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MASTER

Central Unresolved Issues in Thermal Energy Storage for Building Heating and Cooling

C. J. Swet
Frank Baylin

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

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FOREWORD

This report is one deliverable from the SERI task on Storage Coordination and Assessment. It outlines some of the major unresolved issues and research to date in thermal energy storage for solar heating and cooling of building applications. A subsequent report will present a similar treatment of thermal energy storage for industrial process heat and other applications. This information will provide an input to U. S. Department of Energy program planners in the Office of Advanced Conservation Technologies and to researchers in the field. It also provides a framework to aid in planning additional SERI programs.

This document is a result of a joint effort; the organization and content were conceptualized and planned by the authors. Swet, a consultant for this project, wrote the bulk of the material. Baylin reviewed, criticized, and partially rewrote some sections. The report was produced as part of SERI Task 5525, Energy Storage Survey and Assessment.

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SUMMARY

Thermal energy storage is an integral component of many solar energy systems. During this period of remarkable growth in the development and commercialization of solar technologies, thermal energy storage concepts are being invented or rediscovered and are being readied for commercialization or are being actively marketed. In the process, many unresolved issues must be confronted and addressed. The particular emphasis of this document is an exploration of these issues for a specific application—solar heating and cooling of buildings. Throughout this report, the role of thermal energy storage technologies in improving or allowing use of solar systems is explored.

This document explores the frontier of the rapidly expanding field of thermal energy storage, investigates unresolved issues, outlines research aimed at finding solutions, and suggests avenues meriting future research. Issues related to applications include value-based ranking of storage concepts, temperature constraints, consistency of assumptions, nomenclature and taxonomy, and screening criteria for materials. Issues related to technologies include assessing seasonal storage concepts, diurnal coolness storage, selection of hot-side storage concepts for cooling-only systems, phase-change storage in building materials, freeze protection for solar water heating systems, and justification of phase-change storage for active solar space heating.

In such an effort, no one particular conclusion is forthcoming. The authors expect to leave the reader with an understanding of the important issues and a multitude of suggestions for improving and expediting commercialization of solar energy systems

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INTRODUCTION

The storage of thermal energy is a critical function of many solar energy heating and cooling systems for buildings. The range of technologies is broad and, fortunately, funding for development of thermal energy storage devices has increased rapidly in recent years. Technologies under development range from inexpensive water tanks to rather sophisticated chemical heat pumps. Recent reviews of the field have provided useful data from which both researchers and planners can draw (Baylin 1979; Baylin and Merino 1980; Wyman 1979). In addition, many publications describing the devices currently under development are available.

This document explores the frontier of this rapidly expanding field, investigates the unresolved issues, outlines research aimed at finding solutions, and suggests avenues for future research. This report raises important questions on thermal energy storage for solar heating and cooling of buildings. A subsequent publication will investigate thermal energy storage for industrial process heat and other applications (transportation, etc.).

A substantial effort toward investigating thermal storage technologies, as well as their integration into end-use systems, has been made. For completeness, Figs. 1-1 and 1-2 show a storage technology classification (Baylin 1979) and a schematic illustration of a solar heating and cooling system for buildings paths (U.S. DOE).

This report is organized as follows. Issues relating to applications rather than specific storage technologies are considered in Section 2.0. This is followed by an investigation of important issues relating specifically to technologies in Section 3.0. A thorough list of important references and a bibliography follow in Sections 4.0 and 5.0. The authors feel that it is important to direct the reader toward some of the excellent work in progress and they regret any important omissions. Please note that this report does not identify chemical heat pump/storage systems as an issue because that subject currently is receiving special attention.

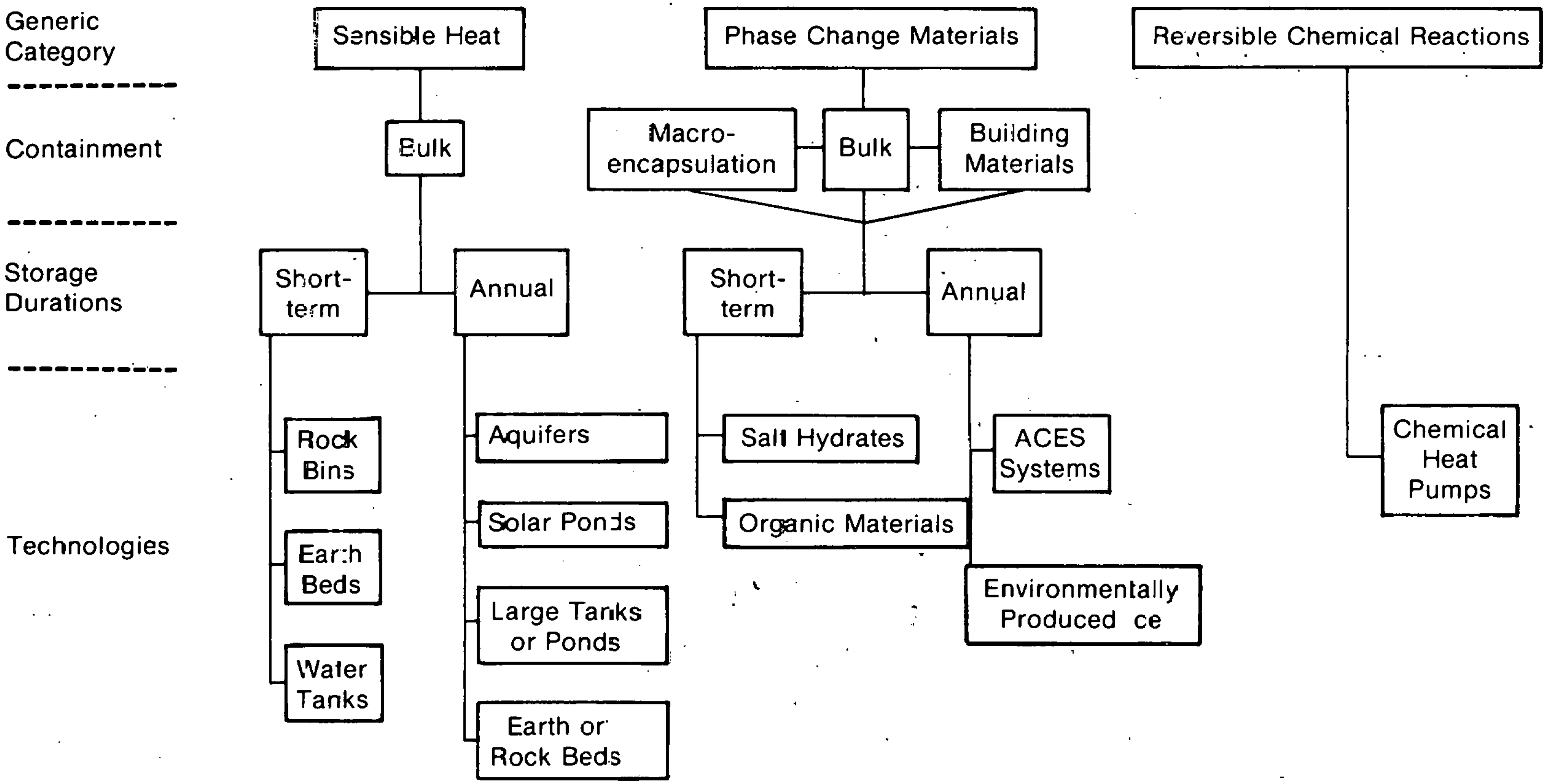

Figure 1-1. Low Temperature Thermal Storage Technology Classification

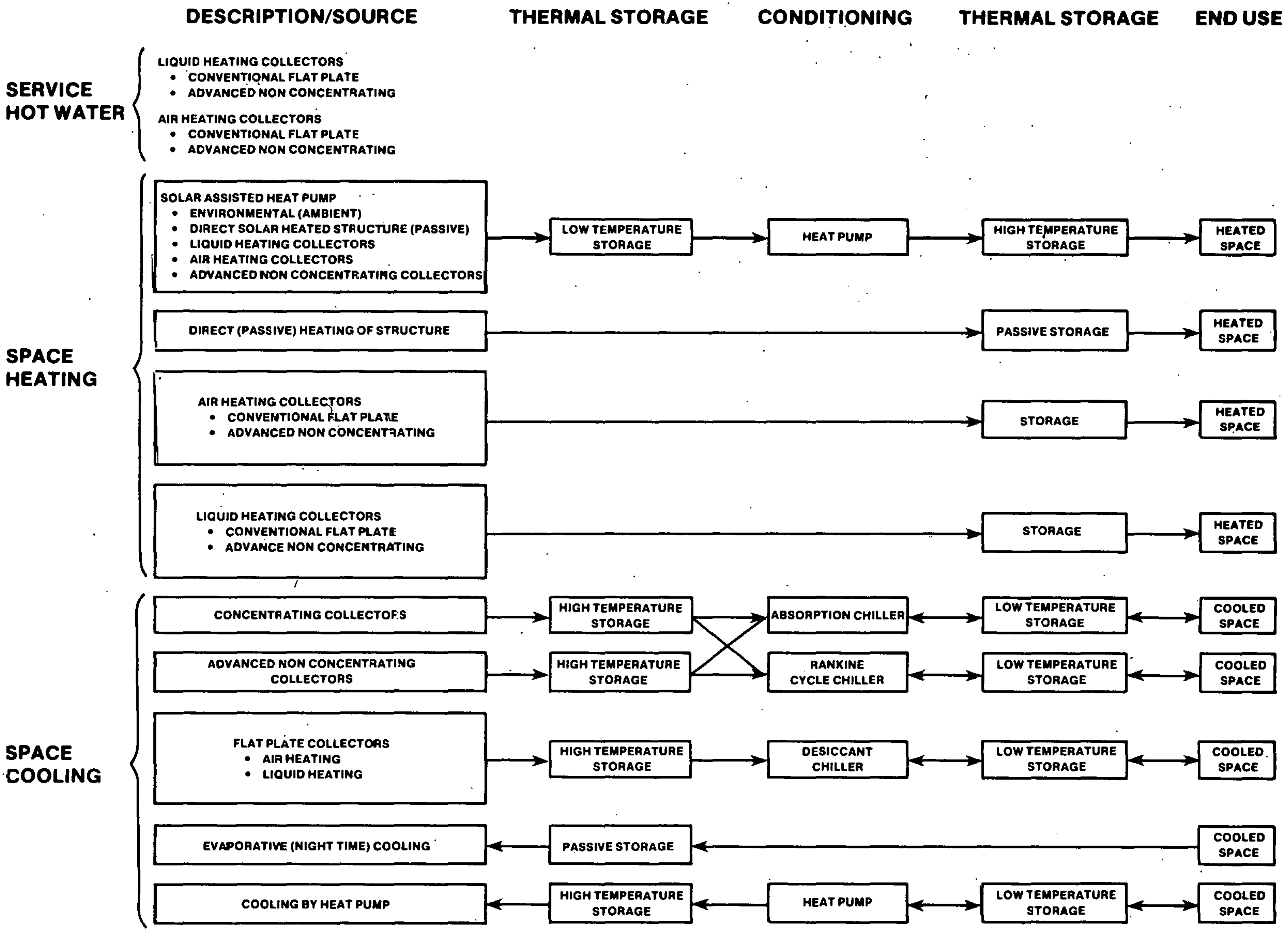

Figure 1-2. SHACOB Path Schematics

SECTION 2.0

ISSUES RELATED TO APPLICATIONS

2.1 VALUE-BASED RANKING OF STORAGE CONCEPTS

Methods are needed for the ranking of candidate storage concepts based on how they affect cost/value relationships of the overall solar energy system. This need has been actively addressed in the solar thermal power program (Copeland 1979) but only to a limited extent for solar space conditioning (Lof 1974). It applies to both active and passive space conditioning systems, but the focus here is on active systems with separately identifiable solar collection and storage elements.

