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SOLAR APPLICATIONS OF
THERMAL ENERGY STORAGE

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I. EXECUTIVE SUMMARY

The objective of this study is to prepare a technology assessment on solar energy systems which use thermal energy storage. The study includes characterization of the current state-of-the-art of thermal energy storage, an assessment of the energy storage needs of solar energy systems, and the synthesis of this information into preliminary design criteria which would form the basis for detailed designs of thermal energy storage. Since the goal of the solar thermal energy storage program is to provide optimum storage units for solar thermal energy systems, this study has focused on storage concepts that are either commercially available or will be commercially available by 1979. The methodology used for this study was as follows:

- Characterize solar thermal energy storage
- Define the storage requirements for each solar application
- Match the storage to each solar application
- Develop the preliminary design criteria.

The following sections summarize the results of this report.

A. Characteristics of Solar Thermal Energy Storage

A major survey including a literature search, telephone conversations, and computer access to DOE/RECON data bases was conducted. Depending on the storage medium, the storage concepts were divided into four categories:

(1) Liquid storage

(2) Solid storage

(3) Phase-change storage

(4) Thermochemical storage.

The survey results are presented in Section II and Appendix A. The type of available information surveyed is also indicated in Figure 1.

STORAGE UNITS	WATER STORAGE REINFORCED PLASTICS KALWALL SOLAR COMPONENTS	WATER STORAGE-WOOD TANK-SUNWAVE ENERGY SYSTEM STORAGE TANK	WATER STORAGE-CONCRETE TANKS-SOLATHERM SOLAR STORAGE TANK	WATER STORAGE-FIBERGLASS TANKS-OWENS-CORNING FIBERGLASS CORPORATION	WATER STORAGE-STEEL TANK-SOLAR ENERGY SYSTEMS, INC.	WATER STORAGE-AQUIFERS-HEAT STORAGE WELL CONCEPT	WATER STORAGE-SALT GRADIENT SOLAR PONDS	PRESSURIZED STEEL TANK	ROCK STORAGE BINS	TROMBE WALL	PCM-SOLARMATIC HEAT BATTERY-GLAUBER'S SALT	PCM-VALMONT INDUSTRIES - ENCRUSTED CONGLOMERATE	PCM-SMC THERMAL STORAGE CELLS - GLAUBER'S SALT	PCM-ARCHITECTURAL RESEARCH CORP. SOL-AR-TILES	PCM-MONSANTO RESEARCH-HDPE PEBBLE BED	PCM-ADD-A-SUN STORAGE CHAMBER	PCM-ACES	PCM-CALMAC MANUFACTURING - Na_2SO_4
CONTAINERIZATION	●	●	●	●	●	○	○	●	●	●		○	○	●		○	○	○
STORAGE MATERIAL	●	●	●	●	●	●	○	●	●	●	○			●	●	○	●	○
INTERFACE REQUIREMENTS	●	●	●	●	●	○	○	●	○[1]	●				○	○		○	○
UNIT PERFORMANCE	○	●	●	●	●	○	○	○	●	○				●			○	○
O & M	●	○	●	●	●		○	○	●	●				○			○	
DESIGN GUIDANCE		●[3]	●[3]	●[3]	●[3]		○	○	○[1]	○				○			○	○
COST	●	●	●	●	●		○		○	○	●		●	●	○	●	○	○
COMMERCIAL AVAILABILITY	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	1979	1979	1979	NOW[2]	NOW	NOW	NOW[2]

1 - Some types, such as thermosyphon designs, are not fully researched.
2 - Storage material is available, not the unit package.
3 - Heat pump interface information is scarce.

☐ LITTLE OR NO INFORMATION AVAILABLE
○ SOME INFORMATION AVAILABLE
● ADEQUATE INFORMATION AVAILABLE

Figure 1. Survey of Available Information for Thermal Storage Units

1. Liquid Storage

Among various liquids, water remains one of the most useful thermal storage materials because of its low cost, availability, nontoxicity, and high specific heat. The major component of water storage is the container. There are large quantities of commercially available containment vessels suitable for water storage. However, these containers are not necessarily designed specifically for water storage. One example of each type of container material has been selected for illustrative purposes. The selected container materials are reinforced plastics, wood, concrete, fiberglass, and steel.

For seasonal storage, a large underground water tank, aquifer, or salt-gradient solar pond offer attractive alternatives. Depending on the storage temperature, the storage could supply energy either directly to end use or combine with a heat pump to satisfy load requirements.

2. Solid Storage

Rock and the Trombe Wall were selected as typical examples of solid storage. Rock is one of the most useful solid storage media because of its abandance, low cost, long life, and favorable heat transfer characteristics when coupled with air heating collectors. Ample experience and knowledge is available for constructing rock storage in space heating applications. The Trombe Wall is an example of thermal mass storage that can be used for passive systems or active systems using forced convection over the surface of the wall. These storage methods are seldom found on the commercial market. Depending on each application, storage can be more cost effective to build on-site than to purchase as a unit.

3. Phase-Change Storage

In solar thermal storage applications, phase-change materials have two potential advantages over solid or liquid sensible storage materials. These are:

(a) The energy density (Btu/lb or Btu/ft^3) for a given temperature swing across phase-change temperature can be higher.

(b) The phase-change materials, having the ability to store thermal energy within a narrow temperature range, act as a temperature regulator by storing or releasing thermal energy at phase-change temperature.

The selected phase-change storage methods that are commercially available now or will be available by 1979 have been indicated in Figures 1, 2, and 3.

The sodium sulfate pebble of Calmac Manufacturing Corporation is a solid-to-solid transformation material storing thermal energy at a temperature range of 400 to 600°F. The heat battery of Solarmatic, Inc., the encrusted conglomerate of Valmont Industry, and the thermal storage cells of Solar Marketing, Inc., are all using Glauber's salt as the thermal energy storage material, changing phase at approximately 90°F.

Add-A-Sun of Addison Products Company is using "slack wax" as the energy storage material changing phase at 115°F. Monsanto Research Corporation has used the high density polyethylene (HDPE) pellets as the storage material changing phase at 266°F. An interesting product for passive design is Sol-Ar-Tile of Architectural Research Corporation. Sol-Ar-Tile uses a eutectic mixture with Glauber's salt, and can be mounted as ceiling tile operating at the phase-change temperature of 73°F.

4. Thermochemical Storage

The development of thermochemical storage is still in the beginning stage. No example has been selected for developing preliminary design criteria. The sulfuric acid-water system and the magnesium chloride-dihydrate system discussed in Section II are selected for illustrative purpose only.

B. Storage Requirements in Solar Applications

The solar applications studied were the paths indicated on DOE's program. Figure 4 shows the solar heating and cooling of buildings (SHACOB) path schematics, and Figure 5 represents the agricultural and industrial process heat (AIPH) path schematics. On these path schematics the potential thermal storage locations within each path have been indicated. The requirements of storage in solar applications were characterized by the following evaluating criteria:

▲ ACCEPTABLE COMBINATION

BASED ON
- TEMPERATURE RANGE
- PATH APPLICATION
- COMMERCIAL AVAILABILITY

THERMAL ENERGY STORAGE COMPONENTS COMMERICALLY AVAILABLE BY 1977 (data sheets 1–16) / OTHER THERMAL STORAGE (data sheets 17–23)

PATH NO	PATHS DESCRIPTION SOURCE	STORAGE REQUIREMENT	WATER STORAGE REINFORCED PLASTICS KALWALL	WATER STORAGE WOOD TANK SUNWAVE	WATER STORAGE CONCRETE TANKS SOLATHERM	WATER STORAGE FIBERGLASS TANKS OWENS CORNING	WATER STORAGE STEEL TANK SOLAR ENERGY SYSTEMS INC	WATER STORAGE AQUIFERS	WATER STORAGE SALT GRADIENT SOLAR PONDS	WATER STORAGE PRESSURIZED STEEL TANK	SOLID STORAGE ROCK STORAGE BINS	SOLID STORAGE TROMBE WALL	PHASE CHANGE SOLARMATIC HEAT BATTERY GLAUBER S SALT	PHASE CHANGE VALMONT INDUSTRIES ENCRUSTED CONGLOMERATE	PHASE CHANGE SMC THERMAL STORAGE CELLS GLAUBER S SALT	PHASE CHANGE ARCHITECTURAL RESEARCH CORP SOLAR TILES	PHASE CHANGE MONSANTO RESEARCH HDPE PEBBLE BED	PHASE CHANGE ADD A SUN STORAGE CHAMBER	PHASE CHANGE ACES	PHASE CHANGE CALMAC MANUFACTURING Na_2SO_4	PHASE CHANGE SOLAR ONE STORAGE BIN Na_2SO_4 $10H_2O/NaCl/NH_4Cl$	PHASE CHANGE SOLAR ONE STORAGE BIN $Na_2S_2O_3$ $5H_2O$	PHASE CHANGE UNIVERSITY OF PENNSYLVANIA $Na_2S_2O_3$ $5H_2O$	PHASE CHANGE UNIVERSITY OF PENNSYLVANIA PARAFFIN WAX	PHASE CHANGE GE ROLLING CYLINDER GLAUBER S SALT	PHASE CHANGE GE ROLLING CYLINDER $Na_2S_2O_3$ $5H_2O$	CHEMICAL STORAGE ROCKET RESEARCH CORP SULFURIC ACID WATER	CHEMICAL STORAGE MAGNESIUM CHLORIDE HYDRATE
		DATA SHEET NO	1	2	3	4	5		6	*	7	8	9	10		12	13	14	15	16	17	18	19	20	21		22	23
H1	SOLAR ASSISTED HEAT PUMP																											
	a ENVIRONMENT	LOW TEMP SIDE							▲																			
		HIGH TEMP SIDE																										
	b DIRECT SOLAR HEATED STRUCTURE	LOW TEMP SIDE	▲									▲																
		HIGH TEMP SIDE																										
	c LIQUID HEATING COLLECTORS	LOW TEMP SIDE		▲	▲	▲	▲	▲											▲									
		HIGH TEMP SIDE																										
	d AIR HEATING COLLECTORS	LOW TEMP SIDE	▲								▲			▲	▲													
		HIGH TEMP SIDE																										
	e ADVANCED NONCONCENTRATING COLLECTORS	LOW TEMP SIDE																										
		HIGH TEMP SIDE																										
H2	DIRECT (PASSIVE) HEATING OF STRUCTURE	PASSIVE STORAGE	▲								▲	▲				▲												
H3	AIR HEATING COLLECTOR																											
	a FLAT PLATE	STORAGE									▲							▲										
	b ADVANCED NONCONCENTRATING	STORAGE									▲						▲	▲										
H4	LIQUID HEATING COLLECTORS																											
	a CONVENTIONAL FLAT PLATE	STORAGE		▲	▲	▲	▲								▲													
	b ADVANCED NONCONCENTRATING	STORAGE			▲		▲			▲			▲				▲											
C1	CONCENTRATING COLLECTORS																											
	a ABSORPTION CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲			▲								
	b RANKINE CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲			▲								
C2	ADVANCED NONCONCENTRATING COLLECTORS																											
	a ABSORPTION CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲											
	b RANKINE CYCLE CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲											
C3	DESICCANT CHILLER FLAT PLATE COLLECTORS																											
	a AIR HEATING	LOW TEMP SIDE									▲																	
		HIGH TEMP SIDE									▲																	
	b LIQUID HEATING	LOW TEMP SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP SIDE			▲		▲																					
C4	EVAPORATIVE COOLING NIGHT TIME	PASSIVE STORAGE		▲	▲	▲	▲																					
C5	COOLING BY HEAT PUMP	LOW TEMP SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP SIDE																										

* DATA SHEET IS NOT AVAILABLE

Figure 2. Matching of Thermal Storage Units With SHACOB Paths

▲ ACCEPTABLE COMBINATION

BASED ON
- TEMPERATURE RANGE
- PATH APPLICATION
- COMMERCIAL AVAILABILITY

PATHS

PATH NO	DESCRIPTION SOURCE	STORAGE REQUIREMENT	THERMAL ENERGY STORAGE COMPONENTS COMMERCIALLY AVAILABLE BY 1979																		OTHER THERMAL STORAGE							
		DATA SHEET NO	1	2	3	4	5	*	6	*	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	-	22	23
			WATER STORAGE-REINFORCED PLASTICS-KALWALL	WATER STORAGE-WOOD TANK-SUNWAVE	WATER STORAGE-CONCRETE TANKS-SOLATHERM	WATER STORAGE-FIBERGLASS TANKS-OWENS-CORNING	WATER STORAGE-STEEL TANK-SOLAR ENERGY SYSTEMS, INC	WATER STORAGE-AQUIFERS	WATER STORAGE-SALT GRADIENT SOLAR PONDS	WATER STORAGE-PRESSURIZED STEEL TANK	SOLID STORAGE-ROCK STORAGE BINS	SOLID STORAGE-TROMBE WALL	PHASE CHANGE-SOLARMATIC HEAT BATTERY-GLAUBER'S SALT	PHASE CHANGE-VALMONT INDUSTRIES-ENCRUSTED CONGLOMERATE	PHASE CHANGE-SMC THERMAL STORAGE CELLS-GLAUBER'S SALT	PHASE CHANGE-ARCHITECTURAL RESEARCH CORP SOL AR TILES	PHASE CHANGE-MONSANTO RESEARCH-HDPE PEBBLE BED	PHASE CHANGE-ADD-A-SUN STORAGE CHAMBER	PHASE CHANGE-ACES	PHASE CHANGE-CALMAC MANUFACTURING-Na_2SO_4	PHASE CHANGE-SOLAR ONE STORAGE BIN-Na_2SO_4 $10H_2O/NaCl/NH_4Cl$	PHASE CHANGE-SOLAR ONE STORAGE BIN-$Na_2S_2O_3$ $5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-$Na_2S_2O_3$ $5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-PARAFFIN WAX	PHASE CHANGE-GE ROLLING CYLINDER-GLAUBER'S SALT	PHASE CHANGE-GE ROLLING CYLINDER-$Na_2S_2O_3$ $5H_2O$	CHEMICAL STORAGE-ROCKET RESEARCH CORP -SULFURIC ACID WATER	CHEMICAL STORAGE-MAGNESIUM CHLORIDE HYDRATE
HO	DIRECT (PASSIVE) SHELTER HEATING	PASSIVE	▲								▲	▲																
HA	AIR HEATING COLLECTORS	STORAGE									▲																	
HL	LIQUID HEATING COLLECTORS	STORAGE		▲	▲	▲	▲						▲		▲													
HP	SOLAR ASSISTED HEAT PUMP (Same as HI)		▲	▲	▲	▲	▲	▲	▲		▲	▲	▲	▲					▲									
DD	DESICCANT DRYING	LOW TEMP SIDE									▲																	
		HIGH TEMP. SIDE									▲																	
DA	DRYING-AIR HEATING COLLECTORS	STORAGE									▲																	
DL	DRYING-LIQUID HEATING COLLECTORS	STORAGE		▲	▲	▲	▲											▲										
SL	ADVANCED LIQUID HEATING COLLECTORS	STORAGE								▲	▲						▲			▲								
SA	ADVANCED NONCONCENTRATING COLLECTORS	STORAGE									▲									▲								
CO	PASSIVE COOLING	STORAGE		▲	▲	▲	▲				▲																	
CH	COLLECTOR AND HEAT ENGINE	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE			▲		▲				▲						▲											
CP	HEAT PUMP COOLING	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE		▲	▲	▲	▲				▲																	

*DATA SHEET IS NOT AVAILABLE

Figure 3. Matching of Thermal Storage Units With AIPH Paths

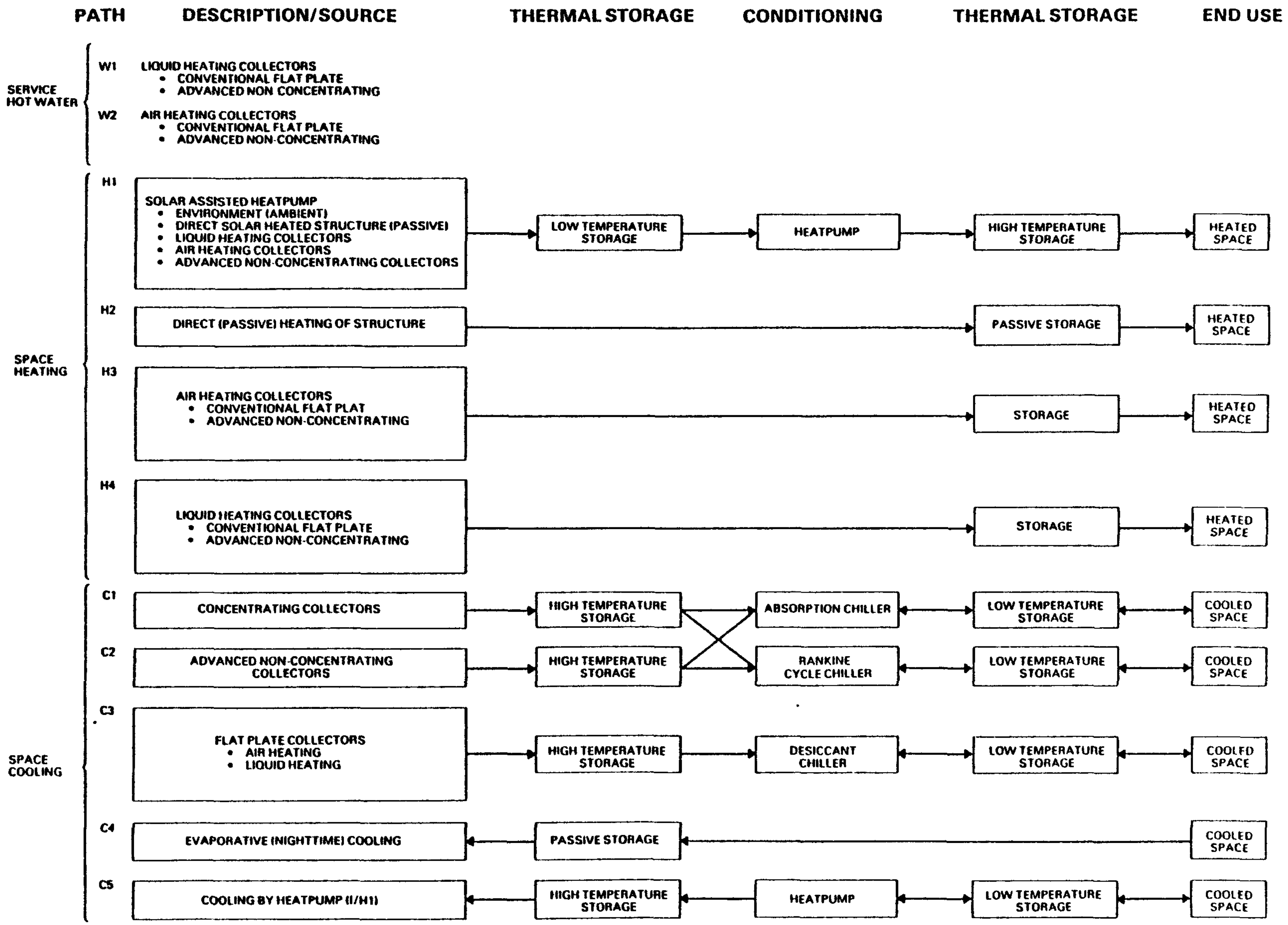


Figure 4. SHACOB Path Schematics (1)

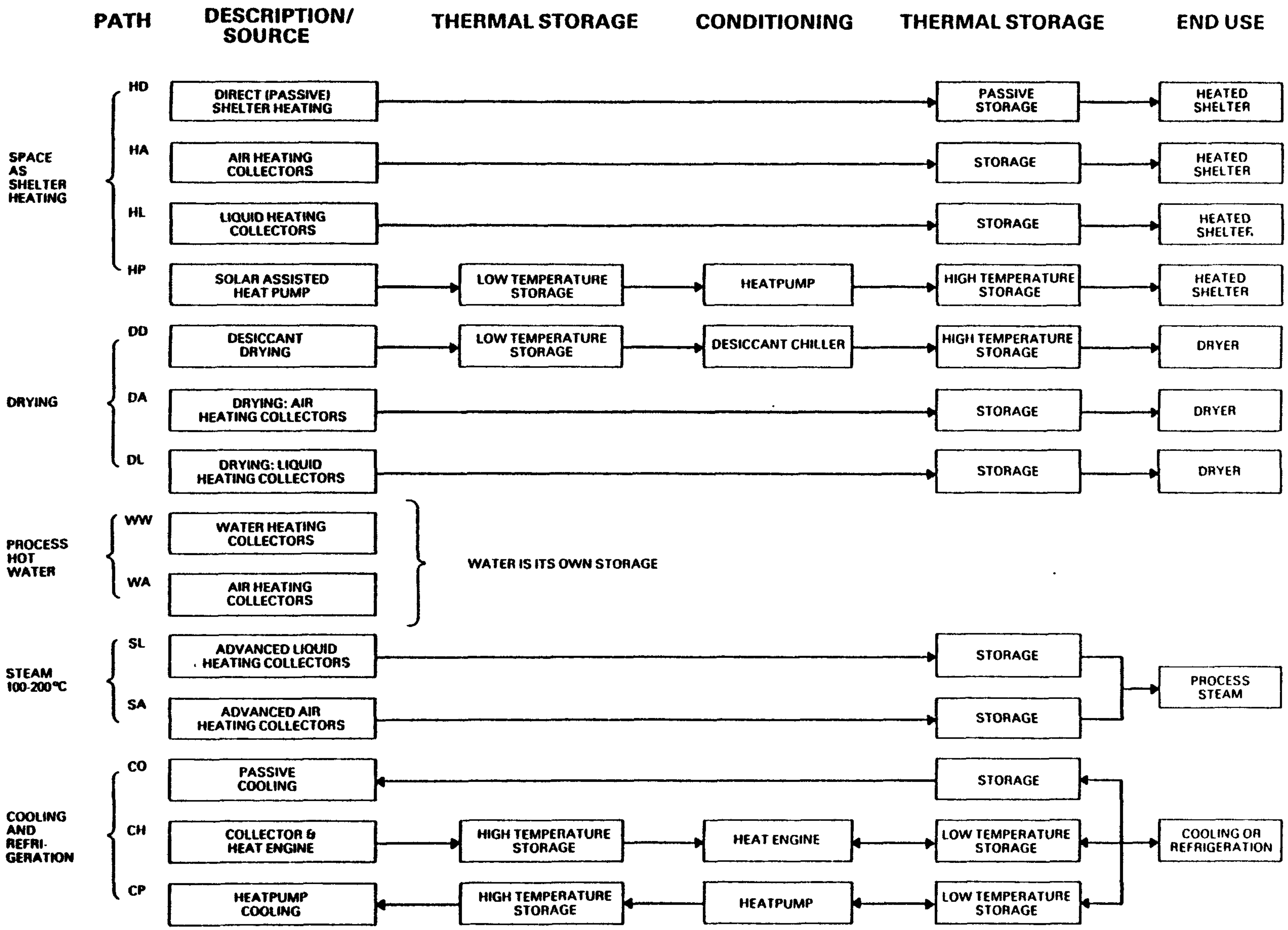


Figure 5. AIPH Path Schematics (1)

(1) Storage temperature range

(2) Energy storage capacity

(3) Length of storage time

(4) Charge time per cycle

(5) Discharge time per cycle

(6) Thermal energy losses

(7) Acceptable cost level.

The results are presented in Section III and Appendix B.

C. Matching Storage Units to Each Application

Potentially attractive energy storage alternatives were identified by matching the characteristics of the storage units with the storage requirements in each application. The main criteria used for matching were commercial availability, temperature range, and path application. The results are presented in Figures 2 and 3 cited above.

D. Development of Preliminary Design Criteria

A selected number of storage applications from Figures 2 and 3 have been developed into preliminary design criteria. In these criteria, the following information was discussed:

(1) Storage type, material, stage of development, and container type

(2) Interface requirements

(3) Storage performance

- Operating principle
- Temperature range
- Storage requirements
- Charge rate
- Discharge rate
- Thermal energy

(4) Operation and maintenance

(5) Cost

(6) Other design considerations.

The goal of the preliminary design criteria is to provide first-cut information showing the limitation in a path application. The results are presented in Chapter IV.

II. CHARACTERISTICS OF THERMAL ENERGY STORAGE

The purpose of this chapter is to identify the characteristics of the major available thermal energy storage units. Depending on the storage medium the storage units are divided into four major types: liquid, solid, phase-change, and thermochemical storage. Selected thermal energy storage for each category is discussed. The characteristics of each selected storage alternative are presented in Appendix A.

A. Sensible Storage of Thermal Energy in Liquids

Since water is the dominating material in liquid storage, only water storage will be discussed. Because of its low cost, availability, nontoxicity, and high relative specific heat, water is regarded as one of the most useful thermal storage materials currently available. At the present stage of development, the storage tanks and associated ancillary equipment (pumps, pipes, heat exchangers, valves, controls, etc.) are readily available as off-the-shelf items. Also, the professionals and skilled tradespeople who are involved in the design and construction of water systems are likely to be familiar with water-handling technology and its associated hardware.

Along with the advantages are some associated disadvantages to using water as a thermal energy storage medium. Water causes chemical and electrochemical corrosion. Either corrosion-inhibiting materials must be added to the water, or container materials which resist corrosion must be used. In cases where the storage vessel may be subjected to freezing temperatures, provision must be made for draining the tank, preventing the water from freezing by adding thermal energy from an auxiliary source and insulating the tank, or adding anti-freeze to the water.

1. The Thermal Storage Characteristics of Water

Water has a higher heat capacity than any other substance except hydrogen (2). Its specific heat in the temperature range 32 to 212°F is essentially 1 Btu/lb-°F. Water has a latent heat of fusion of 144 Btu/lb at 32°F, and a latent heat of vaporization of 947.4 Btu/lb at 212°F at 14.7 psia.

A water system storing 250,000 Btu in the temperature range 110 to 160°F would require 5000 lbs of water occupying approximately 82 cubic feet of space (4'x 4'x 5.1'). Expressing this on a per-unit basis, one cubic foot of water can store about 62 Btu for every Fahrenheit degree increment.

2. Water Storage in Containers

There is a wide variety of commercially available vessels suitable for water storage. A recent issue of *Solar Engineering* lists 14 manufacturers of steel tanks and 17 manufacturers of plastic or fiberglass tanks (3). There are undoubtedly many more. To try to present information on all the available containment vessels is not necessary. A commercially available storage vessel was selected to represent each type of construction material and its characteristics.

a. Reinforced Plastics. The Solar Components Division of the Kalwall Corporation manufactures a standard line of water storage tanks using a fiberglass-reinforced plastic (4,5). The containers are marketed under the name "Sun-lite Storage Tube" and are available in the standard sizes of 3,6,9, and 18-cubic feet (see Figure 6). They were designed as combined solar collectors and thermal storage units, with passive applications in mind. Ambient room air circulates over plastic tubes filled with hot water. With a temperature rise of 40°F, the 18 cubic-foot unit stores 44,080 Btu. For additional details refer to Data Sheet 1 in Appendix A.

b. Wood Tanks. Acorn Structures, Inc., is currently marketing, in kit form, a cylindrical tank constructed of 3/8-inch exterior plywood reinforced with galvanized steel bands (6,7). The tank, shown in Figure 7, supports an inner vinyl liner. Insulation is provided by a 3-1/2 inch fiberglass batt on the vertical section and on the top of the tank. A combination of 3 inches of vermiculite and 1 inch of styrofoam insulate the bottom of the tank. Tempered hardboard 1/8-inch thick surrounds the insulation. The tank is rated to 160°F. Using an operating range of 110 to 160°F, the 2000-gallon tank will store 815,507 Btu of usable thermal energy. For additional details refer to Data Sheet 2 in Appendix A.

c. Concrete Tanks. The Solatherm Corporation is currently marketing rectangular solid precast concrete storage tanks for hot water storage in 1000-, 1500-, 2000-, and 2500-gallon capacities (8,9). The tank consists of a reinforced concrete shell with foam insulation and a waterproof liner (see Figure 8). The tank is designed to be buried. The standard insulation supplied with the tank has an R-value of 18. The tank has a rated operating temperature for hot water storage of 210°F. Allowing for a tem-

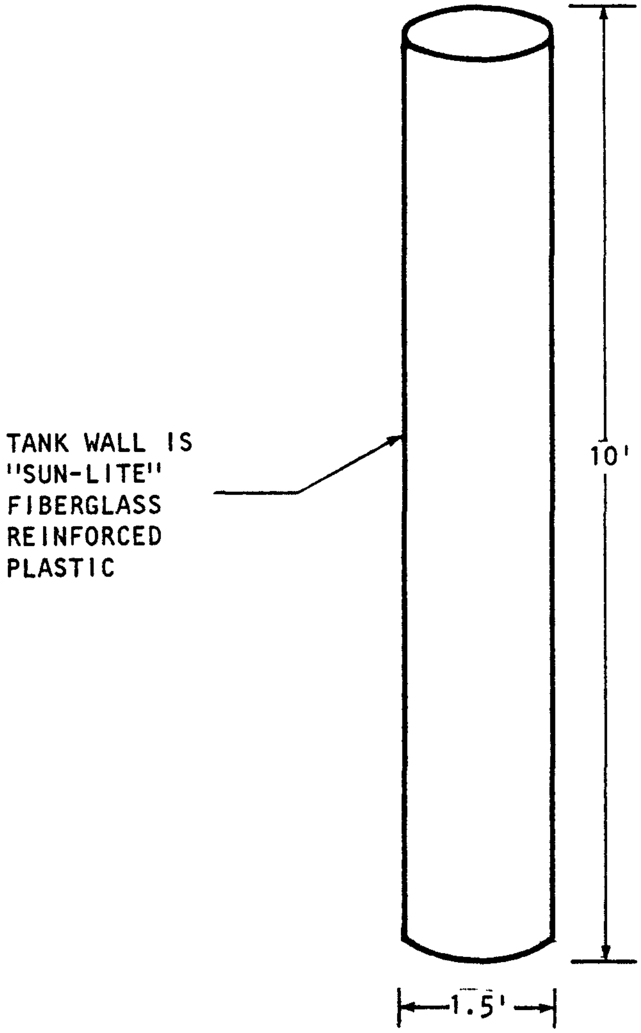
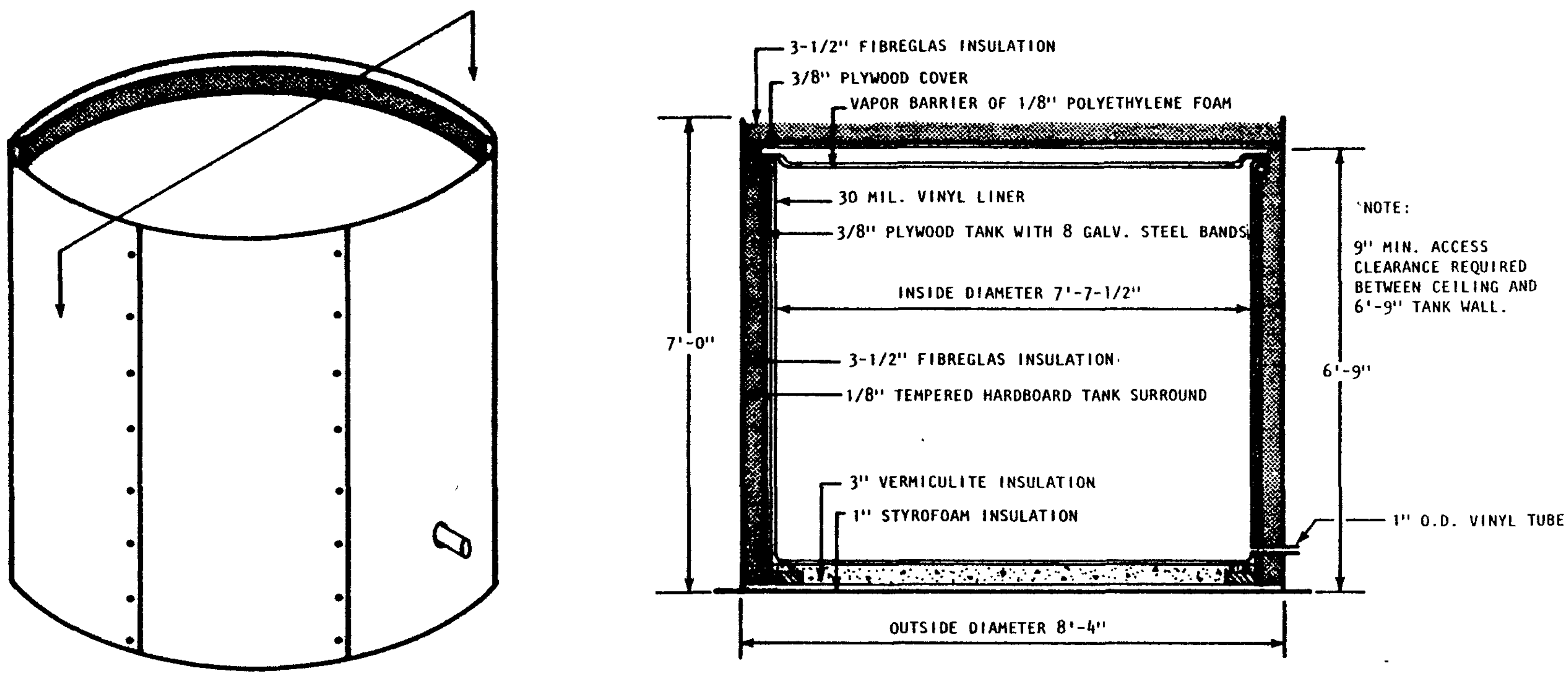


