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SERI/RR-54-164

July 1979

MASTER

Low Temperature Thermal Energy Storage: A State-of-the-Art Survey

Frank Baylin

Solar Energy Research Institute
A Division of Midwest Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

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Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $6.50

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SERI/RR-54-164
UC CATEGORY: UC-59,59A,59B,59C

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FRANK BAYLIN

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FOREWORD

This document is part of a coordinated effort at the Solar Energy Research Institute (SERI) to examine all aspects of energy storage technologies having applications in solar power systems. Storage systems are perceived as being critically important to many solar energy applications.

The data in this report are designed to aid the planning efforts of the Chemical and Thermal Energy Storage Branch under John Gahimer in the Division of Energy Storage at the Department of Energy (DOE). A contract issued by this branch has funded a substantial part of this work (earlier funding was from Energy Technology). A second report will include an evaluation of the economic and programmatic aspects of low temperature thermal energy storage technologies.

Related work is progressing in three other groups within SERI. A report by Charles Wyman (Thermal Conversion Branch) describes thermal energy storage technologies and outlines FY79 SERI programs [1]. A report by Bob Copeland (Systems Analysis Branch) describes ongoing research in evaluation of thermal energy storage technologies for solar thermal power applications [2]. The Special Programs Office is examining the feasibility of SERI managing storage-related contracts.

The author wishes to express his appreciation to a number of associates who contributed both information and critical reviews of this document. They include Alan Michaels of Argonne National Laboratories; Mike Davis, Alan Michaels, and C. J. Swet of DOE; Bob Kedl of Oak Ridge National Laboratories; Taz Bramlette of Sandia; Bob Copeland, Frank Kreith, Lyle Groome, Ken Touryan, and Charles Wyman of SERI; and numerous other researchers listed in this report. Jim Stice, presently at Kalwall Corporation, aided in assembling much of the information on phase-change-material storage while employed at SERI. He also provided a valuable critical review of this document.

The author would appreciate useful criticisms and feedback about errors or omissions. Such information will be helpful in compiling later editions and in aiding DOE and National Lab personnel in program planning.

Richard S. Stevenson, Chief
Program Planning Branch

Approved for:
SOLAR ENERGY RESEARCH INSTITUTE

Melvin Simmons, Assistant Director
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SUMMARY

This report is the preliminary version of an analysis of activities in research, development, and demonstration of low temperature* thermal energy storage (TES) technologies having applications in renewable energy systems. Storage technologies considered here have applications in heating and cooling of residential and commercial buildings and, to a certain extent, in agricultural and industrial processes. Three major categories of thermal storage devices are considered:

- sensible heat;
- phase change materials (PCM); and
- reversible thermochemical reactions.

Both short-term and annual thermal energy storage technologies based on principles of sensible heat are discussed. Storage media considered are water, earth, and rocks. Annual storage technologies include solar ponds, aquifers, and large tanks or beds of water, earth, or rocks. PCM storage devices considered employ salt hydrates and organic compounds. The sole application of reversible chemical reactions outlined is for the chemical heat pump. In all cases, advantages and disadvantages associated with these technologies are discussed. Also presented is a brief survey of applications of low temperature TES.

A number of other technologies which can be classified as TES have been excluded from this report for two reasons. First, attempts were made to consider those technologies included in the Thermal Energy Storage program of the Division of Energy Storage (STOR) in DOE. Second, there is often a substantial overlap between TES and other forms of energy storage, and also between TES and some energy supplies technologies. Two important omissions include photochemical storages (research sponsored by the Chemical Storage Program in STOR; see Fig. 2-2) and open cycle chemical devices, such as desiccant chillers (research sponsored by the System Development Branch of the Office of Solar Applications in DOE; see Fig. 2-5 and Fig. 2-6).

All program processes from basic research through commercialization efforts are investigated. DOE programs under the auspices of the Assistant Secretaries of Energy Technology (ET) and Conservation and Solar Application (CS) which are directly engaged in developing low temperature TES technologies are described. Management structure, goals, funding, and technical substance of these programs are discussed. Relevant programs include the Division of Energy Storage (STOR) in ET and a number of elements of the Solar Applications Division (SA) in CS. Nongovernment-funded industrial programs and foreign efforts are outlined as well.