The economic value of a solar space conditioning system is independent of the system concept or the storage subsystem configuration. It is determined only by the solar fraction* and the life-cycle cost of the conventional system being supplemented or replaced, i.e., by fuel savings and by factors such as climate, building characteristics, and the projected costs of money and commercial energy.** It can be defined as the investment cost of a system, producing a certain solar fraction in a given scenario, which will have a life-cycle cost equal to that of a reference nonsolar system. Sometimes it is called the marginal or break-even cost. System value is expressed here in terms of solar fraction, rather than storage capacity or duration, because solar fraction is a direct measure of fuel savings while storage capacity and duration are configuration-dependent parameters.

A storage system has no quantifiable economic value per se; together with the collection subsystem it produces a solar fraction which imparts value to the overall system. Various combinations of collector size and storage capacity can produce the same solar fraction and system value in a given scenario. A given combination of size and capacity can produce different solar fractions and system values depending on the efficiency and operating limits of each component; performance of each component in turn depends on the selected design concepts. Any meaningful economic ranking of candidate storage concepts must be performed in a total systems context and must be based on overall system value.

System value can be presented as a function of solar fraction and commercial energy cost escalation rate for a given scenario, as indicated in Fig. 2-1 by solid lines. The scenario would define a specific geographic region, building size and type, and non-solar baseline space conditioning system, using generally accepted economic assumptions (see Sec. 2-3). The solid lines represent overall solar system break-even costs that must be matched or bettered by an economically justifiable system concept. Suitably interpreted, a presentation such as this applies more broadly to any system, solar or other, that reduces the use of commercial energy.

The dashed lines in Fig. 2-1 illustrate how candidate solar-cum-storage concepts could be ranked economically when the solar fraction has not been predetermined. Every point on these lines represents a least-cost combination of solar collector size and storage

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*Solar fraction is the fraction of the total annual load supplied by solar energy.

**Commercial energy means electricity or fossil fuels from public utilities or commercial suppliers.

capacity corresponding to a specific solar fraction, and each line represents a specific storage concept coupled with a specific type of solar collector. The line labelled "Concept A," for example, might be the least-cost locus of a hot water tank storage subsystem coupled with evacuated tube collectors; that labelled "Concept B" might be for phase-change storage with flat-plate collectors. Concept A is seen to be more economical at a solar fraction of unity, where it matches the break-even cost at an escalation rate of 2% based on energy savings alone. The baseline system might not be required as backup at unity solar fraction; its cost would be credited and Concept A would be economically justified at an escalation rate of only about 0.5%. Concept B is most economical at 0.8 solar fraction and 2% escalation but must retain the baseline system as backup; therefore, Concept A without backup is ranked higher. Other concepts might be found to rank still higher (see Sec. 3-1), and in other scenarios the relative ranking of concepts A and B might be reversed (these curves are fictitious, intended only to illustrate methodology).

When the designer or evaluator of storage subsystems must start with a solar energy collection and delivery system of predetermined size and configuration which lacks only the storage element, candidate storage concepts can be ranked in a different fashion. In this case, differences in solar fraction and system value are solely attributable to differences in the candidate storage concepts, so storage costs can be related to system value as shown in Fig. 2-2. It must be stressed that value-based rankings of different storage configurations for an otherwise predetermined system configuration are valid only if all of the storage subsystems are interchangeable and equally compatible with the system.

2.2 TEMPERATURE CONSTRAINTS

The rational selection of storage media and concepts for solar heating and cooling continues to be inhibited by the lack of clearly defined and generally accepted temperature constraints. Much of the data on which these constraints could be based are available (Fanger 1970; Clark and Allen 1979; Wray 1979), but guidelines are lacking on the conversion of well-known thermal criteria to thermal storage temperature requirements.

For coolness storage, no defined lower limits are needed other than those imposed by impaired chiller performance or the winter ambient environment. The upper limit (which is determined by a mix of factors including the latent heat load, type of storage, storage container, heat transfer media, and A-coil configuration) needs fuller definition to guide the development of phase change systems and to enable optimal sizing of chilled water systems.

For active space heating storage, there are upper limits (maximum temperatures) imposed by comfort, heat loss, and safety considerations, but such limits are seldom approached in practice with conventional heat delivery systems and probably need not be defined. The lower limits (minimum temperatures) are a subject of considerable controversy; their determination, based on both comfort and economic considerations, would establish the practical range of application for low-melting-point, phase-change materials such as Glauber's salt and calcium chloride hexahydrate. For active space cooling storage (hot side), the minimum generator inlet temperature should be specified for each chiller concept.

For passive solar heat storage, both the upper limits and the comfort zone ranges need definition. The building's interior structure and trim, intended to absorb and store direct

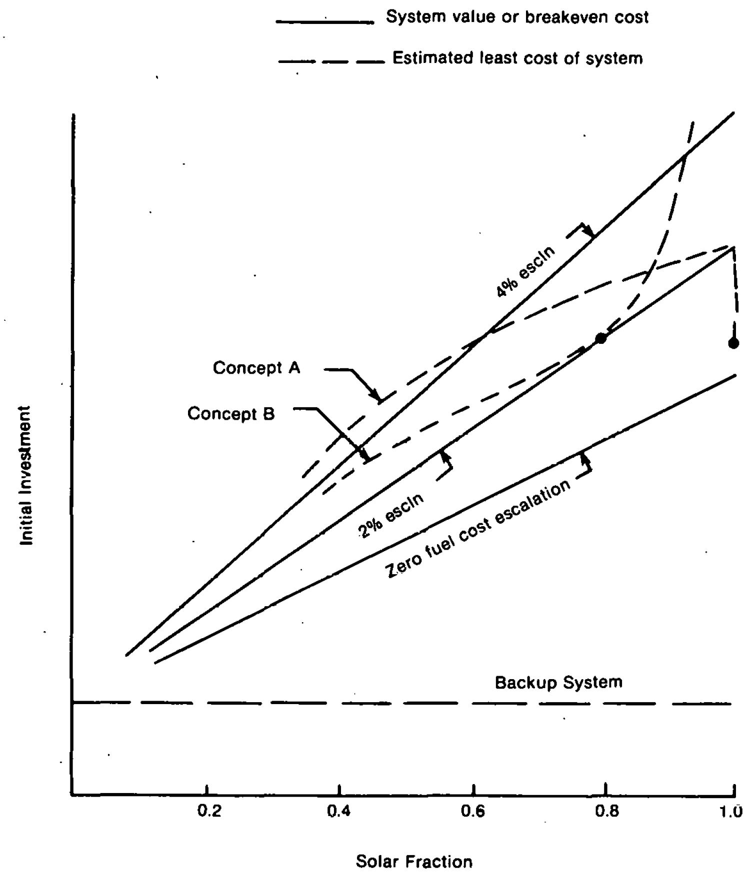


Figure 2-1. Representative Cost/Value Relationships

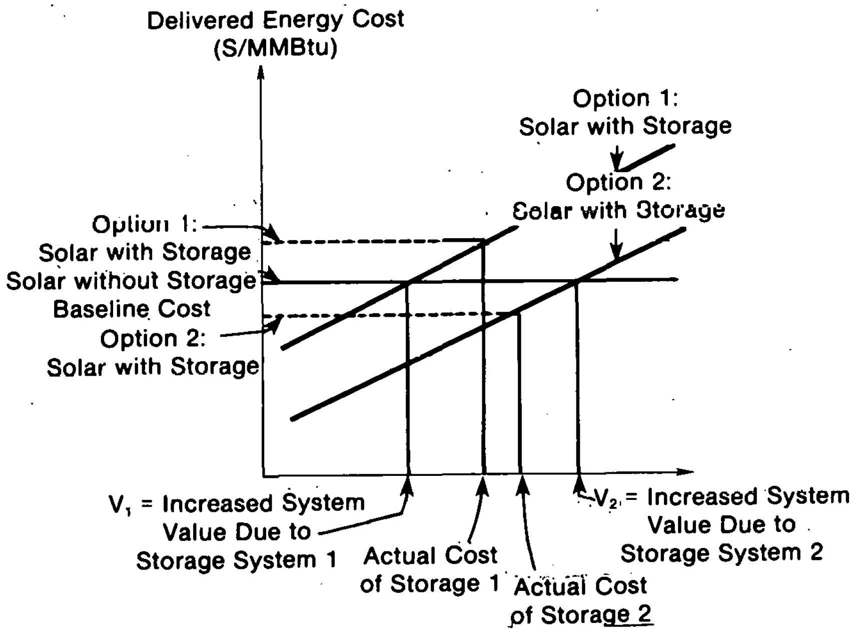


Figure 2-2. Delivered Energy Cost as a Function of Storage Cost and System Value

solar gain, cannot be allowed to reach uncomfortably high surface temperature although this would seldom occur. There also should be preferred surface temperatures for optimal radiative and/or convective transfer to the heated space. Knowledge of such constraints will help determine the need for and melting temperatures of phase-change additives. Developers of building materials with phase-change additives would benefit greatly from precise guidelines on desired temperature profiles for passive maintenance of the comfort zone temperature by storage materials that are not exposed to direct solar gain.

2.3 CONSISTENCY OF ASSUMPTIONS

In all areas of solar technology, economic comparisons of competing concepts have been made difficult by nonuniform assumptions used in various estimates of capital investment cost and of annualized mean cost of delivered energy. The problem is widely recognized and steps are being taken to find solutions in the solar thermal power program (Thornton). In the area of storage for solar heating and cooling the Department of Energy has efforts underway in the System Simulation and Economic Analysis Program.

Assumptions vary widely in estimates of storage system fabrication and installation costs. Often, the distinction between the cost to the seller and the price to the buyer is ignored or blurred, and cost estimates for similar units tend to be based on different assumptions regarding production volume, labor rates (which depend on the assumed geographical region), and capital investment in development and tooling. Estimates of in-place costs of storage media are affected greatly by assumed freight charges (which in many cases also depend heavily on the assumed geographic region). Some steps toward a unified approach to storage system costing are being taken (Arthur D. Little, Inc.) but consistent guidelines are still lacking in many important areas of investment cost estimation.

Inconsistent assumptions also abound in calculations of system life-cycle cost and the annualized mean cost of energy delivered by the solar system, which enter into determinations of system value (see Sec. 2.1). These include assumptions regarding the current cost of commercial energy (which is heavily region-dependent as well as source-dependent), projected escalation rates, startup date, system lifetime, cost of money, and operation and maintenance costs (which are affected by assumptions regarding component and storage media replacement frequency). Where the assumptions involve projections into the future, on which consensus is unlikely, the uniformity would take the form of agreed-upon ranges of values to assure comparable parametric analyses.

2.4 NOMENCLATURE AND TAXONOMY

The lack of universally accepted storage terminology and family trees often has created confusion. A good glossary would eliminate the many ambiguities and needless variants in verbal descriptions of solar energy storage concepts and components. Standard graphic descriptions of the more common types of storage systems, if sufficiently clear and simple, would add greatly to the value of overall solar system schematics. Good presentations of the conceptual groupings and hierarchies, both functional and configurational, would aid in the selection of system components and in the identification of areas where research may be needed (see Fig. 1-1). Work along these lines is underway for solar thermal power, but no comparable action appears to be planned for solar heating and cooling.

To convey an idea of the needed level of standardized detail, Fig. 2-3 shows some possible stylized depictions of liquid sensible-heat storage units. The symbols should be open and simple enough to permit the addition of important nonstandard features, as indicated in the last symbol.

Figure 2-4 shows how the various functions and placements of storage might be presented, expanding on the notion of "paths" used by the DOE Office of Solar Applications' research and development program (see Fig. 1-2). In this presentation, the path for a solar absorption cooling system without coolness storage would be 1/11/20. If the same system has coolness storage and preheated service water storage, the path would be 1/11/18/19/13. For clarity, the usual bypasses around storage are omitted in this illustration.

Figure 2-5 shows how a representative path through storage might be described in terms of heat transport fluid, storage medium, and method of heat exchange. Probably, the levels of subdivision should be finer than shown in this illustration. The bullets indicate how a specific configuration (in this case, an air-rock system) might be identified.