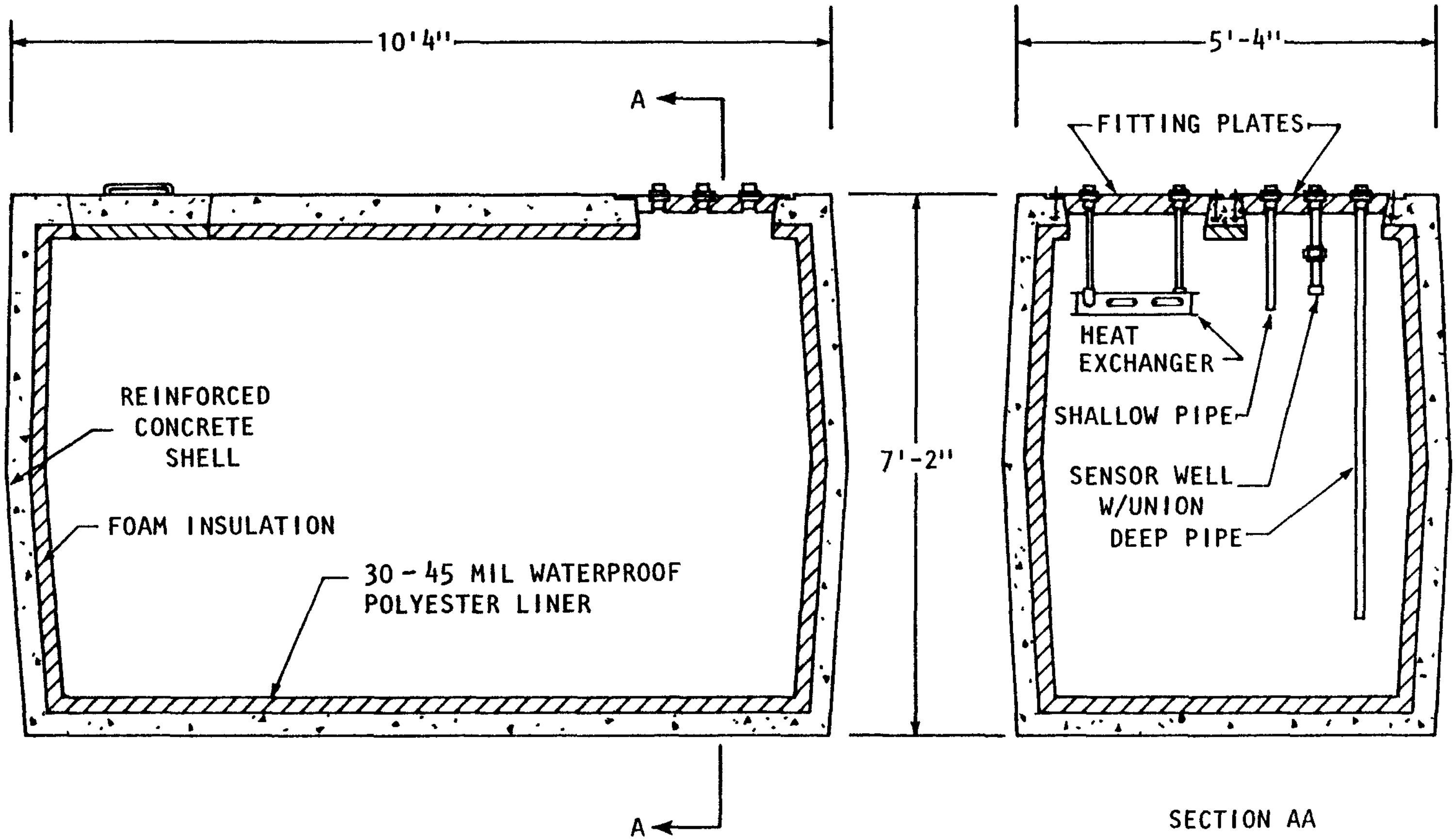
Figure 6. Sun-Lite Storage Tube 17.67 ft^3



A. FREE STANDING TANK

B. SECTION THROUGH STORAGE TANK

Figure 7. Sunwave Energy System Storage Tank



Source: SOLATHERM Corp.

Figure 8. "SOLATHERM" Solar Storage Tank 2000 Gallon Capacity

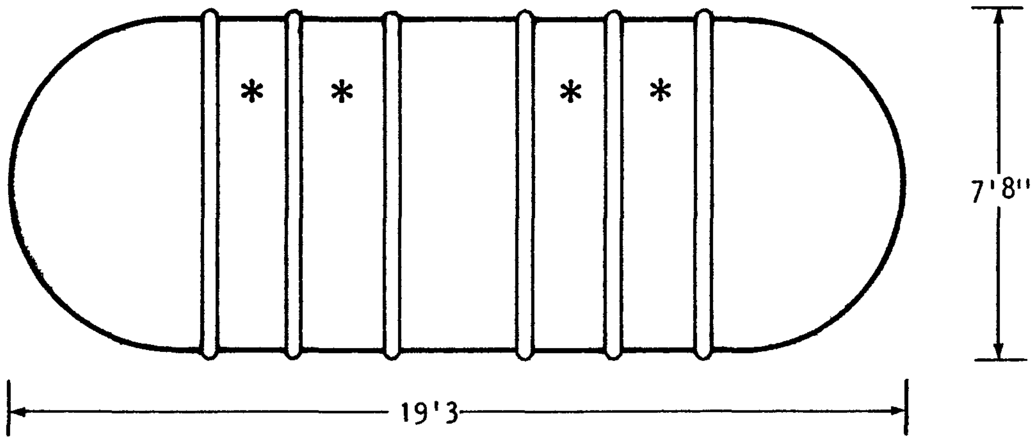
perature swing of 100° (110 to 210°F), the 2000-gallon tank will store about 1.6 million Btu of usable thermal energy. For additional details see Data Sheet 3 in Appendix A.

d. Fiberglass Tanks. The Owens-Corning Fiberglass Corporation manufactures a complete line of fiberglass tanks suitable for underground hot water storage (10). The tanks are available in standard sizes ranging from 550 gallons to 48,000 gallons (see Figure 9). The standard tanks are rated up to 150°F using the standard buried configuration with pea gravel backfill. An insulating backfill must be used to control thermal energy loss. A material such as K-Crete is recommended as it has the desired backfill characteristics for the tank and the insulating value of 1 inch of fiberglass for each foot of the material used (11). The tanks are also available with a high-temperature biphenol resin which raises the maximum sustained storage temperature rating to 180°F using the pea gravel backfill. Refer to Data Sheet 4 in Appendix A.

e. Steel Tank Storage. Solar Energy Systems, Inc., manufactures a standard line of steel tanks for the underground storage of solar heated water (12). The tanks, shown in Figure 10, are standard steel tanks such as those used for underground gasoline storage. They are available in sizes of 1,000 to 10,000 gallons of capacity. The tank is sold with an anticorrosive phenolic lining and 2 inches of polyurethane insulation on the outside. The tank is divided into three sections; two are for storage and one serves as a manhole area and dry area for the pumps, piping, and differential thermostats. The primary storage section is for solar-heated fluids, while the secondary storage section can be equipped with an immersion-type electric heating element. This solar energy storage unit, with an electric resistance backup, is designed to provide total hot water and space heating requirements. Water up to 200°F can be stored in the tank. For additional details refer to Appendix A, Data Sheet 5.

3. Hot Water Storage in Aquifers

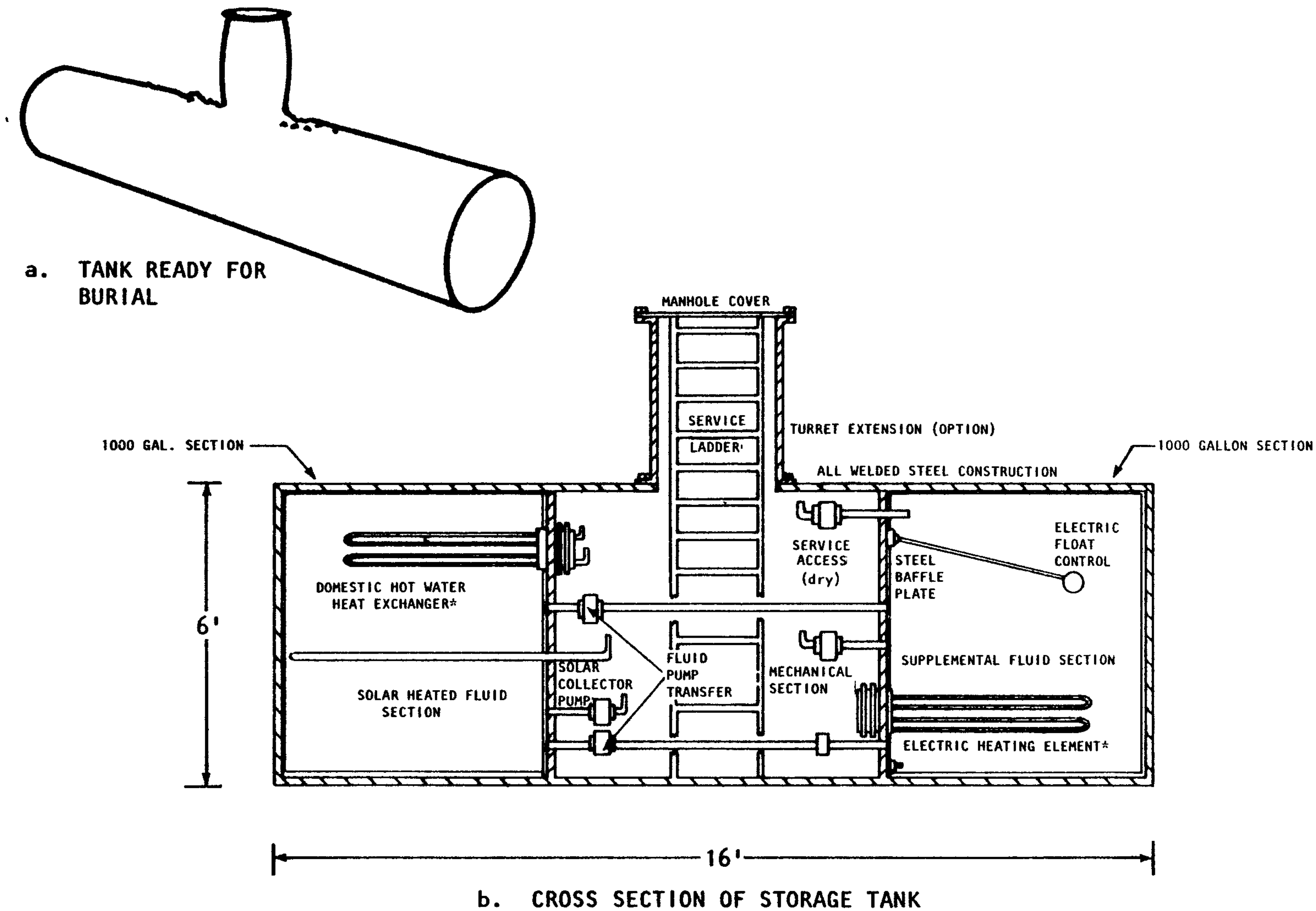
Recently, there has been considerable interest in the technical community in using aquifers as storage reservoirs for heated water in the moderate-to-high temperature range (140 to 400°F). An aquifer is defined as an underground stratum or zone that is water bearing (13). In order to store hot water in an aquifer, a well is drilled down from the surface to the aquifer. This well is then used to force the heated water into the aquifer. When the hot water is needed, it is pumped out of the aquifer through the well. Two wells can be used, one for injecting and one for withdrawing the hot water.



LEGEND

4" NPT STANDARD
FITTING POSITIONS

Figure 9. Owens-Corning 4000 Gallon Fiberglass Water Storage Tank Model D-3



SOURCE: SOLAR ENERGY SYSTEMS, INC.

Figure 10. Solar STOR 2000 Gallon (Total) Storage Tank

A test of this concept has been performed by the Water Resources Research Institute of Auburn University near the Alabama Power Company's Barry Steam Plant (14). An injection well was drilled 160 feet below the surface 30 feet into the chosen aquifer. Two million gallons of heated water (97°F) were stored for 36 days. The calculated energy recovery factor was 68 percent. For commercialization of the hot water storage well, further research on ground water impact to environment is needed.

4. Hot Water Storage in Salt Gradient Solar Ponds

A body of water exposed to sunlight will absorb a large amount of solar energy through the course of the year, but the water temperature tends to remain below that of the daytime ambient air. Convection currents in the body of water convey the absorbed energy to the surface, where it is quickly lost. It was observed that certain naturally occurring salty lakes had bottom temperatures substantially higher than their surface temperatures. It was found that these lakes had nonuniform vertical distribution of salts resulting in a vertical density gradient. These density gradients are nonconvective and prevent circulation. The solar flux (in the visible and ultraviolet wave lengths) is absorbed in the bottom of the lake or pond. Because circulation is cut off and because water is a poor conductor of thermal energy and opaque to infrared reradiation, the solar thermal energy is effectively trapped.

Such a pond was built at the University of New Mexico in 1975 (15). The pond was constructed with a top diameter of 492 feet, a depth of 8.2 feet, and a bank angle of 34° from horizontal (see Figure 11). The total capacity of the pond was 8123 cubic feet, with an average storage capacity of 4592 cubic feet. The pond was created using sodium chloride as the salt. A convective layer 71-inches thick containing high-salinity brine by weight was established. A gradient region 28-inches thick was established. Peak recorded temperature was 196°F on August 6, 1977; minimum temperature was 88°F recorded on January 30, 1977. Heat extraction can be accomplished by pumping heated brine in the convective layer through a heat exchanger and flowing back in a closed loop system. For additional details refer to Data Sheet 6 in Appendix A.

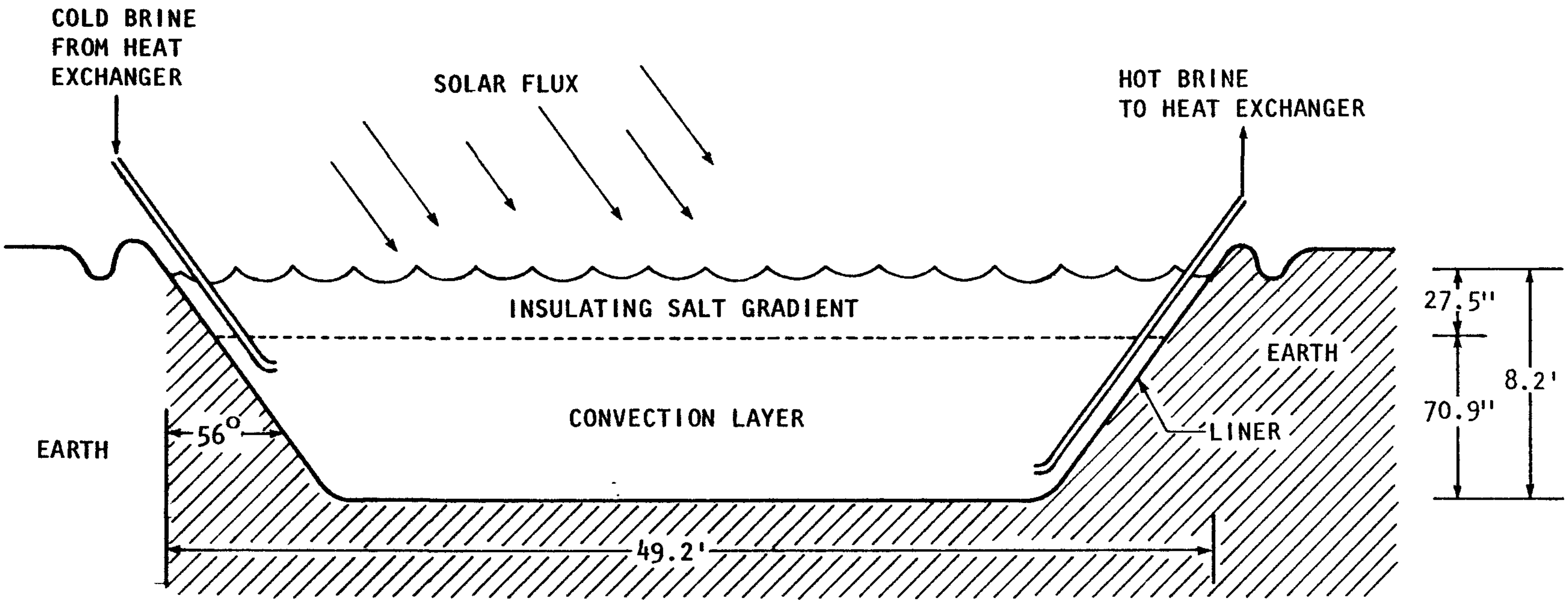


Figure 11. Cross Section of University of New Mexico
Solar Pond

B. Sensible Storage in Solids

1. Rock Storage

Rock storage was one of the earliest methods used in solar applications; it remains popular in residential construction. The popularity of this low-technology method stems from the fact that rock storage, when used in an air system, offers the following benefits:

(a) High storage capacity per unit cost

(b) Plentiful storage medium in nature

(c) Container/system leaks present little problem because air leaks are safe

(d) Corrosion problems are eliminated

(e) Container can be constructed of common building materials

(f) Excessive insulation is not needed because of low conductivity of the rock

(g) Temperature stratification in rocks allows for heat removal at temperatures greater than the average temperature for the rock bed

(h) Need for heat exchangers is eliminated

(i) System requires little or no maintenance

(j) Lifetime of system is commensurate with that of building.

Rock storage units are not without their drawbacks. The most common problems of rock storage are:

(a) Low storage capacity per unit volume

(b) Systems are not easily interfaced with domestic hot water heating systems

(c) Airborne dust and particulate matter can result from using rocks that have not been properly cleaned

(d) Care must be taken to insure uniform size of rocks to avoid having smaller rocks fill in the voids between larger rocks, thus restricting air flow.

Few commercial rock storage units exist today because it is less expensive to have contractors construct the storage bin on-site than to have the containers factory-constructed, shipped, and installed. This is because no special tools, materials, or quality control are needed for the construction of rock storage units. Ample experience and knowledge exist for estimating performance of and constructing rock storage units for domestic space heating systems. Further study is needed of unit applicability for annual storage, high-temperature storage, and heat pump assistance. Commercialization of any of the aforementioned applications is restrained only by testing and cost studies, since the equipment and technology needed already exist. Some theoretical work is being done on high-temperature and large-scale storage in rocks; as yet, however, little has been done in the way of constructing and testing actual systems (16,17,18,19). For additional details see Data Sheet 7 in Appendix A.

2. Thermal Mass Storage

Thermal mass storage can be one of the simplest methods of storing solar radiation because the storage medium can also be the collector. These systems can be passive, utilizing natural convective currents and/or radiation, or they can be active, using forced convection over the surface of the mass. The Trombe Wall is an example of thermal mass storage that was originally designed as a passive system but has recently been incorporated in several hybrid systems that actively remove excess daytime thermal energy for storage in rock beds or use in remote rooms of the building. The Trombe Wall is basically a glass wall placed in front of a darkened concrete wall that has openings in the bottom to permit circulation of room air. The air is heated, rises, and reenters the room through openings at the top of concrete wall. The wall also radiates thermal energy to occupied spaces. Since 1956, when the first prototype using a Trombe Wall was constructed in France, its performance has been extensively documented. Forty percent of the building heating requirement can be supplied by solar energy when a passive Trombe Wall is used (20). Data Sheet 8 in Appendix A provides more information.

Another application of thermal mass storage can be seen in the use of brick and other masonry materials for floor surfaces. The floor collects, stores, and releases the solar energy that enters the windows during the day. The thermal lag of the materials decreases the auxiliary heating needed until the sleeping hours, when thermostat setback can take place.

The above storage methods are available today and have been found to be feasible as low-technology applications to assist home heating.

Other solids have been examined for use in sensible storage of thermal energy in much the same way as rock is used. These solids could be melted and processed into spheres of uniform size, or cast into grid shapes, to allow air to circulate and remove or add thermal energy. A small list of possibilities is shown in Table 1. The table provides a comparison between various solids for energy storage.

TABLE 1. CANDIDATES FOR SENSIBLE STORAGE OF THERMAL ENERGY FROM 77°F TO 900°F (21)

Material	lb/ft^3	Btu/lb	Btu/ft^{3+}	$/100 lb*	Output (Btu/$)*+
Al	168	200	34,000	53.00	380
Steel	489	99	48,300	20.00	490
$Al_2(SO_4)_3$	169	202	34,000	6.85	2,950
Al_2O_3	250	200	50,000	5.50	3,640
MgO	223	208	46,000	6.00	3,470
KCl	124	140	17,400	2.00	7,000
K_2SO_4	167	180	30,000	.10	180,000
NaCl	136	180	24,500	2.75	6,545
Rocks	140	180	25,200	.50	36,000

*July 1978 prices.

+ Δt = 823°F.

The use of hollow steel ingots for storing high-temperature solar energy has also been modelled in the laboratory. It has yet to be tested in practical applications.

C. Phase-Change Materials

Thermal energy storage using phase-change materials (PCMs) is an attractive alternative to sensible storage in rocks and water. Storage using PCMs exploits the well-known property of substances to absorb heat isothermally when undergoing a change of phase.

From the standpoint of the design of thermal energy storage equipment, phase-change materials have two primary advantages (and associated disadvantages) over sensible storage materials. First, the energy density is higher; the amount of thermal energy that can be stored in a given volume over the same temperature variation is greater. Water, for example, has a specific heat of 1 Btu/lb-°F. This means that one Btu is required to raise the temperature of one pound of water one degree Fahrenheit (effectively 1 Btu has been stored). To melt the same pound of water from its solid phase as ice to its liquid phase isothermally at 32°F, requires 144 Btu (effectively storing 144 Btu). When space is at a premium in a particular application and when large containers are cost prohibitive, PCMs have a distinct advantage over sensible storage materials.

Second, PCMs have the ability to store thermal energy over a narrower temperature range than do sensible storage materials. When integrated into a building structure, PCMs will act as temperature regulators, absorbing and releasing thermal energy at the phase-change temperature. An additional disadvantage of sensible systems occurs when the storage temperature gets close to the collector operating temperature resulting in a decrease in collection efficiency. By absorbing thermal energy isothermally, PCMs store thermal energy without lowering temperature differentials. In a heat pump application the coefficient of performance (COP) of a heat pump tends to decrease as the heat source temperature decreases. If the heat source is a sensible storage system, the COP tends to go down as the thermal energy is extracted from storage. Using a PCM storage allows the designer to optimize heat pump performance by using a single temperature for the heat source. Along with these advantages there is one disadvantage of PCM for thermal energy storage. Since each PCM has a characteristic temperature, a PCM must be identified for each temperature application and a system designed and built around its particular characteristics.

Researchers at the Institute of Gas Technology have devised the following general temperature range breakdown in order to describe potential storage applications more conveniently (22).

Temperature Range	Application
40 to 60°F	Cooling
60 to 200°F	Heating and cooling
200 to 600°F	Commercial/industrial applications
600°F and above	Power generation and high-temperature processing

Phase-change transformations may be classified as follows (23):

(1) Liquid-gas transformation

(2) Solid-gas transformation

(3) Solid-liquid transformation

(4) Solid-solid transformation.

Although the liquid-gas and solid-gas transformations do store large amounts of thermal energy, the large volume changes associated with them require complicated storage vessel designs. Because of this, not much emphasis has been placed on studying potential materials in those classes of thermal storage materials. Hence, this effort has involved the study of solid-liquid and solid-solid transformations, where the volume changes associated with the phase change are smaller.

1. Solid-Liquid Transformation

Considerable work has been done to identify potential phase-change materials at various temperatures. Researchers at Dow Chemical have identified over 200 substances which melt at temperatures from 50 to 194°F with characteristics worthy of laboratory evaluation (24). A recent compilation by the National Bureau of Standards provides a compendium of melting points and compositions of 6,000 molten salt eutectic mixtures which melt in the range of -216 to 3072°F (25). Researchers at General Electric have identified 81 potential PCMs for storage in the 40 to 60°F range (26).

In the late forties, Dr. Maria Telkes constructed and designed a thermal energy storage unit for a solar house using sodium sulfate decahydrate as the phase-change material (27). More recently Dr. Telkes has been responsible for the development of the thermal energy storage system on "Solar One," a solar test house built at the University of Delaware (28).

The Solar One system, shown in Figure 12, combined heating and cooling capacity storage using two phase-change materials. Heating capacity storage was provided by 294 plastic 21 x 21 x 1-in rectangular trays. Each pan contained 23.8 lbs of sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$) with a melting point of 120°F and a heat of fusion of 90 Btu/lb. The trays were constructed with plastic separators to allow air to flow freely through the bin. Cooling capacity storage was provided by an eutectic salt mixture of sodium sulfate decahydrate, sodium chloride, and ammonium chloride ($Na_2SO_4 \cdot 10H_2O/NaCl/NH_4Cl$) melting at 55°F with a heat of fusion of 78 Btu/lb. The eutectic salt was contained in twenty 1.25-in (outside diameter) by 72-in tubes, each containing 4.02 lbs of the mixture. The tubes were stacked using plastic separators so air could flow freely through the bin. The two storage arrays were integrated into a single 6 x 6 x 6-ft container. With a rise in temperature of 70 to 126°F, the total thermal energy stored in the bin was 807,000 Btu. The total cooling capacity stored or the thermal energy that the unit would absorb when the temperature rose from 50 to 75°F was 242,000 Btu. See Data Sheets 17 and 18 in Appendix A for specific information.

Researchers at the University of Pennsylvania have designed and constructed two thermal energy storage systems using PCMs (29). The first system melted sodium thiosulfate pentahydrate ($Na_2S_2O_3 \cdot 5H_2O$) at 119°F with a heat of fusion of 90 Btu/lb. The PCM was placed in a 1 x 1 x 4-ft plastic module. The total system contained a stack of sixteen modules. The thermal energy storage capacity of the unit was 500,000 Btu in 64 cubic feet using 5,560 lbs of sodium thiosulfate pentahydrate. The heat transfer was accomplished by circulating a water and ethylene glycol mixture through the center of the module. See Data Sheet 19 in Appendix A for additional details and system parameters.

The second thermal energy storage unit in the University of Pennsylvania study melted Sunoco 116 paraffin wax at 116°F with a heat of fusion of 90 Btu/lb (4400 Btu/ft^3). The paraffin was placed in 0.54 x 12 x 50-in trays. These trays were stacked in 12 x 12 x 50-in modules using plastic spacers to allow circulation of the heat transfer fluid. A 250,000-Btu unit was made up of twenty such modules initiating up to 83 ft^2. The unit contained 2,000 lbs of 116 paraffin (see Data Sheet 20 for additional details).

Researchers at the Dayton Laboratory of the Monsanto Research Corporation have developed a form-stable crys-

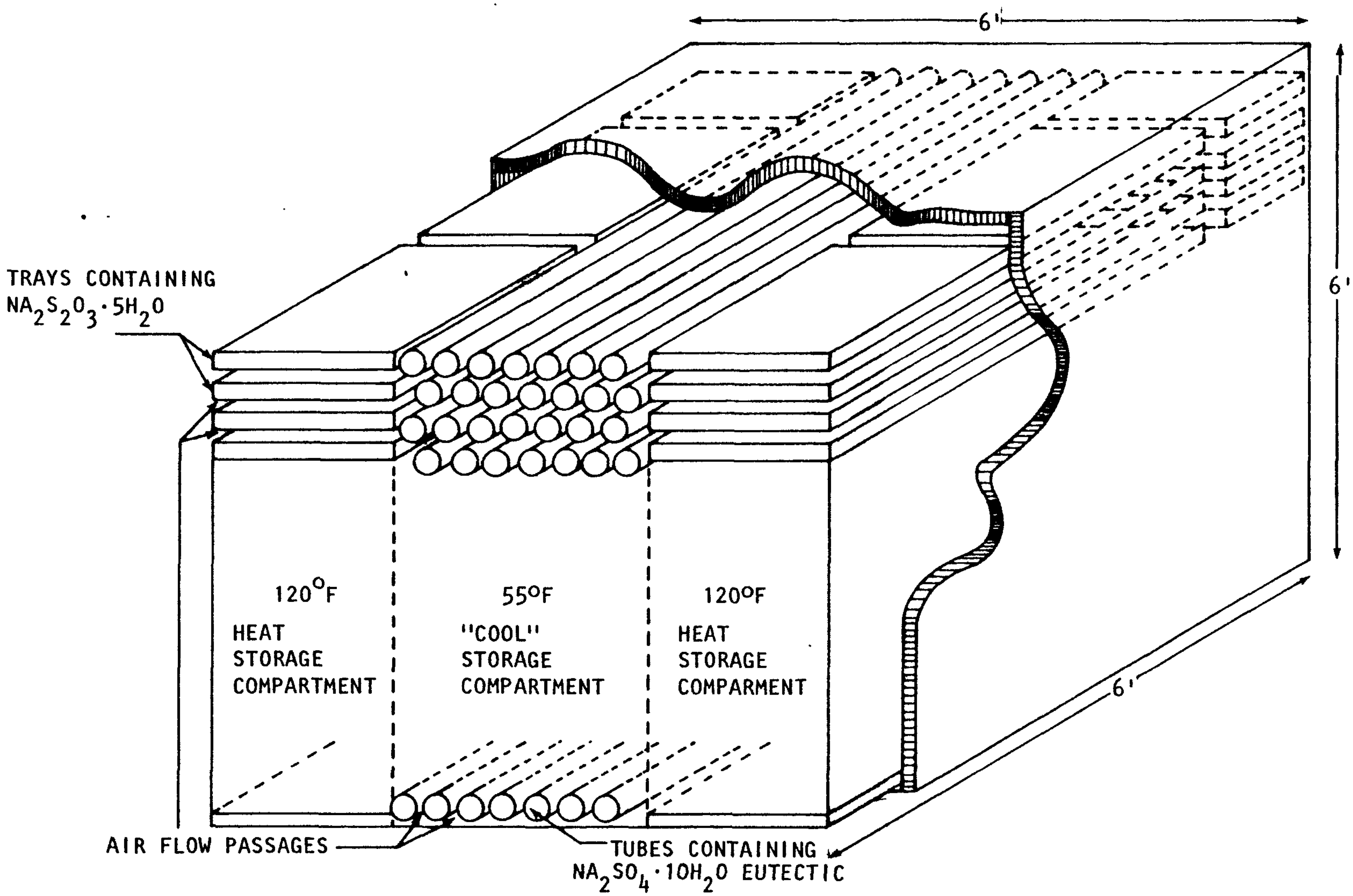


Figure 12. Solid Cross Section of Solar One Thermal Storage Bin

talline polymer-pellet thermal storage material with a high heat of fusion (83 Btu/lb) at a melting temperature of 266°F (36). The polyethylene pellets were rendered form-stable upon melting through cross-linking, allowing them to be used as a pellet bed for fluid or for air direct-flow heat transfer. Samples of the pellets have been put through 400 melt/freeze cycles with little degradation of their initial heat of fusion value, excellent retention of their form-stability characteristics, and little or no interparticle adhesion. A 60-gal pressurized storage system using 250 lbs of the PCM and storing 29,400 Btu was constructed and tested. Results indicated that a thermal storage system based on this concept would be practical. It was determined that a 0.25 in-diameter pellet provided no heat transfer problems. Additional information is provided in Data Sheet 13.