Data describing low temperature TES activities are presented also as project descriptions. Projects for all these programs are grouped into seven categories: short-term sensible heat storage; annual sensible heat storage; PCM storage; heat transfer and exchange; industrial waste heat recovery and storage; reversible chemical reaction storage; and models, economic analyses, and support studies. Summary information

*Low temperature is defined as temperatures below 250° C in accordance with DOE terminology.

about yearly funding and brief descriptions of project goals and accomplishments are included.

This publication will: (1) provide an overview of low temperature TES technologies; (2) summarize contents and goals of DOE and other programs leading to development and commercialization of low temperature TES devices; (3) catalog and describe all recently completed and ongoing projects sponsored both privately and publicly; and (4) generate comparative and summary information.

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NOMENCLATURE

ACES	Annual Cycle Energy System
AIPH	Agricultural and Industrial Process Heat
ANL	Argonne National Laboratory
BCS	Office of Buildings and Community Systems in CS
BNL	Brookhaven National Laboratory
CHIC	DOE Chicago Operations Office
CHP	Chemical Heat Pump(s)
COP	Coefficient of Performance
CS	Conservation and Solar Applications Division of DOE
DOE	Department of Energy
ET	Energy Technology, DOE
F	Storage Project in a Foreign Country (Other Than IEA)
HTTES	High Temperature Thermal Energy Storage Subprogram in STOR
I	Funded Independently of U.S. Government
IEA	International Energy Agency
LASL	Los Alamos Scientific Laboratory
LBL	Lawrence Berkeley Laboratory
LLL	Lawrence Livermore Laboratory
LTTES	Low Temperature Thermal Energy Storage Subprogram in the Chemical and Thermal Storage Branch in STOR
ORNL	Oak Ridge National Laboratory
PCM	Phase Change Material(s)
ROI	Return on Investment
SA	Office of Solar Applications Program in CS
SA-C	Collector Subprogram, SA
SA-D	Demonstration Subprogram, SA

SA-P	Passive Subprogram, SA
SA-S	Thermal Storage/Heat Exchangers Subprogram, SA
SAN	DOE San Francisco Operations Office
SLL	Sandia Livermore Laboratories
SST	Office of Small Scale Technology in CS
STOR	Division of Energy Storage in ET
TEA	Technical and Economic Analysis Branch in STOR
TES	Thermal Energy Storage
TEST	Thermochemical Energy Storage and Transport Subprogram in the Chemical and Thermal Storage Branch in STOR
TS	Low Temperature TES Programs (from LTTES and TEST) in STOR
TVA	Tennessee Valley Authority
USDA	United States Department of Agriculture

SECTION 1.0

INTRODUCTION: OVERVIEW OF STORAGE TECHNOLOGIES

1.1 GENERAL CONSIDERATIONS

A broad range of technical options is available for storing low temperature thermal energy (see Fig. 1-1). Acceptable thermal energy storage devices must be durable and result in equal or lower capital and operating costs per unit delivered energy when integrated into renewable energy supply systems. In most cases this constraint mandates choosing the lowest cost storage appropriate to each application.

All low temperature technologies share a number of characteristics and limitations that directly reflect cost and performance. A critical design feature is the heat transfer between energy source, storage, and thermal load. Small differences between storage and load temperatures reduce the driving force behind heat transfer. Design tradeoffs are complex. For example, storage volume can be reduced if energy is generated and stored at a higher temperature but then the potential for corrosion problems is greater and round-trip storage efficiency may be lower. Some storage devices require smaller volumes of an active storage medium but larger heat exchange areas. The optimal temperature change during a cycle and the rate of charge and discharge of storage must be determined in each application.

Low temperature storage, especially sensible heat storage, tends to be bulky. To date, volume reductions obtained by using higher energy density storage media are offset by the requirement for more expensive containers or heat exchangers.