2.5 SCREENING CRITERIA FOR MATERIALS

Candidate energy storage materials typically are examined in a rather cursory fashion for safety, durability, reliability, environmental impact, and economic feasibility at an early stage of exploration, long before the system concept in which they might be used is subjected to more rigorous scrutiny. In the absence of uniform criteria for initial screening, the examinations tend to be subjective and quite variable. Sometimes, the judgments are overly optimistic and result in wasted effort before fatal flaws are finally discovered. Often, though, worthy concepts die at inception because of unjustifiably severe initial judgments. In any case, the judge (whether the originator or the prospective funder) would benefit from better guidelines than are available currently.

Storage materials that are toxic, flammable, or otherwise potentially hazardous are not categorically prohibited from use in buildings by major building codes, although some local codes may be more restrictive. In nearly all cases, the hazard potential can be reduced almost to zero by proper design and other safeguards; therefore, the problem of determining acceptability of a material is mainly one of justifying the cost of needed safeguards. Yet, there is a natural intuitive inclination to discount the use of such materials in dwellings. Such an inclination might be tempered if tools were available for estimating the cost-benefit of safeguards. Examples of such materials are ammonia, methanol, paraffin waxes, polyolefins, sodium hydroxide, and strong acids.

Storage materials derived from petroleum or natural gas, such as paraffin waxes, oils, and polyolefins, sometimes are rejected summarily on the basis of considerations of resource depletion and/or escalating cost. Certainly, these are legitimate concerns when considering materials, but they are not necessarily "show stoppers." The price of special waxes is less dependent on the cost of petroleum than on market competition with other residual products, and polyethylene prices are rising less rapidly than oil prices because of expanding and more efficient production facilities. From the standpoint of resource depletion, an allowance should be made for the fact that these are essentially one-time uses and that the impact of full market penetration might be acceptably small. There also is the prospect of polymer synthesis from coal and other carbonaceous sources and from plant life. Of course, such materials could also be used at any future time for fuel. Because of so many variables to weigh when selecting energy storage materials, access to suitably presented data could reduce the guesswork.

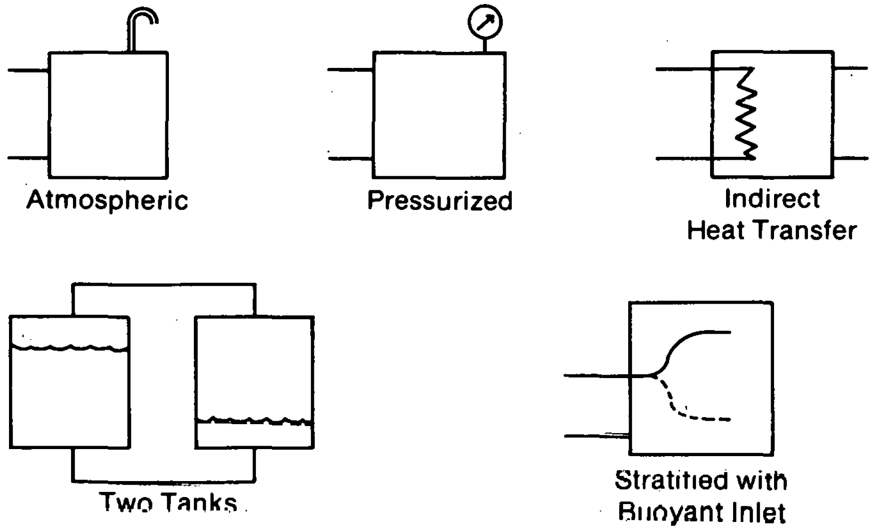
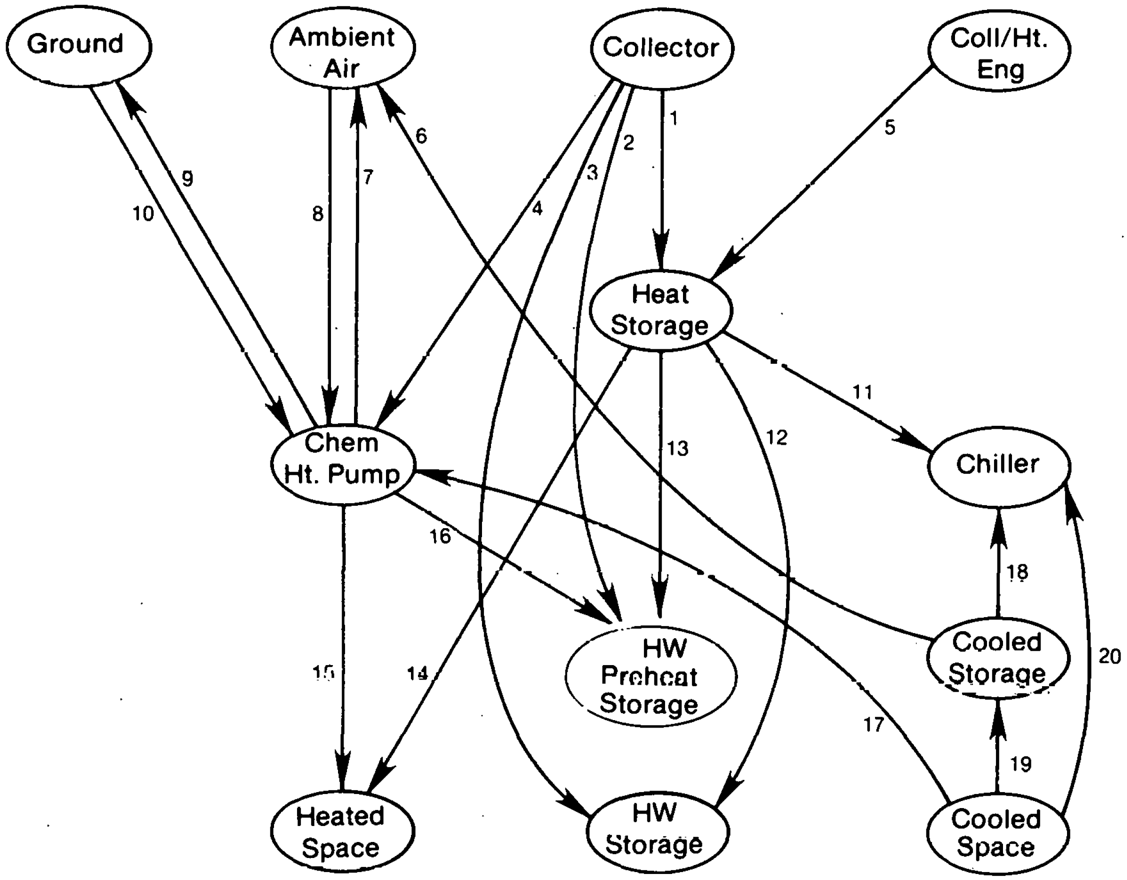


Figure 2-3. Standard Depictions of Liquid Sensible-Heat Storage Units



Note: Passive heating and solar assisted heat pumps omitted to preserve clarity.

Figure 2-4. Active Paths through Storage for Solar Heating, Cooling, and Hot Water

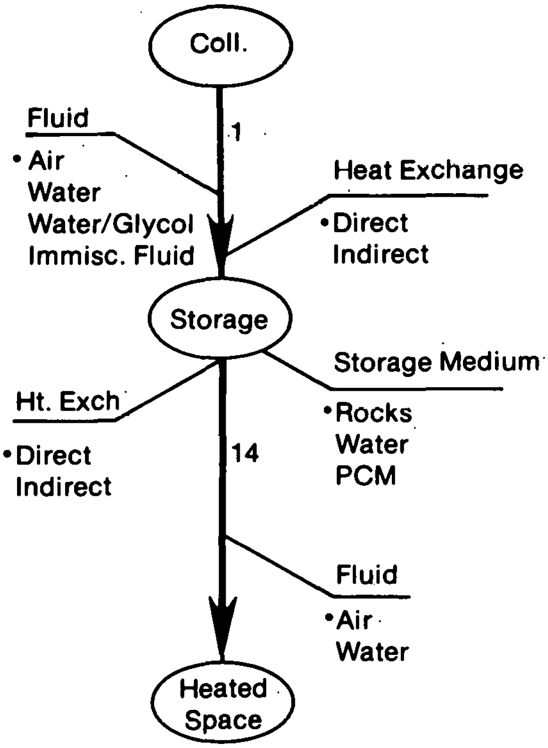


Figure 2-5. **Configurational Family Tree for Representative Paths through Storage**

Attention solely to high unit cost can prompt unwarranted early rejection. For example, consider the postulated use of a water-glycol mixture as the storage medium for a small solar heating and cooling system. Its high cost and low heat capacity compared with water would tempt one to discard this fluid immediately. A closer look, using additional criteria, might show that its use would eliminate the need for a separate water-glycol collector loop and heat exchanger, thereby reducing the collector size and cost. It might also reveal that the higher boiling point would permit a higher temperature and more efficient chiller operation without a pressurized storage tank and that these combined effects might outweigh the high cost of glycol (such might not actually be the case; the example is chosen to illustrate the importance of proper criteria selection and use at the earliest stages of concept exploration).

Considerations of the environmental impact of using certain materials do not seem to have discouraged the development of meritorious energy storage concepts for solar heating and cooling. On the contrary, salt gradient pond and aquifer storage concepts continue to be vigorously pursued despite some still unanswered questions about possible harmful impact on the surrounding environment.

SECTION 3.0

ISSUES RELATED TO TECHNOLOGIES

3.1 ASSESSMENT OF SEASONAL STORAGE CONCEPTS

The concept-ranking methodology outlined in Section 2.1 applies to solar space conditioning systems which produce any solar fraction, but the special case of seasonal storage (unity solar fraction) calls for additional technical discussion because of its emerging importance. There is also a relative lack of familiarity with the exceptionally wide range of conceptual approaches to seasonal storage. In this section, the principal applications and technical approaches are categorized and briefly discussed with the view of facilitating comparisons of concepts based on factors other than cost-value relationships.

The term seasonal storage is used here as a generic description covering a number of different ways of achieving unity (or nearly unity) solar fraction. It applies to all nominally "zero backup" systems which require essentially no auxiliary energy other than for parasitic power, relying instead on large amounts of stored thermal energy (heat, coolness, or chemical potential) to bridge long periods of supply/demand imbalance. The storage for such systems may be totally interseasonal, as in the case of winter chill retention for summer cooling, or it may be seasonal in a looser sense to permit year-round collection and storage of solar energy for winter heating. It may be part of a yearly averaging system for solar heating and cooling, in which the storage charge level fluctuates with the seasonally varying ratio of solar input to building load. It may also be intraseasonal; i.e., of sufficiently large capacity to assure nearly unity solar fraction when coupled with a sufficiently large collector without depending on collection and storage charging throughout the year. The term applies whether or not the storage capacity is large enough to accept the collector output at all times. It also could apply to so-called "passive" solar systems in which the distinction between energy collection and storage is less clear, although such systems are not considered in this discussion.

In this discussion, seasonal storage concepts are broadly grouped by application into three categories:

- space heating only,
- space cooling only, and
- space heating and cooling.

After a general exposition of common issues, each of these three categories and their specific subissues are examined separately in greater detail. Water heating is also a major application and should be considered in the evaluation of most space-conditioning concepts but it is not singled out because it typically is a nearly continuous load that can be largely if not fully satisfied by space heating systems or by space heating and cooling systems that have seasonal storage.

Many different concepts, ranging from speculative inquiry to prototype system demonstration, are being pursued in all three applications of seasonal storage, sponsored by a multitude of private, state, and federal activities both in the United States and abroad. Still other concepts have been proposed, were judged potentially meritorious, but were not pursued. Funding levels are widely disparate, partially reflecting the natural spread in program maturity attributable to the particular year in which the given concepts emerged, as well as attributable to some unavoidable budgetary constraints. However, funding frequently is determined by the persuasiveness of individual proponents coupled with the lack of communication among sponsors and the absence of adequate tools for comparative evaluations. These deficiencies are seen as serious but removable obstacles to the formulation of rational program priorities in both the public and private sectors. Of these deficiencies, the absence of rational ranking criteria appears most critical; the inevitable contention arising from its correction seems certain to promote the needed communication.