Solarmatic, Inc., a division of OEM Products, is currently marketing a heat storage unit called a "Heat Battery." A 6-ft cylinder, with a 3-ft diameter, stores 340,000 Btu using Glauber's salt as the phase-change material. This unit is also compatible with hypo as the phase-change material. The tank (see Figure 13) is filled with Glauber's salt up to the 4-1/2-ft level. A floating filter interface a few inches thick is then poured on the salt. The remainder of the tank is filled with a low-viscosity oil. A coil of copper tubing inserted into the oil layer is used as a heat exchanger. A novel pump feed pipe has been devised to circulate heat in the tank. The hot oil is bubbled through the pipes up through the salt until it rises back to the oil level. The heat transfer media, oil, is in direct contact with salt during the bubbling process. For more details refer to Data Sheet 9 in Appendix A.

Valmont Industries, in a joint venture with the American Technological University in Texas, is planning to market by a thermal storage component using an encrusted conglomerate of Glauber's salt as the phase-change material by late 1978 (30). The encrusted conglomerate consists of 97 percent Glauber's salt and 3 percent additives. This mixture, developed by Dr. Maria Telkes, stores 100 Btu/lb at 89°F in a phase-change transformation. The additives create a honeycomb structure of closed cells locking the Glauber's salt crystal into a rigid latticework (see Figure 14). These cells remain rigid as the Glauber's salt is alternately melted and solidified. It is claimed that this solves many of the problems associated with the segregration by gravity of the eutectic mixture when in the liquid phase. The conglomerate will be packaged in high-impact polyethylene trays containing 20 lbs of the mixture. Refer to Data Sheet 10 in Appendix A.

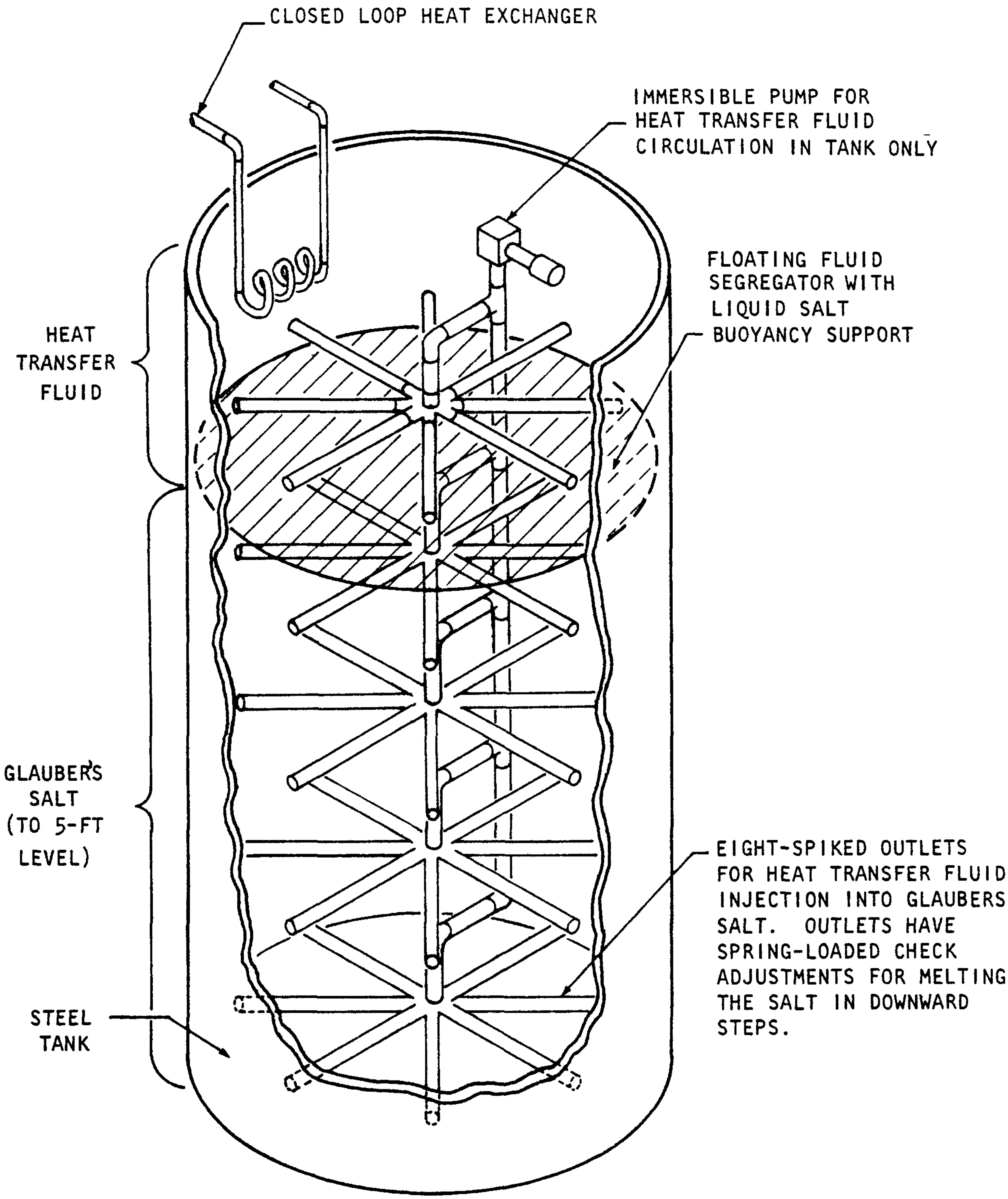
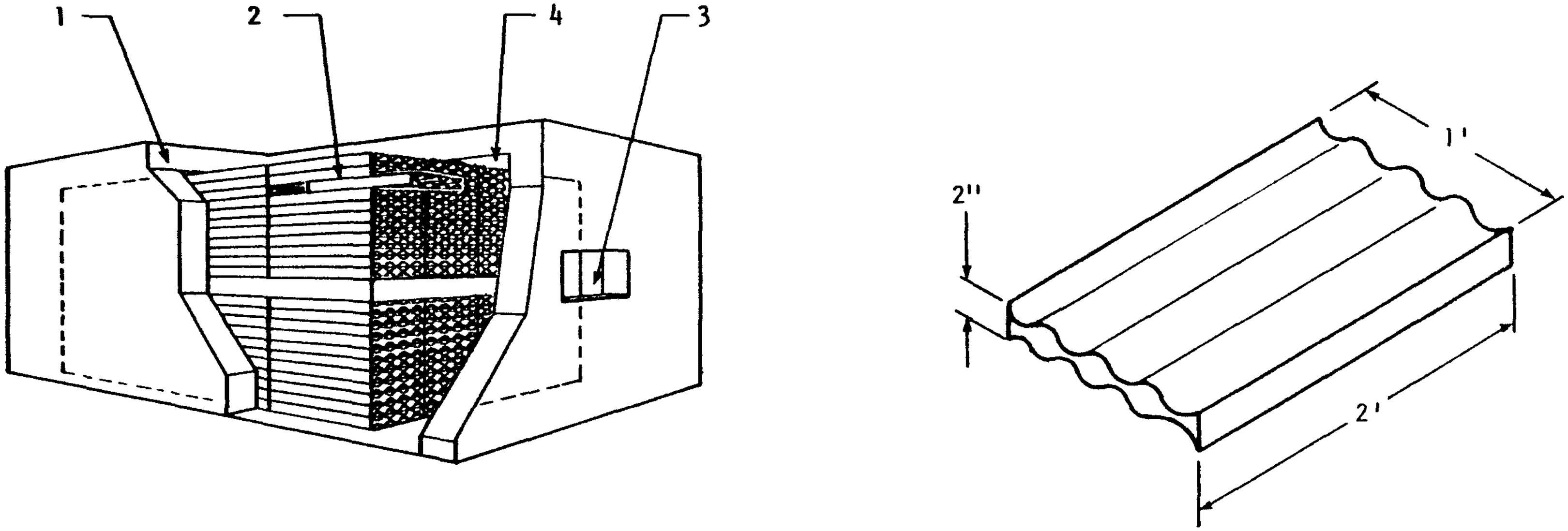


Figure 13. Solarmatic Heat Battery



A. STORAGE CONCEPT

1. INSULATED STORAGE CABINET
2. EUTECTIC SALT STORAGE CONTAINERS
3. AIR DUCT CONNECTION
4. AIR CHAMBER WITH ACCESS

B. CONTAINER TRAY 20lbs. EACH

Figure 14. Encrusted Conglomerate Valmont Storage Unit

Solar Marketing Corporation in Nebraska is planning to make available a storage product they call SMC Thermal Storage Cells by the end of 1978 (31). The phase-change material is Glauber's salt melting at 90°F, storing 91 Btu/lb as heat of fusion. The cells will be sold as units containing 3.85 lbs of the eutectic mixture enclosed in high-density polyethylene. The cells are designed to be charged and discharged using hot-air heat transfer. Refer to Data Sheet 11 in Appendix A for system parameters.

Architectural Research Corporation is currently marketing a ceiling tile, shown in Figure 15, which uses a eutectic mixture with Glauber's salt as the active material with the phase-change at 73°F. The tiles, which are 24 x 24 x 1-1/4-in and weigh 44 lbs, store 880 Btu per tile over a range of 10°F (68 to 78°F). The tile is a sandwich of 24 lbs of the eutectic contained in two plastic bags, each 3/8-in thick. Twenty pounds of polyester concrete surround the eutectic. The system is now designed to be used as a passive building element to be charged by direct (or reflected) insolation or to absorb and store "waste" thermal energy from bodies and appliances (32,33). Refer to Data Sheet 12 in Appendix A.

Researchers at the General Electric Research and Development Center are developing a thermal energy storage unit using Glauber's salt as the PCM. A cylindrical drum, shown in Figure 16, is 95-percent filled with Glauber's salt and rotated along its axis at 3 rpm by a small motor (34). During thermal energy extraction, this slow rotation provides enough agitation to keep the salt temperature uniform and prevent the salt from solidifying on the wall of the container and slowing down the heat transfer process. A recent technical publication by General Electric Company's Research and Development Division lists the following experimental results (35):

(a) One hundred percent crystallization of $Na_2SO_4 \cdot 10H_2O$.

(b) Repeatable freeze-thaw cycling without degradation after 150 cycles.

(c) Satisfactory repeatable nucleation.

(d) High heat transfer rates -- solids do not adhere to the heat transfer surface.

(e) High volumetric efficiency.

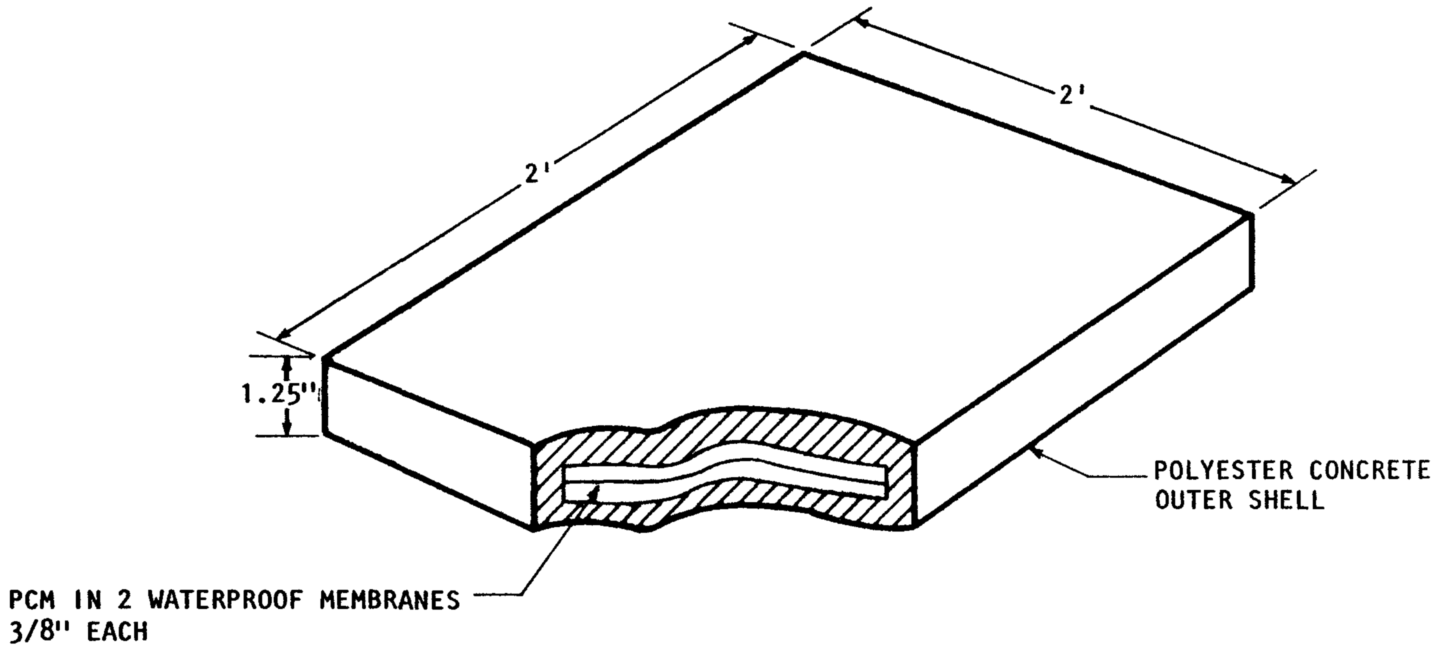
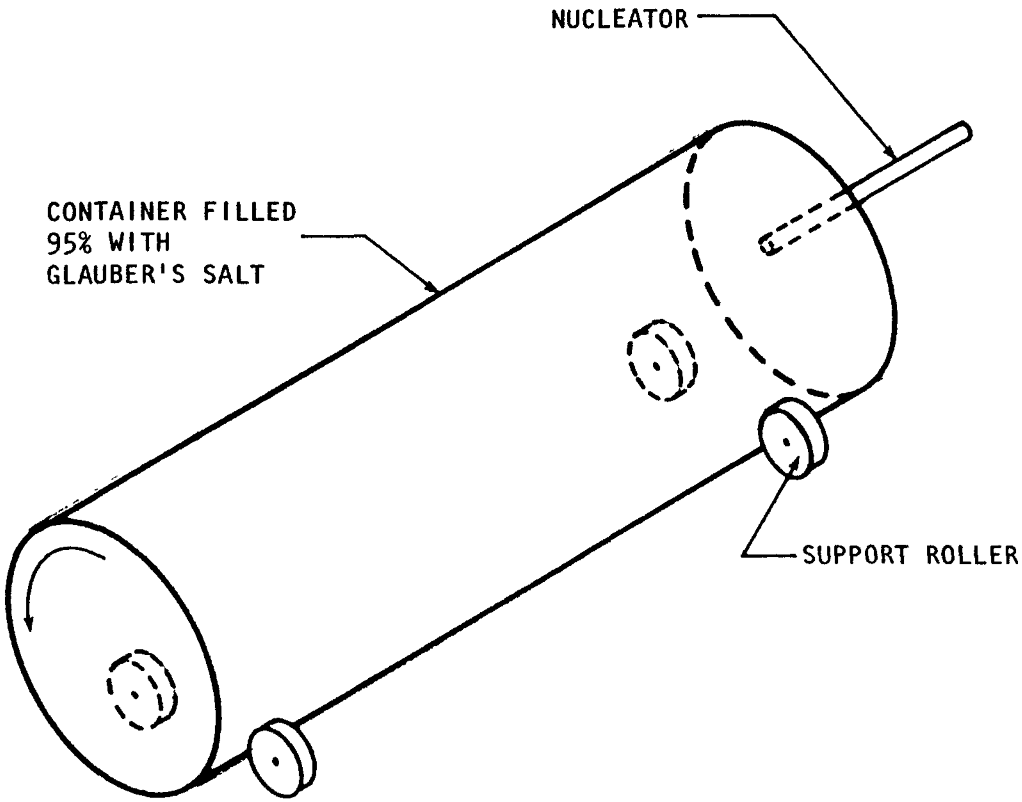


Figure 15. SOL-AR-TILE With Cross Section



SOURCE: GENERAL ELECTRIC

Figure 16. Rolling Cylinder Thermal Energy Storage Unit

(f) Melt-thaw volume change is not a problem.

(g) Corrosion in the metal-walled vessel has been controlled by additives without affecting the crystallization behavior.

(h) Noise levels have been low. No noise problem is evident.

A storage system built on this concept would require an 850-gallon cylinder filled to 94 percent capacity with Glauber's salt to store 1 x 10^6 Btu. GE is now involved in a project to design, build, and test a prototype system using the rolling cylinder with a capacity of approximately 200,000 Btu. Refer to Data Sheet 21 for additional details.

The Addison Products Company of Addison, Michigan, is currently marketing a thermal energy storage unit using a "slack wax" as the PCM (37,38). The wax changes phase at about 115°F. The wax is sealed in standard one-gallon metal cans. These cans are stacked twenty to a shelf with seven shelves per storage chamber. The chamber enclosure is a 6 x 6 x 3-ft bin with 4 inches of polystyrene for insulation in the walls. Hot air enters at the top and flow through each shelf in succession, exiting through the bottom of the opposite side (see Figure 17). Storage capacity of the chamber is about 125,000 Btu. See Data Sheet 14 in Appendix A for additional details.

The Annual Cycle Energy System (ACES) is a residential and commercial heating and air-conditioning system that also provides domestic water heating. Water is frozen during the winter season and the stored ice provides "free" air-conditioning during the summer (39). The major elements of an ACES are:

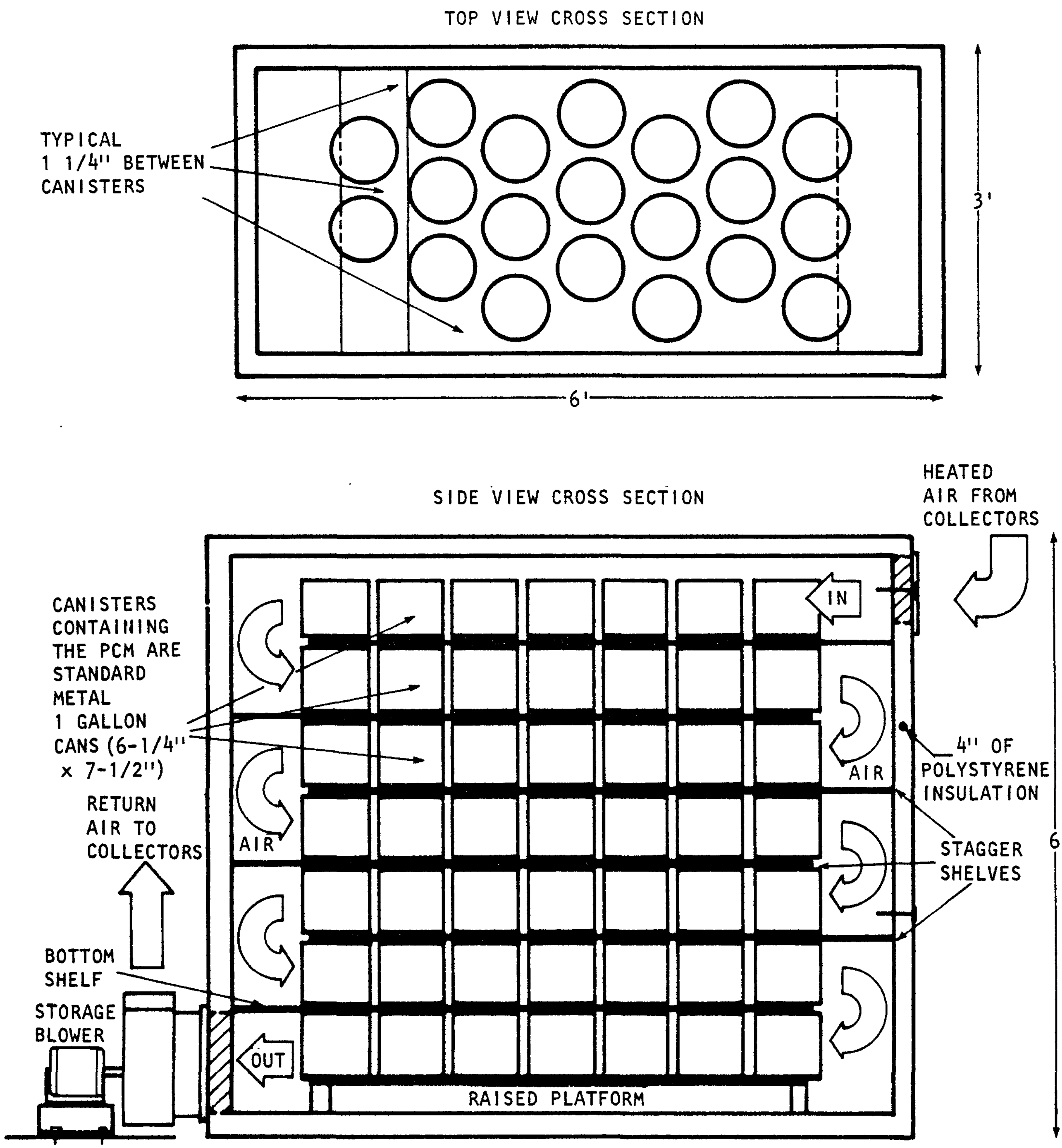
(a) A high efficiency heat pump with refrigerant-to-brine heat exchangers on both the evaporating and condensing sides.

(b) An ice storage tank to store ice.

(c) Ice building coils to make ice.

(d) A forced-air circulating system with a fan coil for space heating and cooling.

(e) A tank for storing domestic hot water.



Source: Addison Products Company

Figure 17. Add-A-Sun Storage Chamber

(f) A refrigerant-to-water heat exchanger.

The ACES is shown schematically in Figure 18. Space heating is accomplished by circulating brine from the heating condenser through the fan coil and transferring the heat to the living space by the circulating air system. Space cooling is accomplished by circulating brine from the ice storage tank through a fan coil unit to lower the temperature of circulating air distributed to space. The selector valves choose the brine circuit for heating or cooling as required. The domestic water is heated by recirculation through the hot-water condenser.

The criteria used for selecting the ice bin size vary. In climates where the heating load considerably exceeds the cooling load the ice bin is sized to store adequate ice for the cooling season but is not large enough to provide full heating requirements. The deficiency of available heat from the ice bin is made up by the radiant/convector panel. In climates where the cooling load exceeds the heating load, the ice bin is sized based on the heating load. If the ice is exhausted before the end of the cooling season, the compressor will be permitted to operate at night when the air temperature falls below a predetermined temperature of about 80° to chill the water and perhaps make ice.

The demonstration house is a 2,000 ft^2 single family housing unit with an ice inventory of 2,000 ft^3. The cooling and heating capacities of the system is 25,000 Btu/hr at 25°F brine outlet and 30,000 Btu/hr at 105°F condensing. See Data Sheet 15 for additional information.

2. Solid-Solid Transformation

Calmac Manufacturing Corporation, under a grant from NASA, has developed a PCM storage unit using sodium sulfate (Na_2SO_4) for high-temperature storage (41). The sodium sulfate was formed, using a proprietary process developed by Calmac, into compressed pebbles hard enough to use as a pebble bed. The unit, shown in Figure 19, stores thermal energy over a range of 400 to 600°F. The phase change is a solid-to-solid transition which occurs at 465°F. The thermal energy storage principle is a combination of sensible heat storage of solid and the latent heat storage of the phase changing. Although a liquid (Therminol-X) was used as the heat-transfer fluid (being circulated through the tank over the pebble bed), use of an air-heat transfer system is possible. Pebbles of prepared sodium sulfate are commercially available from Calmac in industrial lots. For construction and unit performance parameters, refer to Data Sheet 16 in Appendix A.

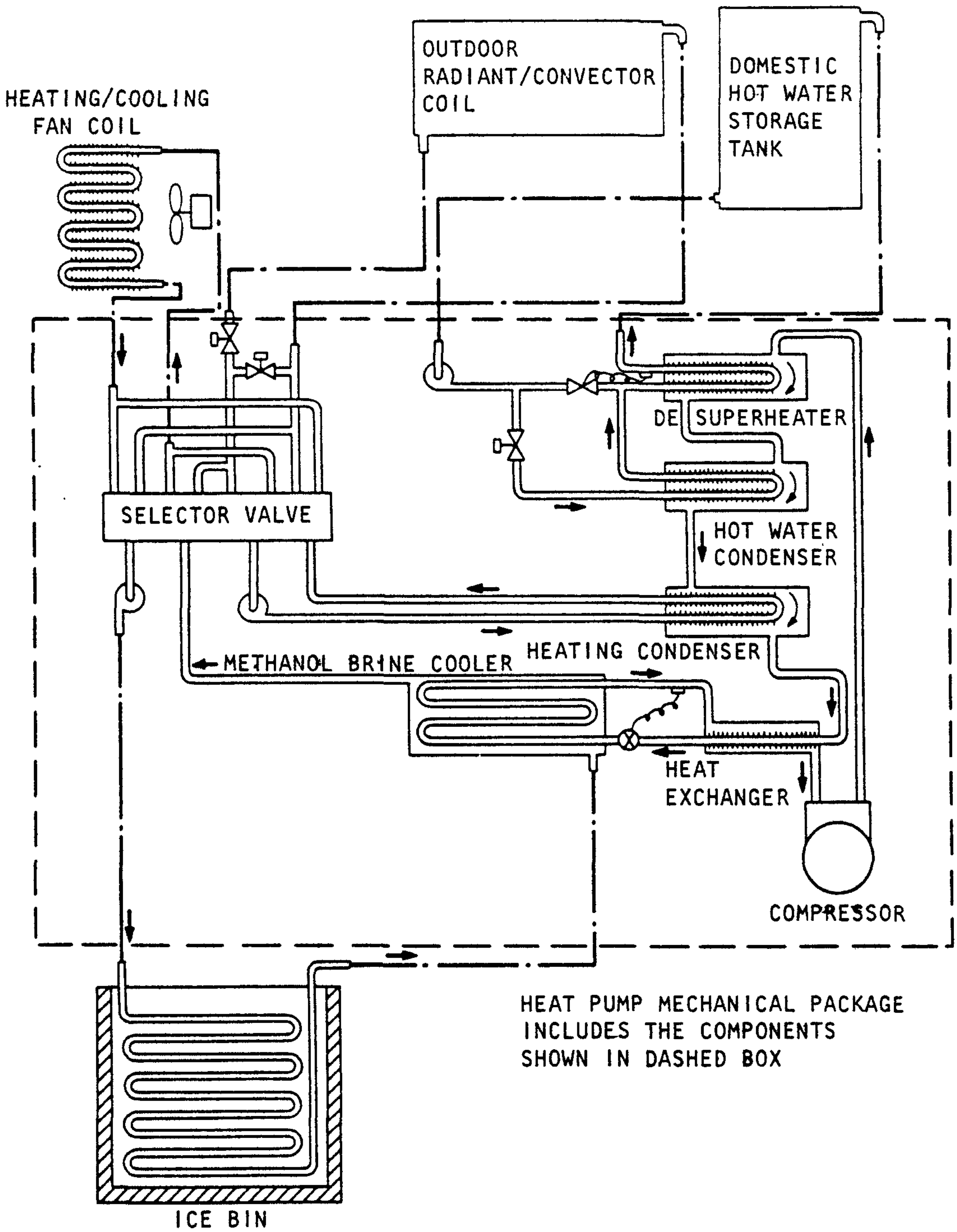


Figure 18. System Schematic (ACES)

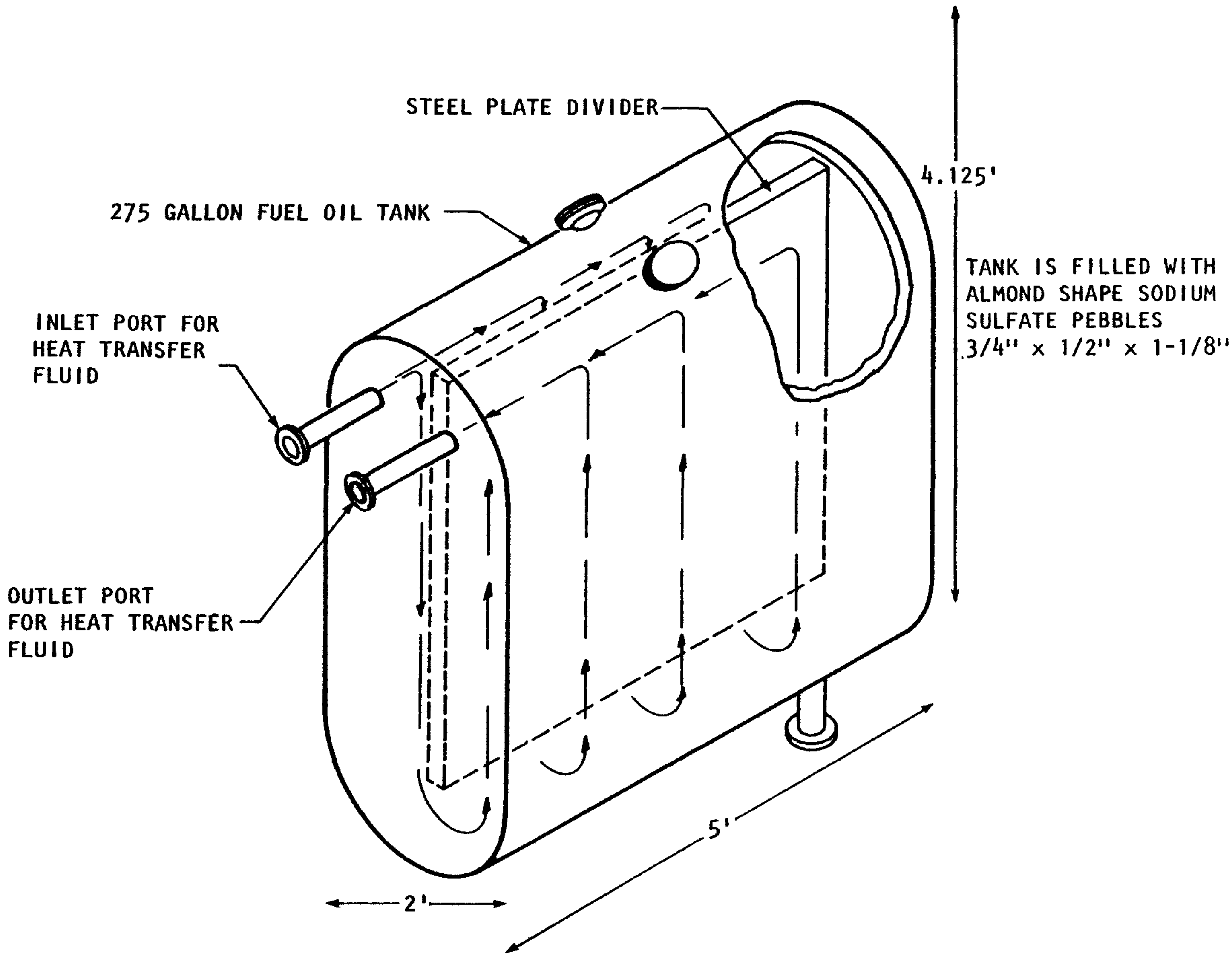


Figure 19. Calmac's Sodium Sulfate Storage Tank

D. Thermochemical Energy Storage

1. Introduction

Energy storage using the principle of reversible chemical reactions is thermochemical energy storage (TCES). The primary interests in thermochemical energy storage technology have been in solar thermal electric power plant and nuclear power plant applications (42,43,44,45). Chemical heat pipes using thermochemical technology are of considerable interest in energy transmission and distribution for coal gasification plants (open loop heat pipe), high-temperature nuclear reactor (high-temperature heat pipe), and moderate temperature source applications including nuclear, solar and fossil energies (low-temperature heat pipe) (42). Chemical heat pump storage with its reversible chemical reaction is also attractive in solar heating and cooling for buildings. TCES offers several basic advantages.