Another important design criterion affecting system cost and performance is duration of storage. Annual storage systems, if properly designed, can substantially reduce the need for solar collectors, are not sensitive to short-term weather variations, and may provide 100% solar heating and/or cooling contributions. Although the seasonal variation is quite large, the total yearly insolation at higher latitudes is approximately the same as that at lower latitudes. Therefore, it is reasonable to collect summer radiation for use in winter [3,4,5]. In warmer climates, where higher temperatures are obtainable with a given collector and where winter heat load is low and summer air-conditioning load is high, storage durations of a day or less may be more appropriate.

A number of solar systems integrate energy collection and storage into one operation. For example, a salt gradient solar pond collects and stores insolation near its bottom. In general, however, the energy collection method and the end-use application influence the choice of storage device. For example, if 100°C heat is required for powering an absorption air conditioner, use of alternatives to water sensible heat storage are preferred. Even so, a wide range of systems can be devised for a specific application using a specific collection device. Ultimately, economic considerations limit the options. Equipment such as heat exchangers to transfer heat from one medium to another, ducting, or plumbing add substantially to total system costs and mandate use of

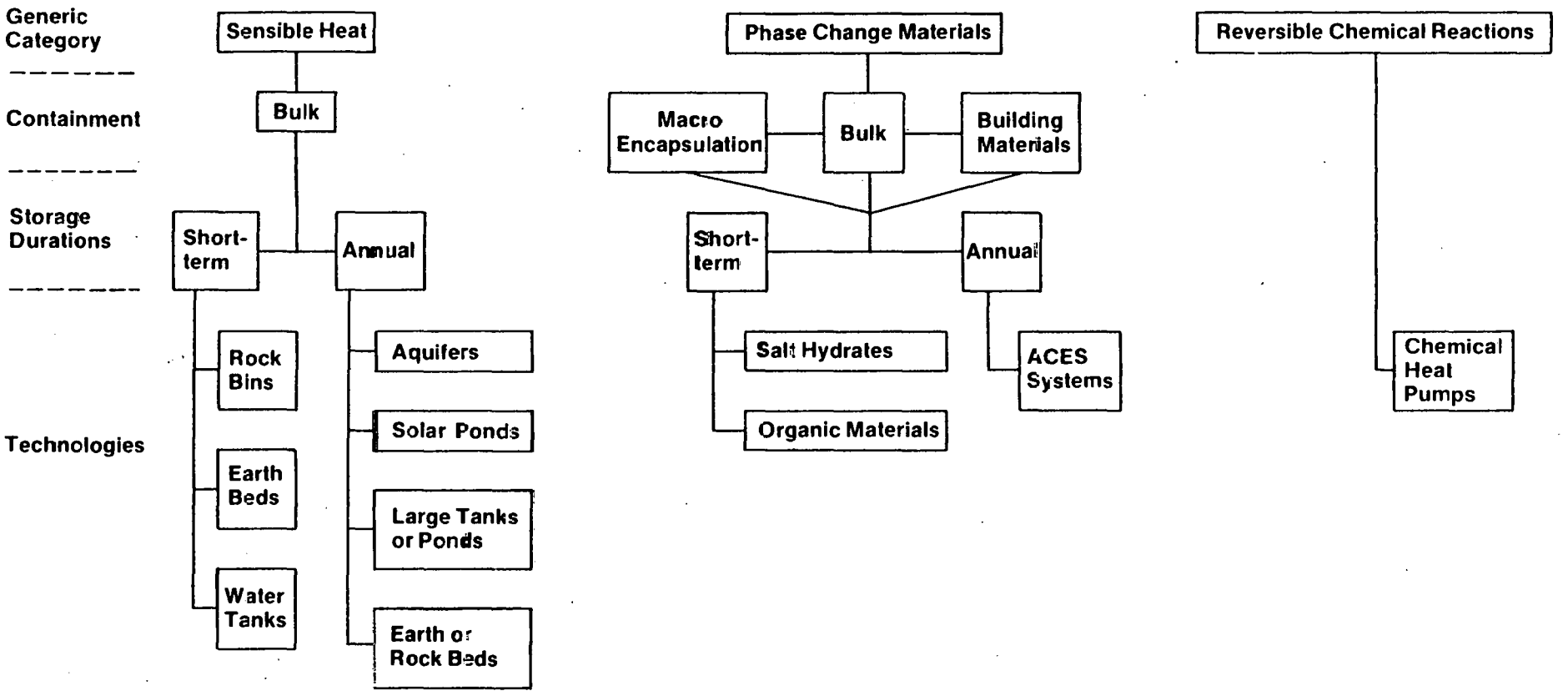


Figure 1-1. LOW TEMPERATURE THERMAL STORAGE TECHNOLOGY CLASSIFICATION

the simplest appropriate storage device. System studies are directed toward improving heat transfer into and out of storage, determining optimal duration of storage and size of temperature swings, and correctly sizing storage capacity.

Energy storage devices are applicable to many energy sources. Thus, many low temperature thermal storage technologies may be used with nonsolar energy sources such as off-peak electricity derived from nuclear or fossil fuels or heat extracted from groundwater. These combinations may either enhance or hinder the economic viability of solar technologies by lowering the cost of the conventional alternatives.

1.2 SENSIBLE HEAT STORAGE

Storage of thermal energy in tanks containing fluids (oils, water) or in rock, sand, or earth beds with heat exchange by fluids or heat pipes is an existing practice. The quantity of energy stored in such devices is determined by the product of the heat capacity or specific heat and the difference between storage input and withdrawl temperature. Water is the most attractive liquid for use in low temperature storage applications; it is cheap, nontoxic, nonflammable, and has a very high specific heat. However, at temperatures exceeding 100° C, pressurized tanks are required and the oil or other forms of thermal storage become more attractive. At temperatures below freezing, antifreeze solutions or drain-down systems may increase costs. Rock, sand, or earth have approximately half the heat capacity of water and require twice the volume for a given storage capacity. However, such beds have a number of advantages which are discussed below. Development is being pursued in three areas: containment, system stability, and cost reduction.