Concept assessments should include consideration of the entire space-conditioning and water heating system and allow for the cost and probability of successful development. For each of the three applications of seasonal storage, the candidate concepts must be examined in a number of scenarios (see Section 2.1) with special attention in the case of community-scale systems to geological and institutional constraints. For each scenario, baseline concepts must be selected that are dependent on proven technologies (such as fossil fuel combustion or electric heat pumps) or on less mature but possibly more economical concepts such as the Annual Cycle Energy System (ACES). The challenge is to conduct these complex and potentially threatening evaluations with the cooperation of all affected parties.

3.1.1 Seasonal Storage for Space Heating

This category of seasonal storage applies to buildings or communities which, because of climate or use, have dominant demand for only comfort heating and hot water. On the two following pages are preliminary orderings of the better-known concepts in categories that can be examined generically in various scenarios, a list of likely baseline concepts, and a list of sponsored activity in the field (see tables).

The concepts categorized in Table 3-1 are based only on sensible heat and chemical storage. Plausible concepts for seasonal storage in latent heat appear to be lacking. All of the listed concepts might in some fashion be adapted to space cooling as well, but the purpose of the table is to indicate configurations that are intended only for solar hot water and space heating. Some of the concepts listed in Table 3-1 have attributes that call for special examination from an environmental or sociological viewpoint or that require proof of feasibility for special features. Storage in a lake or solar pond might conflict with other land uses, and aquifer storage might conflict with other uses for groundwater. The feasibility of storage in the ground or in natural aquifers is highly site dependent and might not prove amenable to evaluation on a broad regional basis because of microvariations in local geology. Solar ponds must be designed with salt spills in mind, and acid heat pumps must be shown to be nonhazardous. These and other potential problems ordinarily would be characterized and resolved during the course of conceptual development, but must be anticipated and dealt with at an early stage in order to impact the ranking process.

The baseline concepts listed in Table 3-2 are presented in no particular order purposely to suggest the kinds of proven technologies that might compete for selection as the preferred baseline for each scenario. For example, gas heat might be most economical in the near future for a small residence in a region with poorly accessible groundwater and high electric rates, while the heat pump might be cheapest elsewhere. Table 3-3 is intended as a starting point for the more complete and fully descriptive compilation of present and proposed activity in the field.

Table 3-1. CANDIDATE SEASONAL STORAGE CONCEPTS FOR SPACE HEATING

Mode	Medium	Containment
Sensible heat	Water	Constructed tank Natural aquifer Artificial aquifer[a] Insulated lake Solar pond (salt gradient or other)
	Undisturbed earth	Unconfined
	Disturbed earth	Confined
	Rocks	Packed bed
Chemical heat pumping	Sulfuric acid/water or other pairs	Lined and unlined tanks

[a] Aquifer constructed by filling an excavation with gravel and subsequently sealing the opening.

Table 3-2. LIKELY BASELINE CONCEPTS FOR SPACE AND WATER HEATING

Gas furnace and water heater

Off-peak electric resistance heat with storage

Groundwater source electric heat pump

Solar-assisted heat pump

Oil furnance

Table 3-3. ACTIVITY IN SEASONAL STORAGE CONCEPTS FOR SPACE HEATING

Organization	Concept	Status	Sponsor
Univ. of Toronto	Water tank	Operating	Can. Gov't and DOE-SA
Bihler Assoc.	Water tanks	Cost study	DOE-STOR
Argonne National Lab.	Water tanks	Cost study	DOE-STOR
Studsvik	Water tank	Operating	Swedish Gov't
Univ. of Virginia	Covered pond	Discontinued	DOE-SA
Auburn Univ.	Natural aquifer	Field exp. (no solar)	DOE-STOR
Lawrence Berkeley Labs.	Natural aquifer	Modeling	DOE-STOR
Oak Ridge National Labs.	Natural aquifer	Env. assmt.	DOE-STOR
Ohio State Univ.	Solar ponds	Operating	
Rocket Research Corp.	Acid heat pump	Subscale eng. test	DOE-STOR
George Washington Univ.	Disturbed earth	Cost study	NSF and DOE-STOR
City of Miamisburg, Ohio	Salt gradient pond	Operating	Municipal

3.1.2 Seasonal Storage for Space Cooling

This category of seasonal storage applies to buildings or communities that, because of climate or use, have predominant demand for only comfort cooling and hot water. Considerations for space cooling are much the same as for space heating, but winter chill storage and phase-change storage are additional candidate concepts.

From earliest times, naturally occurring ice and snow have been gathered in the winter and stored to use their coolness in summer. This practice was largely abandoned with the advent of mechanical refrigeration, but sharply rising energy costs and summer power peaks have stimulated renewed interest in the notion of storing "free" winter cold for summer cooling. Many such concepts are now being investigated for air conditioning applications to replace conventional vapor compression or absorption chillers by systems that freeze or chill water through exposing water to the winter environment, storing the cold product until summer, then releasing the coolness as needed. Sources of cold include ambient air, surface water, and natural snow. Heat is rejected by a spray pond, fan, cooling tower, heat pipe, or tubular heat exchanger.

Although phase-change materials appear inappropriate for seasonal storage of solar heat, their use is more credible for intraseasonal storage in connection with solar-powered chillers. A recent study (Offenhartz forthcoming) shows that in some climates only three or four days of thermal storage can eliminate the need for backup chiller power. Thus, the combination of a moderate increase in both storage capacity and the solar collection area might become cost competitive with other approaches. Since absorption chillers require generator temperatures close to 100° C, there is a strong incentive to exploit the isothermal properties of phase-change storage (see Section 3-3). Ice is an appropriate phase-change material for interseasonal storage of coolness.

Table 3-4 is meant to categorize the principal conceptual approaches rather than to list all plausible variants of winter chill storage or itemize every potentially suitable phase-change material. No attempt was made in Table 3-5, which lists likely baseline concepts for space cooling, to include the various types of electrically or thermally driven chillers used in large buildings, although they would ultimately have to be selected in certain scenarios. Note that a separate baseline water heater must also be selected. Table 3-6 is a preliminary partial list of activity in this field, much of which is not yet described in citable literature.

The notion of using year-round collection and storage of solar heat for space cooling and water heating alone is clearly less attractive than using annual storage for heating and hot water alone, since much of the heat must be carried over from a time of low insolation to one of relative plenty. However, if the storage is a chemical process at near-ambient temperature, the standby losses might be acceptably low. A consideration peculiar to the storage of water which is chilled by direct contact with ambient air is that oxygenation may cause excessive corrosion or harmful chemical reactions in an aquifer. Eliminating this potential problem by using indirect heat transfer would reduce the available temperature swing and require greater storage volume.

3.1.3 Seasonal Storage for Space Heating and Cooling

This category of seasonal storage applies to buildings or communities that need comfort heating, comfort cooling, and hot water. It is probably the most important mission for seasonal storage, partly because the potential market and conservation value for combined heating and cooling systems are greater than for heating only and for cooling only, but largely because this use of seasonal storage appears to offer the highest economic payoff.

On one hand, some of the attractive concepts for heating only or for cooling only appear to be less applicable for combined heating and cooling systems. An example is the use of phase-change materials for hot-side storage in solar absorption air conditioners, which might be competitive in a cooling-only application where the delivery temperature must remain near the fusion temperature of roughly 100° C. In winter, the collector efficiency is lower at that temperature, which substantially exceeds the delivery temperature required for heating, so the heat of fusion cannot be adequately utilized. Another example is the use of hot water storage for solar-absorption chillers, which also might be competitive for intraseasonal storage in the cooling-only application. If a single tank is used for yearly averaging storage, however, the storage temperature must be boosted nearly instantaneously in the spring from its degraded condition at the end of the heating season to the much higher temperature needed for absorption cooling. On the other hand, some concepts may be enhanced in value, particularly when the same components serve dual purposes. An example is the use of aquifer storage for both heating and cooling, which offers opportunities to use common pumps and piping. Another is the use of multiple large water tanks where the total tank volume might be reduced by scheduled year-round utilization.

Table 3-4. CANDIDATE SEASONAL STORAGE CONCEPTS FOR SPACE COOLING

Source of Coolness	Mode	Medium	Containment	Remarks
Snow	Sensible heat	Chilled water	Natural aquifer	Interseasonal
Surface water			Tanks	
Ambient air	Sensible heat			
Ambient air	Latent heat	Ice	Tank	
Solar absorption chiller	Latent heat	PCM	Packed bed	Hot side, intraseasonal
Solar absorption chiller	Sensible heat	Hot water	Tank	
Solar chemical heat pump	Chemical	Sulfuric acid/water Calcium chloride/methanol	Tanks	Combines storage and chiller functions

Table 3-5. LIKELY BASELINE CONCEPTS FOR SPACE COOLING

Electric air conditioning and off-peak electric resistance water heater
Solar absorption chiller with diurnal storage and gas-fired standby and water heater

Table 3-6. ACTIVITY IN SEASONAL STORAGE CONCEPTS FOR SPACE COOLING

Organization	Concept	Status	Sponsor
Argonne National Lab.	Ambient air/ice/tank/ heat pipes indirect HX	Lab. exp.	DOE-SA
Univ. of Minn.	Ambient air/ice/tank/ circ. brine indirect HX	Op'l	Minn. Energy Agency
Johns Hopkins Univ. APL	Ambient air/ice/insul basin/fan spray direct HX	Proposal	
Texas A&M	Ambient air/chilled water/aquifer/spray pond direct HX	Field exp.	DOE-STOR
Desert Reclamation and ORNL	Ambient air/chilled water/aquifer/indirect cooling twr HX or indirect with surface water	Studies and well drilling	DOE-STOR
Univ. of Yamagata	Snow/chilled water/ aquifer/indirect HX	Op'l	
Southern Ill. Univ.	Ambient air/chilled water/cistern/direct HX	Subscale prototype op'l	
Rocket Res. Co.	Acid/water solar chem. heat pump	Eng. exp.	DOE-STOR
EIC Corp.	Calcium chloride/ water chem. ht. pump	Lab exp.	DOE-SA
EIC Corp.	Calcium chloride/ methanol chemical heat pump	Lab exp.	DOE STOR

The concepts categorized in Table 3-7 represent in some cases a consolidation of the concepts that are identified in Table 3-1 (heating only) and Table 3-2 (cooling only). An example is the "Solaterre" concept (Davison 1975) which stores winter-chilled water in one part of an aquifer and solar-heated water in another part. The list in Table 3-8 includes ACES and ground-coupled electric heat pump systems even though they are not thoroughly proven concepts, mainly because they might not otherwise be subjected to such comparisons. Activity in the field of seasonal storage for combined heating and cooling is not compiled here because all of the available information is mentioned already in Tables 3-3 and 3-6.

Table 3-7. CANDIDATE SEASONAL STORAGE CONCEPTS FOR SPACE HEATING AND COOLING

Concept	Medium	Containment	Remarks
Solar heat & winter chill	Heated & chilled water	Natural aquifer	"Solaterre"
	Heated water & ice	Multiple tanks	Various ice-making options
Solar heating and cooling	Sulfuric acid & water	Multiple tanks	Other chemical heat pump concepts are possible
	Water		

Table 3-8. LIKELY BASELINE CONCEPTS FOR SPACE HEATING, SPACE COOLING, AND HOT WATER

- Ground-coupled summer-winter electric heat pump
- Same with off-peak electricity and storage
- Conventional summer-winter electric heat pump
- Annual Cycle Energy System (ACES)

3.2 DIURNAL COOLNESS STORAGE

Diurnal storage of coolness is sometimes integrated into solar space-cooling systems in order to reduce chiller cycling frequency during periods of low demand. It may be used in such systems to permit off-peak operation of a standby electric air conditioner. In some cases the same storage medium also can be used for space heating. There is no clear consensus regarding the justification of using coolness storage as a means of reducing chiller cycling frequency; contrasting conclusions have even been drawn from the same operating experience with the same system (Duff et al. 1978; Ward et al. "Integration"). However, the diverse conclusions tend to be based only on chiller performance analysis in a specific scenario using a specific coolness storage technology; neither economic aspects nor additional uses of the storage are considered (Anand et al. 1978; Ward et al. "Integration"). Clearly, there is a need for value analysis that considers complementary uses in many scenarios (see Section 2-1.).