(a) Chemicals can be stored separately under atmospheric conditions and the storage time can be extended indefinitely without using insulation.

(b) Energy density (energy content per unit mass) for TCES is relatively high.

(c) TCES can be used as a heat pump.

2. Storage Principle

The basic principle of TCES can be described by the following example. A chemical compound, AB, decomposes into reactants A and B at a higher temperature level. The chemical reaction:

$$AB \longrightarrow A + B$$

is endothermic where energy is stored into the chemical reactants A and B. The reactants A and B can be stored separately and then recombined at a later time. The chemical reaction:

$$A + B \longrightarrow AB$$

is exothermic where the stored energy is released at a lower temperature level. For effective application of TCES the reversible chemical reaction:

$$AB \underset{\text{exthothermic}}{\overset{\text{endothermic}}{\rightleftarrows}} A + B$$

selected should have controllable chemical reactions at the desired temperature range. The reactants A and B should be easily separable immediately after decomposition to avoid recombination. The candidate reactions are listed in Tables 2 and 3.

3. Discussion

The storage of thermal energy in reversible chemical reactions is a relatively new field. The technology is just beginning to be explored, and only limited information is available.

Some of the work being done on TCES is listed in Table 4 (47). Most of the TCES reactions require operating temperatures above 300°C. Only sulfuric acid systems are in the temperature range of 90 to 150°C. A selected sufuric acid-water system will be discussed in Section 4 of this chapter.

Chemical heat pumps (CHP) are of considerable interest. A chemical heat pump has the advantage of a reversible thermal chemical reaction but does not require any moving parts to operate. A CHP is driven by the pressure difference generated between two interconnected chemical reactors. Using a heat pump analogy, reactor A is an evaporator where a chemical compound is decomposed and energy is added either by solar or by other means. The vapor pressure of decomposed gaseous reactant will drive the gaseous reactant itself through the passage to the reactor B where a lower temperature will be maintained. Reactor B is a condenser where the gaseous reactant is condensed to liquid. The energy released due to condensation is removed either by air or by water depending on the available source. The charge cycle is then complete and the energy is stored in reactor B. During the discharge cycle, the chemical reaction is reversed. When the temperature of reactor A drops, the vapor pressure of the gaseous reactant in reactor A will be lower than that of reactor B. The gaseous reactant will flow from reactor B through the passage to reactor A where the chemical compound is formed and energy is released. This energy could be a source for space heating. At reactor B, however, gaseous reactant evaporates and energy is drawn from a space where cooling may be needed.

The potential candidate reactions for CHP are many. Inorganic salt substrate with methanol gas (CH_3OH), water vapor absorption with magnesium chloride dihydrate ($MgCl_2 \cdot 2H_2O$), sulfuric acid with water dilution, and paired ammoniated

TABLE 2. ENERGY CONTENT OF CANDIDATE CHEMICAL ENERGY STORAGE REACTIONS, SYSTEMS EXCLUDING SOLID CONSTITUENTS (45)

Reaction exothermic ⇄ endothermic	Reaction Enthalpy at 298°K (77°F)		Temperature (°K) at which	
	Ws/g [a]	Btu/lb	90% Formed	90% Dissociated
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(L)$	7,345	3,160	–	–
$CO(G) + 3H_2(G) \rightleftharpoons CH_4(G) + H_2O(G)$	6,053	2,604	754	1,466
$C_2H_4(G) + H_2(G) \rightleftharpoons C_2H_6(G)$	4,561	1,962	841	1,205
$2\,CO(G) + 2\,H_2(G) \rightleftharpoons CH_4(G) + CO_2(G)$	4,118	1,772	778	1,152
$CO(G) + 2\,H_2(G) \rightleftharpoons CH_3OH(L)$	3,996	1,718	345	434
$N_2(G) + 3\,H_2(G) \rightleftharpoons 2\,NH_3(L)$	3,861	1,661	–	–
$N_2(G) + 3\,H_2(G) \rightleftharpoons 2\,NH_3(G)$	2,695	1,159	346	528
$2\,NO(G) + O_2(G) \rightleftharpoons N_2O_4(L)$	1,750	753	549	930
$SO_2(G) + Air \rightleftharpoons SO_3(G)$*	1,544	644	806	1,270
$SO_2(L) + 1/2\,O_2(G) \rightleftharpoons SO_3(L)$	1,517	652	792	1,235
$SO_2(G) + 1/2\,O_2(G) \rightleftharpoons SO_3(G)$	1,235	531	792	1,235
$NO(G) + 1/2\,O_2(G) \rightleftharpoons NO_2(G)$	1,243	535	549	930
$CO(G) + Cl_2(L) \rightleftharpoons CO\,Cl_2(L)$	1 172	504	628	881
$NO_2(G) + NO_2(G) \rightleftharpoons N_2O_4(L)$	932	401	288	381
$SO_3(L) + H_2O(L) \rightleftharpoons H_2SO_4(L)$	885	381	535	723
$SO_2(G) + Air \rightleftharpoons SO_3(G)$	727	313	806	1,270
$NO(G) + 1/2\,Cl_2(L) \rightleftharpoons NO\,Cl(L)$	695	299	425	819
$H_2O(L) + H_2SO_4(L) \rightleftharpoons H_2SO_4 \cdot H_2O(L)$	230	99	–	–
For comparison:				
$H_2(G) + 1/2\,O_2(G) \rightleftharpoons H_2O(G)$	13,423	5,775	2,830	5,600

* Based on SO_2 weight only. Air open cycle.

[a] Ws/g represents watt-second per gram. One Ws/g is equivalent to 2,326 Btu/lb.

TABLE 3. ENERGY CONTENT OF CANDIDATE CHEMICAL ENERGY STORAGE REACTIONS, SYSTEMS WITH SOLID CONSTITUENTS (46)

Reaction exothermic ⇌ endothermic	Reaction Enthalpy at 298°K (77°F)		Temperature at which $P_{Diss.}$ =		
	Ws/g [a]	Btu/lb	0.1 bar [b]	1 bar	$P_{Cond.}$
$Li(S) + 1/2\ H_2(G) \rightleftharpoons LiH(S)$	11,403	4,906	1,181	1,223	–
$NaF(S) + (HF)_n(L) \rightleftharpoons NaHF_2(S)$	4,442	1,911			
$Li_2O(S) + CO_2(G) \rightleftharpoons Li_2CO_3(S)$	3,029	1,303			
$Na_2O(S) + CO_2(G) \rightleftharpoons Na_2CO_3(S)$	3,014	1,296		2,445	
$Mg(S) + H_2(G) \rightleftharpoons MgH_2(S)$	2,893	1,245	~500	560	–
$CaO(S) + SO_3(L) \rightleftharpoons CaSO_4(S)$	2,539	1,092			
$CaO(S) + CO_2(G) \rightleftharpoons CaCO_3(S)$	1,776	764	1,028	1,171	
$MgO(S) + CO_2(G) \rightleftharpoons MgCO_3(S)$	1,387	597		670	
$BaO(S) + CO_2(G) \rightleftharpoons BaCO_3(S)$	1,353	582		1,473	
$NiCl_2(S) + 6\ NH_3(L) \rightleftharpoons [Ni(NH_3)_6]Cl_2(S)$	1,301	560			
$NH_3(L) + H_2SO_4(L) \rightleftharpoons NH_4HSO_4(S)$	1,256	540	–	–	–
$KF(S) + (HF)_n(L) \rightleftharpoons KHF_2(S)$	1,031	444			
$CaO(S) + H_2O(L) \rightleftharpoons Ca(OH)_2(S)$	880	378	722	820	676
$MgO(S) + H_2O(L) \rightleftharpoons Mg(OH)_2(S)$	644	277	614	649	598
$BaO(S) + H_2O(L) \rightleftharpoons Ba(OH)_2(S)$	598	257	1,052	1,271	961
$FeCl_2(S) + 6\ NH_3(L) \rightleftharpoons [Fe(NH_3)_6]Cl_2(S)$	302	129			
$CaCl_2(S) + 6\ NH_3(L) \rightleftharpoons [Ca(NH_3)_6]Cl_2(S)$	210	90			

[a] Ws/g represents watt-second per gram. One Ws/g is equivalent to 2,326 Btu/lb.

[b] One bar is equivalent to 14.5 lb/in^2.

TABLE 4. SELECTED CHARACTERISTICS AND STATUS OF VARIOUS THERMOCHEMICAL ENERGY STORAGE APPROACHES (47)

Reaction (discharge →, ← charge)	Energy Concentration		Temperature (°C)		Material Costs		System Complexity	Major Difficulties	Current Status of Research	Potential Applications
	WH/lb [a]	WH/in.^{3} [b]	Discharge	Charge	$/lb	$/KWH				
$H_2O(l) + H_2SO_4(l) \rightleftharpoons H_2SO_4 \cdot H_2O(l)$	29	1 5	<100	<100	0.025	0 9	Low	Toxicity and corrosiveness of sulfuric acid	Lab studies	Residential solar heating
$SO_3(l) + H_2O(l) \rightleftharpoons H_2SO_4(l)$	112	3.4 [c]	260	450	–	–	Moderate	Separating SO_3 and H_2O	Lab. studies	Residential solar heating/cooling
$SO_2(g) + 1/2\,O_2(g) \rightleftharpoons SO_3(g)$	156	2.6 [c]	520	960 [d]	0 09	0 6	Very high	Toxicity and corrosiveness of SO_3	"Paper" feasibility studies	Solar-thermal electric
$CO(g) + 3H_2(g)$ [e] $\rightleftharpoons CH_4(g) + H_2O(g)$	926	1.3 [f]	480	1200 [g]	–	–	Very high	Complexity of chemical processes and energy exchanges	"Paper" feasibility studies	Thermal energy distribution
$CaO(s) + H_2O(l) \rightleftharpoons Ca(OH)_2(s)$	111	5.8	<520 [g]	520	0 09	0.8	Moderate	Kinetics of porous bed reactor, lifetime	Lab. studies	Residential solar heating/cooling
$MgO(s) + H_2O(l) \rightleftharpoons Mg(OH)_2(s)$	81	4.0	<375	375	0.20	2.5	Moderate	Same as above	Lab. studies	Residential solar heating/cooling
$Mg_2Ni(s) + H_2(g) \rightleftharpoons Mg_2N_2H_4(s)$	200		<300	300	1.0	3.6	Moderate/high	Storage of H_2 and cost of hydride	"Paper" feasibility studies	Residential solar total energy
Hydride alone (ρ_{HD} = 80 lb/ft^3)		9.2								
Hydrogen stored as a gas at 2000 psi		1.4								
Hydrogen stored in FeTi hydride		3.7								

[a] Energy density (watt-hour/lb) based on weight of reactants
[b] Energy density (watt-hours/in^3) based on storage of both reactants and products
[c] Both SO_2 and SO_3 stored as liquids
[d] Temperatures without the use of a catalyst
[e] Reaction often used for chemical heatpipe system
[f] All gases stored at 2000 psi
[g] < means temperature varies during heat release and can be controlled to be less than value indicated

salts have been investigated (48,49,50,51). However, more exploration and laboratory tests are still needed.

4. Selected Examples

The development of TCES is in the beginning stage and there is no TCES unit available for immediate commercialization. Two examples are selected for illustrative purposes to explain how TCES works.

a. Sulfuric Acid-Water Storage. The sulfuric acid-water storage is of some interest at the present time. This is because sulfuric acid is an inexpensive chemical commercially available in large quantities and the industry has accumulated extensive information. The energy storage density is approximately 120 to 200 Btu/lb. The disadvantage of this TCES is that the toxicity and corrosiveness of the acid are hazardous.

Rocket Research Corporation has proposed a sulfuric acid-water energy storage unit (50). It has a separator which is heated by solar energy, where the water is separated by evaporation from a sulfuric acid-water solution at a temperature of approximately 615°F. The separated water in the form of steam is condensed and stored in a water storage tank. The remaining hot sulfuric acid at approximately 98 percent concentration passes through some heat exchangers and is stored at approximately 200°F in an acid storage tank. When thermal energy is required, the water and concentrated acid will be recombined in a mixer reactor where the energy will be released for heating or for absorption cooling. The diluted sulfuric acid-water solution is then stored at approximately 100°F in a diluted acid storage tank. The diluted acid will then be transferred to the separator where the cycle began. A simulated application of seasonal storage using a sulfuric acid-water system has been presented for a 20,000 sq-ft building located on the eastern seaboard. The schematic diagram and flow diagrams of the seasonal systems are shown in Figures 20 and 21. More detailed information is shown on Data Sheet 22 in Appendix A. Rocket Research Corporation has recently developed a sulfuric acid/ water heat pump/energy storage subsystem which operates at a temperature range of 150 to 400°F (68).

b. Magnesium Chloride Dihydrate System. This technology has been applied to heat pump operation and the carrier gas is water vapor (49). The process is best explained by referring to the vapor pressure-temperature diagram in Figure 22. The system is composed of a vaporizer containing liquid water, interconnected by a tube with an absorber containing magnesium chloride dihydrate (MgCl

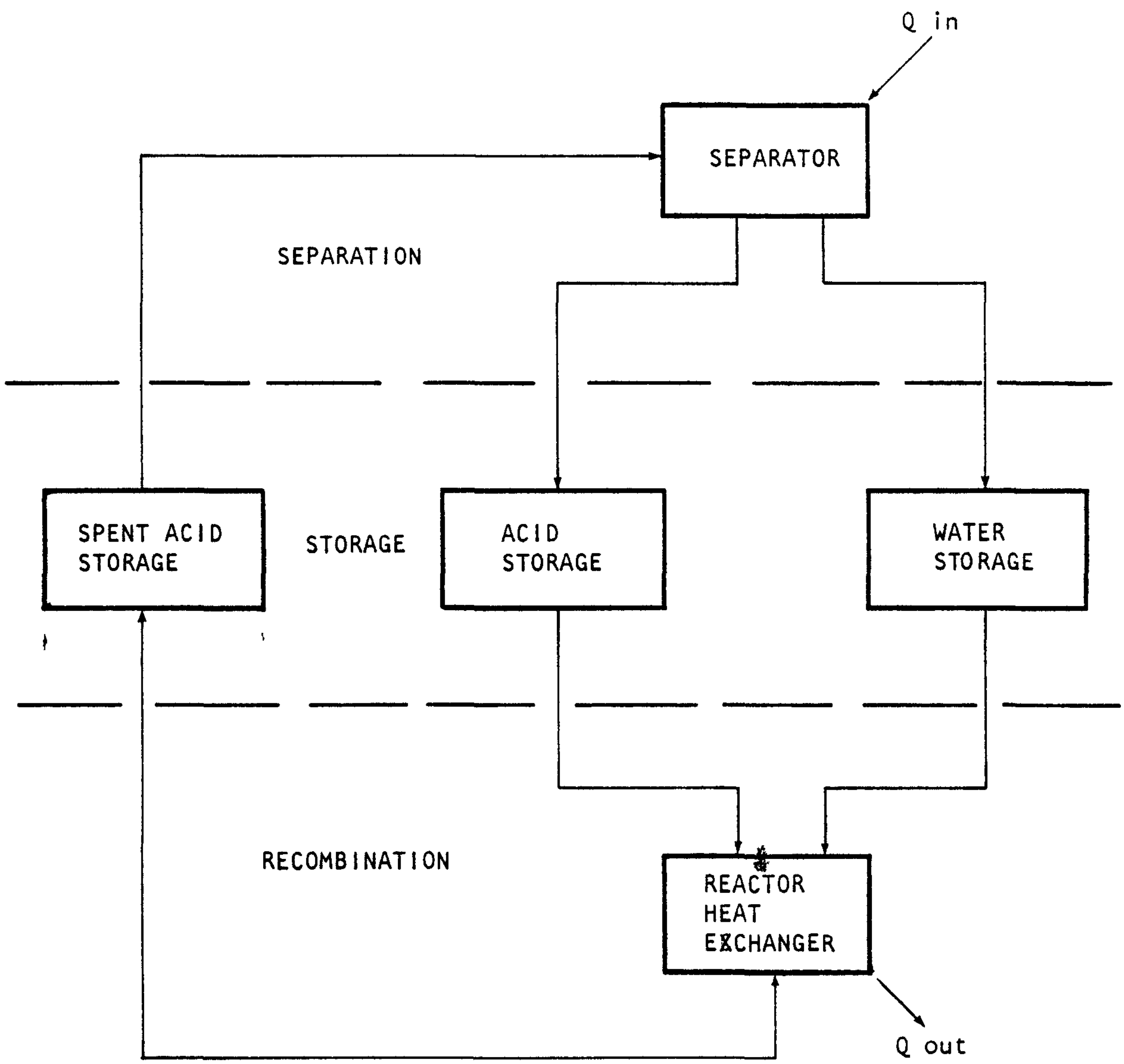
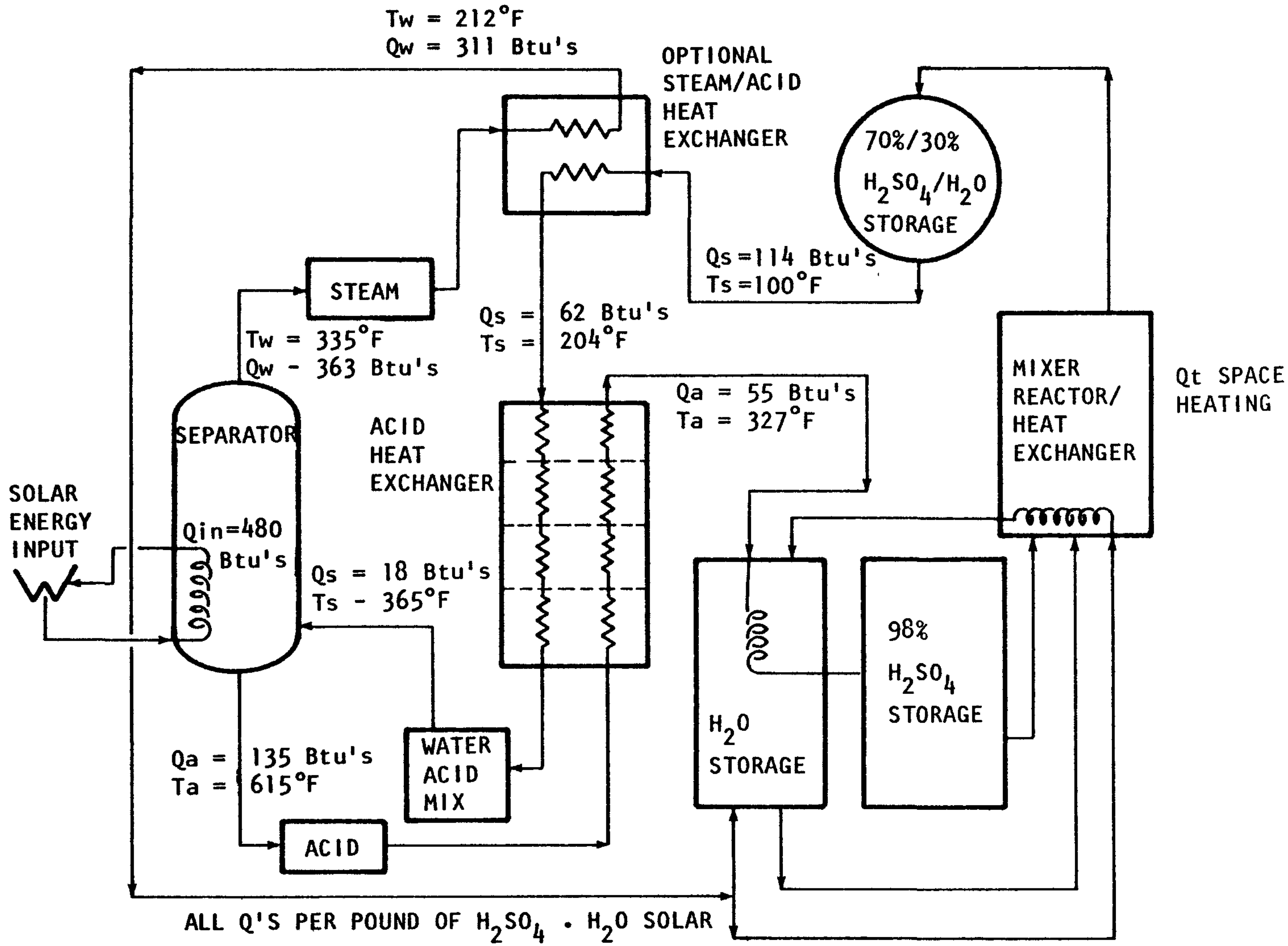
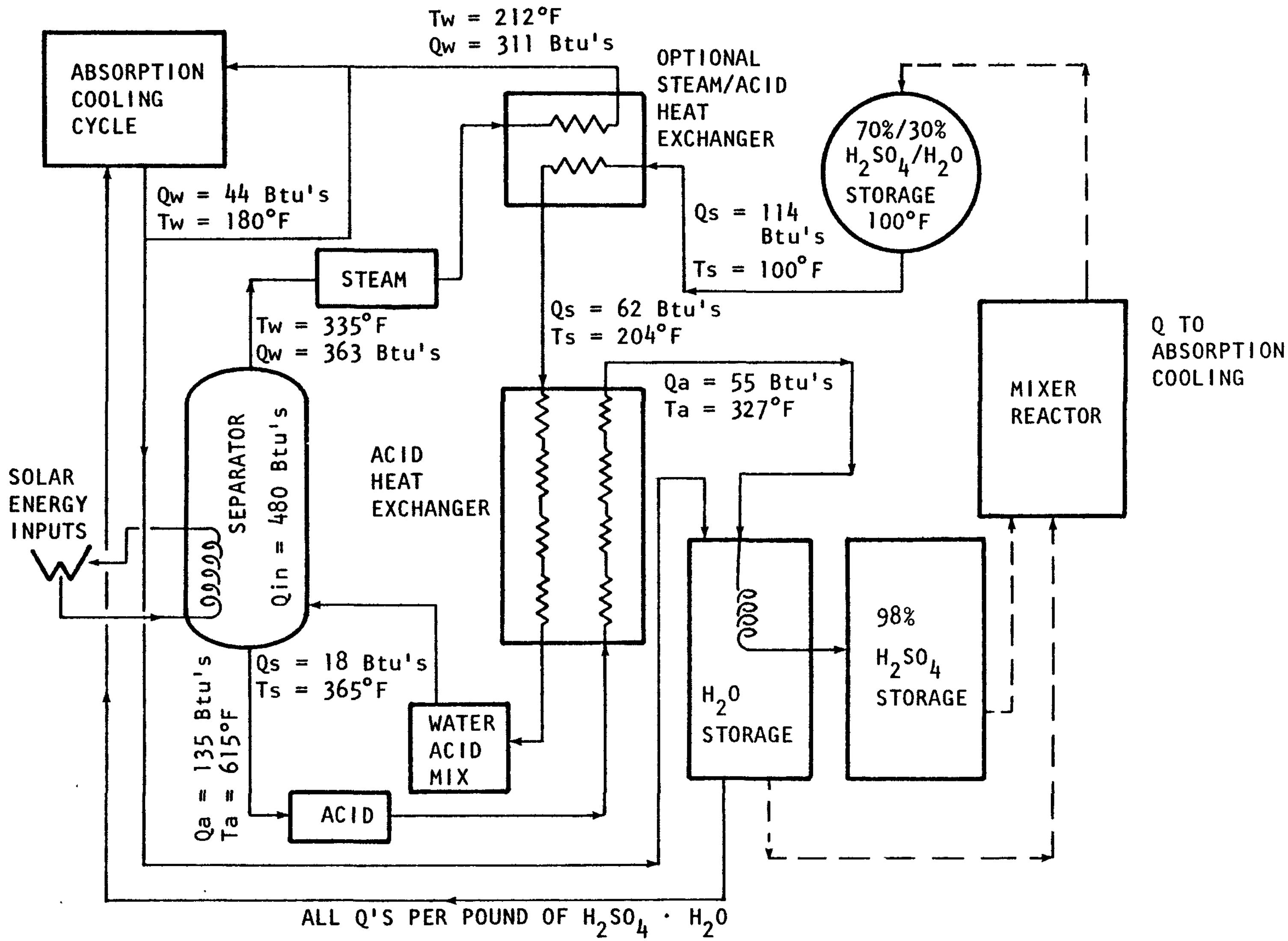


Figure 20. Schematic Diagram - Sulfuric Acid-Water System



WINTER APPLICATION

Figure 21.a. Seasonal Sulfuric Acid-Water System for Heating and Cooling of Buildings



SUMMER APPLICATION

Figure 21.b. Seasonal Sulfuric Acid-Water System for Heating and Cooling of Buildings

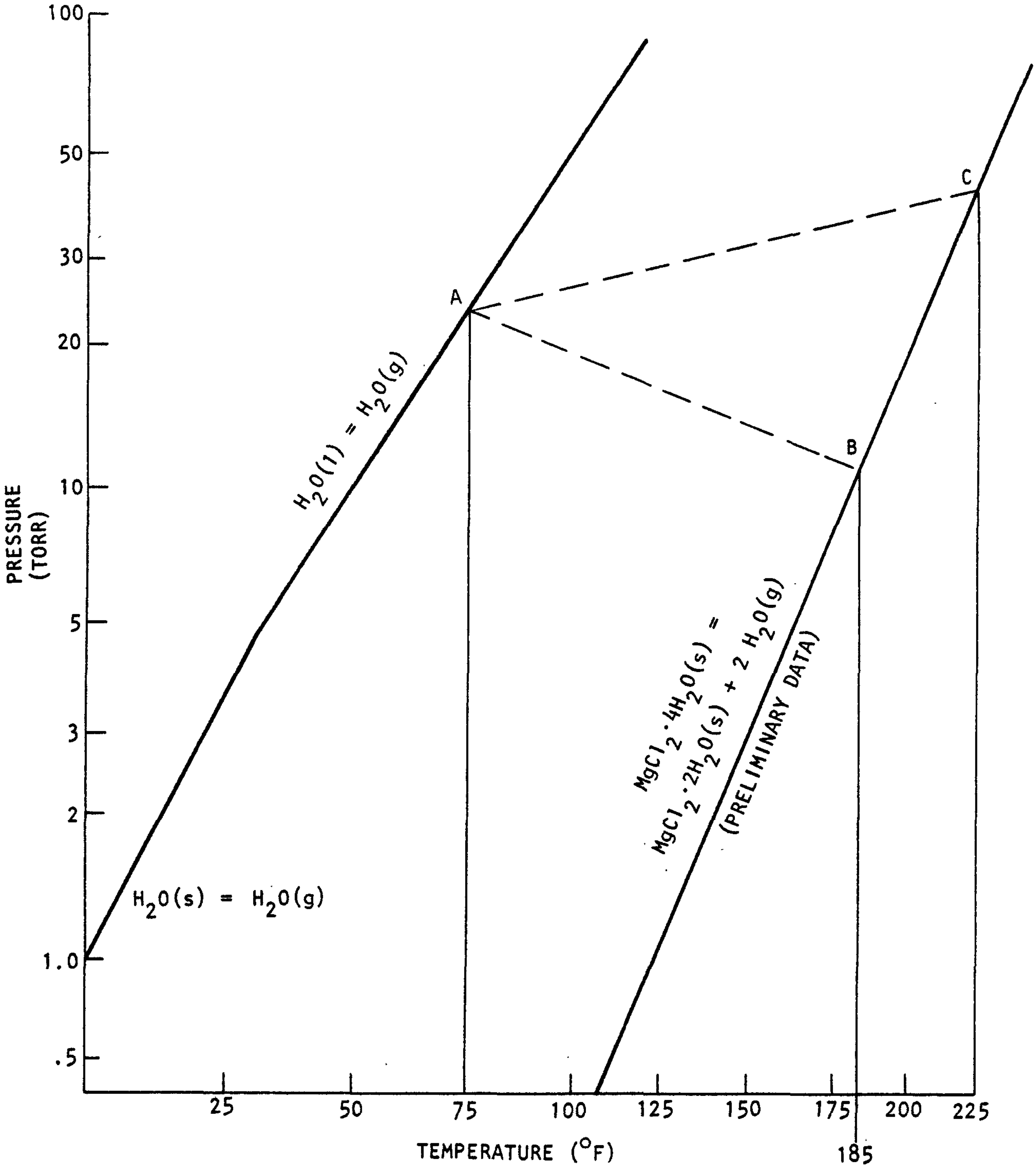


Figure 22. Vapor Pressure-Temperature Relationship for a Water-Magnesium Chloride System

$2H_2O$). In the heating mode, the water vapor pressure at 75°F in the vaporizer, as indicated by point A, is much higher than that of the absorber at point B. Water vapor will be transferred through the interconnected tube to the absorber from the vaporizer. In the vaporizer, the energy is drawn from the environment. In the absorber, the water vapor will be combined with magnesium chloride dihydrate ($MgCl_2 \cdot 2H_2O$) to form magnesium chloride tetrahydrate ($MgCl_2 \cdot 4H_2O$) and energy will be released for space heating. The temperature of the absorber can be kept at 185°F as indicated by point B. The thermal energy storage density is approximately 350 Btu/lbm. During the reverse cycle, solar energy is added to the absorber to raise the temperature to 225°F (point C), where the absorber vapor pressure will be higher than that of the evaporator represented by point A. Water vapor then will be transported to the evaporator. The excess water vapor in the evaporator will be condensed. The energy released due to condensation is dissipated to the environment. In the cooling mode, the operation is similar except that the vaporization temperature will be kept lower for space cooling purposes and the absorber temperature will also be lower to maintain a workable vapor pressure difference. The chemical heat pump for this system is shown in Figure 23. More detailed information will be found in Data Sheet 23 in Appendix A.