Containers serve two functions: retaining the storage material and retaining the thermal energy. When either manmade or naturally existing containers are used with liquids, attention must be paid to leakage of the storage material, and thermal energy must be retained for as long as possible. Containers can be insulated in a variety of ways. Larger storage volumes have a lower surface area to volume ratio and therefore a lower percentage of heat loss. In these cases dry soil may be a viable alternative to expensive insulation (10cm of very dry soil is equivalent to 1.3cm of polyurethane [6]).

Thermal stratification in storage tanks or beds allows solar collectors to operate in higher efficiency ranges because fluid input temperatures to collectors are low. Withdrawal of energy from storage is also facilitated because energy can be extracted at higher temperatures and the storage fluid temperatures returning to the collectors are substantially lower. Maintaining thermal stratification is especially useful for applications in which storage fluid is consumed because smaller capacity devices can maintain required output temperatures in spite of influx of ambient temperature fluid. Ensuring a constant temperature output in smaller sensible heat storage devices is difficult because of the relatively large influx and exflux of thermal energy.

In most cases, the feasibility of sensible heat storage has been amply demonstrated so that efforts are directed more toward cost reduction than toward finding technical

solutions. Some of the larger scale technologies offer substantial economics of scale because container volume increases at a greater rate than surface area. (Both heat and storage material can be lost only at the surface.) Also, container costs per unit volume or unit of stored heat are reduced as size increases.

Sensible heat storage technologies are categorized below into short-term storage and annual cycle storage. Intermediate durations of TES using these technologies combined with a variety of renewable energy sources may be economically viable in certain applications.

1.2.1 Short-Term Storage

Low temperature sensible heat storage is viable with water, rock, sand, or earth as the storage medium. The basis for the technology is well understood except for the case of earth storage. Studies are underway to more thoroughly understand thermal conductivities of soils. There are many possible combinations of heat exchangers, storage materials and containers, and hybrid systems.