Coolness storage is beneficial in that it reduces the duration of low-efficiency transient operation by reducing the chiller cycling frequency, thereby improving the annual coefficient of performance and increasing the solar fraction. By permitting more nearly continuous chiller operation, coolness storage also reduces the installed tonnage requirement. Countering these economies are (1) the coefficient-of-performance penalty imposed by the lower evaporator temperature needed to overcome any additional temperature differential and (2) the investment and operating costs of added coolness storage. Most of the analysis has examined absorption systems which account for the bulk of all installations to date, but similar methodology presumably applies also to Rankine and desiccant systems. At least one installation of a Rankine system with coolness storage uses the same storage medium (water) and tank for both heating and cooling (Nishiyama et al. 1979). Coolness storage may be easier to justify for large systems with chilled water distribution to multiple fan coils than for smaller systems with one combined evaporator/fan coil.

If the solar cooling system is provided with a backup electric air conditioner, then favorable off-peak electric rates could help justify a common coolness storage system. Thermal energy storage for off-peak electric resistance heating commonly is used in Europe and is becoming increasingly popular in the United States with the growing availability of time-of-day pricing. Opinion is divided about the merit of its integration into solar heating systems (Hughes et al. "Simulation Study"; Asbury et al. 1978). Coolness storage for off-peak use of conventional air conditioners has been examined both analytically and experimentally (EPRI 1977; Asbury et al. 1977), but the possibility of combining off-peak storage with a solar cooling system does not appear to have been systematically studied.

A solar heating and cooling system that uses hot water storage for heating might advantageously adapt the same tanks to coolness storage as well, depending on the relative storage capacities selected for heating and cooling. With multiple tanks, the capacity might be divided into hot-side and cool-side storage, with perhaps two cool-side storage temperatures. Combined systems, though, may pose severe control problems during spring and fall transition periods, and the expense of solving such problems might negate the more obvious savings in shared function.

Candidate technical concepts for diurnal coolness storage include the use of ice, chilled water, saturated aqueous solutions, phase-change materials that melt at 7-10°C, and refrigerant storage. Ice storage (Cook and Krubsack 1977) is a strong contender for conventional electric air conditioners because of its small volume and commercial availablility. However, the low freezing point reduces the coefficient of performance of solar chillers that typically operate at generator temperatures below 100°C. Chilled water is the only widely used storage medium in existing solar cooling systems. It has been used in stratified and nonstratified single tanks (Nishiyama et al. 1979; Hedstrom et al. 1978; Lockheed 1977) and in two tanks of different temperatures (Ward et al. "Integration"), but the cost effectiveness of this approach has been challenged in view of the low energy density and consequently high tank cost. Saturated aqueous solutions with high heats of solution offer some promise of substantial volume reduction and lower first cost, but these benefits may be offset by the need for frequent fluid replacement (Kaufman et al. 1977). Most of the current development effort is on phase-change materials that melt at a temperature low enough for effective dehumidification but high enough to avoid excessive degradation of chiller performance. Among the most promising schemes is one in which a Glauber's salt mixture (Rice and Sliwkowski 1979) is encased like sausage in a plastic film "chub" (Frysinger 1978), but a salt mixture with the desired combination of optimal melting temperature and high heat of fusion has not been found yet (Calmac 1979). Refrigerant storage appears to have performance advantages (Baughn and Jackman 1974; Grassie and Sheridan 1977) but requires pressure vessels and yet has not been examined adequately from a cost standpoint.

3.3 SELECTION OF HOT-SIDE STORAGE CONCEPTS FOR COOLING-ONLY SYSTEMS

Solar absorption and Rankine chillers may have to operate at generator temperatures above 100°C in order to be economically competitive, in which case alternatives to unpressurized hot water storage must be selected. The need for high temperature (hence higher efficiency) operation is most critical if the solar collectors are only for cooling. Suitable candidate concepts appear to be limited to those using pressurized hot water, high boiling-point liquids, and phase-change materials (which are strong contenders if they need not also provide lower temperature storage for heating).

Some operating experience has been gained already with pressurized hot water storage (Hedstrom et al. 1978). If a single tank is used, good stratification is essential; two-tank storage systems can be designed so that one tank operates at atmospheric pressure, but steel tanks may require ASME certification above a certain size even though they never operate at more than one atmosphere. In some cooling-only applications no special provisions need to be made for freeze protection, but this point should be checked thoroughly. High boiling-point liquids, such as ethylene glycol or the various heat-transfer oils, permit the use of atmospheric tanks (or a single stratified tank) with the same caveat about ASME certification, but the lower heat capacities call for larger tank volumes.

Of the candidate phase-change materials, two stand out. Magnesium chloride hexahydrate melts near-congruently at about 240°F and freezes with minimal supercooling with a heat of fusion of about 72 Btu/lb (Cantor 1978). It is fairly inexpensive but corrosive, and poses problems of heat exchange common to all salt hydrates (Calmac 1979). Partially crosslinked, high-density polyethylene pellets "melt" at about 250°F without changing shape or agglomerating, so they can be used in a packed bed with direct heat exchange to and from a high boiling point heat transport fluid (Botham et al. 1977). Their heat of fusion is about 81 Btu/lb, but the material cost is substantially higher than that of the salt hydrate although cost of heat exchangers may be less. Other polymers with different melting temperatures (Botham et al. 1978) can be used in a similar fashion. Work also is under way to identify other suitable phase-change materials (Moszynski 1978).

3.4 PHASE-CHANGE STORAGE IN BUILDING MATERIALS

Passive solar architecture uses the thermal mass of building materials to extend direct-gain solar comfort heating into the night and to make nighttime coolness available during the day. The required thermal energy storage typically is provided by materials such as brick or concrete or by water in metal or plastic containers, all of which rely entirely on sensible heat storage; i.e., the product of specific heat, mass, and temperature swing. In most solar applications, the main objective is to hold building temperature in the comfort zone by accepting, retaining, and discharging heat at temperatures in or near the comfort zone. Adding a heat of fusion component to the storage capability of common building materials improves their effectiveness by decreasing the required temperature swing and mass for a given storage capacity. The potential advantages of this approach have been established analytically and experimentally (Berlad et al. 1976; Faunce et al. 1978; Johnson et al. 1977; Habraken and Johnson 1977), but totally satisfactory methods of incorporating phase-change storage into building materials have yet to be developed.

At least three important solar applications of phase-change storage in building materials have been identified: south-facing absorber/storage walls, interior trim or structure exposed to direct solar gain, and nonirradiated or indirect gain interior elements. South-facing absorber/storage walls are often made of poured concrete or concrete block (so-called "Trombe walls") and can serve as load-bearing structures. Adding a phase-change material that melts at a temperature somewhat above the comfort zone would reduce the required south-face temperature and, as a consequence, also reduce front-end heat losses, the required wall area, and the required wall thickness (which typically exceeds that needed for structural integrity). Similar considerations apply to irradiated interior floors or walls or to ceilings that absorb reflected radiation, except that comfort rather than thermal loss reduction is the main reason for minimizing the absorbing surface temperature. Nonirradiated interior trim or structure can serve the dual function of heat and coolness storage by the addition of one phase-change material with a broad melting range that spans the comfort zone or by adding many materials with many slightly different melting points that span the zone.

Totally satisfactory technologies have not been developed yet for any of these applications. Microencapsulation of $CaCl_2 \cdot 6H_2O$ in a polyester wall panel was successful except for the inability to prevent moisture gain and loss (Lane and Rossow 1976). Infusion of calcium chloride hydrates into sealed porous concrete blocks and tiles appeared initially to be a successful approach (Hamilton and Chahroudi 1978). Samples survived hundreds of melt/freeze cycles without apparent thermal or mechanical degradation, but they swelled and cracked after several months of shelf life because of chemical incompatibility between the salt and cement. Ways of correcting these problems have been proposed (Suntek 1978) but not yet demonstrated. Another development effort, which resulted in a commercial product, involved the encapsulation of thickened Glauber's salt in flat plastic pillows encased in a polymer concrete ceiling tile (Johnson 1977). Mechanical integrity was good, and a small sample of the thickened salt mixture appeared to retain the desired properties after many cycles, but the assembled tiles exhibit only about one-third of their theoretical heat of fusion (Habraken and Johnson 1978). Methods were explored to micro- and macroencapsulate various phase-change materials in cement and polymer concrete mixes, but satisfactory coatings were not found (Sansome 1978a, and 1978b). Dispersions of paraffin waxes in a concrete mortar filler matrix were investigated also (Godfrey and Mumma 1976), but the suitability of waxes in this application has not been verified (King 1976). Other technical approaches have been proposed to the U.S. Department of Energy but not funded, and foreign work has been reported (Heap 1975; Bourdeau and Jaffrin "Latent Heat" and "Phase Change").

The generally unimpressive results are due only partly to the severity of technical problems; some of the problems encountered in discontinued projects appear solvable with moderate additional effort. They stem largely from a lack of sustained commitment and firm program goals reflected in fluctuating funding levels and the absence of cost-benefit analyses on which to base goal setting and evaluations. Particularly lacking is guidance to current and prospective technology developers on desired cost, geometries, sizes, loading densities, transition temperatures (see Section 2.2), heat-transmission characteristics, surface properties, and structural strength. Adequate guidance cannot be provided without the cooperation of all concerned U.S. Department of Energy activities: solar applications, building technology, and energy storage.

3.5 FREEZE PROTECTION FOR SOLAR WATER HEATING SYSTEMS

In most parts of the United States, protection against freezing is a costly but necessary element of current solar water heating systems, whether used for space heating, industrial process heating, or domestic hot water production. This problem involves not only the collectors and other external portions of a solar water-heating system but also the storage system with which these components are coupled. The wide variety of freeze-protection concepts being explored and in current use (Teagan 1976) attests to a continuing need for more cost-effective solutions or, at least, for a rational method of ranking the various concepts. Since no single concept may prove superior or even adequate in all scenarios, it is important to rank all credible concepts in each scenario and determine the best directions, if any, for further development.

The many conceptual approaches to freeze protection include those based on freeze prevention:

- air heating collectors with air/water indirect heat exchange,
- nonfreezing liquids in isolated collector loops with liquid/liquid indirect heat exchange,
- nonfreezing immiscible liquids with liquid/liquid direct heat exchange,
- automatic draining,
- warm water circulation, and
- electric resistance heating;

those based on freeze retardation:

- low-loss evacuated tube collectors, and
- well-insulated piping;

and those based on freeze tolerance:

- collectors with elastomeric liquid passages, and
- elastic crushable inserts.

Freeze prevention by the use of air heating collectors is a straightforward approach. However, the heat exchanger must be large and expensive because of poor air-to-water heat transfer, and its unavoidably large temperature drop imposes severe collector performance penalties. The indirect heat exchange also limits potential benefits from storage tank stratification. Rocks are a more acceptable storage media for such systems.

The use of antifreeze liquids in an isolated collector loop is a more commonly employed approach. Liquid/liquid heat exchange is less expensive than gas/liquid heat exchange, and lower temperature drops are attainable, but the penalties due to required temperature differences (de Winter 1975) and the inability to exploit stratification are still significant. Special provisions must be made for relieving the high temperatures and/or pressures associated with no-flow conditions, while often conflicting considerations of corrosion, toxicity, viscosity, and heat exchange characteristics enter into the selection of a suitable antifreeze liquid. Even reportedly nontoxic fluids may produce toxic products of decomposition at elevated no-flow temperatures.

Nonfreezing liquids that are immiscible with water permit direct heat exchange and the avoidance of large temperature drops. However, the problems of antifreeze fluid selection are compounded by requirements for immiscibility, safety, and suitably high density. Although a prototype system is being developed (Loss et al. 1976), the cost effectiveness of this approach remains uncertain.