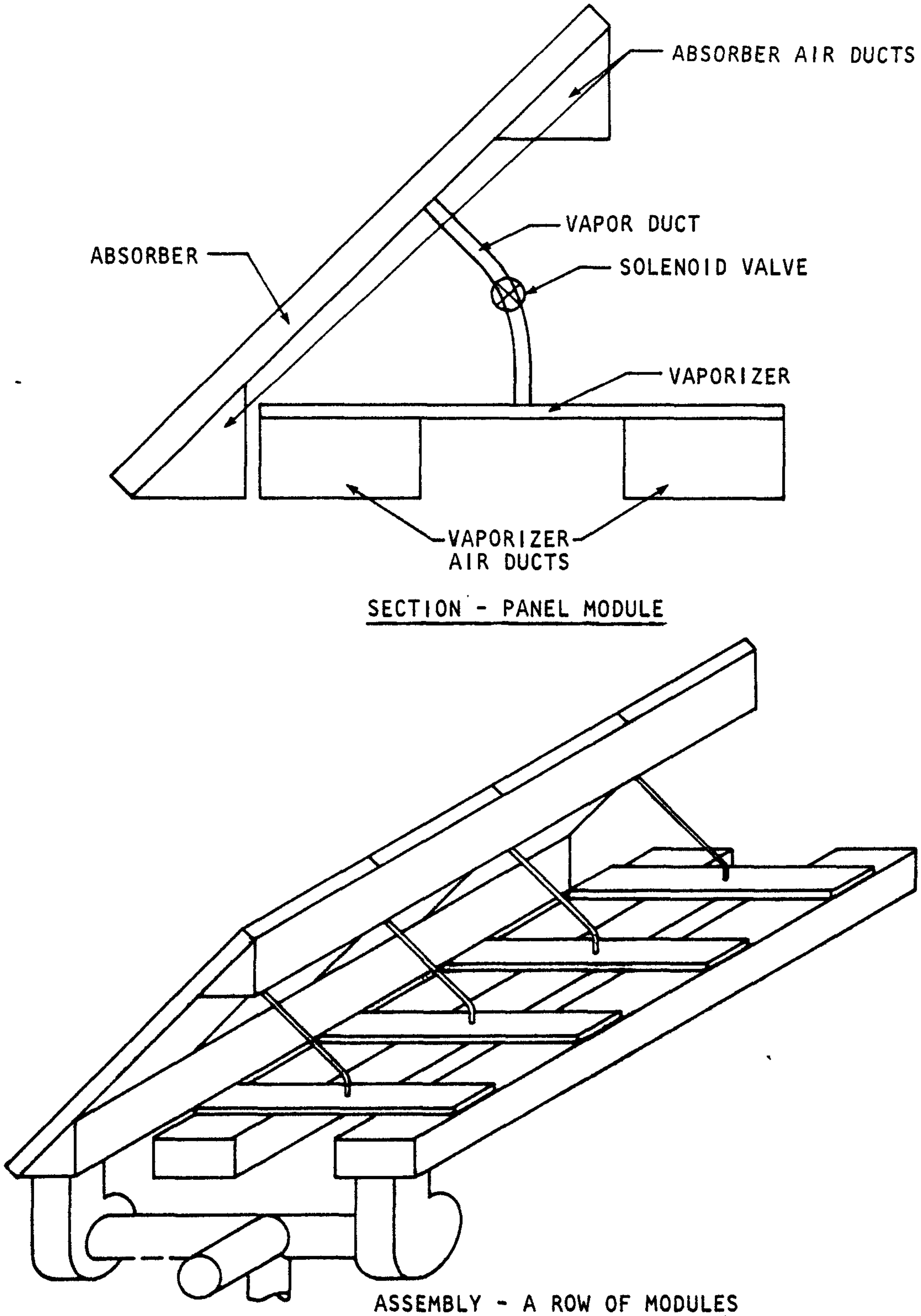


Figure 23. Magnesium Chloride Hydrate System - Chemical Heat Pump

III. STORAGE REQUIREMENTS FOR SOLAR APPLICATIONS

Solar applications under consideration are those paths indicated in Figure 24 for Solar Heating and Cooling of Buildings (SHACOB) and in Figure 25 for Agricultural Industrial Process Heating (AIPH) (1). Each path shows a group of applications using a certain type of energy collector to achieve a particular end use such as space heating or space cooling.

The primary subject of this chapter is the general storage requirements for each path. Storage requirements for solar applications are characterized by the following criteria:

- Storage temperature range
- Energy storage capacity requirement
- Length of storage time
- Charge-discharge rates required
- Energy losses to environment
- Acceptable cost.

These criteria, as applied to storage units for each path, are presented in Appendix B. A discussion of each item follows.

A. Storage Temperature Range

Storage temperatures are determined by the characteristics of interfacing equipment such as collectors and heat pumps, etc, which may be used in particular applications, and by the requirements of the end use. Depending on the application, thermal storage may be required over a wide range of temperatures. For the applications covered in Appendix B the storage temperatures fall in the range of 0°F to 700°F.

B. Energy Storage Capacity Requirements

The amount of thermal energy to be stored depends on each specific system application. Generally speaking, a storage unit should satisfy a short-term storage need of a

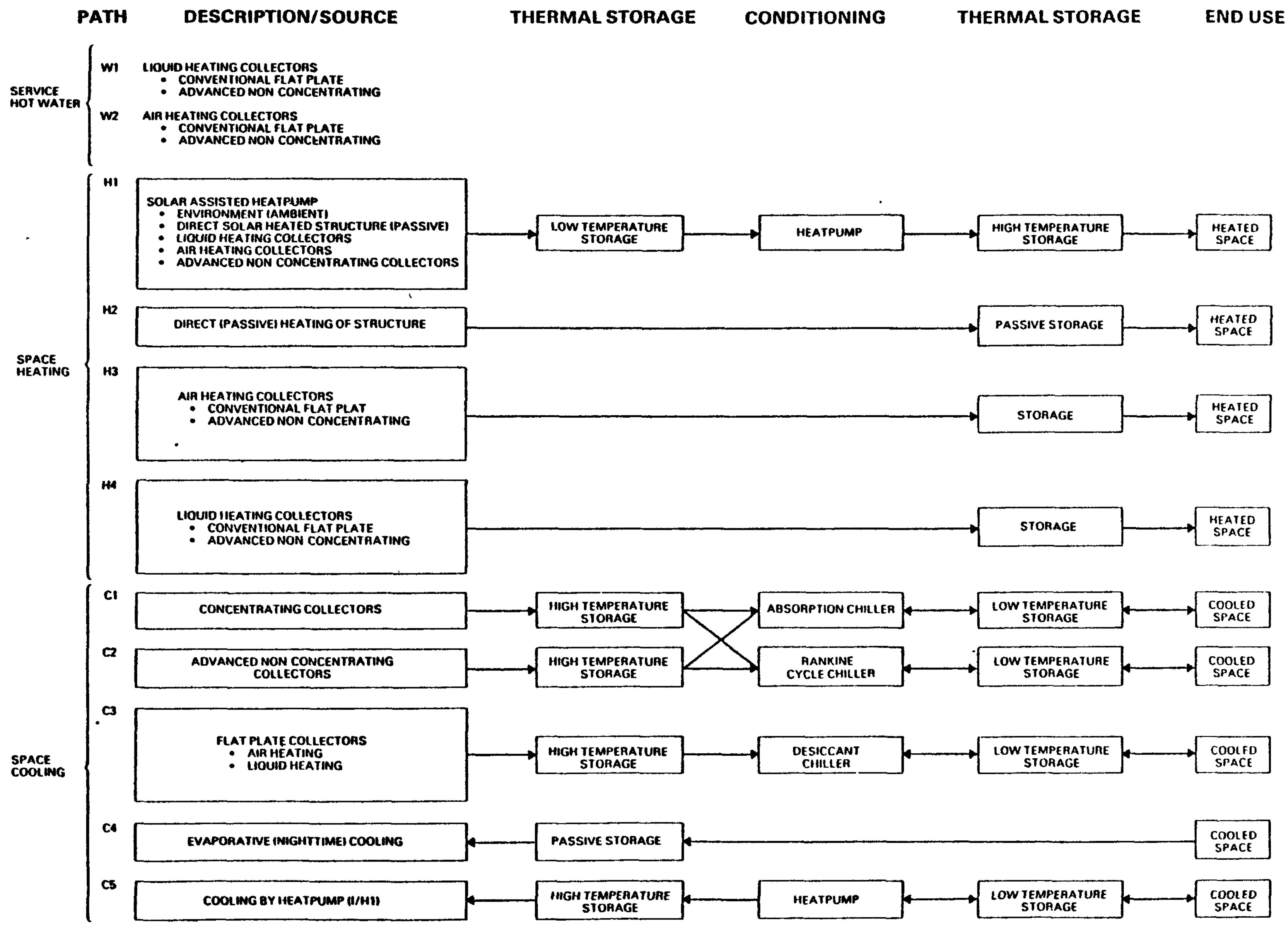


Figure 24. SHACOB Path Schematics (1)

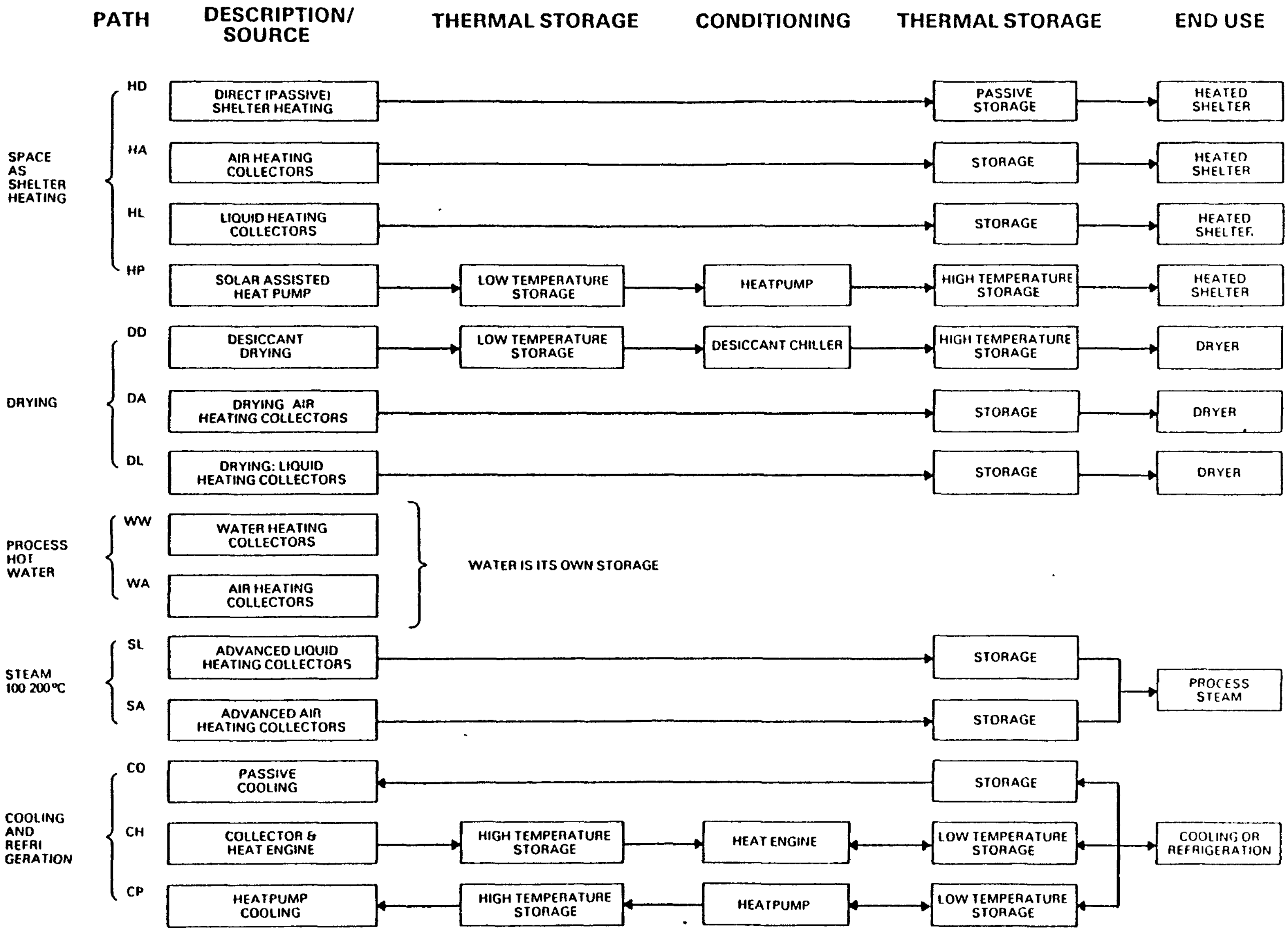


Figure 25. AIPH Path Schematics (1)

few days at a rate of 60 to 80 percent of the daily average load during a heating or cooling season. An application using 100 percent solar energy on a short-term basis would not be economical because the collector area and storage volume would have to be large enough to meet peak loads which occur only on a few days during the heating or cooling seasons. A standby system is required if the end-use function cannot be disrupted. However, in certain geographical areas and for some systems, long-term storage such as seasonal storage can be more cost effective than short-term storage (52,15,39). When storage container size increases, the construction cost per unit volume decreases. This is because the volume is a function of the cube of the dimension and the surface area of the container is a function of the square of the dimension. A large storage tank for seasonal storage can supply 100 percent solar heating or cooling and also minimize the collector area. Since the energy required for winter heating can be collected in summer at a higher insolation level, the collector area could be small compared to short-term storage. In winter on the other hand, cooling capacity can be stored for summer cooling requirements (39). The optimum amount of storage depends on the economics of all components of a complete system including nonsolar energy, labor, material, operations, and maintenance through the expected life of the system. A marginal cost analysis has been suggested by Kahan and Estes (69) in which the upper limit cost can be established for a new system by incorporating lifetime energy saving into life cycle cost analysis.

C. Length of Storage Time

The ideal storage duration corresponds to the desired time to hold full charge without serious thermal losses. The time period can be a few days for short-term storage or several months for long-term storage. As the temperature rises, thermal energy losses increase because of the increased temperature differential. In seasonal storage, the temperature in a storage vessel is normally below 180°F to minimize this loss. However, for chemical storage, the storage time is not a function of temperature. The chemicals can be stored indefinitely at ambient conditions and recombined to generate higher temperatures when needed.

D. Energy Losses

A general discussion regarding energy losses of a storage unit is given in this section. Energy losses from an above-ambient storage unit to the environment or energy gains into a below-ambient storage unit, are a function of temperature differential, storage time, and the coefficient of heat transfer. The coefficient of heat transfer can be reduced if the geometry of the container and insulation materials are properly designed. In addition to the heat transfer loss or gain of a storage unit, there is parasitic loss due to operation of controls, pumps, or fans required for the storage unit. Parasitic energy loss is normally in the form of heat generated from electrical energy. In heating applications, the parasitic loss could be recovered in a manner similar to electrical resistance heating. In cooling applications, this heating loss becomes part of the cooling load. Similarly, the heat loss from a storage tank located inside a building may be recovered for a heating system or may cause additional load for a cooling system. A storage unit designed for the short-term can tolerate a higher rate of heat loss than a long-term storage unit. To maintain a reasonably good storage efficiency of 90 percent, the heat losses should be limited to three percent per day up to several days for short-term storage, and three percent per month up to several months for long-term storage.

The larger the storage container, the greater the thermal efficiency. This is because the exposed heat transfer area per unit mass is smaller for larger containers. Calculations based on 200°F water stored in a 300-ft diameter underground cavity for 90 days indicate a loss of approximately 25 percent (53). However, for 200°F water stored in a buried 10 x 5 x 3-ft uninsulated water tank, the heat loss over 48 hours is more than 50 percent. If a six-inch insulating blanket having a thermal conductivity of 0.25 Btu in/ft^2-hr-°F is applied, the same 10 x 5 x 3-ft tank will lose only about 10 percent in 48 hours. Insulation is an effective method of improving storage thermal efficiency. Parasitic losses due to pump or fan operation should be included in calculations of storage unit efficiency. These losses are normally not more than three to six percent of the storage capacity. Standard methods of testing storage units based on thermal performance have been developed through ASHRAE (54).

Heat transfer for underground tanks is a complicated phenomenon depending on such factors as soil type, moisture content, water table, and capillary action. A detailed discussion is given in Reference 55.

E. Acceptable Cost

The acceptable cost of a solar thermal storage unit is application dependent and difficult to judge without establishing a specific application. One approach is to compare the life cycle cost of a solar system with storage to the life cycle cost of a likely competitive conventional system that will achieve the same end-use purpose.

An energy storage unit is just one portion of an entire solar energy system designed either for heating and cooling of buildings, or for agricultural or industrial applications. There are many interfacing and coordinating requirements between the storage unit and the other components to insure that the entire system functions properly. The considerations given for short-term and seasonal storage apply not only to the storage devices but also to the related collector areas, heat exchangers, piping, and other interfacing requirements. Compared to short-term storage in a heating application, the collector area for seasonal storage can be small since the collector will also operate in summer months at a high insolation level. However, for a short-term storage system, the collectors must operate during winter months while the insolation is at a lower level. Because there are obvious design differences in the containers of these two storage units, the piping arrangement, heat exchanger, etc., may also be different. The cost analysis should include the entire system, rather than just the storage component.

A new system to be commercially competitive, must be attractive economically when compared with existing systems. For solar heating and cooling applications, the heat pump system is one of the strongest competitors. The acceptable cost of a solar system will depend on how well it compares with a commercially available heat pump system for the same application. Similarly, if natural gas is available for a certain locality, the solar heating system may have to be competitive with a natural gas heating system.

A life-cycle cost analysis can successfully incorporate into the expected life span of a system the material and labor costs for construction and the future operating costs including fuel, maintenance, taxes, and insurance. The life-cycle cost analysis technique incorporated into value engineering analysis has been applied to new construction programs of the Environmental Protection Agency (EPA) and the General Services Administration (GSA). Various references (56) are also available.

Cost information regarding storage devices in a complete system is difficult to obtain. The scope of this study does not include the development of such information. The storage component costs are scattered. An estimate of 1975 prices to construct thermal storage tanks in residential applications indicated that the cost, depending on the sizes, for concrete tanks ranged from $.50 to $.67 per gallon; steel tanks from $.51 to $.70 per gallon; wooden tanks $.45 to $1.30 per gallon; and fiberglass-reinforced plastic tanks from $.94 to $1.77 per gallon (55). These are partial costs of a complete system. In Appendix B, the acceptable cost does not address the actual estimate but indicates the most likely competitor of a solar system for each path.

IV. DEVELOPMENT OF PRELIMINARY DESIGN CRITERIA

A. Matching Storage Units to Solar Applications

Based on the information gathered while characterizing thermal energy storage units and defining storage requirements for each application, potentially suitable energy storage alternatives were matched to each solar energy application. The criteria used for matching were commercial availability, temperature range, and path application. The results are shown in Figures 26 and 27.

Since design is a site specific function, hardly more than a qualitative judgment is possible. This consisted of rating the available units either good or fair in their applicability to the particular SHACOB or AIPH path. Temperature range and interface requirements are the two factors used in judging the suitability of a storage unit for a particular path.

B. Development of Preliminary Design Criteria

The objective of developing the preliminary design criteria of the solar thermal energy storage units is to establish the relationship between the thermal energy storage unit and the overall solar energy system. Design criteria for one selected storage unit for each path in Figures 26 and 27 are summarized in the following pages. Each description corresponds to a path and outlines a thermal energy storage unit which applies to that path. The selected unit for each path will satisfy path criteria and is considered one solution to those requirements. It should be noted that it is not possible to select the best match at the present time.

Most information collected in developing preliminary design criteria is obtained from the Data Sheets in Appendix A and from the storage criteria in Appendix B. Information on storage units commercially available by 1979 is quantified in Figure 28, including availability of information on containerization, storage material, interface requirements, unit performance, operation and maintenance, design guidance, and cost.

From a designer's point of view, the intention of the preliminary design criteria is to provide a general understanding of a storage unit applied in a path rather than

▲ ACCEPTABLE COMBINATION

BASED ON
- TEMPERATURE RANGE
- PATH APPLICATION
- COMMERCIAL AVAILABILITY

PATH NO	PATHS DESCRIPTION SOURCE	STORAGE REQUIREMENT	WATER STORAGE-REINFORCED PLASTICS-KALWALL	WATER STORAGE-WOOD TANK-SUNWAVE	WATER STORAGE-CONCRETE TANKS-SOLATHERM	WATER STORAGE-FIBERGLASS TANKS-OWENS-CORNING	WATER STORAGE-STEEL TANK-SOLAR ENERGY SYSTEMS, INC	WATER STORAGE-AQUIFERS	WATER STORAGE-SALT GRADIENT SOLAR PONDS	WATER STORAGE-PRESSURIZED STEEL TANK	SOLID STORAGE-ROCK STORAGE BINS	SOLID STORAGE-TROMBE WALL	PHASE CHANGE-SOLARMATIC HEAT BATTERY-GLAUBER'S SALT	PHASE CHANGE-VALMONT INDUSTRIES-ENCRUSTED CONGLOMERATE	PHASE CHANGE-SMC THERMAL STORAGE CELLS-GLAUBER'S SALT	PHASE CHANGE-ARCHITECTURAL RESEARCH CORP. SOL-AR-TILES	PHASE CHANGE-MONSANTO RESEARCH-HDPE PEBBLE BED	PHASE CHANGE-ADD-A-SUN STORAGE CHAMBER	PHASE CHANGE-ACES	PHASE CHANGE-CALMAC MANUFACTURING-Na_2SO_4	PHASE CHANGE-SOLAR ONE STORAGE BIN-Na_2SO_4 $10H_2O/NaCl/NH_4Cl$	PHASE CHANGE-SOLAR ONE STORAGE BIN-$Na_2S_2O_3 \cdot 5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-$Na_2S_2O_3 \cdot 5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-PARAFFIN WAX	PHASE CHANGE-GE ROLLING CYLINDER-GLAUBER'S SALT	PHASE CHANGE-GE ROLLING CYLINDER-$Na_2S_2O_3 \cdot 5H_2O$	CHEMICAL STORAGE-ROCKET RESEARCH CORP -SULFURIC ACID WATER	CHEMICAL STORAGE-MAGNESIUM CHLORIDE HYDRATE
			THERMAL ENERGY STORAGE COMPONENTS COMMERICALLY AVAILABLE BY 1979																		OTHER THERMAL STORAGE							
		DATA SHEET NO	1	2	3	4	5	*	6	*	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	*	22	23
H1	SOLAR ASSISTED HEAT PUMP																											
	a. ENVIRONMENT	LOW TEMP. SIDE							▲																			
		HIGH TEMP SIDE																										
	b. DIRECT SOLAR HEATED STRUCTURE	LOW TEMP SIDE	▲									▲																
		HIGH TEMP. SIDE																										
	c. LIQUID HEATING COLLECTORS	LOW TEMP SIDE		▲	▲	▲	▲	▲											▲									
		HIGH TEMP SIDE																										
	d. AIR HEATING COLLECTORS	LOW TEMP SIDE	▲								▲			▲	▲													
		HIGH TEMP SIDE																										
	e. ADVANCED NONCONCENTRATING COLLECTORS	LOW TEMP SIDE																										
		HIGH TEMP. SIDE																										
H2	DIRECT (PASSIVE) HEATING OF STRUCTURE	PASSIVE STORAGE	▲								▲	▲				▲												
H3	AIR HEATING COLLECTOR																											
	a. FLAT PLATE	STORAGE									▲							▲										
	b ADVANCED NONCONCENTRATING	STORAGE									▲						▲	▲										
H4	LIQUID HEATING COLLECTORS																											
	a. CONVENTIONAL FLAT PLATE	STORAGE		▲	▲	▲	▲								▲													
	b. ADVANCED NONCONCENTRATING	STORAGE			▲		▲			▲				▲			▲											
C1	CONCENTRATING COLLECTORS																											
	a. ABSORPTION CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲			▲								
	b RANKINE CHILLER	LOW TEMP. SIDE		▲	▲	▲	▲																					
		HIGH TEMP. SIDE			▲		▲			▲							▲			▲								
C2	ADVANCED NONCONCENTRATING COLLECTORS																											
	a. ABSORPTION CHILLER	LOW TEMP SIDE		▲	▲	▲	▲																					
		HIGH TEMP. SIDE			▲		▲			▲							▲											
	b. RANKINE CYCLE CHILLER	LOW TEMP. SIDE		▲	▲	▲	▲																					
		HIGH TEMP SIDE			▲		▲			▲							▲											
C3	DESICCANT CHILLER FLAT PLATE COLLECTORS																											
	a. AIR HEATING	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE									▲																	
	b LIQUID HEATING	LOW TEMP SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP SIDE			▲		▲																					
C4	EVAPORATIVE COOLING NIGHT-TIME	PASSIVE STORAGE		▲	▲	▲	▲																					
C5	COOLING BY HEAT PUMP	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE																										

*DATA SHEET IS NOT AVAILABLE

Figure 26. Matching of Thermal Energy Storage with SHACOB Paths

▲ ACCEPTABLE COMBINATION

BASED ON:
- TEMPERATURE RANGE
- PATH APPLICATION
- COMMERCIAL AVAILABILITY

PATHS

PATH NO.	DESCRIPTION SOURCE	STORAGE REQUIREMENT	THERMAL ENERGY STORAGE COMPONENTS COMMERCIALLY AVAILABLE BY 1979																		OTHER THERMAL STORAGE							
		DATA SHEET NO.	1	2	3	4	5	*	6	*	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	*	22	23
			WATER STORAGE-REINFORCED PLASTICS-KALWALL	WATER STORAGE-WOOD TANK-SUNWAVE	WATER STORAGE-CONCRETE TANKS-SOLATHERM	WATER STORAGE-FIBERGLASS TANKS-OWENS-CORNING	WATER STORAGE-STEEL TANK-SOLAR ENERGY SYSTEMS, INC.	WATER STORAGE-AQUIFERS	WATER STORAGE-SALT GRADIENT SOLAR PONDS	WATER STORAGE-PRESSURIZED STEEL TANK	SOLID STORAGE-ROCK STORAGE BINS	SOLID STORAGE-TROMBE WALL	PHASE CHANGE-SOLARMATIC HEAT BATTERY-GLAUBER'S SALT	PHASE CHANGE-VALMONT INDUSTRIES-ENCRUSTED CONGLOMERATE	PHASE CHANGE-SMC THERMAL STORAGE CELLS-GLAUBER'S SALT	PHASE CHANGE-ARCHITECTURAL RESEARCH CORP. SOL-AR-TILES	PHASE CHANGE-MONSANTO RESEARCH-HOPE PEBBLE BED	PHASE CHANGE-ADD-A-SUN STORAGE CHAMBER	PHASE CHANGE-ACES	PHASE CHANGE-CALMAC MANUFACTURING-Na_2SO_4	PHASE CHANGE-SOLAR ONE STORAGE BIN-$Na_2SO_4 \cdot 10H_2O/NaCl/NH_4Cl$	PHASE CHANGE-SOLAR ONE STORAGE BIN-$Na_2S_2O_3 \cdot 5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-$Na_2S_2O_3 \cdot 5H_2O$	PHASE CHANGE-UNIVERSITY OF PENNSYLVANIA-PARAFFIN WAX	PHASE CHANGE-GE ROLLING CYLINDER-GLAUBER'S SALT	PHASE CHANGE-GE ROLLING CYLINDER-$Na_2S_2O_3 \cdot 5H_2O$	CHEMICAL STORAGE-ROCKET RESEARCH CORP.-SULFURIC ACID WATER	CHEMICAL STORAGE-MAGNESIUM CHLORIDE HYDRATE
HD	DIRECT (PASSIVE) SHELTER HEATING	PASSIVE	▲								▲	▲																
HA	AIR HEATING COLLECTORS	STORAGE									▲																	
HL	LIQUID HEATING COLLECTORS	STORAGE		▲	▲	▲	▲						▲		▲													
HP	SOLAR ASSISTED HEAT PUMP (Same as HI)		▲	▲	▲	▲	▲	▲	▲		▲	▲	▲	▲					▲									
DD	DESICCANT DRYING	LOW TEMP. SIDE									▲																	
		HIGH TEMP. SIDE									▲																	
DA	DRYING-AIR HEATING COLLECTORS	STORAGE									▲																	
DL	DRYING-LIQUID HEATING COLLECTORS	STORAGE		▲	▲	▲	▲											▲										
SL	ADVANCED LIQUID HEATING COLLECTORS	STORAGE								▲	▲						▲			▲								
SA	ADVANCED NONCONCENTRATING COLLECTORS	STORAGE									▲									▲								
CO	PASSIVE COOLING	STORAGE		▲	▲	▲	▲				▲																	
CH	COLLECTOR AND HEAT ENGINE	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE			▲		▲				▲						▲											
CP	HEAT PUMP COOLING	LOW TEMP. SIDE		▲	▲	▲	▲				▲																	
		HIGH TEMP. SIDE		▲	▲	▲	▲				▲																	

*DATA SHEET IS NOT AVAILABLE

Figure 27. Matching of Thermal Energy Storage With AIPH Paths

STORAGE UNITS	WATER STORAGE REINFORCED PLASTICS KALWALL SOLAR COMPONENTS	WATER STORAGE-WOOD TANK-SUNWAVE ENERGY SYSTEM STORAGE TANK	WATER STORAGE-CONCRETE TANKS-SOLATHERM SOLAR STORAGE TANK	WATER STORAGE-FIBERGLASS TANKS-OWENS-CORNING FIBERGLASS CORPORATION	WATER STORAGE-STEEL TANK-SOLAR ENERGY SYSTEMS, INC.	WATER STORAGE-AQUIFERS-HEAT STORAGE WELL CONCEPT	WATER STORAGE-SALT GRADIENT SOLAR PONDS	PRESSURIZED STEEL TANK	ROCK STORAGE BINS	TROMBE WALL	PCM-SOLARMATIC HEAT BATTERY-GLAUBER'S SALT	PCM-VALMONT INDUSTRIES - ENCRUSTED CONGLOMERATE	PCM-SMC THERMAL STORAGE CELLS - GLAUBER'S SALT	PCM-ARCHITECTURAL RESEARCH CORP. SOL-AR-TILES	PCM-MONSANTO RESEARCH-HOPE PEBBLE BED	PCM-ADD-A-SUN STORAGE CHAMBER	PCM-ACES	PCM-CALMAC MANUFACTURING - Na_2SO_4
CONTAINERIZATION	●	●	●	●	●	○	○	●	●	●		○	○	●		○	○	○
STORAGE MATERIAL	●	●	●	●	●	●	○	●	●	●	○			●	●	○	●	○
INTERFACE REQUIREMENTS	●	●	●	●	●	○	○	●	○ 1	●				○	○		○	○
UNIT PERFORMANCE	○	●	●	●	●	○	○	○	●	○				●			○	○
O & M	●	○	●	●	●		○	○	●	●				○			○	
DESIGN GUIDANCE		● 3	● 3	● 3	● 3		○	○	○ 1	○				○			○	○
COST	●	●	●	●	●		○		○	○	●		●	●	○	●	○	○
COMMERCIAL AVAILABILITY	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	NOW	1979	1979	1979	NOW 2	NOW	NOW	NOW 2

1 - Some types, such as thermosyphon designs, are not fully researched.
2 - Storage material is available, not the unit package.
3 - Heat pump interface information is scarce.