Certain design tradeoffs are apparent. Liquid storage media permit convective transfer of heat by virtue of their ability to move with thermal gradients and are, thus, better suited than rocks for heat transfer. For the same reason, liquids are less suited for maintaining thermal stratification gradients. Liquids are more suited than rocks, earth, or sand to retrofit applications because of smaller storage volume requirements. Water has an additional advantage for applications such as industrial washing processes or residential hot water in that it is both storage material and product. Conversely, liquids have disadvantages because of requirements for freeze protection in most climates.

1.2.2 Annual Cycle Storage

Annual cycle storage of thermal energy has the advantages mentioned in Section 1.1. Three types of systems are being developed: large storage tanks, earth or rock beds; aquifers; and solar ponds.

1.2.2.1 Large Storage Tanks/Beds

Large storage tanks or beds differ from smaller scale units only in construction details. Problems involved with excavation, moving materials, and plumbing are simply larger scale. Design considerations may permit use of uninsulated surfaces in large underground systems because the surface area to volume ratio is so low. In retrofit applications space is a limiting consideration, whereas in new construction such devices can be built underneath or adjacent to structures.

1.2.2.2 Aquifers

Seasonal storage of heat or cold in large underground aquifers is both technically feasible and economically attractive. Proposed energy inputs include solar heat, environmental heat and cold, and waste heat from electrical generating stations [7]. Use of the latter would both reduce heat pollution and raise overall conversion efficiencies.

Aquifers are large geological formations (often on the order of 10 million m^3) found at depths from metres to several kilometres. The caprock and bedrock materials of the confined aquifers seal these vaults and have low thermal conductivities. Aquifers are capable of storing hot water under pressure and, therefore, storage temperatures to 400° F (200° C) are possible. Groundwater movement in many aquifers is slow enough to allow designers to ignore their effects. Another advantage is their widespread distribution. It has been conservatively estimated [8] that 80% of Texas is underlain by groundwater aquifers.

Recent progress toward large scale demonstration of aquifer technology has been rapid. The potentially most serious problem is clogging of wells [9]. This can be caused by introduction of foreign fluids that precipitate compounds, introduction of unwanted biological activity by aeration of water in cooling ponds or precipitation of iron compounds by oxygenation of aquifer water. Another potential problem is solution of various salts from the aquifer in the water with subsequent precipitation in pipes, etc., especially in the pressurized, higher temperature water storage systems. In some cases, infiltration or loss of water from imperfectly confined aquifers could be a problem.

A 68% round-trip efficiency of storage (energy out to energy in) has been observed [9] and theoretical studies suggest that within a few injection withdrawal cycles 80% storage efficiencies will be attainable because of preheating effects [10].

Aquifer storage is attractive for other reasons. Although use of water tanks or rock beds in applications such as district heating would require massive tanks and other materials to store the millions of gallons of hot water, in aquifers space is no limitation; aquifers simply require two or more wells for access. The comparative economics look very favorable, especially if assumptions about long lifetimes are accepted. There are some environmental and institutional concerns that must be addressed. For example, fracture of an aquifer could cause serious heat pollution problems. Such formations have been used for liquid waste disposal and storage of fresh water, oil products, and gas [10]; therefore, some conclusions about environmental feasibility can be established based on past data.

1.2.2.3 Solar Ponds

Solar ponds are both low temperature solar collectors and long-term thermal energy storage devices. Solar radiation can penetrate deeply into a natural body of water and heat the walls, bottom, and contained water by absorption. Although water is a poor heat conductor and is opaque to infrared radiation, thermal expansion of warm deeper

layers of water establishes convective currents which equilibrate pond temperatures with those of the surrounding environment as heat is lost. If an adequate downwardly increasing salt gradient can be established, the increased salt density at lower levels can offset the effect of thermal expansion and suppress convection. A solar pond with a uniform-density convective layer for heat storage and an overlying gradient layer for insulation is relatively insensitive to week-long fluctuations in solar input and ambient temperature (see Fig. 1-2).

