratory in Richland, Washington. The STES Library listings (which include nonaquifer references) are lengthy and will be published in a separate report. Presented here is a "library" of references specific to nonaquifer STES. Also listed are references selected from the bound, unbound (u), and microfiche (m) portions of the general STES Library.

Figure 4 lists the alternative TES methods and their respective references as they are numbered in the STES library and in this bibliography. Since these references are selected references, their numeration is not consecutive. Use of Figure 4 will allow the reader to refer to the references associated with each of the alternative TES methods.

Alternate Methods	STES Library		Nonaquifer STES References
	Bound	Unbound	
General (Large Variety)	1,2,3,4,31,36,48,49,50,58	31,32,38,48,62,69,70	10a,15a,20a,23a,25a,37a, 40a,49a,56a,58a
Sensible TES			
Water	1,47,58,69	119,120,212,122,123	4a,8a,9a,22a,31a,37a,44a, 57a
Pressurized Water (HTW)	2,3,36,39	44,70,72	42a
Earth	1,3,69	109,152	59a,60a
Rock and Gravel	3,17,36,43,69	34,44,56,63,65,70,104,105,106, 114	13a,30a,32a,55a
Oil	36,39,43	44,70,126	37a
Metal	36		24a,27a
Ceramic	36	3	14a,53a
Sulphur	36		
Sand	36		
Latent TES			
Salt	2,3,17,29,36,49,50,53, 58,62,67	5,6,18,57,70,108,111	17a 1a,5a,7a,11a,16a,24a,35a,38a, 39a,41a,45a,47a,50a,51a
Ice	58	14,71	8a
Phase Change Materials	2,3,29,31,36,39,48,49,52, 53,58,60,62,63,66,69	35,57,70,107,113	2a,3a,6a,14a,19a,28a,29a, 34a,44a,48a
Thermochemical TES	2,3,4,29,36,58,60,69	47,110,115,130,131,132	12a,21a,27a,36a,43a,52a
Miscellaneous			
Brayton Power Plants	14,41	9,133,134,135,137,138	26a
Heat Pump	1,2,3,14,51,53,69	27,35,39,71,87,152	8a,9a,44a
Aquifers	1,2,3,36,39,43,44,58,69	21,59,61,71,100,101,102,142 143,144,145,146,147,149,150	3a,33a
Rankine Cycle	14,69	87,91	18a,35a
Sterling Engine	14	83,94	1a

FIGURE 4. References for Alternate TES Methods

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APPENDIX
TES CONCEPT DESCRIPTIONS

APPENDIX

TES CONCEPT DESCRIPTIONS

A potpourri of TES concept schematics was found in the literature. Some of the concepts are listed in this Appendix as follows:

<u>Concept</u>	<u>Figures</u>
<u>Sensible TES</u>	
Ponds	A.1 and A.2
Lakes	A.3 and A.4
Tanks	A.5 to A.9
Caverns	A.10 to A.13
Earth	A.14 to A.16
Rocks	A.17 to A.23
Sand	A.24 and A.25
Ceramic	A.26 to A.29
Metal	A.30
Hybrids	A.31 to A.35
<u>Latent TES</u>	A.36 to A.46
<u>Thermochemical TES</u>	A.47 to A.51
<u>Hybrid TES</u>	A.52 and A.53

Where applicable, the sources from which the schematics were drawn are acknowledged by reference number (from the bibliography of this report) and by author(s).

FIGURE A.1. Engineered Pond Storage

FIGURE A.2. Schematic Representation of Salt Gradient Solar Pond
(58; Baylin 1979, p. 7)

FIGURE A.3. Insulation Principle for Lake Reservoir (31a; Margen 1978, Fig. 5)

Transparent protective layer (or several layers)
to prevent radiation and convection

FIGURE A.4. Diagram of Combined Solar Collector and Lake Reservoir
(31a; Margen 1978, Fig. 8)

FIGURE A.5. District Heating System Flow Schematic Electrical Home Topping (43; Katter and Hoskins 1978, p. 86)

FIGURE A.6. Domestic Hot Water Heater

To Receive Energy from District Heating System (43: Katter and Hoskins 1978)

FIGURE A.7. Schematic of a Grain Drying System Using Energy Stored in Water by a Solar Collector (56a; Misra and Keener 1979, p. 304)

FIGURE A.8. Variable Pressure Accumulator Provides Thermal Energy Storage Capability (31a; Margen 1978, p. 5)

FIGURE A.9. Displacement Accumulator with Flash Evaporators (39; Hausz, Berkowitz and Hare 1978, p. 2-14)

FIGURE A.10. Hot-Oil Thermocline System for Thermal Storage in Solar-Thermal Power Generation (1; TRW 1979 p. 10)

FIGURE A.11. Doublet Cavern System for Thermal Storage in Solar-Thermal Power Generation (1; TRW 1979, p. 10)

- CHARGE: LIVE STEAM THROTTLED TO REFILL VARIABLE-PRESSURE ACCUMULATOR
- DISCHARGE: VARIABLE PRESSURE FLASHED STEAM GOES TO PEAKING TURBINE
EFFICIENCY = 90 - 95 PERCENT
- SPHERICAL CAVITY IN COMPETENT ROCK
CONCRETE FOR STRESS TRANSFER AND INSULATION

COST OF CONTAINMENT
150 - 300 \$/M³

FIGURE A.12. Lined Cavern with High-Temperature H₂O (39; Hausz, Berkowitz and Hare 1978, p. 3-20)

FIG. 4. Accumulator with dry insulation and internal steam expansion volume.