☐ LITTLE OR NO INFORMATION AVAILABLE
○ SOME INFORMATION AVAILABLE
● ADEQUATE INFORMATION AVAILABLE

Figure 28. Survey of Available Information for Thermal Storage Units

handbook-type details for specific design guidance. The designer would obtain from this the first-cut description of the storage unit as well as the limits and bounds in a path application. If a particular design has to be materialized, more detailed information would be needed. The items under discussion in the development of the preliminary design criteria are:

(1) Storage unit name or type, material, stage of development, and container type

(2) Interface requirements

(3) Storage performance

  (a) Operating principle

  (b) Temperature range

  (c) Storage requirements

  (d) Charge rate

  (e) Discharge rate

  (f) Heat losses

(4) Operation and maintenance

(5) Cost

(6) Other design considerations.

Certain cautions that may require special attention to design are provided in the discussion of other design considerations. References can be consulted for additional details if a storage design is to be further pursued. The results of this discussion for each storage type in a path application follow.

SHACOB - Path H1a.
Solar Assisted Heat Pump Using Environment

(1) Salt Gradient Solar Pond* (57,58,15).

(a) Storage material - water-salt solution.

(b) Storage container - Ponds are built using existing earth excavation techniques and conventional swimming pool or reservoir liners. Optimum materials and techniques for this application have not been defined.

(2) Interface Requirements: A water-to-air heat pump is required with a source temperature range of 40 to 100°F. When pond temperature exceeds 100°F the heat pump should be by-passed to a water-to-air heat exchanger.

(3) Storage Performance:

(a) Operating principle - passive collection and sensible storage.

(b) Operating temperature - 50 to 90°F.

(c) Charge rate - dependent on available insolation, salt concentrations, and transmissivities.

(d) Discharge rate - dependent on heat exchanger size.

(e) Heat loss - dependent on pond temperature, condition and qualities of surrounding earth, and covers provided, if any.

(f) Size - solar ponds can be built in any size if space is available. The larger sizes appear to be more cost effective.

(4) Operating and Maintenance Requirements: The salt gradient must be maintained against mixing due to waves, evaporation, and disturbance. Also, biological growth (algae, bacteria) and debris in the pond will need to be removed periodically.

(5) Cost: 140 m^2 pond - $5,850, estimated in Reference 57.

* Whether salt gradient pond can be considered as Path H1a using environment is still subject to argument.

(6) Other Design Considerations: In the Ohio area a solar pond should be about equal in volume and surface area to the space it is going to heat.

SHACOB - Path H1b.
Solar Assisted Heat Pump Using Direct Solar
Heated Structure

(1) Sun-Lite Storage Tubes (59,60).

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - fiberglass-reinforced plastic tubes (e.g., Kalwall or equivalent).

(2) Interface Requirements:

(a) Storage units must be located behind a south-facing window wall.

(b) Ducting must be provided to connect plenum area around units with evaporator side (heating cycle) of air-to-air heat pump.

(3) Storage Performance;

(a) Operating principle - passive collection and sensible storage. See Figure 29.

(b) Operating temperature - Temperature of air supply to evaporator coil of heat pump is from 50 to 90°F. Temperature of water in the tubes is 60° to 120°F.

(c) Storage requirement - storage should be short-term (1-2 days) at 60 to 80 percent of the seasonal average daily load.

(d) Charge rate - A daily insolation of 1500 Btu/ft^2 will provide a temperature rise of 20 to 25°F.

(e) Discharge rate - 1400 Btu/hr for a tube 12 inches in diameter and 10 feet high. 2100 Btu/hr for a tube 18 inches in diameter and 10 feet high. Air flow velocity is under 500 fpm at 30°F temperature differential.

(f) Heat loss - heat loss through the glazing is relatively high since insulation is not provided on the surface of the tube.

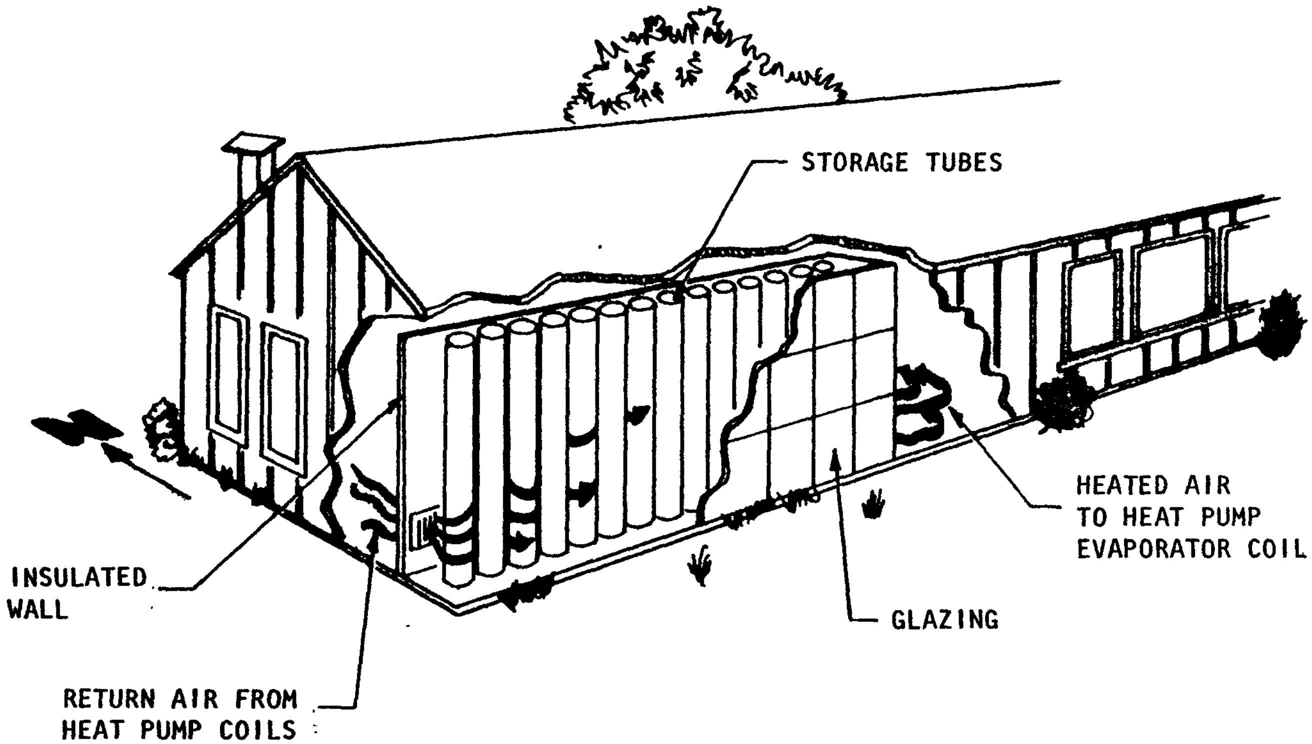


Figure 29 - Solar Water Wall Assisted Heat Pump System

(4) Operating and Maintenance: Shade is required to cut off insolation in summer. No maintenance work is required for storage tubes.

(5) Cost: $10/ft^3 for small tubes to $3/ft^3 for large tubes.

(6) Other Design Considerations:

(a) South-facing exposure is required.

(b) Water supply and drain should be provided.

(c) Data regarding physical dimensions and available capacities are given in References 59 and 60. A design manual is available in Reference 60.

SHACOB - Path H1c. Solar-Assisted Heat Pump With Liquid Heating Collectors

(1) Solarmatic Heat Battery

(a) Storage material - Glauber's Salt.

(b) Storage container - steel tank with heat exchanger.

(c) Stage of development - available commercially in small quantities.

(2) Interface Requirements:

(a) Heat source for charging is a flat plate hot water collector.

(b) Unit will operate with a water-to-air heat pump.

(3) Storage Performance:

(a) Operating principle - latent storage.

(b) Temperature range - storage tank 90°.

(c) Storage requirement - The solar collector-storage combination should be sized to supply all the heat input needs of the heat pump.

(d) Charge rate - not available from the manufacturer.

(e) Discharge rate - not available from manufacturer.

(f) Heat loss - not available from manufacturer.

(4) Operation and Maintenance:

(a) It should be determined if the charge rate of a solidified tank is adequate under real operating conditions.

(b) A test of performance should be made by an independent lab to determine operating and maintenance characteristics.

(5) Cost: \$2,278 F.O.B. for a 340,000 Btu/43 ft^3 system.

(6) Other Design Considerations: To optimize such a system a heat pump with an evaporator range of around 90°F is needed.

SHACOB - Path H1d.
Solar-Assisted Heat Pump Using Air Heating Collectors

(1) Valmont Energy System - Encrusted Conglomerate.

   (a) Storage material - Glauber's salt.

   (b) Storage container - polyethylene trays.

   (c) Stage of development - available in 1979.

(2) Interface Requirements:

   (a) Heat source for charging is a flat plate hot air collector.

   (b) Should operate in series with an air-to-air heat pump and a forced air circulating system.

(3) Storage Performance:

   (a) Operating principle - latent storage.

   (b) Operating temperature - Collectors and heat pump should be chosen for optimum performance around the 89°F phase-change temperature of the Glauber's salt.

   (c) Storage requirement - not available.

   (d) Charge rate - not available.

   (e) Discharge rate - not available.

   (f) Heat loss - no loss if the storage unit is in the conditioned space, otherwise heat loss depends on the insulation provided.

(4) Operating and Maintenance: No maintenance is required for the storage unit. No estimate of its life has been given.

(5) Cost: Not available from manufacturer.

(6) Other Design Considerations: At this time (10/78) the charge and discharge rates for the unit are not available. This information should be obtained before incorporating this storage unit in any system.

SHACOB - Path H2.
Direct Passive Heating of Structures

(1) SOL-AR-TILE

(a) Storage material - Eutectic of Glauber's salt.

(b) Stage of development - Commercially available.

(c) Storage container - Polymer concrete.

(2) Interface Requirements:

(a) A south-facing window-wall is required.

(b) Reflection device is required if tiles are ceiling mounted. Reflective louvers are suggested.

(3) Storage Requirements:

(a) Operating principle - latent storage.

(b) Operating temperature - liquid-to-solid phase change occurs at approximately 73°F.

(c) Discharge rate - maximum 17 Btu/hr-ft^2.

(d) Heat loss - none, since the storage is within the conditioned space.

(e) Physical dimensions - each tile is 24x24x 1-1/4 inches.

(f) Storage requirement - The tile area should be twice the south window area. The window area is found by taking 80 percent of the heat loss for March (March is an average heating month) and dividing that product by March's solar gain through one square foot of glazing, as shown in the following equation:

$$HL_M \times 80\%/SHG_M = AREA_W$$

where: HL_M = March heat loss.

SHG_M = March solar heat gain through one square foot of glazing.

$AREA_W$ = Window area.

(4) Operation and Maintenance: Shading is required during the summer. Louvers can be used to reflect radiation outward in the summer and direct it onto the tiles in the winter.

(5) Cost: $3 to $3.5 per tile ($.75 to $.88 per square foot), $3,400 per MBtu of storage.

(6) Other Design Considerations:

(a) Southern exposure is required.

(b) Tiles must be mounted horizontally.

(c) Overheating is eliminated because of low phase-change temperature.

SHACOB - Path H3.
Air Heating Collector

(1) Rock storage bin.

   (a) Storage material - washed river rocks.

   (b) Stage of development - fully developed.

   (c) Storage container - Constructed on site. Bin can be made of wood, concrete, or lined hole.

(2) Interface Requirements: Ducts, blowers, and controls.

(3) Storage Performance

   (a) Operating principle - sensible storage.

   (b) Temperature range - 100°F to 180°F.

   (c) Storage requirement - Rock requirements are usually 50 to 100 lbs/ft^2 of collector area.

   (d) Air flow rate - The superficial velocity (flow rate/cross section area) should be between 15 and 25 ft/min.

   (e) Air flow direction - To optimize the benefit of temperature stratification, the air flow should be downward during the charging mode and upward during the discharge mode. In any case, charge and discharge flows should be in opposite directions.

(4) Operation and Maintenance Requirements: If rocks are not sufficiently cleaned the air filters will need to be changed often.

(5) Cost: Cleaned gravel costs around $6.50 per ton. Delivery costs range from $3 to $4 per ton.

(6) Other Design Considerations: Uniform size rocks must be used to insure sufficient air space around rocks. Rock settling can be avoided by using chicken wire mesh in horizontal layers. The rock bed must be kept dry to prevent fungal growth.

SHACOB - Path H4.
Liquid Heating Collectors

(1) Water Storage.

  (a) Storage material - water.

  (b) Stage of development - commercially available.

  (c) Storage container - Concrete, wood, reinforced plastic, and steel tanks are commercially available.

(2) Interface Requirements: Heat exchangers.

(3) Storage Performance:

  (a) Operating principle - sensible storage.

  (b) Operating temperature - Water temperature in the tank should be 110 to 160°F.

  (c) Storage requirement - approximately 3 gallons per square foot of collector.

  (d) Charge rate - dependent on heat exchanger.

  (e) Discharge rate - dependent on heat exchanger.

  (f) Heat loss - dependent on size, configuration, storage temperature and amount of insulation of the storage tank.

  (g) Available size - Tanks may be bought or custom built to meet any size requirement.

(4) Operation and Maintenance: Anticorrosion additives, freeze protection, and periodic upkeep of pumps may be required.

(5) Costs: Dependent on the type of tank chosen.

SHACOB - Path C1.
Concentrating Collectors for Space Cooling

(1) Water storage in steel pressurized tanks (61).

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - steel pressurized tank.

(2) Interface Requirements: Heat exchangers from collectors to storage and from storage to chiller.

(3) Storage Performance:

(a) Operating principle - sensible heat storage.

(b) Temperature range - 185 to 400°F.

(c) Storage requirement - capacity equal to 24 to 28 hours of chiller energy requirement.

(d) Charge rate - dependent on heat exchanger sizing only.

(e) Discharge rate - dependent on heat exchanger sizing only.

(f) Heat loss - dependent on tank insulation thickness.

(g) Size - available in any size.

(4) Operation and Maintenance: A corrosion inhibitor additive in the water is recommended.

(5) Cost: $2 to $4 per gallon, depending on size of tank and pressure range.

(6) Other Design Considerations:

(a) Water supply and drain should be provided.

(b) Must meet ASME Boiler Code and Local and State Code for Pressure Vessels.

(7) Design Data: See ASME Boiler Code.

SHACOB - Path C2.
Advanced Non-Concentrating Collectors for Space Cooling

(1) Water storage in steel or concrete tanks.

- (a) Storage material - water.
- (b) Stage of development - commercially available.
- (c) Storage container - steel or concrete tank.

(2) Interface Requirements: Heat exchangers from collectors to storage and from storage to chiller.

(3) Storage Performance:

- (a) Operating principle - sensible heat storage.
- (b) Temperature range - 180 to 210°F.
- (c) Storage requirement - capacity equal to 24 to 48 hours of chiller energy requirement.
- (d) Charge rate - dependent upon heat exchanger sizing only.
- (e) Discharge rate - dependent on heat exchanger sizing only.
- (f) Heat loss - dependent on tank insulation thickness (optimum insulation thickness R-30 to R-50).

(4) Operation and Maintenance: A corrosion inhibitor additive in the water is recommended.

(5) Cost: $1 to $3 per gallon, depending on type and size of tank.

(6) Other Design Considerations: Water supply and drain should be provided.

SHACOB - Path C4.
Evaporative Nighttime Cooling

(1) Skytherm System (62,63,64,65).

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - Neoprene water bags or swimming pool type liners with transparent covers.

(2) Interface Requirements:

(a) Roof must be highly conductive to allow for adequate heat transfer between the occupied space and the roof pond.

(b) A movable insulation must be provided to cover the roof during the sunlight hours.

(3) Storage Performance:

(a) Operating principle - Water, periodically sprayed on the bagged roof ponds, evaporates to cool the water in the bags. Additional cooling occurs through skyward radiation. During the day building air temperature is lowered by convective heat transfer to the cooled roof pond.

(b) Temperature range - If correctly designed the water pond temperature stays around $67 \pm 2°F$.

(c) Storage requirement - water volume suitable to meet cooling load in a diurnal cycle.

(d) Charge rate - depends on radiation and evaporation cooling gains and convective cooling losses.

1. Radiation heat flow is determined by the temperature of the pond and the ambient air, and the dew point of the surrounding atmosphere which determines the emissivity and absorptivity of the sky (62,63). Evaporation is related to the water temperature and

the wind speed by the following equation:

$$Q_{evap} = 0.093 \times \text{latent heat of vaporization} \times (1 + 0.38V)(Pv)$$

Where:

V = Wind speed in miles per hour.

Pv = Difference in pond and atmosphere vapor pressures in inches of mercury.

Q_{evap} = Evaporative cooling gain in Btu/hr-ft^2 (64).

2. Convective cooling losses occur when the nighttime ambient is higher than storage temperature.

(e) Discharge rate - depends on ceiling construction and its conduction and radiation characteristics.

(f) Heat loss - Loss of cooling capacity due to inflow of thermal energy from ambient air depends on the R value of the movable insulation provided and the temperature differential.

(4) Operation and Maintenance: Opening and closing of the movable insulation may be done manually or automatically. Some maintenance will be required for moving parts and control elements.

(5) Cost: Depends on location, prevailing winds, earthquake region, and architecture. $3/ft^2 more than a conventional house at Atascader (65).

(6) Other Design Considerations: Phillip W.B. Niles, California Polytechnic State University, has developed a noncomputer model to predict internal building temperature swing (65).

SHACOB - Path C5.
Heat Pump Cooling

(1) Water storage.

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - steel tank with heat exchanger.

(2) Interface Requirements: Heat exchangers.

(3) Storage Performance:

(a) Operating principle - sensible storage.

(b) Temperature range - 35 to 50°F.

(c) Storage requirement - information not available.

(d) Charge rate - dependent on heat exchanger sizing.

(e) Discharge rate - dependent on heat exchanger sizing.

(f) Heat gain - dependent on tank insulation, water temperature, and ambient temperature.

(4) Operation and Maintenance: Corrosion protection may be necessary.

(5) Cost: $6 to $3 per gallon, depending on type and size of tank.

(6) Other Design Considerations: Uniform size rocks must be used to insure sufficient air space around rocks. Rock setting can be avoided by using chicken wire mesh in horizontal layers.

(1) Water storage (66).

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - Concrete, wood, reinforced plastic, and steel tanks are commercially available.

(2) Interface Requirements: Heat exchangers.

(3) Storage Performance:

(a) Operating principle - sensible storage.

(b) Temperature range - the operating temperature depends on the application. If the water-to-air heat exchanger is used for storage the temperature should be 40 to 50°F above the desired temperature in the conditioned space.

(c) Storage requirement - approximately 3 gallons per square foot of collector.

(d) Charge rate - dependent on heat exchanger sizing.

(e) Discharge rate - dependent on heat exchanger sizing.

(f) Heat loss - Depends on the storage temperature, ambient air temperature, and insulation thickness. Heat loss is prevented by locating the storage tank inside the shelter.

(4) Operation and Maintenance: Corrosion protection may be necessary. Associated pumps and ancillary equipment will require maintenance.

(5) Cost: $1 to $3 per gallon, depending on type and size of tank chosen.

(6) Other Design Criteria: The current sources of thermal energy for agricultural products are liquid propane (LP), methane, and electricity.

Much is known about liquid-collector heating and water storage for space heating. However, until the cost of such systems appears feasible to the poultry or animal producer - they are not likely to make much impact.

AIPH - Path DA.
Drying-Air Heating Collectors

(1) Rock storage bin.

  (a) Storage material - washed river rocks.

  (b) Stage of development - fully developed.

  (c) Storage container - Constructed on site. Bin can be made of wood, concrete, or lined hole.

(2) Interface Requirements: Ducts, blowers, or controls.

(3) Storage Performance:

  (a) Operating principle - sensible storage.

  (b) Temperature range - the temperature range is determined by the item to be dried. For higher collector efficiencies the temperature range should be no greater than 120°F.

  (c) Storage requirement - dependent on the application being supplied.

  (d) Air flow rate - The superficial velocity (flow rate/cross section area) should be between 15 and 25 ft/min. These figures are optimized for charge and discharge and may have to be changed to meet air flow requirement for drying.

  (e) Air flow direction - To optimize the benefit of temperature stratification, the air flow should be downward during charging mode and upward during discharge mode. In any case, charge and discharge flows should be in opposite directions.

(4) Operation and Maintenance Requirements: If rocks are not sufficiently cleaned before installation the air filters will need to be changed often.

(5) Cost: Cleaned gravel costs around $6.50 per ton. Delivery costs range from $3 to $4 per ton.

(6) Other Design Considerations: Uniform size rocks must be used to insure sufficient air space around

rocks. Rock settling can be avoided by using chicken wire mesh in horizontal layers.

AIPH - Path DL.
Liquid Heating Collectors

(1) Water Storage (67).

(a) Storage material - water.

(b) Stage of development - commercially available.

(c) Storage container - Concrete, wood, reinforced plastic, and steel tanks are commercially available.

(2) Interface Requirements: Heat exchangers.

(3) Storage Performance:

(a) Operating principle - sensible storage.

(b) Temperature range - dependent on application being supplied.

(c) Storage requirement - This is very application dependent. If the time from harvest to obtaining the dryed crop is critical, storage can make the drying time comparable to that obtained with conventional methods. If the drying period duration is not critical storage may be small or not necessary at all.

(d) Charge rate - dependent on heat exchangers.

(e) Discharge rate - dependent on heat exchanger sizing.

(f) Heat loss - dependent on the insulation provided, the storage temperature and the ambient conditions.

(4) Operation and Maintenance: Corrosion protection may be necessary. Associated pumps and ancillary equipment will require maintenance.

(5) Cost: $1 to $3 per gallon, depending on type and size of tank chosen.

(6) Other Design Considerations: It is more difficult to obtain the temperature controlled conditions necessary for drying certain crops than with con-

ventional systems. For some crops this will require more elaborate control strategy than the usual space heating solar system.

AIPH - Path CO.
<u>Passive Cooling</u>

The selected unit is a Skytherm described in Path C4. The application of such a unit would be identical except that greater temperature swings are tolerated by most animals.

AIPH - Path CH.
Process Cooling Using a Heat Engine

Storage requirements for this path are identical to Paths C1 and C2, depending on the collector selected (concentrating or advanced non-concentrating).

AIPH - Path HP.
Solar Assisted Heat Pump

Storage requirements for this path are identical to Path H1 for applications with temperatures similar to those used in SHACOB.

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APPENDIX A

DATA SHEETS FOR SELECTED STORAGE UNITS

THERMAL ENERGY STORAGE UNIT DATA SHEET #1

STORAGE UNIT NAME: Sun-Lite Storage Tubes

MANUFACTURER: Kalwall Solar

(or DEVELOPER) Components Division

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: Ambient- 160 °F

COMPONENT SIZE: 17.66 ft^3 (1.5 ft. dia. by 10 ft. long)

COMPONENT ENERGY DENSITY: 43,797 Btu $\Delta T = 40^\circ F$

UNIT SIZE: -

UNIT ENERGY CAPACITY: - Btu

COMPONENT COST: $ 49/tube

STORAGE UNIT COST: $ -

MATERIAL COST/10^6 BTU: $ 1,127

STORAGE PRINCIPLE: Sensible

ACTIVE MATERIAL: Water
Reinforced plastic tank

LATENT HEAT: Btu/lb

PHASE CHANGE TEMP: °F

SPECIFIC HEAT: ~1 Btu/lb-°F

DENSITY: ~62 lb/ft^3

SYSTEM LIFE: 20 years estimated

CYCLE EFFICIENCY: (3) %

SUGGESTED CYCLE TIME(S): Daily

STAND-BY LOSSES: (3) Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Direct Passive Absorption

OUT: Forced Air

HEAT TRANSFER RATE:

CHARGE: (1) Btu/h

DISCHARGE: 2,100 Btu/h

SUGGESTED INTERFACE:
Passive

ANCILLARY EQUIPMENT Fans or Blowers

COMMENTS:

(1) Under an insolation of 1725 Btu/sq. ft. the temperature in this tube will rise from 65°F to about 90°F in a full day.

(2) $\Delta T = 30^\circ F$ and air flow 500 ft/min.

(3) A function of the insulation of the enclosing container.

THERMAL ENERGY STORAGE UNIT DATA SHEET #2

STORAGE UNIT NAME: Sunwave Energy System Storage Tank

MANUFACTURER: (or DEVELOPER) Acorn Structures, Inc. Concord, Masschusetts

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: Ambient - °F

COMPONENT SIZE: -

COMPONENT ENERGY DENSITY: -

UNIT SIZE: 2,000 gal. (8'-11" Dia. x 7'-0")

UNIT ENERGY CAPACITY: 815,500 Btu ΔT=50 °F

COMPONENT COST: $ -

STORAGE UNIT COST: $ 954 (1)

MATERIAL COST/10^6 BTU: $ 1,170

STORAGE PRINCIPLE: Sensible

ACTIVE MATERIAL: Water

Wood tank with 30-mil. vinyl liner

LATENT HEAT: - Btu/lb

PHASE CHANGE TEMP: - °F

SPECIFIC HEAT: 1 Btu/lb-°F

DENSITY: ~ 62 lb/ft^3

SYSTEM LIFE: Not Available

CYCLE EFFICIENCY: - %

SUGGESTED CYCLE TIME(S): Daily several days of storage

STAND-BY LOSSES: Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Pump hot water

OUT: Pump hot water

HEAT TRANSFER RATE:

CHARGE: Not Available Btu/h

DISCHARGE: Not Available Btu/h

SUGGESTED INTERFACE:

Hot water collectors

ANCILLARY EQUIPMENT Pump

COMMENTS:

(1) Price includes 2,000 gallon tank, insulation and liner as shown in Figure 7.

THERMAL ENERGY STORAGE UNIT DATA SHEET #3

STORAGE UNIT NAME: Solatherm Solar Storage Tank	STORAGE PRINCIPLE: Sensible
MANUFACTURER: Solatherm Corporation	ACTIVE MATERIAL: Water Reinforced concrete tank with R-18 foam insulation and 30-45 mil re-inforced polyester liner
(or DEVELOPER)	LATENT HEAT: - Btu/lb
STAGE OF DEVELOPMENT: Commercially Available	PHASE CHANGE TEMP: °F
	SPECIFIC HEAT: 1 Btu/lb-°F
TEMP. RANGE: Ambient- 210 °F	DENSITY: ~62 lb/ft³
COMPONENT SIZE: -	SYSTEM LIFE: 10 years (1)
COMPONENT ENERGY DENSITY: -	CYCLE EFFICIENCY: (2) %
UNIT SIZE: 2,000 gallons (10'-4"x 7'-2"x5'-4")	SUGGESTED CYCLE TIME(S): Daily, several days
UNIT ENERGY CAPACITY: 1.6×10^6 Btu ΔT=100 °F	
	STAND-BY LOSSES: (2) Btu/h @ °F ΔT =
COMPONENT COST: $ -	
STORAGE UNIT COST: $ 1,695 (3)	
MATERIAL COST/10^6 BTU: $ 2,118 ΔT=50 °F	

HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: Fluid heat exchanger or water removal	Hot water collectors
OUT: Fluid heat exchanger or water removal	ANCILLARY EQUIPMENT Pumps to circulate water out of storage
HEAT TRANSFER RATE:	
CHARGE: N/A Btu/h	
DISCHARGE: N/A Btu/h	

COMMENTS:

(1) 10 years claimed for innerliner which can be replaced for the cost of the liner and installation labor.

(2) A function of the insulation enclosing the tank.

(3) 2,000 gallon tank supplied with insulation, liner, fitting and heat exchanger as shown in Figure 8. Price does not include delivery.

THERMAL ENERGY STORAGE UNIT DATA SHEET #4

STORAGE UNIT NAME: Owens-Corning Fiberglass Tank

MANUFACTURER: Owens-Corning (or DEVELOPER) Fiberglass Corporation

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: - 40° - 150 °F

COMPONENT SIZE: -

COMPONENT ENERGY DENSITY: - Btu/lb°F

UNIT SIZE: 4,320 gal. (7'-8" dia. x 19'3")

UNIT ENERGY CAPACITY: 1.6×10^6 Btu $\Delta T=40°F$

COMPONENT COST: $ -

STORAGE UNIT COST: $ 3,200

MATERIAL COST/10^6 BTU: $ 2,000 $\Delta T=40°F$

STORAGE PRINCIPLE: Sensible

ACTIVE MATERIAL: Water

Fiberglass container

LATENT HEAT: N/A Btu/lb

PHASE CHANGE TEMP: N/A °F

SPECIFIC HEAT: 1 Btu/lb-°F

DENSITY: ~62 lb/ft^3

SYSTEM LIFE: 20 years (estimated)

CYCLE EFFICIENCY: (2) %

SUGGESTED CYCLE TIME(S): Daily, three day storage

STAND-BY LOSSES: (2) Btu/h

@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Heat exchanger or fluid injection

OUT: Heat exchanger or fluid removal

HEAT TRANSFER RATE:

CHARGE: Not available Btu/h

DISCHARGE: Not available Btu/h

SUGGESTED INTERFACE: Hot water collectors

ANCILLARY EQUIPMENT Pumps and/or heat exchangers

COMMENTS:

(1) Tanks rated to 180°F are available. Cost of a 4,320 gallon tank was quoted at $8,640.

(2) A function of the amount of insulation enclosing the tank.

THERMAL ENERGY STORAGE UNIT DATA SHEET #5

STORAGE UNIT NAME: Solar STOR Storage Tank

MANUFACTURER: (or DEVELOPER) Solar Energy Systems, Inc.