Automatic drainage of the collectors and associated external piping is another commonly used method of freeze prevention. It avoids all of the penalties associated with indirect heat exchange and antifreeze liquids. And, by reintroducing warm water from storage, it shortens the waiting period for resumed hot water production. Typically, drainage to the storage tank is implemented by an assortment of solenoid valves, vent valves, and vacuum breakers. Often, it is supplemented by introducing a nitrogen gas inert blanket to minimize corrosion and, in some cases, to permit drainage uphill from the collectors (Veltkamp 1979). The additional sensors, controls, and piping add to system cost and maintenance, but more importantly they increase the probability of failure leading to irreparable damage. Some draindown systems have operated successfully for several years, but many carefully engineered systems have failed for a variety of unanticipated reasons.

Warm water recirculation from storage is a simpler way to avoid the problems associated with antifreeze liquids and indirect heat exchange; it merely involves activation of the circulating pump whenever the sensed collector outlet temperature approaches freezing (Nishio and Sugiura 1979). However, warm water circulation still depends on the absolute reliability of a sensor and controls. Where prolonged freezing conditions are infrequent, the substantial heat losses might be acceptable and the probability of concurrent failure might be sufficiently small.

Electric resistance heating of the collector and external piping, using "heat tape" (Wilcox and Barnaby 1975), is a comparable alternative to the recirculation method. It also is limited in application to regions where freezing conditions seldom occur.

In regions with mild winters, the use of low-loss evacuated tube collectors and heavily insulated external piping often can retard freezing for the duration of the longest cold night while preventing it during overcast cold days (Ward et al. 1979). Instances of total reliance on this approach have been reported by R. Bruno of The Philips Research Laboratories, Aachen, but available information suggests that backup controls have been provided on all surviving systems in moderate climates.

Freeze tolerance is a relatively unexplored but potentially promising approach that appears to avoid nearly all the deficiencies of freeze preventing and retarding concepts. One version is based on the use of collectors with elastomeric fluid passages that expand to accommodate the expansion due to freezing. Another version involves elastically deformable inserts at critical locations in rigid fluid passages and piping.

Plastic collectors are commercially available that, more or less, meet the requirements for freeze tolerance by virtue of elastic expansion, but other provisions must be made for the piping to which they connect, according to J. Armstrong, Calmac Manufacturing Corporation. Also, the volume of their liquid passages tends to be too large for rapid thawing. A design with much less water volume and with pipe connections projecting downward into heated space was partially developed but discarded because of excessive material costs (Swet et al. 1975).

Successful experiments with a deformable insert were conducted several years ago, using a sealed, air-filled flexible tube inside a rigid pipe (Bickle "Passive Freeze Protection"). A system using glycol-filled silicone rubber tubes inside rigid collector tubes has been operating in Holland since 1977 with apparent success (van Koppen and Thomas "Preliminary Performance"). In this system, glycol is expelled from the freeze-compressed rubber tube into a small, slightly pressurized reservoir. The tubes automatically refill when the ice melts. Installation of this system is described as "rather laborious," and no mention is made of the possibility of glycol introduction into the water system in the event of tube rupture or leakage.

3.6 JUSTIFICATION OF PHASE-CHANGE STORAGE FOR ACTIVE SOLAR SPACE HEATING

Phase-change storage has been widely viewed as a clearly superior "second generation" technology that ultimately will supersede sensible heat storage in active solar space heating systems, but that view is increasingly contested. Proponents cite as compelling advantages the small volume (hence, more living space and easier retrofit) and the isothermal storage (hence, lower charging temperature and consequently more efficient solar collection). Countering these considerations are others, notably higher investment cost and unsuitability of many phase-change storages for combined heating and cooling systems, which suggest that the net advantage might be marginal in many cases. Justification of federal support for further development should be based on more comprehensive cost-benefit analyses than are presently available.

The prevalent enthusiasm for phase-change storage stems largely from early approximate estimates of its volumetric energy storage density relative to rocks and water. One such comparison (Telkes 1974) indicated that a Glauber's salt system would have eight times the energy density of water and 17 times that of rocks, based on a 20°F temperature swing and 20% void fraction. Other comparisons of volumetric storage densities, based on design studies (Lorsch 1974) and overall system simulations (Morrison and Abdel-Khalik 1978; Jurinak and Abdel-Khalik 1979b; van Gallen and den Ouden 1979; Ziegenbein 1979), are less dramatic (see Table 3-9). No firm conclusions can be drawn from the tabulated data other than the obvious lack of consistent assumptions and methodologies (see Section 2-3). In only one study (Jurinak and Abdel-Khalik 1979b) was an attempt made to express the added value of phase-change storage in terms of the cost of floor space.

In principle, the charging temperature for a material that stores heat isothermally can be substantially lower than that for a sensible heat storage material. In practice, the difference might be modest, depending on the actual transition temperature, relative input/output temperature drops, sharpness of phase transition, heat of fusion, relative specific heats, selected solar fraction, degree of stratification, and other factors. This attribute is seldom examined separately, but its effect has been included in solar space-heating simulations using solar fraction as the figure of merit (Morrison and Abdel-Khalik 1976 and 1978; Jurinak and Abdel-Khalik 1978, 1979a, and 1979b; van Gallen and den Ouden 1979; Ziegenbein 1979). At near-maximal solar fractions, the reported improvements range from slightly negative to perhaps 5%.

Table 3-9. COMPARISON OF PHASE CHANGE AND SENSIBLE HEAT (Storage System Volume)

	Temp. swing					
Storage Medium	20°F[a]	20°F[a]	b	b	b	24-56°C
Rocks	17.0	4.0	-	4.7	-	-
Water[c]	8.0	6.3	2.0	-	2.0	2.0
Sunoco P-116 wax	2.6	2.0	2+	2.5	-	-
$Na_2S_2O_3$ $10H_2O$	1.0	-	-	-	-	-
Na_2HPO_4 $12H_2O$	-	-	-	1.1	1.0[d]	-
Na_2SO_4 $10H_2O$	1.0	1.0	1.0	1.0	-	-
Wax m.p. 24°C	-	-	-	1.2	-	-
Wax m.p. 15-25°C	-	-	-	-	-	1.0

[a] Equal capacity.

[b] Not stated; for approximately equal solar fractions.

[c] Assumed to be fully mixed (no benefit from stratification).

[d] No voids.

Adding to or subtracting from the economies due to smaller volume and isothermal storage are differences in the investment cost of phase-change and sensible-heat systems. In one study (Lorsch 1974), costs per unit capacity of two phase-change systems were compared with those of water storage for various capacities, temperature swings, and material unit costs. Another costing study (Arthur D. Little, Inc. "Economic Assessment") compared four other phase-change materials, each in a different system configuration, with water tanks and rockbeds. In most of the examined cases, the phase-change systems were shown to be more expensive, but one extremely inexpensive phase-change system concept was identified. That concept, based on the use of stabilized Glauber's salt encased in plastic film "chubs" similar in shape to sausages, might be of questionable value if the melting temperature (89°F) is found to be unacceptably low (see Section 2.2). Application of the same general packaging technique to phase-change materials with higher melting points has been attempted unsuccessfully (Lane et al. "Macro-Encapsulation") but might be worth more exploration.

Programmatic decisions regarding federal funding of further development must be based, at least in part, on overall system cost/value relationships (see Section 2-1). This should be done even though separate examination of relative volume, achievable solar fraction, storage unit cost, etc. is useful for screening purposes and adds insight.

In selecting scenarios having substantial national impact, special consideration should be given to the fact that phase-change materials most suitable for space heating applications (melting temperatures of roughly 35-45° C) are unsuitable for either absorption or Rankine solar space-cooling systems, which typically call for input temperatures above 80° C. If heating-only applications are seen to have a relatively small potential market, the incentive to sponsor development of phase-change systems solely for that purpose might vanish even though economies on a unit basis may be apparent.

Small volume clearly is favored in retrofit situations, as it is in new construction, other things being equal. The special advantage of smallness in a retrofit situation is the ability to deliver a complete factory-built storage unit through existing building openings with minimal rigging expense and/or structural alterations. Whether or not phase-change systems can meet the requirements of small dimensions, maneuverable geometry, moderate shipping weight, and structural integrity while being handled, without excessive cost penalties, remains to be seen. If they can, their competitive edge over water tanks depends heavily on whether the relative volume is closer to 2 or to 8 (see Table 3-9) and whether the tank also is designed with retrofit in mind. If the storage material must be shipped separately and loaded in place, the system is more comparable to a "kit" rockbed.

Justification of support for continued development of phase-change systems should consider not only the merits of phase-change storage versus rocks and water, but also the merits of phase-change storage versus other "advanced" storage technologies such as thermochemical heat pumps. Possibly, phase-change storage will be found clearly superior to sensible-heat storage in most important respects but not merit support because these other storage approaches could be developed in the same time and would compete for limited funds.

SECTION 4.0

REFERENCES

Anand, D. K.; et al. 1978. *Control Strategy Studies of Solar Heating and Cooling Systems*. College Park, MD: Dept. of Mechanical Engineeering, University of Maryland.

Arthur D. Little, Inc. 1979. *Economic Assessment of Thermal Energy Storage Technologies. Draft Final Report*. Chicago, IL: Argonne National Laboratory.

Asbury, J. G.; et al. 1977. "Commercial Feasibility of Thermal Storage in Buildings for Utility Load Leveling." *Proceedings of the American Power Conference*. Vol. 39.

Asbury, J. G.; Giese, R. F.; Mueller, R. O. 1978. "The Interface with Solar Alternative Auxiliary Supply Systems." *Proceedings of International Solar Energy Conference*, 1977; New Delhi.

Baughn, J.; Jackman, A. 1974. *Solar Energy Storage within the Absorption Cycle*. ASME 74-WA/HT-18. Washington, D.C.: American Society of Mechanical Engineers.

Baylin, F. 1979. *Low Temperature Thermal Energy Storage: A State of the Art Assessment*. SERI/RR-54-164. Golden, CO: Solar Energy Research Institute.

Baylin, F.; Merino, M. Forthcoming 1980. *Survey of Thermal Energy Storage Projects*. Golden, CO: Solar Energy Research Institute.

Berlad, A.; et al. 1976. *Comfort Range Thermal Storage*. CONF-761107-9. Washington, D.C.: U.S. Department of Energy.

Bickle, L. W. "Passive Freeze Protection for Solar Collectors." *Solar Energy*. Vol. 17: p. 373.

Botham, R. A.; et al. 1977. *Form-Stable Crystalline Polymer Pellets for Thermal Energy Storage*. Phase 1, Final Report. Washington, D.C.: U.S. Department of Energy.

———. 1978. *Form-Stable Crystalline Polymer Pellets for Thermal Energy Storage: High Density Polyethylene Intermediate Products*. ORNL/Sub-7398/4; MRC-DA-760. Oak Ridge, TN: Oak Ridge National Laboratories.

Bourdeau, L.; Jaffrin, A. *Latent Heat Diode Wall*. Nice, France: Laboratoire CNRS d'Ecothermique Solaire, Observatoire de Nice 06.

———. *Phase Change Collector Wall Versus Water Collector Wall*. Nice, France: Laboratoire CNRS d'Ecothermique Solaire, Observatoire de Nice 06.

Calmac Mfg. Corp. 1979. Technical status and progress reports through July 1979.

Cantor, S. 1978. "Thermophysical Properties and Behavioral Characteristics of Phase Change Materials." *Proceedings: Third Annual Thermal Energy Storage Contractors' Information Exchange Meeting*. CONF-781231. Washington, D.C.: U.S. Department of Energy.

Chahroudi, D.; Miller-Wellesley, S. 1976. "Thermocrete Heat Storage Materials: Applications and Performance Specifications." Proceeding of Joint Conference of ASISES and Solar Energy Society of Canada, Winnipeg.

Clark, G.; Allen, C. 1979. "Sensible and Latent Comfort Cooling Requirements of Conventional and Passively Cooled Residences in American Cities." No. 799057. Proceedings of 14th IECEC.

Cook, R. E.; Krusback, P. E. 1977. "Concept and Development of a Residential Ice Storage System." CH-77-10#2. ASHRAR Trans. Vol. 83; Part 1.