Four similar types of solar ponds have been identified: salt gradient [11]; gel or viscosity stabilized; saturated [12]; and naturally existing saline solar ponds. The latter can occur in undisturbed shallow portions of salty bodies of water. Gel stabilized ponds employ transparent thickening agents to reduce convection. Saturated ponds have rather unique behavior as salt can crystallize out on the bottom. If a large solar pond were formed in parts of the Dead Sea or the Great Salt Lake, it would have low efficiency and relatively unstable operation because of its relatively low salt concentrations. These natural ponds may, however, have some important applications (see Section 1.5). To date, most research efforts have concentrated on salt gradient ponds.

The largest cost component of solar ponds is salt which must be safe, readily available, and inexpensive. Salt solutions in water must be relatively transparent to solar radiation and, in order to suppress diffusion and enhance stability, the salt should have a strongly temperature-dependent solubility. Although sodium chloride does not satisfy this latter condition, it is the most convenient, economical, and widely used.

The solar pond is a combined energy collector and storage device. The container must be as leak-proof as possible to both thermal energy and salt water. Depending on the soil composition, a plastic liner may or may not be necessary. In many very large ponds, it is expected that salt will form a natural seal as in the Great Salt Lake; however, the possibility of groundwater contamination must not be overlooked.

Maintaining stability of the salt gradient insulating layer is critical. Approximately 35% of the insolation penetrates to the convective layer in a 2.5-m deep pond [11]. Twenty percent is retained. Temporary breakdown can result in almost complete loss of stored energy. This is a serious occurrence considering that pond heatup durations are on the order of a year. Although stability is virtually assured when salt concentration is high, the cost of high salt concentrations is also increased and environmental problems are accentuated [13]. Instability can be triggered in a number of ways [11]. Strong winds can induce convective currents. Heating of gradually sloping pond walls also causes local convection. Similarly, rapid night cooling of the surface layer establishes stress on the upper portion of the gradient layer.

Heat is removed from the top of the convective layer by either a submerged heat exchanger or by extraction of hot saline solution from the pond for external heat exchange. The larger the thermal mass of the pond, the smaller the induced change in temperature and the more stable the operation.

Upward diffusion of salt and evaporation from the surface of the pond in dry climates can be countered by trickling fresh water over the surface, overflow of excess water, and