STAGE OF DEVELOPMENT: Commercialized

TEMP. RANGE: Ambient - 200°F

COMPONENT SIZE: -

COMPONENT ENERGY DENSITY: -

UNIT SIZE: 2,000 gallons

UNIT ENERGY CAPACITY: 815,000 Btu $\Delta T=50°F$

COMPONENT COST: $ -

STORAGE UNIT COST: $ 3,500 (1)

MATERIAL COST/10^6 BTU: $ 4,292

STORAGE PRINCIPLE: Sensible

ACTIVE MATERIAL: Water
Steel tank with 2'-polyurethane and phenolic liner and accessories

LATENT HEAT: - Btu/lb

PHASE CHANGE TEMP: - °F

SPECIFIC HEAT: 1 Btu/lb-°F

DENSITY: 62 lb/ft^3

SYSTEM LIFE: -

CYCLE EFFICIENCY: (2) %

SUGGESTED CYCLE TIME(S): Daily, several days of storage

STAND-BY LOSSES: (2) Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Pumped Water

OUT: Pumped Water

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:

Hot Water Collectors

ANCILLARY EQUIPMENT Pumps

COMMENTS:

(1) Price includes pumps, heat exchangers, tank sections, access, service ladder, etc. as shown in Figure 10.

(2) A function of the amount of tank insulation.

THERMAL ENERGY STORAGE UNIT DATA SHEET #6

STORAGE UNIT NAME: Solar Pond	STORAGE PRINCIPLE: Sensible
MANUFACTURER: (or DEVELOPER) University of New Mexico	ACTIVE MATERIAL: Brine (2)
STAGE OF DEVELOPMENT: Research & Development	LATENT HEAT: - Btu/lb
TEMP. RANGE: Ambient - 200 °F	PHASE CHANGE TEMP: - °F
COMPONENT SIZE: -	SPECIFIC HEAT: (3) Btu/lb-°F
COMPONENT ENERGY DENSITY: - Btu/lb°F	DENSITY: (3) lb/ft³
UNIT SIZE: 4,592 cubic feet ~~(492' dia. x 8.2' deep)~~	SYSTEM LIFE:
UNIT ENERGY CAPACITY: 268,700 x ΔT Btu	CYCLE EFFICIENCY: N/A %
COMPONENT COST: $ -	SUGGESTED CYCLE TIME(S): Seasonal storage
STORAGE UNIT COST: $5,700 (1)	STAND-BY LOSSES: N/A Btu/h @ °F ΔT =
MATERIAL COST/10^6 BTU: $	
HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: Direct and reflective insolation	
OUT: Fluid heat exchangers	ANCILLARY EQUIPMENT Pumps
HEAT TRANSFER RATE:	
CHARGE: N/A Btu/h	
DISCHARGE: N/A Btu/h	

COMMENTS:

(1) Estimated 1975 dollars including solar pond, pumps, pipes and heat exchangers.

(2) 20% solution by weight of NaCl in water.

(3) Average specific heat and density for 20% NaCl solution at 68°F are 0.815 Btu/lb°F and 71.8 lb/ft³ respectively. However, the actual specific heat and density vary with the salt concentration gradient along the depth of the pond.

THERMAL ENERGY STORAGE UNIT DATA SHEET #7

STORAGE UNIT NAME: Rock Storage

MANUFACTURER:

(or DEVELOPER)

STAGE OF DEVELOPMENT: Developed

TEMP. RANGE: 80° - 180 °F

COMPONENT SIZE: .75 - 1.25" Diameter rocks

COMPONENT ENERGY DENSITY: N/A

UNIT SIZE: (1)

UNIT ENERGY CAPACITY: (1) Btu

COMPONENT COST: $ 9.50-10.50/ton (2)

STORAGE UNIT COST: $ (1)

MATERIAL COST/10^6 BTU: $ 500 (3)

STORAGE PRINCIPLE: Sensible Heat

ACTIVE MATERIAL: Rocks

LATENT HEAT: N/A Btu/lb

PHASE CHANGE TEMP: N/A °F

SPECIFIC HEAT: .195.-.22 Btu/lb-°F

DENSITY: 100-125 (4) lb/ft^3

SYSTEM LIFE: 50 years +

CYCLE EFFICIENCY: 100 %

SUGGESTED CYCLE TIME(S): Diurnal

STAND-BY LOSSES: (1) Btu/h

@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Air

OUT: Air

HEAT TRANSFER RATE:

CHARGE: (1) Btu/h

DISCHARGE: (1) Btu/h

SUGGESTED INTERFACE:

Forced Air System or Heat Pump

ANCILLARY EQUIPMENT Insulated Bin, Ducts, and Air Handling Unit

COMMENTS:
(1) Design Specific

(2) Delivered Price

(3) 50°F Swing

(4) .75 - 1.50" Diameter

THERMAL ENERGY STORAGE UNIT DATA SHEET #8

STORAGE UNIT NAME: Trombe Wall

MANUFACTURER: (or DEVELOPER) Michel, Jacques and Felix Trombe

STAGE OF DEVELOPMENT: Developed

TEMP. RANGE: Ambient - 180 °F

COMPONENT SIZE: 8-10" thick concrete wall

COMPONENT ENERGY DENSITY: 240 Btu/ft^2 of surface (1)

UNIT SIZE: (2)

UNIT ENERGY CAPACITY: (2) Btu

COMPONENT COST: $75/cubic yard

STORAGE UNIT COST: $ -

MATERIAL COST/10^6 BTU: $ 8,680

STORAGE PRINCIPLE: Thermal Mass

ACTIVE MATERIAL: Concrete Wall

LATENT HEAT: N/A Btu/lb

PHASE CHANGE TEMP: N/A °F

SPECIFIC HEAT: .21 Btu/lb-°F

DENSITY: 30.5 lb/ft^3

SYSTEM LIFE: 50$^+$ years

CYCLE EFFICIENCY: 100 %

SUGGESTED CYCLE TIME(S): Daily

STAND-BY LOSSES: (2) Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Direct Gain (Radiation)

OUT: Thermosiphoning and Radiation

HEAT TRANSFER RATE:

CHARGE: (2) Btu/h

DISCHARGE: (2) Btu/h

SUGGESTED INTERFACE:

ANCILLARY EQUIPMENT Glass Wall

COMMENTS:

(1) Cost of concrete in place for @ 9" thickness and 50°F temperature swing.

(2) Design specific.

THERMAL ENERGY STORAGE UNIT DATA SHEET #9

STORAGE UNIT NAME: Heat Battery #3672

MANUFACTURER: Solarmatic Division

(or DEVELOPER) O.E.M. Products, Inc.

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: - 90°F

COMPONENT SIZE: -

COMPONENT ENERGY DENSITY: -

UNIT SIZE: 43 ft^3 (1)

UNIT ENERGY CAPACITY: 340,000 Btu @ 90°F

COMPONENT COST: $ -

STORAGE UNIT COST: $ 2,278 (3)

MATERIAL COST/10^6 BTU: $ 6,700

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Glaubers Salt

LATENT HEAT: 108 Btu/lb

PHASE CHANGE TEMP: 90 °F

SPECIFIC HEAT: Btu/lb-°F

DENSITY: 97 lb/ft^3

SYSTEM LIFE: 20 years claimed

CYCLE EFFICIENCY: %

SUGGESTED CYCLE TIME(S): Daily, several days

STAND-BY LOSSES: Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Fluid Heat Exchanger

OUT: Fluid Heat Exchanger

HEAT TRANSFER RATE:

CHARGE: Btu/h

DISCHARGE: Btu/h

SUGGESTED INTERFACE: Liquid Collector Systems

ANCILLARY EQUIPMENT See below (2)

COMMENTS:

(1) The system contains 34 ft^3 of Glaubers Salt. Models with 23, 86, 124 and 173 ft^3 are available.

(2) The system is supplied with a heat exchanger and an immersible type pump for circulating the working oil through the Glaubers Salt.

(3) Price includes ancillary equipment as shown in Figure 13.

THERMAL ENERGY STORAGE UNIT DATA SHEET #10

STORAGE UNIT NAME: Encrusted Conglomerate (1)

MANUFACTURER: (or DEVELOPER) Dr. Maria Telkes with Valmont Industries, Inc.

STAGE OF DEVELOPMENT: Available in late 1978

TEMP. RANGE: - 89 °F

COMPONENT SIZE: 20 lb trays (3)

COMPONENT ENERGY DENSITY: 6,000 Btu/ft^3

UNIT SIZE: -

UNIT ENERGY CAPACITY: - Btu

COMPONENT COST: $ Not available

STORAGE UNIT COST: $ -

MATERIAL COST/10^6 BTU: $ Not available

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Glaubers Salt (2)

LATENT HEAT: 100 Btu/lb

PHASE CHANGE TEMP: 89 °F

SPECIFIC HEAT: Btu/lb-°F

DENSITY: 97 lb/ft^3

SYSTEM LIFE: 20 years claimed

CYCLE EFFICIENCY: %

SUGGESTED CYCLE TIME(S): Daily, several days

STAND-BY LOSSES: N/A Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Hot Air

OUT: Hot Air

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE: Hot Air Collectors

ANCILLARY EQUIPMENT Fans

COMMENTS:

(1) See Figure 14 for storage unit configuration.

(2) The mixture is 97% Glaubers salt and 3% additive.

(3) Trays are 1' x 2' x 2" and are made of high density polyethylene.

THERMAL ENERGY STORAGE UNIT DATA SHEET #11

STORAGE UNIT NAME: SMC Thermal Storage Cells

MANUFACTURER: Solar Marketing, Inc.

(or DEVELOPER) Meade, Nebraska

STAGE OF DEVELOPMENT: 1979

TEMP. RANGE: - 90 °F

COMPONENT SIZE: 3.85 lbs (1)

COMPONENT ENERGY DENSITY: 350 Btu/cell

UNIT SIZE: -

UNIT ENERGY CAPACITY: - Btu

COMPONENT COST: $ 1.75/cell

STORAGE UNIT COST: $ -

MATERIAL COST/10^6 BTU: $ 5,000 (for cells only)

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Glaubers Salt

LATENT HEAT: 91 Btu/lb

PHASE CHANGE TEMP: 90 °F

SPECIFIC HEAT: Btu/lb-°F

DENSITY: lb/ft^3

SYSTEM LIFE: 20 years projected.

CYCLE EFFICIENCY: %

SUGGESTED CYCLE TIME(S): Daily, several days.

STAND-BY LOSSES: N/A Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Air or liquid

OUT: Air or liquid

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:

Air or liquid collectors

ANCILLARY EQUIPMENT Pumps or fans

COMMENTS:

(1) The cell containers are made of high density polyethylene with 3.85 lbs of a Glaubers salt eutectic.

THERMAL ENERGY STORAGE UNIT DATA SHEET #12

STORAGE UNIT NAME: SOL-AR-TILE

MANUFACTURER: Architectural
(or DEVELOPER) Research Corporation

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: 65 - 75 °F

COMPONENT SIZE: 2' x 2' x 1-1/4" tile (2)

COMPONENT ENERGY DENSITY: N/A

UNIT SIZE:

UNIT ENERGY CAPACITY: Btu

COMPONENT COST: $ 3-3.50/tile

STORAGE UNIT COST: $ -

MATERIAL COST/10^6 BTU: $ 3400.

STORAGE PRINCIPLE: Phase-change

ACTIVE MATERIAL: Glaubers Salt (1)
Polyester concrete shell with water proof membranes (2)

LATENT HEAT: 33 Btu/lb

PHASE CHANGE TEMP: 73 °F

SPECIFIC HEAT: - Btu/lb-°F

DENSITY: - lb/ft^3

SYSTEM LIFE: 2,600 cycles +

CYCLE EFFICIENCY: %

SUGGESTED CYCLE TIME(S): Diurnal

STAND-BY LOSSES: N/A Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Direct (or reflected) insolation

OUT: Radiation convection

HEAT TRANSFER RATE:

CHARGE: Typically 17 Btu/h

DISCHARGE: 17 Btu/h

SUGGESTED INTERFACE:

Passive

ANCILLARY EQUIPMENT None

COMMENTS:

(1) A Eutectic of Glaubers Salt.

(2) See Figure 15 for details.

THERMAL ENERGY STORAGE UNIT DATA SHEET #13

STORAGE UNIT NAME: Cross Linked HDPE Prototype Unit

MANUFACTURER: (or DEVELOPER) Monsanto Research Corporation

STAGE OF DEVELOPMENT: Research & Development

TEMP. RANGE: - 266 °F

COMPONENT SIZE: -

COMPONENT ENERGY DENSITY: -

UNIT SIZE: 60 gallon, 240 lbs

UNIT ENERGY CAPACITY: 29,400 Btu

COMPONENT COST: $ (2)

STORAGE UNIT COST: $ N/A

MATERIAL COST/10^6 BTU: $ N/A

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: HDPE (1) - 60 gallon pressurized container, material not available

LATENT HEAT: 83 Btu/lb

PHASE CHANGE TEMP: 266 °F

SPECIFIC HEAT: - Btu/lb-°F

DENSITY: - lb/ft³

SYSTEM LIFE: 1000 + cycles

CYCLE EFFICIENCY: - %

SUGGESTED CYCLE TIME(S): -

STAND-BY LOSSES: Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Direct air or fluid heat transfer

OUT: Direct air or fluid heat transfer

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:

ANCILLARY EQUIPMENT

COMMENTS:

(1) Silane-grafted/cross-linked high density polyethylene pellets.

(2) It is estimated that the PCM could be produced by processing in a polyethylene plant for a projected price near 26¢/lb.

THERMAL ENERGY STORAGE UNIT DATA SHEET #14

STORAGE UNIT NAME: Add-A-Sun Storage Chamber

MANUFACTURER: Addison Products Co.

(or DEVELOPER) Addison, MI

STAGE OF DEVELOPMENT: Commercially Available

TEMP. RANGE: 113 - 130 °F

COMPONENT SIZE: 1 gal. can (6.5 lbs of wax)

COMPONENT ENERGY DENSITY: 520 Btu/container (latent heat)

UNIT SIZE: 840 lbs of storage

UNIT ENERGY CAPACITY: 100,000-125,000Btu (2)

COMPONENT COST: $ -

STORAGE UNIT COST: $ 1850 (1)

MATERIAL COST/10^6 BTU: $

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Slack Wax
6'6'x3' chamber with 4" polystyrene and one gallon cans for slack wax (3)

LATENT HEAT: 80.1 Btu/lb

PHASE CHANGE TEMP: 113-117 °F

SPECIFIC HEAT: - Btu/lb-°F

DENSITY: - lb/ft^3

SYSTEM LIFE: More than 1500 cycles

CYCLE EFFICIENCY: N/A %

SUGGESTED CYCLE TIME(S): Daily or several days of storage

STAND-BY LOSSES: N/A Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Forced Air

OUT: Forced Air

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:

Air Heating Collectors

ANCILLARY EQUIPMENT Blower fans for air circulation

COMMENTS:

(1) The storage unit cost includes 840 lbs of storage materials, a storage chamber with insulation and a blower fan.

(2) 140,000 Btu is maximum while the lower figure above represents the effect of stratification in the storage chamber. Capacity includes sensible heat storage above 117°F.

(3) For details see Figure 17.

THERMAL ENERGY STORAGE UNIT DATA SHEET #15

STORAGE UNIT NAME: Ice Storage Tank	STORAGE PRINCIPLE: Phase change and sensible heat
MANUFACTURER: Foam Form Canada, Ltd. (or DEVELOPER) Scarborough, Ontario	ACTIVE MATERIAL: Water/ice (2)
STAGE OF DEVELOPMENT: Commercially Available	LATENT HEAT: 144.0 Btu/lb
TEMP. RANGE: $32^{o}F$ - ambient ^{o}F	PHASE CHANGE TEMP: 32 ^{o}F
COMPONENT SIZE:	SPECIFIC HEAT: 1.0 Btu/lb-^{o}F
COMPONENT ENERGY DENSITY: Btu/lb^{o}F	DENSITY: 62.4 lb/ft^3
UNIT SIZE: 2,000 ft^3	SYSTEM LIFE: 20 years
UNIT ENERGY CAPACITY: 18.6×10^6 Btu (1)	CYCLE EFFICIENCY: % combined C.O.P. = 5
COMPONENT COST: $ N/A	SUGGESTED CYCLE TIME(S): Annual
STORAGE UNIT COST: $ N/A	STAND-BY LOSSES: Btu/h @ ^{o}F ΔT =
MATERIAL COST/10^6 BTU: $ N/A	

HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: 20% Methanol Brine	
OUT: Air	ANCILLARY EQUIPMENT Heat pump, the desuperheater, the water heating condenser, the space heating condenser, brine cooler, circulating pumps and control valves.
HEAT TRANSFER RATE:	
CHARGE: 25,000 Btu/h	
DISCHARGE: 30,000 Btu/h	

COMMENTS:

(1) Capacity includes latent heat of ice and the sensible heat of water from $32^{o}F$ to $45^{o}F$.

(2) For system schematic see Figure 18.

THERMAL ENERGY STORAGE UNIT DATA SHEET #16

STORAGE UNIT NAME: Sodium-Sulfate Storage Module

MANUFACTURER: (or DEVELOPER) Calmac Mfg. Corp. Englewood, NJ

STAGE OF DEVELOPMENT: Commercially Available (1)

TEMP. RANGE: 400° - 600 °F

COMPONENT SIZE: Not Applicable

COMPONENT ENERGY DENSITY: Not Applicable

UNIT SIZE: 275 gallons (2)

UNIT ENERGY CAPACITY: 391,000 Btu $\Delta T = 200°F$

COMPONENT COST: $ 0.4/lb of Na_2SO_4

STORAGE UNIT COST: $ 2562 (est.) (3)

MATERIAL COST/10^6 BTU: $ 6550

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Sodium Sulfate

LATENT HEAT: 25 Btu/lb

PHASE CHANGE TEMP: 465 °F

SPECIFIC HEAT: 0.43 Btu/lb-°F

DENSITY: 156 lb/ft^3

SYSTEM LIFE: Not Available

CYCLE EFFICIENCY: %

SUGGESTED CYCLE TIME(S): Daily

STAND-BY LOSSES: N/A Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Direct Contact Fluid Circulation

OUT: Direct Contact Fluid Circulation

HEAT TRANSFER RATE:

CHARGE: 80,000 Btu/h $\Delta T = 15°F$

DISCHARGE: 240,000 Btu/h $\Delta T = 15°F$

SUGGESTED INTERFACE: High Temperature Liquid Collectors

ANCILLARY EQUIPMENT Circulating

COMMENTS:

(1) Although Calmac is not marketing these systems they will sell the sodium sulfate pellets in industrial lot quantities.

(2)

160 gallons of Therminol	-	125,200 Btu	400°-600°F
2800 lbs of sodium sulfate	-	49,686 Btu	400°-465°F
		70,000 Btu	@ 465°F
		115,668 Btu	465°F-600°F
1350 lb Tank & Equipment	-	30,000 Btu	400°-600°F
		390,634 Btu	

(3) Cost includes tanks, steel divider, sodium sulfate and fittings as shown in Figure 19.

THERMAL ENERGY STORAGE UNIT DATA SHEET #17

STORAGE UNIT NAME: Thermal Storage Bin Solar One (1)

MANUFACTURER: Dr. Telkes
(or DEVELOPER) Univ. of Delaware

STAGE OF DEVELOPMENT: R&D Prototype

TEMP. RANGE: - °F

COMPONENT SIZE: 6'x1.25" O.D.; 4.02 lbs.

COMPONENT ENERGY DENSITY: 314 Btu/Tube

UNIT SIZE: 620 Tubes

UNIT ENERGY CAPACITY: 199,400 Btu (3)

COMPONENT COST: $ N/A

STORAGE UNIT COST: $ N/A

MATERIAL COST/10^6 BTU: $ N/A

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: (2)

LATENT HEAT: 78 Btu/lb

PHASE CHANGE TEMP: 55 °F

SPECIFIC HEAT: (solid) .32 Btu/lb-°F

DENSITY: lb/ft³

SYSTEM LIFE: N/A

CYCLE EFFICIENCY: N/A %

SUGGESTED CYCLE TIME(S): Daily

STAND-BY LOSSES: N/A Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Circulating Air

OUT: Circulating Air

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:
Air Systems

ANCILLARY EQUIPMENT Fans

COMMENTS:

(1) This system is described in two parts. This data sheet describes the cooling capacity storage section. Part A describes the heating capacity storage section. For storage unit details see Figure 12.

(2) $Na_2SO_4 \cdot 10H_2O/NaCl/NH_4Cl$

(3) Figure includes 4,400 Btu for sensible storage 50°-55°F.

THERMAL ENERGY STORAGE UNIT DATA SHEET #18

STORAGE UNIT NAME: Thermal Storage Bin - Solar One (1)	STORAGE PRINCIPLE: Phase-Change
MANUFACTURER: Dr. M. Telkes	ACTIVE MATERIAL: $Na_2S_2O_3 \cdot 5H_2O$
(or DEVELOPER) Univ. of Delare	LATENT HEAT: 90 Btu/lb
STAGE OF DEVELOPMENT: Research & Development	PHASE CHANGE TEMP: 120 °F
	SPECIFIC HEAT: .60 Btu/lb-°F
TEMP. RANGE: 120° - 126 °F	DENSITY: lb/ft³
COMPONENT SIZE: 23.8 lb Tray (3)	SYSTEM LIFE: N/A
COMPONENT ENERGY DENSITY: 2,142 Btu/Tray	CYCLE EFFICIENCY: %
UNIT SIZE: 294 Trays	SUGGESTED CYCLE TIME(S): Daily, several days
UNIT ENERGY CAPACITY: 655,000 Btu (4)	STAND-BY LOSSES: 19,000 Btu/h @ °F ΔT =
COMPONENT COST: $ N/A	
STORAGE UNIT COST: $ N/A	
MATERIAL COST/10⁶ BTU: $ N/A	

HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: Circulating Air	Hot Air Collectors
OUT: Circulating Air	ANCILLARY EQUIPMENT Fan
HEAT TRANSFER RATE:	
CHARGE: N/A Btu/h	
DISCHARGE: N/A Btu/h	

COMMENTS:

(1) This system is described in two parts. This Data Sheet describes the heating capacity storage section. Part B describes the cooling capacity storage section. For storage unit details see Figure 12.

(2) Liquid state value; solid state value is .35 Btu/lb°F

(3) Tray measures 1" x 21" x 21"

(4) Figure includes 25,000 Btu sensible heat 120°F - 126°F.

THERMAL ENERGY STORAGE UNIT DATA SHEET #19

STORAGE UNIT NAME: Sodium Thiosulfate Pentahydrate Storage Module

MANUFACTURER: H.G. Lorsch

(or DEVELOPER) Univ. of Pennsylvania

STAGE OF DEVELOPMENT: R&D prototype

TEMP. RANGE: - 119 °F

COMPONENT SIZE: 1'x1'x4'; 450 lbs per module

COMPONENT ENERGY DENSITY: 31,250 Btu/module

UNIT SIZE: 16 modules

UNIT ENERGY CAPACITY: 500,000 Btu

COMPONENT COST: $ N/A

STORAGE UNIT COST: $ N/A

MATERIAL COST/10^6 BTU: $ N/A

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: $Na_2S_3O_3 \cdot 5H_2O$ 16-1'x1'x4' plastic modules

LATENT HEAT: 90 Btu/lb

PHASE CHANGE TEMP: 119 °F

SPECIFIC HEAT: - Btu/lb-°F

DENSITY: 103 lb/ft^3

SYSTEM LIFE: N/A

CYCLE EFFICIENCY: N/A %

SUGGESTED CYCLE TIME(S): Daily, several days of storage

STAND-BY LOSSES: N/A Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Liquid Heat Transfer

OUT: Liquid Heat Transfer

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE: Liquid Collectors

ANCILLARY EQUIPMENT Pumps

COMMENTS:

THERMAL ENERGY STORAGE UNIT DATA SHEET #20

STORAGE UNIT NAME: P116 Paraffin Wax Storage Module

MANUFACTURER: H.G. Lorsch
(or DEVELOPER) Univ. of Pennsylvania

STAGE OF DEVELOPMENT: R&D Prototype

TEMP. RANGE: - 116 °F

COMPONENT SIZE: 1'x1'x4'2" for a module

COMPONENT ENERGY DENSITY: 12,500 Btu/module

UNIT SIZE: 20 modules; 4'x5'x4'2"

UNIT ENERGY CAPACITY: 250,000 Btu

COMPONENT COST: $ N/A

STORAGE UNIT COST: $ N/A

MATERIAL COST/10^6 BTU: $ N/A

STORAGE PRINCIPLE: Phase-change

ACTIVE MATERIAL: Sunoco Paraffin 116
20-1'x1'x4'2" modules. Each module is stacked with 0.54"x12"x4'-2" trays

LATENT HEAT: 90 Btu/lb

PHASE CHANGE TEMP: 116 °F

SPECIFIC HEAT: - Btu/lb-°F

DENSITY: 49 lb/ft^3

SYSTEM LIFE: N/A

CYCLE EFFICIENCY: N/A %

SUGGESTED CYCLE TIME(S): Daily
several days of storage

STAND-BY LOSSES: N/A Btu/h
@ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Liquid Heat Transfer

OUT: Liquid Heat Transfer

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: N/A Btu/h

SUGGESTED INTERFACE:
Liquid Collectors

ANCILLARY EQUIPMENT

COMMENTS:

THERMAL ENERGY STORAGE UNIT DATA SHEET #21

STORAGE UNIT NAME: Rolling Cylinder

MANUFACTURER: (or DEVELOPER) General Electric

STAGE OF DEVELOPMENT: R&D Prototype

TEMP. RANGE: 90.3 °F

COMPONENT SIZE:

COMPONENT ENERGY DENSITY:

UNIT SIZE:

UNIT ENERGY CAPACITY: 1,500 Btu

COMPONENT COST: $ N/A

STORAGE UNIT COST: $ N/A

MATERIAL COST/10^6 BTU: $ N/A

STORAGE PRINCIPLE: Phase-Change

ACTIVE MATERIAL: Glaubers Salt

LATENT HEAT: 90 Btu/lb

PHASE CHANGE TEMP: 90.3 °F

SPECIFIC HEAT: Btu/lb-°F

DENSITY: lb/ft³

SYSTEM LIFE: (1)

CYCLE EFFICIENCY: N/A %

SUGGESTED CYCLE TIME(S): Daily several days

STAND-BY LOSSES: N/A Btu/h @ °F ΔT =

HEAT TRANSFER MECHANISM:

IN: Air

OUT: Air

HEAT TRANSFER RATE:

CHARGE: N/A Btu/h

DISCHARGE: 100 Btu/h ΔT=12°F (2)

SUGGESTED INTERFACE: Hot Air Systems

ANCILLARY EQUIPMENT

COMMENTS:

(1) Researchers claim no visible degradation in the Glauber's Salt after 200 freeze-thaw cycles.

(2) Researchers claim that on the enlarged system heat discharge rates of 100 Btu/h-ft² are achievable.

THERMAL ENERGY STORAGE UNIT DATA SHEET #22

STORAGE UNIT NAME: Sulfuric Acid-Water	STORAGE PRINCIPLE: Chemical
MANUFACTURER: Rocket Research Corp.	ACTIVE MATERIAL: Sulfuric acid-water
(or DEVELOPER)	LATENT HEAT: Btu/lb
STAGE OF DEVELOPMENT: Research & Development	PHASE CHANGE TEMP: - °F
	SPECIFIC HEAT: Btu/lb-°F
TEMP. RANGE: 140 - 374 °F	DENSITY: lb/ft³
COMPONENT SIZE: Separator-14" Dia. x14'long Tank Size-35,000 ft³	SYSTEM LIFE: -
COMPONENT ENERGY DENSITY: -	CYCLE EFFICIENCY: - %
UNIT SIZE: -	SUGGESTED CYCLE TIME(S): Seasonal
UNIT ENERGY CAPACITY: 181,440 Btu	STAND-BY LOSSES: Btu/h @ °F ΔT =
COMPONENT COST: $	
STORAGE UNIT COST: $ 357,000	
MATERIAL COST/10^6 BTU: $ 82,000 (4)	

HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: 600°F from collector to separator	Solar collectors, absorption system
OUT: From reactor to space or absorption chiller	ANCILLARY EQUIPMENT Heat exchangers pumps
HEAT TRANSFER RATE:	
CHARGE: - Btu/h	
DISCHARGE: 181,440 Btu/h	

COMMENTS:

(1) The concept of sulfuric acid-water system is not new. The toxicity and corrosiveness of sulfuric acid are the major obstacles to commercialization.

(2) The seasonal storage system was under study given a 20,000 ft² building located on the eastern seaboard of United States. Hardwares have not been built for testing.

(3) Schematic diagram and flow diagram are given in Figures 21a and 21b.

(4) The storage unit is assumed to discharge at the rate of 181,440 Btu for 24 hours per day. Cost is based on 1976 estimates including collectors, tanks, heat exchangers, piping, pumps, etc.

THERMAL ENERGY STORAGE UNIT DATA SHEET #23

STORAGE UNIT NAME: Magnesium Chloride Hydrate	STORAGE PRINCIPLE: Chemical
MANUFACTURER: (or DEVELOPER) Chemical Energy Specialists	ACTIVE MATERIAL: $MaCl_2 \cdot 2H_2O$
STAGE OF DEVELOPMENT: Research & Development	LATENT HEAT: ______ Btu/lb
TEMP. RANGE: 30 - 180 °F	PHASE CHANGE TEMP: ______ °F
COMPONENT SIZE: 3' x 7' x 1"	SPECIFIC HEAT: ______ Btu/lb-°F
COMPONENT ENERGY DENSITY: ______	DENSITY: ______ lb/ft^3
UNIT SIZE: 1500 ft^2	SYSTEM LIFE: Not available
UNIT ENERGY CAPACITY: 1,000,000 Btu	CYCLE EFFICIENCY: ______ %
COMPONENT COST: $ N/A	SUGGESTED CYCLE TIME(S): 1 cycle/day
STORAGE UNIT COST: $ N/A	STAND-BY LOSSES: ______ Btu/h @ ______ °F ΔT =
MATERIAL COST/10^6 BTU: $ N/A	

HEAT TRANSFER MECHANISM:	SUGGESTED INTERFACE:
IN: Forced air around vaporizer	
OUT: Forced air around vaporizer	ANCILLARY EQUIPMENT Fan
HEAT TRANSFER RATE:	
CHARGE: 111,000 Btu/h	
DISCHARGE: 67,000-73,000 Btu/h	

COMMENTS:

(1) Vaporizer operates between 30-70°F, absorber operates between 140-185°F. Temperature required for recharging is 225°F theoretically, however, 280-300°F is more adequate in experiments.

(2) The system is still in the preliminary studying stage. Only several cycles have been tested.

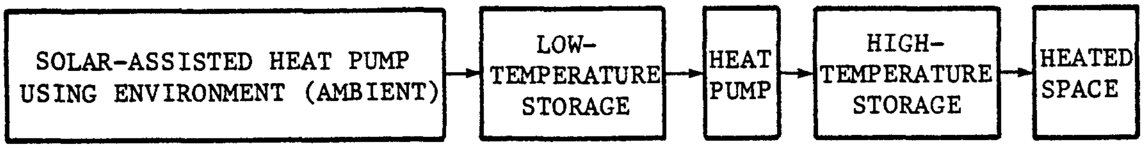
(3) Vapor pressure - temperature relationship is shown in Figure 22.

(4) Hardware configurations are shown in Figure 23.