Copeland, R. J. 1979. The Value of the Thermal Storage in Solar-Thermal Applications: Executive Summary. SERI presentation 3500-RJC-004. Golden, CO: Solar Energy Research Institute.

Davison, R. R.; et al. "Storing Sunlight Underground." Chemtech. Dec. 1975.

de Winter, F. 1975. "Heat Exchange Penalties in Double-Loop Solar Water Heating Systems." Solar Energy. Vol. 17: p. 335.

Duff, W. S.; et al. 1978. "Simulation and Design of Evacuated Tubular Solar Residential Air Conditioning Systems and Comparison with Actual Perfomance." Proceedings of International Solar Energy Conference, 1977; New Delhi.

Electric Power Research Institute. 1977. Cool Storage Assessment Study. EM-468. Palo Alto, CA: Electric Power Research Institute.

Fanger, P. O. 1970. Thermal Comfort. New York: McGraw-Hill.

Faunce, S. F.; et al. 1978. "Application of Phase Change Materials in a Passive Solar System; Solar Collector Storage Wall; Passive Solar Collector Wall Incorporating Phase Change." Proceedings of DOE/ISE-AS 2nd National Passive Solar Conference, University of Pennsylvania.

Frysinger, G. F. 1978. "Life and Stability Testing of Packaged Low-Cost Energy Storage Materials." Third Annual Proceedings of Thermal Energy Storage Contractors' Information Exchange Meeting. CONF-781231. Washington, D.C.: U.S. Department of Energy.

Godfrey, R. D.; Mumma, S. A. 1976. Thermal Performance of Paraffin Phase Change Materials Dispersed in a Concrete Mortar Filler Matrix. ASME 76-WA/HT-33. Washington, D.C.: American Society of Mechanical Engineers.

Grassie, S. L.; Sheridan, N. R. 1977. "Modeling of a Solar-Operated Absorption Air Conditioner System with Refrigerant Storage." Solar Energy. Vol. 19: p. 691.

Habraken, N. J.; Johnson, T. E. 1978. Design Methodologies for Energy Conservation and Passive Heating of Buildings Utilizing Improved Building Components. Progress Report No. 3, Jan 15-April 15, 1978.

Hamilton, L. B.; Chahroudi, D. 1978. "Development of Thermocrete Heat Storage Materials." Proceedings of International Solar Energy Conference, 1977; New Delhi.

Heap, R. D. 1975. "Thermal Storage in Buildings." Build Int (English Edition). Vol. 8 (No. 1): Jan-Feb; pp. 1-16.

Hedstrom, J. C.; Murray, H. S.; Balcomb, J. D. 1978. Control of a Rankine Chiller and an Absoption Chiller in the National Security and Resources Study Center. CONF-7805126-2. Washington, D.C.: U.S. Department of Energy and Los Alamos Scientific Laboratory.

Hughes, P. J.; Duffie, J. A.; Beckman, W. A. "Simulation Study of Several Solar Heating Systems with Offpeak Auxiliary." Solar Energy. Vol. 19: p. 317.

Johnson, T. E. 1977. "Lightweight Thermal Storage for Solar Heated Buildings." Solar Energy. Vol. 19: pp. 669-675.

Johnson, T. E.; Miller-Wellesley, S.; Andrejko, D. 1977. Lightweight Building Materials for the Storage of Solar Energy. Report for May 75-May 77.

Jurinak, J. J.; Abdel-Khalik, S. I. 1978. "Properties Optimization for Phase Change Energy Storage in Air-Based Solar Heating Systems." Solar Energy. Vol. 21: p. 377.

__________. 1979a. "Sizing Phase-Change Energy Storage Units for Air-Based Solar Heating Systems." Solar Energy. Vol. 22: pp. 355-359.

__________. 1979b. "The Sizing and Economics of Phase Change Energy Storage Units in Air-Based Solar Heating Systems." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Kaufman, K. W.; Lorsch, H. G.; Kyllonen, D. M. 1977. Thermal Energy Storage by Means of Saturated Aqueous Solutions. Final Report, July 1976-November 1977. Frankling Inst. Res. Labs.

King, A. P. 1976. Materials for Thermal Energy Storage at Near Ambient Temperatures. ECRC/M-893. Copenhaurst, England: Electricity Council Research Centre.

Lane, G. A.; Kott, A. C.; Rossow, H. E. Macro-Encapsulation of Heat Storage Phase-Change Materials for Use in Residential Buildings. Final Report. Washington, D.C.: U.S. Department of Energy.

Lane, G. A.; Rossow, H. E. 1976. "Encapsulation of Heat-of-Fusion Storage Materials." Proceedings of Second Southeastern Conference on Application of Solar Energy. Baton Rouge, LA; April. DOE CONF-760423. Washington, D.C.: U.S. Department of Energy.

Lee, C. 1979. Solar Applications to Thermal Energy Storage. H-C-199-79-753F. Hittman Associates, Inc.

Lockheed Palo Alto Research Lab. 1977. Santa Clara, California, Community Center Commerical Solar Demonstration Design and Construction Report. SAN-1083-77/1. Palo Alto, CA: Sandia Laboratory.

Lof, G. O. G.; Tybout, R. A. "The Design and Cost of Optimized Systems for Residential Heating and Cooling by Solar Energy." Solar Energy. Vol. 16 (No. 1): p. 9.

Lorsch, H. G. 1974. "Thermal Energy Storage Devices Suitable for Solar Heating." Proceedings of 9th IECEC, 1974.

Loss, W. M.; Ward, J. C.; Lof, G. O. G. 1976. "A Direct Contact Liquid-Liquid Heat Exchanger for Solar Heated and Cooled Buildings." Proceedings of Joint Conference of ASISES and Solar Energy Society of Canada, Winnipeg.

Morrison, D. J.: Abdel-Khalik, S. I. 1976. "Performance of a Solar Heating System Utilizing Phase-Change Storage." Proceedings of Joint Conference of ASISES and Solar Energy Society of Canada, Winnipeg.

Morrison, D.; Abdel-Khalik, S. I. 1978. "Effects of Phase-Change Energy Storage on the Performance of Air-Based and Liquid-Based Solar Heating Systems." Solar Energy. Vol. 20: pp. 57-67.

Moszynski, J. R. 1978. "Development of Intermediate Temperature Thermal Energy Storage Systems." Proceedings of Third Annual Thermal Energy Storage Contractors' Information Exchange Meeting. DOE CONF-781231. Washington, D.C.: U.S. Department of Energy.

Nishio, M.; Sugiura S. 1979. "Solar Heating and Hot Water Supply System of Fuji Electric Solar House." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Nishiyama, E.; et al. 1979. "Test Results of the Solar Powered Rankine Cycle Refrigerator Installed in the Experimental House." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Offenhartz, P. forthcoming Collector Storage Trade-offs in Solar Air Conditioning: Computer Simulations for Washington and Fort Worth. EIC Corporation.

Rice, W. J.; Slikowski, J. J. 1979. "Experimental Study of Coolness Storage Using Sodium Sulfate Decahydrate." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Sansome, M. J. 1978a. Encapsulation of Phase Change Materials in Concrete Masonry Construction. Progress Report No. 1, Aug 77-Feb 78. BNL 50827. Columbus, OH: Battelle National Laboratory.

__________. 1978b. Encapsulation of Phase Change Materials in Concrete Masonry Construction. Progress Report No. 2, March-May 1978. BNL 50896. Columbus, OH: Battelle National Laboratory.

Suntek Research Associates. 1978. "Thermocrete Phase I-A Report." Unpublished, submitted to Oak Ridge National Laboratory.

Swet, C. J.; Ussery, J.; Peterson, E. 1975. "A Freeze-Tolerant Solar Water Heater." Extended Abstracts. Proceedings of 1975 International Solar Energy Society Congress; Los Angeles.

Teagan, W. P. 1976. "Approaches to Freeze Protection for Solar Collectors Using Liquid Heat Transfer Media." Proceedings of Workshop on Solar Energy in Cold Climates; Detroit; 1976. ERDA CONF-760633. Washington, D.C.: U.S. Department of Energy.

Telkes, M. 1974. Storage of Solar Heating/Cooling. ASHRAE Transactions. Vol. 80, Part II.

Thornton, J; et. al. 1980. Comparative Ranking of 0.1-10 Megawatt Solar Thermal Electric Power Systems. SERI/TR-351-461. Golden, CO: Solar Energy Research Institute.

U. S. Department of Energy. National Plan for Solar Heating and Cooling. DOE/SC-0008. Washington, D.C.: U.S. DOE.

van Gallen, E.; den Ouden, C. 1979. "Development of a Storage System Based on Encapsulated P. C. Materials." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

van Koppen, C. W. J.; Thomas, Simon J. P. Preliminary Performance of the Heating System in the Solar House of the Eindhoven University of Technology. WPS3-78.11.R291. Eindhoven, The Netherlands: Department of Mechanical Engineering, Sec. of Heat and Flow Technology, Eindhoven University of Technology.

Veltkamp, W. M. 1979. "A Closed Drain-Down System in a Medium Size Solar Heating System." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Ward, D.; Lof, G. O. G.; Uesaki, T. 1978. "Cooling Subsystem Design in CSU Solar House III." Solar Energy. Vol. 20: p. 119.

Ward, D. S.; et al. 1979. "Integration of Evacuated Tubular Solar Collectors with Lithium Bromide Absorption Cooling Systems." Solar Energy. Vol. 22: p. 335.

Wilcox, B. A.; Barnaby, C. S. 1975. "Freeze Protection for Flat-Plate Collectors Using Electric Resistance Heating." Extended Abstracts. Proceedings of 1979 International Solar Energy Society Congress; Los Angeles.

Wray, W. O. 1979. "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

Wyman, C. E. 1979. Thermal Energy Storage for Solar Applications: An Overview. SERI/TR-34-089. Golden, CO: Solar Energy Research Institute.

Ziegenbein, B. 1979. "Investigation of Latent Heat of Fusion Storage for Solar Heating Systems." Proceedings of 1979 International Solar Energy Society Congress; Atlanta.

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SECTION 5.0

BIBLIOGRAPHY

FOR SECTION 3.1

General

A.T.R.A.C.s.a. "Solar Heating and Inter-seasonal Storage for Groups of Dwellings." Report on research program partly sponsored by the Commission of the European Communities under contract No. 17-76ESB. October 1977.

Davison, R. R. "Long Term and Seasonal Storage Group Report." Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville, VA., 1975. NSF report NSF-RANN-75-041. Washington, D.C.: National Science Foundation.

Dubin-Bloome Associates. Prefeasibility Analysis and Study of the Seasonal Storage Systems for the Pennsylvania Avenue Redevelopment Project. Aug. 1978.

Givoni, B. "Underground Longterm Storage of Solar Energy—An Overview." Solar Energy. Vol. 19 (No. 6): 1977.

Swet, C. J. "Long Duration Storage of Thermal Energy." la Recherche (to be published in 1980).

Natural Aquifers

Davison, R. R.; et. al. "Storing Sunlight Underground" Chemtech Dec. 1975.

Desert Reclamation Industries. "Aquifer Storage at J. F. Kennedy International Airport." Draft Final Report. Aug. 23/78. DOE contract EC-77-C-01-5083.

Earth Sciences Division, Lawrence Berkeley Laboratory. "A Quarterly Review of Aquifer Thermal Energy Storage." ATES Newsletter. Vol. 1 (No. 1): Oct. 1978 through (No. 4): Sept. 1979.

Ebeling, L.; et al. "The Effect of System Size on the Practicality of Aquifer Storage." Proceedings of the 1979 International Solar Energy Society Congress, Atlanta.

Fox, E. C.; Thomas, J. F. A Preliminary Economic Analysis of Winter-Chill Storage at the John F. Kennedy Airport. ORNL/TM-6876. Oak Ridge National Laboratory; 1976.

General Electric-TEMPO. Reports on Large Scale Seasonal Thermal Energy Storage in Aquifers (list available from G-E TEMPO).

Geraghty; et al. "Water Atlas of the United States." Port Washington, NY: Water Information Center, 1973.