A = narrow sealing passage	— = main flow
B = pressure balance tank	— = auxiliary systems
C ₁ = air circulator	--- = steam
C ₂ = air compressor	— = air
I _d = dry insulation	⇨ = night flows
I _w = wet insulation	⇨ = peak load flows (day)
K = air cooler	⇨ = continuous flows
S = stack (to which steam blow-off line can be connected)	
x = sealing flow to prevent intrusion of dissolve gases	
y = steam pressurizing supply	

FIGURE A.13. Accumulator With Dry Insulation and Internal Steam Expansion Volume (30a; Margen, p. 184)

FIGURE A.14. Generic Configuration of Pebble Bed Heat Accumulator (40a; Riaz, Blackshear and Pfannkuch, p. 125)

FIGURE A.15. Basic Concept for Low Cost Underground Storage of Heat
(56a: Kemper, Walker and Sabey 1979, p. 156)

FIGURE A.16. A Solar-Excited Earth Heat Accumulator for Electric Power Generation (40a; Riaz, Blackshear and Pfannkuch, p. 124)

FIGURE A.17. Dehydration System Schematic (56a; Stine and Carnegie 1979, p. 322)

FIGURE A.18. Pebble Bed Storage Unit (56a; Stine and Carnegie, p. 322)

FIGURE A.19. Examples of Surface and Underground Rockbed TES (3; Riaz 1977, p. 265)

FIGURE A.20. D. RBM Modes of Operation (32a; Meredith and Wilbur 1979, p. 274)

FIGURE A.21. Conceptual Design of Packed Bed (2; Hamilton 1978, p. 271)

FIGURE A.22. Diagram Showing the Operation of an Intermittent Heat Source with a Rock Pile Thermal Storage (104u; Close 1964, p. 12)

FIGURE A.23. Diagram Showing the Operation of a Rock Pile Thermal Storage as a Source of Cooling Air Conditioning (104u; Close 1974, p. 12)

FIGURE A.24. Sand Over Pipes Conveyor Belt Transport Heat Storage System (61a; Awaya 1970, p. 927)

FIGURE A.25. Blower Transport Sand Heat Storage System (61a; Awaya 1970, p. 927)

FIGURE A.26. Commercially Available, European Design for an Electric Space Heater with Thermal Storage (1; TRW 1979, p. 6)

- Magnesia (MgO) Brick Checkerwork
- Temperature Swing = 264°C (475°F)
- Critical Technical Problems
 - Brick Erosion
 - He Stream Contamination
 - Large Insulated Pressure Vessels

FIGURE A.27. Sensible Heat Storage Concept (41; Gintz 1977, p. 1-8)

FIGURE A.28. Schematic Diagram of Thermal Energy Storage System
(3; Katter 1977, p. 241)

NOTE: ARROWS SHOW FLOW OF GASES DURING DISCHARGE OF PEAKING STORAGE

FIGURE A.29. Thermal Energy Storage for Waste-Heat Recovery in the Steel Industry (1; TRW 1979, p. 14)

A) Hollow Steel Ingot TSU, Original Concept

NOTES:

- * Header system not shown
- * Blanket insulation exterior, not shown
- * Ingots cross-stacked for stability

b) Many Ingots Stacked to Form a TSU

FIGURE A.30. Hollow Steel Ingot Thermal Storage Units
(3; Turner 1977, p. 223)

FIGURE A.31. Dual-Medium Thermal Storage Concept (39; Hausz, Berkowits and Hare 1978, p. 3-32)

FIGURE A.32. Heat Exchangers for a Sensible Heat Storage System (39; Hausz, Berkowitz and Hare 1978, p. 2-15)

FIGURE A.33. Combine Solar-Thermal and Compressed Air Storage System (2; Hamilton 1978, p. 269)

FIGURE A.34. Hybrid Air and Water Storage
(6; Dean 1978, p. 30)

FIGURE A.35. Water-Filled Containers on Racks Used
with Air Systems (6; Dean 1978, p. 31)

FIGURE A.36. Latent-Heat Thermal Storage in an Active Solar-Thermal Heating System (1; TRW 1979, p. 9)

FIGURE A.37. Thermal Energy Storage Module - Chubs
(56a; Frysinger 1979, p. 223)

FIGURE A.38. Chub Applications (2; Frysinger 1978, p. 57)

FIGURE A.39. Tank-Type Capacitor (56a; Murray 1979, p. 315)

FIGURE A.40. Salt TES WI Sterling Engine (2; Farahat 1978, p. 249)

FIGURE A.41. Full-Scale Storage Unit Calcium Chloride Hexahydrate Encapsulated in HDPE Cylinders (2; Lane 1978, p. 125)

FIGURE A.42. Liquid/PCM/Liquid Heat Exchanger
(7; Turner 1978, p. 85)

FIGURE A.43. Phase Change Storage Concept (41; Gintz 1977, p. 1-11)

FIGURE A.44. Calmac Corporation-PCM Storage Device (58; Baylin 1979, p. 78)

FIGURE A.45. Shot Tower Process (34a; Nichols and Green, p. 3956)

FIGURE A.46. Immiscible Fluid-Heat of Fusion Storage System (3; Edie 1977, p. 34)

FIGURE A.47. $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ Chemical Heat Pump (3; Clark 1977, p 350)

FIGURE A.48. Solar/CHP/TES System Schematic (56a; Clark and Hiller 1979, p. 443)

FIGURE A.49. Subscale $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ Chemical Heat Pump Schematic (2; Clark 1978, p. 422)

FIGURE A.51. $\text{CaO}/\text{Ca(OH)}_2$ Energy Storage System Preliminary Process Flowsheet Endothermic Mode ($\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$) (2; Smith 1978, p. 362)

FIGURE A.52. The NRL Thermal Storage Concept (7; Turner 1978, p. 91)

FIGURE A.53. Energy Storage-Boiler Tank (56a; Gordon 1979, p. 63)

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