APPENDIX B

STORAGE REQUIREMENTS FOR SOLAR APPLICATIONS

SHACOB - PATH H1a



	LOW-TEMPERATURE STORAGE (not required)	HIGH-TEMPERATURE STORAGE[1]
Temperature Range:	-	85° to 120°F
Storage Capacity:		
Long Term -	-	1 day's supply of heating design load.[2]
Short Term -	-	
Storage Time:		
Long Term -	-	-
Short Term -	-	1 day
Charge Time Per Cycle:		
Long Term -	-	-
Short Term -	-	6 to 12 hours
Discharge Time Per Cycle:		
Long Term -	-	-
Short Term -	-	1 c/day
Acceptable Life Cycle Cost (LCC)	-	System LCC should not exceed LCC for heat pump without high temperature storage.

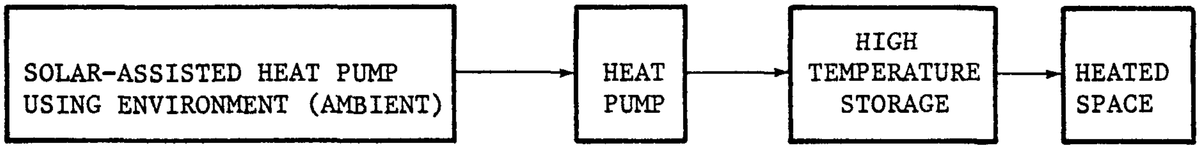
---

1. High temperature storage allows peak load shaving by use of a heat pump during off-peak hours.

2. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. However, only 60 to 80 percent of the seasonal heating load is expected to be furnished by solar energy.

SHACOB - PATH H1a
(Continued)

Suggested path H1a:

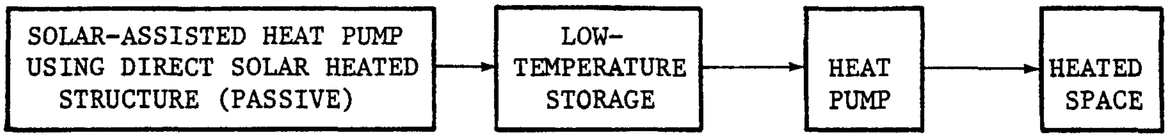


SHACOB - PATH H1b

SOLAR-ASSISTED HEAT PUMP USING DIRECT SOLAR HEATED STRUCTURE (PASSIVE) → LOW-TEMPERATURE STORAGE → HEAT PUMP → HIGH-TEMPERATURE STORAGE → HEATED SPACE

	LOW-TEMPERATURE STORAGE[1]	HIGH-TEMPERATURE STORAGE[1]
Temperature Range:	60° to 140°F[2]	85° to 120°F
Storage Capacity:		
Long Term -	-	-
Short Term -	1-3 days supply of heat pump evaporator input at design load[3]	1-3 days supply of design load[3]
Storage Time:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Charge Time Per Cycle:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Discharge Time Per Cycle:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Acceptable Life Cycle Cost (LCC)	a. The LCC of a heat pump system with low-temperature storage should not exceed the LCC of a heat pump system without storage but provided with electric resistance heater	a. The LCC of a heat pump system with high-temperature storage should not exceed the LCC of heat pump system with low temperature storage and heat pump system having no storage but provided with electric resistance heater
	b. The LCC of heat pump with storage should not exceed the LCC of a fan operated forced-air system distributing thermal energy from storage to building plus a conventional cooling unit.	b. The LCC of heat pump with storage should not exceed the LCC of a fan operated forced air system distributing thermal energy from storage to building plus a conventional cooling unit.

Suggested path H1b:

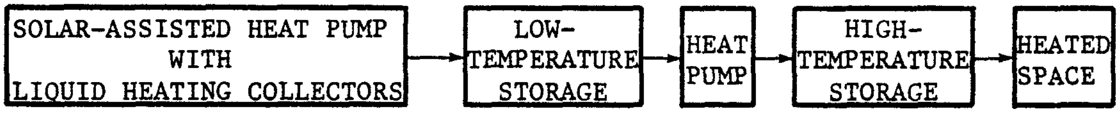


1. The low temperature storage provides for an above-ambient temperature energy input to the heat pump evaporator. Additional storage for load leveling on the condenser side would generally be difficult to justify on a life cycle cost basis. The use of storage units when the heat pump is operating in the cooling mode must also be considered in the design of a system for a specific application.

2. The most convenient heat transfer fluid for a direct solar heated structure is air. For an air-to-air heat pump, the temperature of the air which transfers energy from structure storage to the evaporator could be controlled at a favorable range of 50° to 70°F even at a much higher storage temperature of 60° to 140°F.

3. The heating design load is selected ASHRAE 97-1/2 percent winter design conditions. However, only 60 to 80 percent of the seasonal heating load is expected to be furnished by solar energy.

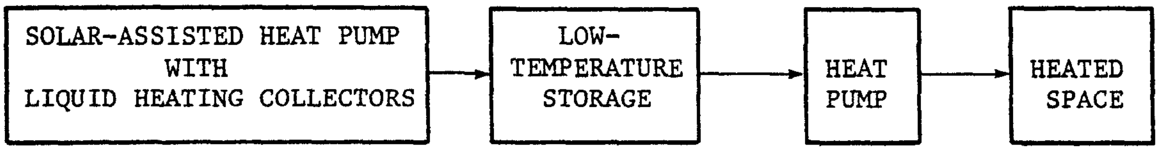
SHACOB - PATH H1c



	LOW-TEMPERATURE STORAGE[1]	HIGH-TEMPERATURE STORAGE[1]
Temperature Range:	40° to 90°F[2]	85° to 120°F
Storage Capacity:		
Long Term -	90 to 100 percent seasonal heating energy input required for heat pump evaporator	-
Short Term -	1-3 days supply of heat pump evaporator input at design load[3]	1-3 days supply of design load[3]
Storage Time:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Charge Time Per Cycle:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Discharge Time Per Cycle:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Acceptable Life Cycle Cost (LCC)	The LCC of a heat pump system with low-temperature storage should not exceed the LCC of heat pump system without storage but provided with electric resistance heater	The LCC of a heat pump system with high-temperature storage should not exceed the LCC of a heat pump system without high-temperature storage or without any storage

SHACOB - PATH H1c
(Continued)

Suggested path H1c:

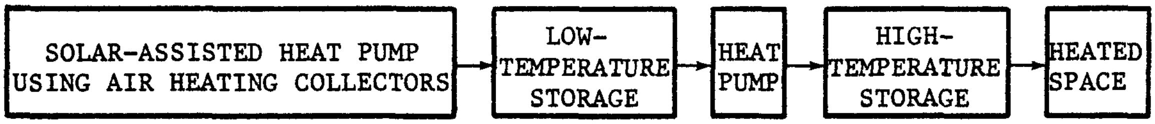


1. The low-temperature storage will in general provide the storage capacity needed to operate a heat pump. Additional high-temperature storage on the condensing side of the heat pump is not justified.

2. If the temperature exceeds 90°F in low-temperature storage, the heat pump may be bypassed.

3. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. For a series heat pump system, the capacity of the solar supplied low-temperature storage should be selected to provide 80 to 100 percent of the seasonal energy required by the heat pump evaporator. For a parallel system, this percentage could be lower since the heat pump is selected for stand-alone operation.

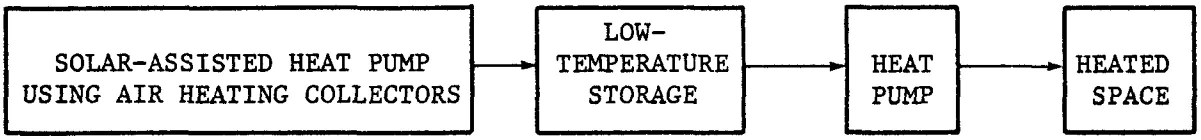
SHACOB - PATH H1d



	LOW-TEMPERATURE STORAGE[1]	HIGH-TEMPERATURE STORAGE[1]
Temperature Range:	40° to $90^{\circ}F$[2]	85° to $120^{\circ}F$
Storage Capacity:		
Long Term -	-	-
Short Term -	1-3 days supply heat pump evaporator input design load[2]	1-3 days supply at the design load[2]
Storage Time:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Charge Time Per Cycle:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Discharge Time Per Cycle:		
Long Term -	-	-
Short Term -	1-3 days	1-3 days
Acceptable Life Cycle Cost (LCC):	The LCC of a heat pump system with low-temperature storage should not exceed the LCC of a heat pump without storage but provided with electric resistance heater	The LCC of a heat pump system with high-temperature storage should not exceed the LCC of a heat pump system with low temperature storage and heat pump system having no storage but provided with electric resistance heater
Acceptable Cost Level:	This system is competing with a heat pump system without storage	This system is competing with a heat pump system without high-temperature storage or without any storage

SHACOB - PATH H1d
(Continued)

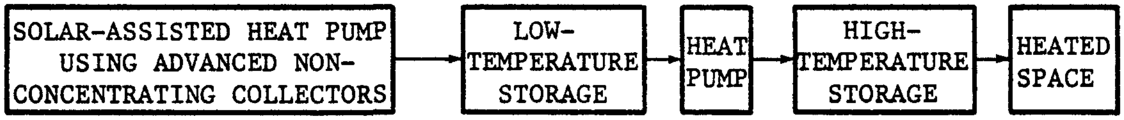
Suggested path H1d:



1. The low temperature storage provides for an above-ambient temperature energy to the heat pump evaporator. Additional storage for load leveling on the condenser side would generally be difficult to justify on a life cycle cost basis. The use of storage units when the heat pump is operating in the cooling mode must also be considered in the design of a system for a specific application.

2. For air collector applications with heat pump, the air-to-air heat pump provides is a good match. This type of heat pump can operate with a wide range of evaporator temperatures, from -20° to 110°F. The commonly applied favorable heat source temperature is approximately 40° to 60°F. The heating design load is selected to be at ASHRAE 97-1/2 percent winter design conditions. However, only 60 to 80 percent of the seasonal heating load is expected to be furnished by solar energy storage.

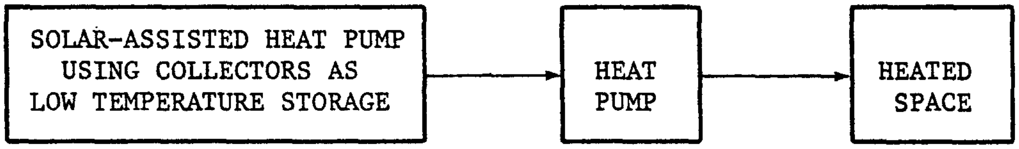
SHACOB - PATH H1e



	LOW-TEMPERATURE STORAGE[1]	HIGH-TEMPERATURE STORAGE[1]
Temperature Range:	40° to 90°F[2]	85° to 120°F
Storage Capacity:		
Long Term -	90 to 100 percent seasonal heating energy input required for heat pump evaporator	-
Short Term -	1-3 days supply of a heat pump evaporator input at design load[3]	1-3 days supply of design load[3]
Storage Time:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Charge Time Per Cycle:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Discharge Time Per Cycle:		
Long Term -	3-6 months	-
Short Term -	1-3 days	1-3 days
Acceptable Life Cycle Cost (LCC):	The LCC of a heat pump system with low-temperature storage should not exceed the LCC of heat pump system without storage but provided with electric resistant heater	The LCC of a heat pump system with high-temperature storage should not exceed the LCC of a heat pump system without high-temperature storage or without any storage

Suggested path H1e:

The path H1e may be deleted since the selection of an advanced non-concentrating collector and heat pump would normally not be an economical combination. On the other hand, a group of storage units which are also acting as the collector has not been covered by DOE's program paths. Specific examples are fiberglass storage tubes of Kalwall Corporation and a salt gradient solar pond. A new path is suggested as follows:



1. The low temperature storage provides for an above-ambient temperature energy to the heat pump evaporator. Additional storage for load leveling on the condenser side would generally be difficult to justify on a life cycle cost basis. The use of storage units when the heat pump is operating in the cooling mode must also be considered in the design of a system for a specific application.

2. If the temperature exceeds $90^{o}F$ in low-temperature storage, the heat pump may be bypassed.

3. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. For a series heat pump system, the capacity of the solar supplied low-temperature storage should be carefully selected to provide 80 to 100 percent of the seasonal energy required by heat pump evaporator. For a parallel system, this percentage could be lower since the heat pump is selected for stand-alone operation.

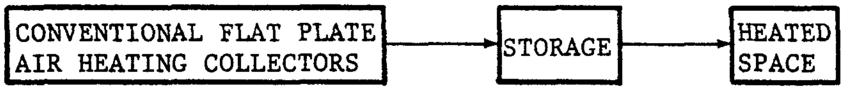
SHACOB - PATH H2

Temperature Range:	65° to 140°F
Storage Capacity:	
Long Term -	-
Short Term -	1 day supply of heating design load[1]
Storage Time:	
Long Term -	-
Short Term -	10 to 20 hours
Charge Time Per Cycle:	
Long Term -	-
Short Term -	4 to 10 hours
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	1 day
Losses:	
Acceptable Life Cycle Cost (LCC)	If a standby system is required, the passive heating system LCC should not exceed the Life Cycle fuel saving of the standby system.

---

1. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. However, a seasonal heating load supply of 50 to 70 percent for a passive heating system may be satisfactory.

SHACOB - PATH H3a



Temperature Range:	85° to 140°F
Storage Capacity:	
Long Term -	-
Short Term -	1-3 days supply of the design load[1]
Storage Time:	
Long Term -	-
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	-
Short Term -	1-3 days
Acceptable Life Cycle Cost (LCC)	If a standby system is required, the LCC of a solar heating system should not exceed the life cycle fuel saving of the standby system.

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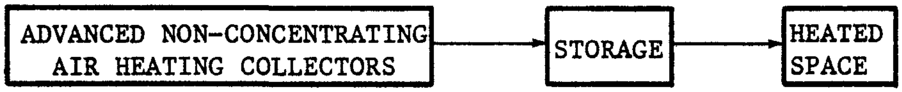
1. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions, however, an average of 60 to 80 percent of seasonal heating load is expected to be provided.

SHACOB - PATH H3b

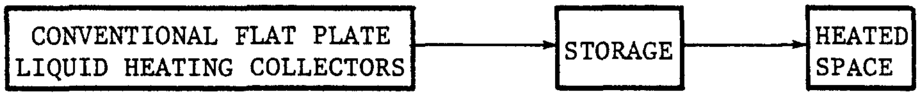


Temperature Range:	85° to 200°F
Storage Capacity:	
Long Term -	-
Short Term -	1-3 days supply of the design load[1]
Storage Time:	
Long Term -	-
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	-
Short Term -	1-3 days
Acceptable Life Cycle Cost (LCC)	The LCC of this system has to compete with should not exceed the life cycle fuel saving due to shorter operating time of a standby heating system.

---

1. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions, however, an average of 60 to 80 percent of seasonal heating load is expected to be provided.

SHACOB - PATH H4a

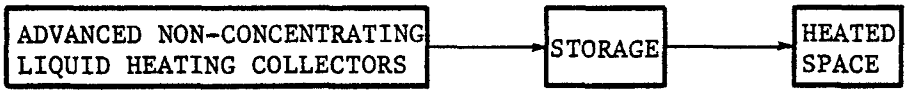


Temperature Range:	85 to 160^{o}F
Storage Capacity:	
Long Term -	80-100% seasonal heating load
Short Term -	1-3 days supply of the design load[1]
Storage Time:	
Long Term	3-6 months
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	3-6 months
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	3-6 months
Short Term -	1-3 days
Acceptable Life Cycle Cost (LCC):	a. The LCC of a solar heating system with a seasonal or short term storage should not exceed the LCC of an oil heating system. b. The LCC of a solar heating system with a seasonal or short term storage, plus a conventional cooling system should not exceed the LCC of a heat pump system.

---

1. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. However, only 60-80 percent of the seasonal heating load is expected to be furnished by solar energy.

SHACOB - PATH H4b



Temperature Range: 85 to 200°F

Storage Capacity:

- Long Term - 80-100% seasonal heating load
- Short Term - 1-3 days supply of the design load[1]

Storage Time:

- Long Term - 3-6 months
- Short Term - 1-3 days

Charge Time Per Cycle:

- Long Term - 3-6 months
- Short Term - 1-3 days

Discharge Time Per Cycle:

- Long Term - 3-6 months
- Short Term - 1-3 days

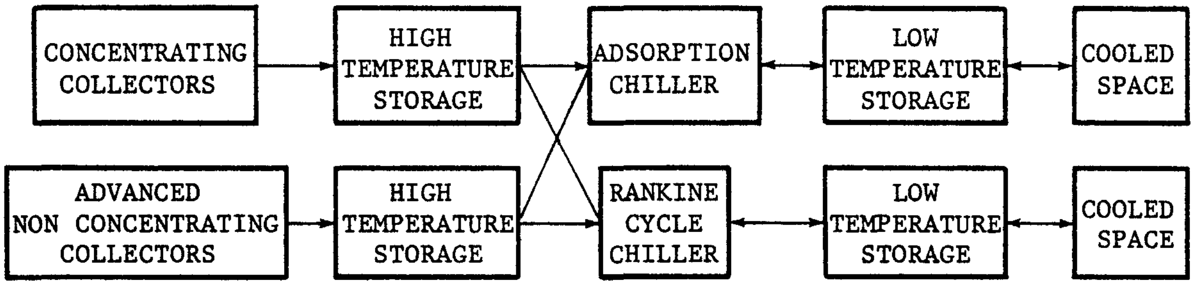
Acceptable Life Cycle Cost (LCC):

a. The LCC of a solar heating system with a seasonal or short term storage should not exceed the LCC of an oil heating system.
b. The LCC of a solar heating system with a seasonal or short term storage, plus a conventional cooling system should not exceed the LCC of a heat pump system.

---

1. The heating design load is selected at ASHRAE 97-1/2 percent winter design conditions. However, only 60-80 percent of the seasonal heating load is expected to be furnished by solar energy.

SHACOB - PATHS C1 AND C2



C1. CONCENTRATING COLLECTORS

C2. ADVANCED NON-CONCENTRATING COLLECTORS

	HIGH-TEMPERATURE STORAGE[1]	LOW-TEMPERATURE STORAGE[1]
Temperature Range:	Rankine (C1): 300° to 700°F Rankine (C2): 180° to 350°F Absorption (C2): 180° to 350°F	Sensible: 35° to 50°F PCM: 45° to 50°F
Storage Capacity:		
Long Term -	-	-
Short Term -	Avg. daily load[1]/avg. COP	Avg. daily load
Storage Time:		
Long Term -	-	-
Short Term -	1 to 3 days	1 to 3 days
Charge Time Per Cycle:		
Long Term -	-	-
Short Term -	1 day	1 day
Discharge Time Per Cycle:		
Long Term -	-	-
Short Term -	1 day	1 day

SHACOB - PATHS C1 AND C2
(Continued)

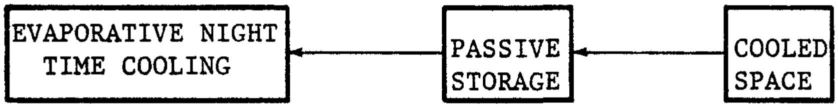
	HIGH-TEMPERATURE STORAGE[1]	LOW-TEMPERATURE STORAGE[1]
Acceptable Life Cycle Cost (LCC);	The LCC of a solar cooling system with high-temperature storage should not exceed the LCC of a steam absorption cooling system.	The LCC of a solar cooling system with low-temperature storage should not exceed the LCC of the same system without low-temperature storage.

---

1. Average daily load should be estimated over the cooling season.

2. Depending on system design and contribution made by storage to system technical performance and economics, storage cost for solar cooling systems is generally about 5 to 10 percent of installed system cost.

SHACOB - PATH C4



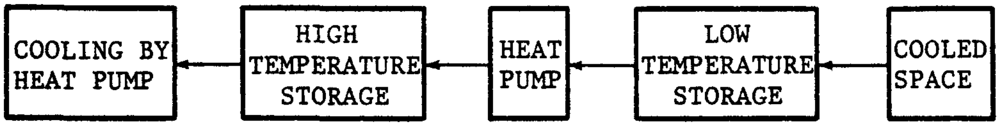
Temperature Range:	35 to 70°F
Storage Capacity:	
Long Term -	-
Short Term -	1 day supply of cooling design load[1]
Storage Time:	
Long Term -	-
Short Term -	8~20 hours
Charge Time Per Cycle:	
Long Term -	-
Short Term -	8~10 hours
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	10~12 hours
Acceptable Life Cycle Cost (LCC):	The LCC of evaporative or nighttime cooling system should not exceed the LCC of a conventional cooling system, or a heat pump system.

---

1. Cooling design load is selected at ASHRAE 5 percent summer design conditions.

2. The weater conditions for effective evaporative and/or nighttime cooling are high outdoor temperature differentials between daytime and nighttime and low humidity. If the daytime humidity is low, an evaporative cooling system may work effectively. If the nighttime temperature is low, nighttime radiation plus night time evaporation may be satisfactory.

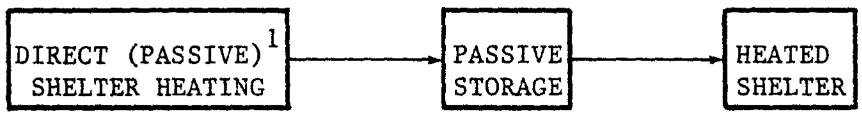
SHACOB - PATH C5



Similar to solar assisted heat pump paths H1a through H1e, except that

- The process is reversed where the evaporator becomes the condenser and the condenser becomes the evaporator
- The high temperature storage becomes the low temperature storage, and the low temperature storage becomes the high temperature storage
- The heat pump may reject thermal energy directly to environment, or to storage and then dissipate the energy via collectors, fan-coil units or cooling towers.

AIPH - PATH HD



Temperature Range:	45 to 140°F
Storage Capacity:	
Long Term -	-
Short Term -	1 day's supply of heating design load[2]
Storage Time:	
Long Term -	-
Short Term -	10-20 hours
Charge Time Per Cycle:	
Long Term -	-
Short Term -	4-10 hours
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	10-20 hours
Acceptable Life Cycle Cost (LCC):	If a standby system is required, the LCC of a passive heating system with storage should not exceed the Life Cycle fuel saving of the standby system.

---

1. To insulate a passively heated material is rather difficult. A permanent insulation installation requires high emissivity and low conductivity material. A portable insulation requires tight fit, light weight and should be easy to operate twice a day.

2. The heating design load is selected at ASHRAE 97-1/2 percent winter weather conditions. The indoor design conditions may vary from applications to applications.

AIPH - PATH HA

Temperature Range: 45 - 150°F

Storage Capacity:

- Long Term - -
- Short Term - 1-3 days' design load[1]

Storage Time:

- Long Term - -
- Short Term - 1-3 days

Charge Time Per Cycle:

- Long Term - -
- Short Term - 1-3 days

Discharge Time Per Cycle:

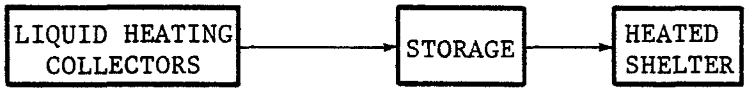
- Long Term - -
- Short Term - 1-3 days

Acceptable Life Cycle Cost (LCC): If a standby system is required, the LCC of a solar heating system should not exceed the life cycle fuel saving of the standby system.

---

1. The heating design load varies considerably with the intended application. The industrial and agriculture shelter heating applications could range from freeze protection to rather hot tropical weather conditions. The winter outdoor weather for design is selected at ASHRAE 97-1/2 percent winter design conditions and the indoor design conditions are application dependent.

AIPH - PATH HL



Temperature Range:	60 - 180°F
Storage Capacity:	
Long Term -	90 10 percent seasonal heating load
Short Term -	1-3 days design load[1]
Storage Time:	
Long Term -	3-6 months
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	3-6 months
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	3-6 months
Short Term -	1-3 days
Acceptable Life Cycle Cost (LCC):	a. The LCC of a solar heating system with a seasonal or short-term storage should not exceed the LCC of an oil heating system. b. The LCC of a solar heating system with a seasonal or short-term storage, plus a conventional cooling system should not exceed the LCC of a heat pump system.

---

1. The heating design load varies considerably with the intended application. The industrial and agriculture shelter heating applications could range from freeze protection to rather hot tropical weather conditions. The winter outdoor weather for design is selected at ASHRAE 97-1/2 percent winter design conditions and the indoor design conditions are application dependent.

<u>AIPH - PATH DA</u>

Temperature Range:	85-200°F or above 200°F for advanced air heating collectors
Storage Capacity:	
Long Term -	-
Short Term -	5 - 100% of average daily needs[1]
Storage Time:	
Long Term -	-
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	-
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	8-24 hours
Acceptable Life Cycle Cost (LCC):	a. The LCC of a dryer with storage should not exceed the LCC of a dryer without storage. b. The LCC of a dryer with storage should not exceed the LCC of a conventional gas, oil or propane dryer.[2]

---

1. The range of industrial and agriculture drying applications can be very wide. To supply a small portion of energy for a large drying operation, the solar energy collected can be supplied directly from collectors to dryer without having a storage system. The air heating collectors and storage may be sized to supply 100 percent of average daily drying need. Depending on the design, a storage system capacity can vary from 5 percent to 100 percent of daily energy needs.

2. A solar thermal storage system for drying may not be cost effective for crop drying since the crop season is short. Other non-drying applications associated with a drying system should be designed to offset the system cost.

AIPH - PATH DL

LIQUID HEATING COLLECTORS FOR DRYING → STORAGE → DRYER

Temperature Range:	85 to 200°F or 200 to 500°F for concentrating collectors
Storage Capacity:	
Long Term -	80 - 100% of the total drying load[1]
Short Term -	5 - 100% of the daily drying load[2]
Storage Time:	
Long Term -	3-6 months
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term	3-6 months
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	1-3 weeks
Short Term -	8 24 hours
Acceptable Life Cycle Cost (LCC):	a. The LCC of a dryer with storage should not exceed the LCC of a dryer without storage. b. The LCC of a dryer with storage should not exceed the LCC of a conventional gas oil, or propane dryer.[3]

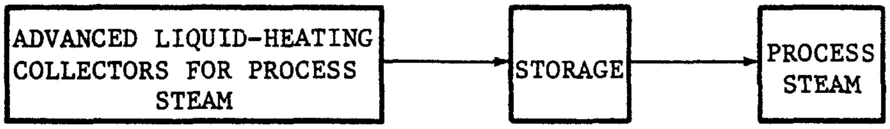
---

1. The storage capacity for a long term storage system is selected to be 80 100 percent of the total drying load. A long-term storage system for drying could mean that the thermal energy required for drying is collected and stored for a long period of time, however, the drying process may be completed in a very short period of 1-3 weeks since the crop season is short.

2. The short term storage capacity can have a very wide range depending on applications. One can have a storage system only supply a small portion of the total load with a complete standby system independent of solar energy. Or one may have a drying system heavily depending on solar energy.

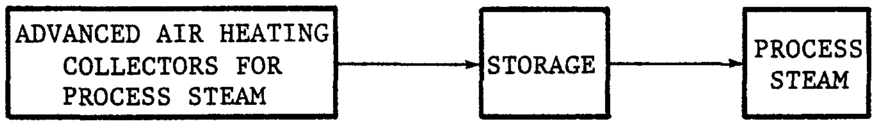
3. A solar thermal storage system for crop drying alone may not be so cost effective. Since the crop season is short. Other non-drying applications associated with a drying system should be designed to offset the system cost.

<u>AIPH - PATH SL</u>



Temperature Range:	Greater than 230^{o}F
Storage Capacity:	
Long Term -	-
Short Term -	Application dependent
Storage Term:	
Long Term -	-
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	-
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	Application dependent
Acceptable Life Cycle Cost (LCC):	The LCC of a process steam generating system using solar energy should not exceed the LCC of a steam generating system burning fossil fuel or coal.

AIPH - PATH SA



Temperature Range:	Greater than 230°F
Storage Capacity:	
Long Term -	-
Short Term -	Application dependent
Storage Time:	
Long Term -	-
Short Term -	1-3 days
Charge Time Per Cycle:	
Long Term -	-
Short Term -	1-3 days
Discharge Time Per Cycle:	
Long Term -	-
Short Term -	Application dependent
Acceptable Life Cycle Cost (LCC):	The LCC of a process steam generating system using solar energy should not exceed the LCC of a steam generating system burning fossil fuel or coal.

<u>AIPH - PATH CO</u>

Temperature Range: 35 to 70°F

Storage Capacity:
- Long Term - -
- Short Term - 1 day supply of cooling design load[2]

Storage Time:
- Long Term - -
- Short Term - 8 - 20 hours

Charge Time Per Cycle:
- Long Term - -
- Short Term - 8 - 10 hours

Discharge Time Per Cycle:
- Long Term - -
- Short Term - 10 - 12 hours

Acceptable Life Cycle Cost (LCC):

a. The LCC of an evaporative or nighttime cooling system with storage should not exceed the LCC of a conventional cooling system.
b. The LCC of an evaporative or nighttime cooling system with storage plus a conventional heating system should not exceed the LCC of a conventional heat pump system.

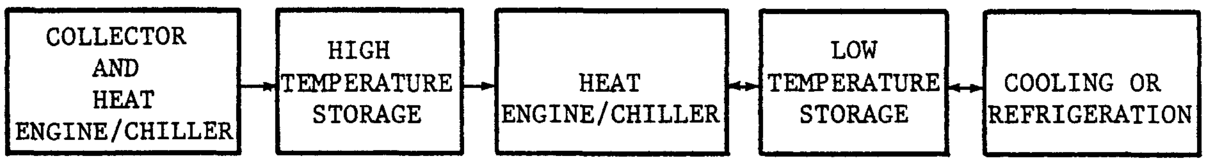
---

1. A passive cooling system may be an evaporative cooling system, a nighttime radiative cooling system, or a combination of both.

2. Cooling design load is selected at ASHRAE 5 percent summer design conditions.

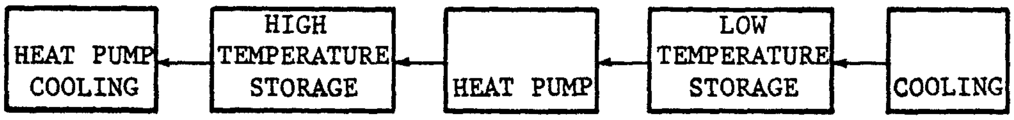
3. The weather conditions for effective evaporative and/or nighttime cooling are high daily outdoor temperature differential and low humidity. If the daytime humidity is low, an evaporative cooling system may work effectively. If the nighttime temperature is low, nighttime radiation combining with nighttime evaporation may be satisfactory.

AIPH - PATH CH



	HIGH-TEMPERATURE STORAGE	LOW TEMPERATURE STORAGE
Temperature Range:	180°-700°F	0° to 50°F
Storage Capacity:	Depends on application	
Storage Time:	Depends on application	
Charge Time Per Cycle:	Depends on application	
Discharge Time Per Cycle:	Depends on application	
Acceptable Life Cycle Cost (LCC):	Depends on application	

AIPH - PATH CP



Similar to solar assisted heat pump paths H1a through H1e, except that:

- The process is reversed where the evaporator becomes the condenser and the condenser becomes the evaporator
- The high temperature storage becomes the low temperature storage, and the low temperature storage becomes the high temperature storage
- The heat pump may reject thermal energy directly to environment, or to storage and then dissipate the energy via collectors, fan-coil units or cooling towers.