Menjoz, A.; Joos, B. "Simulation du Comportement des Nappes Souterraines par Modeles Numeriques." (in French) Presented at symposium SIMULATION 77, Montreux, Switzerland, 22-24 June 1977.

Messerschmitt-Boelkow-Blohm GmbH. "Summary-Study Report on Seasonal Heat Storage Systems in the Low-Termperature Range" (English Translation). MBB report UR-317-76, May 26. Prepared for W. German Federal Ministry of Research and Technology. Also, complete translation of Vol. 1, parts 1 and 2. with title differently translated to "Study of Annual Heat Storage Wells with Low Temperature Levels," ERDATR-269.

Molz, F. J.; Parr, A. D.; Andersen, P. F. "Thermal Energy Storage in Aquifers: Experimental Study." *Proceedings of the 14th IECEC,* 1979.

Powell, W. R. "The Case for CASES." *Environment.* Vol. 20 (No. 6): Jul/Aug 78.

Proceedings of the Thermal Energy Storage in Aquifer Workshop, May 10-12, 1978, Berkeley, CA. CONF-780540 (contains many references). Washington, D.C.: U.S. Department of Energy.

Schaetzle, W. J.; Brett, C. E.; Grubbs, D. M. "Energy Storage in Groundwater Aquifers." *Proceedings of the 1979 International Solar Energy Society Congress.* Atlanta.

Shell, G. L.; Wendt, R. C. "Spray Cooling: an Alternative to Cooling Towers." *Pollut Eng.* Vol. 9 (No. 7): July 1977; pp. 32-36.

Tsang, C. F. *Aquifer Thermal Energy Storage.* CONF-780714-2. Washington, D.C.: U.S. Department of Energy; 1978.

__________. *Summary of Current Studies in Aquifer Thermal Energy Storage.* CONF-780443-2. Washington, D.C.: U.S. Department of Energy; March 1978.

Warman, J. C.; Moltz, F. J.; Jones, T. E. *Subsurface Waste-Heat Storage: Experimental Study: Final Report, Nov. 15/75—June 30/77.* ORO/5003-1. Washington, D.C.: U.S. Department of Energy; January 1978.

Ground

Benet, J. C.; P-made, P.; Hinzelin, P. "Measurement of the Thermal Conductivity of Soils by Cyclindrical Probe in Transitory Regime. Study of the Effect of the Method of Placing the Probe." *Mater Constr Mater Struct.* Vol. 10 (No. 60): Nov-Dec 77; p. 385-392.

Crawford, M. "Transient Conduction in the Space Surrounding a Ring of Holes." ASME paper 77-WA/HT-12, 1977.

Dijkmans, A. P. G.; Fischer, L. S.; van Koppen, C. W. J. "The Long Term Storage of Solar Heat in the Ground."

Eckert, E. R. G. "The Ground Used as Energy Source, Energy Sink, or for Energy Storage." Working Papers. NATO Science Committee Conference on Thermal Energy Storage, Turnberry, Scotland, March 1-5, 1976.

Fischer, L. S.; van Koppen, C. W. J.; Puts, J. J. "Basic Aspects of the Seasonal Storage of Solar Heat in the Ground." Abstract R-III-B-2 (complete paper). Proceedings of the 1979 International Solar Energy Society Congress, Atlanta.

Nicholls, R. L. "Optimal Proportioning of an Insulated Earth Cylinder for Storage of Solar Heat." Solar Energy. Vol. 19 (No. 6): 1977.

Shelton, J. "Underground Storage of Heat in Solar Heating Systems." Solar Energy. Vol. 17. (No. 2): 1975.

Torrenti, R. "Seasonal Storage in Solar Heating Systems—Results of a 3-year Program." Proceedings of the 1979 International Solar Energy Congress, Atlanta.

Vachaud, G.; Ausseur, J-V. "The 'Soil Therm' System for Interseasonal Earth Storage of Solar Heat for Individual Housing." Abstract R-III-B-6 (complete paper). Proceedings of the 1979 SolarEnergy Society Congress, Atlanta.

Yuan, S. W.; Bloom, A. M. Long Duration Earth Storage of Solar Energy, Final Report for the Period of June 1, 1977—January 31, 1978. Oak Ridge National Laboratory.

__________. "Technical and Economical Aspects of Solar Energy Earth Storage." International Solar Energy Symposium on Technical, Economical and Organizational Aspects, Belgrade, October 1978.

Yuan, S. W.; Bloom, A. M.; Nazli, M. "Heat Transfer in Solar Energy Storage." Paper 77-HT-38. AIChE-ASME Heat Transfer Conference, Salt Lake City, Utah, August 15-17, 1977.

Water (other than in natural aquifers)

B. & A. Engineers, Ltd. "An Assessment of the Technoeconomic Feasibility of Seasonal Thermal Energy Storage." Chicago, IL: Argonne National Laboratory, 1979.

Baylin, F.; Monte, R.; Sillman, S. Annual-Cycle Thermal Energy Storage for a Community Solar System - Details of Sensitivity Analyses. Golden, CO: Solar Energy Research Institute; SERI/TR-355-575; April 1980.

__________. Sensitivity Analyses of a Community Solar System Using Annual Cycle Thermal Energy Storage. 2nd Miami International Conference on Alternative Energy Sources, Miami, FL; December 10-13, 1979. Golden, CO: Solar Energy Research Institute; 1979.

Beard, J. T.; et al. "Annual Collection and Storage of Solar Energy for the Heating of Buildings." Proceedings of the 1979 International Solar Energy Conference, New Delhi.

Besant, R. W.; Dumont, R. S.; Schoenau, G. "Saskatchewan House: 100 Percent Solar in a Severe Climate." (Includes a critique by Amory Lovens.) Solar Age. pp. 18-24, May 1979.

Cavallei, G.; Foligno, G. "Proposal for the Production and Seasonal Storage of Hot Water to Heat a City." Solar Energy. Vol. 19: pp. 677-683, 1977.

Dickey, J. W.; et al. "Annual Collection and Storage of Solar-Heated Water for the Heating of Buildings." Proceedings of the Workshop on Solar Energy in Cold Climates. CONF-760633. Washington, D.C.: U.S. Department of Energy; 1976.

Fischer, L. S.; van Koppen, C. W. J.; Mennink, B. D. "The Thermodynamics and Some Practical Aspects of Thermally Layered Heat Storage in Water." Working Papers. NATO Science Committee Conference on Thermal Energy Storage, Turnberry, Scotland, March 1-5, 1976.

Hollands, K. G. T.; Gladwell, G. M. L.; Schneider, G. E., "Conductive Heat Transfer from Hemispherical, Buried Tanks with Application to Solar Heating." Proc. Int'l. Heat Transfer Conf., 6th, Toronto, 1978.

Hooper, F. C.; Attwater, C. R., "Design Method for Heat Loss Calculation for In-ground Heat Storage Tanks." CONF-771120-4. Washington, D.C.: U.S. Department of Energy, 1977.

——————— "Optimization of an Annual Storage Solar Heating System over Its Life Cycle." paper 16-11. Proceedings of 1977 Annual Meeting, American Section of the International Solar Energy Society, Orlando.

——————— "Solar Space Heating Systems Using Annual Heat Storage." Progress Reports July 1, 1976 through Dec. 30, 1977. Report COO/2939-1. Washington, D.C.: U.S. Department of Energy.

Lilleleht, L. U.; Fafarman, L. M.; Beard, J. T. "Earth-conducted Heat Losses from Thermal Storage Systems." Proc. Thermal Storage and Heat Transfer in Sol. Energy Syst., Symp. ASME Winter Annual Mtg., 1978.

Lovens, A.; Bethe, H. Correspondence Series. Foreign Affairs. April 1977.

Lunde, P. J. "Prediction of the Performance of Solar Heating Systems Utilizing Annual Storage." Solar Energy. Vol. 22 (Vol. 1): 1979.

Margen, P. "Central Plants for Annual Heat Storage." Solar Age. Vol. 3 (No. 10): Oct. 1978, pp. 22-26.

Mueller, R. O.; et al. "Optimal Design of Seasonal Storage for 100% Solar Space Heating in Buildings." Proceedings AAS Symposium on Efficient Comfort Conditioning, 1978 Winter Annual Meeting.

——————— "Optimization of Central Solar Heat Stations with or without Use of Heat Pump." Paper VVS 78. AB Atomenergi, Studsvik, Sweden.

Rabl, A.; Nielsen, C. "Solar Ponds for Space Heating." Solar Energy. Vol. 17: pp. 1-12, 1975.

Roseen, R. Central Solar Heat Station in Studsvik. Report STUDSVIK/ET-78/77. Aktiebolaget Atomenergi, Sweden.

Scholl, G. "Grosswarmespeicher." In German

——————— "Warme fur eine Million Menschen." In German

——————— "Large Scale Hot Water Storage Facilities." Working Papers. NATO Science Committee Conference on Thermal Energy Storage, Turnberry, Scotland, March 1-5, 1976.

Speyer, E. "Optimum Storage of Heat with a Solar House." Solar Energy. Vol. 3 (No. 4): pp. 24-48.

Stickford, G. H., Jr.; Holt, C. F.; Whitacre, G. R. "An Analysis of Buried Heat Storage Tank Losses." Proc. Joint conf ASISES and SE Soc of Canada, Winnipeg, 1976.

Taylor, T. B. Low Cost Solar Energy. International Scientific Forum on an Acceptable Nuclear Energy Future of the World, Sunrise Inn, Ft. Lauderdale, FL, Nov. 11, 1977.

Roseen, R. Central Solar Heat Station in Studsvik. Report STUDSVIK/ET-78/77. Aktiebolaget Atomenergi, Sweden.

Williams, G. T.; Attwater, C. R.; Hooper, F. C. "A Design Method to Determine the Optimal Distribution and Amount of Insulation for In-ground Heat Storage Tanks." Abstract R-III-B-8 (complete paper), Proceedings 1979 ISES Congress, Atlanta.

Ice

Bahadori, M. N.; Kousar, A. "Performance of the Natural Ice Makers." Proceedings of the 1979 International Solar Energy Conference, New Delhi.

Bligh, T. P. "Description of Ice Storage System." Building Systems Design. Oct/Nov 1976. See also in NSF-RA-760006, National Science Foundation, Washington, D.C.

Cerruti, D. "Dual Phase Annual Cycle for Residential Heating and Cooling." Proceedings of the Joint Conference of the ASISES and Solar Energy Society of Canada, Winnipeg, 1976.

——————— "Dual Phase Annual Cycle, Index of Application." Paper 16-25.

Gorski, A. J. Long Term Ice Storage for Cooling Applications Using Passive Freezing Techniques—ANL Activity No. 49583. Technical Status Report 10/1/76-5/31/79. Chicago, IL: Argonne National Laboratory.

Wilson, S. R.; Quarls, H. F.; Markeloff, R. G. "Modeling and Heat Transfer Between an Ice-Water Storage Reservoir and Its Surroundings." DOE contract W-7405-ENG-26, 23 April 75.

Yang, K.T.; Delich, M. "The Application of Thermosyphon in a Long-Duration, Low Temperature Storage System for Residential Cooling." Proceeding of Solar Energy Storage Options Workshop, San Antonio, TX; March 19-20, 1979. CONF-790328-P1. Washington, D.C.; U.S. Department of Energy, 1979.

Chemical

Clark, E. C. "Sulfuric Acid and Water Chemical Heat Pump/Chemical Energy Storage Program — Final Report - Phase II-A (Draft) March 1977 - Feb 1978." RRC-79-R-627. Palo Alto, CA: Sandia Corp.

Clark, E. C.; Hiller, C. C. "Sulfuric Acid—Water Chemical Heat Pump/Energy Storage System Demonstration." CONF-781202-1. Washington, D.C.: U.S. Department of Energy, Aug 78.

Hiller, C. C.; Clark, E. C. "Development of the Sulfuric Acid-Water Heat Pump/Chemical Energy Storage System for Solar Heating and Cooling." Proceedings of the 1979 International Solar Energy Society Congress, Atlanta, 1979.

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