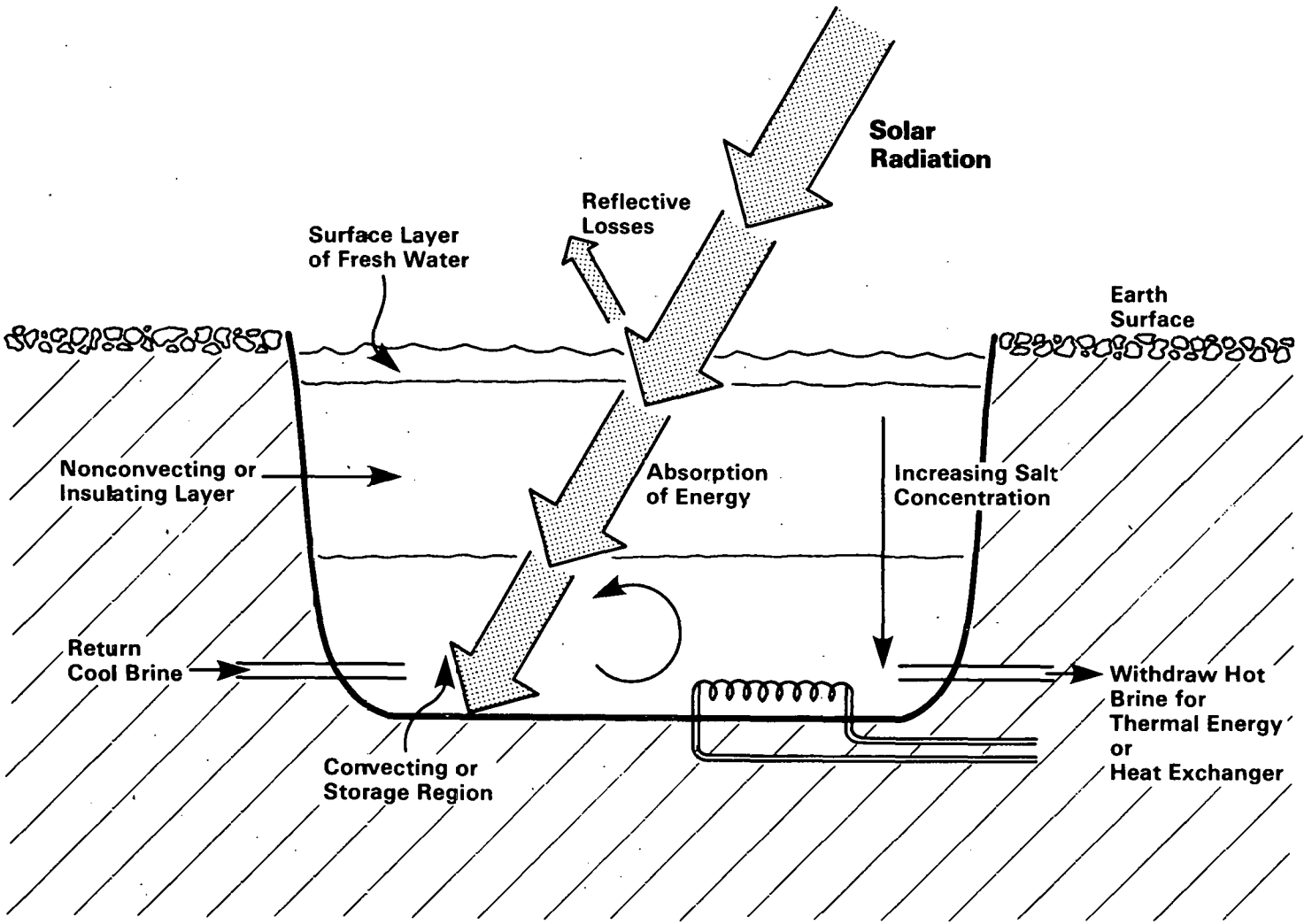


Figure 1-2. SCHEMATIC REPRESENTATION OF SALT GRADIENT SOLAR POND

injection of concentrated saline solution into the lower depths. This process also aids in maintaining clarity. In general, it is found that much, but not all, of the debris settles to the bottom of the pond and actually enhances absorption of radiation. Using plastic liners above or under water is another possibility, although this technique can also increase cost and reduce transmission of radiation. Biological growth in a solar pond is eliminated by adding copper sulfate.

Solar ponds are potentially attractive economically. Energy accumulated over months can be extracted in relatively short times. To date, modest efforts in solar pond RD&D have yielded promising results. Two potentially serious problems remain. First, the cost of decommissioning a salt gradient pond may be substantial because of the massive amount of dissolved salt. Second, reestablishing a salt gradient in a completely destabilized pond may require long periods of time although a technique recently devised to fill the large Miamisburg pond may be used to overcome this difficulty.

1.3 PHASE CHANGE MATERIALS (PCM)

Freezing or melting of substances occurs within a narrow temperature range with a relatively large exchange of heat with the surrounding environment. The potential for large volume reductions by use of PCM in thermal storage devices was explored initially by Telkes [14] and has been the subject of considerable recent work [15-24]. Candidate materials must be readily available, inexpensive, safe, minimally corrosive, and have a high heat of fusion. It is also desirable to have a reasonably small volume change and low vapor pressure over the useful range of temperatures so as to place no undue stress on storage containers, although flexible packaging techniques can allow for these volume changes. Two classes of compounds are attractive: salt hydrates and organic compounds. Only substances with solid-liquid phase change transitions have proven to be economically feasible for use in thermal storage (some PCM storage systems are commercially available; see Section 3.3).

1.3.1 Salt Hydrates

1.3.1.1. Definition

The solid-liquid transformation of salt hydrates is actually a dehydration or hydration of the salt, although this process resembles melting or freezing thermodynamically. Three types of behavior can be identified: congruent, incongruent, and semicongruent melting. Congruent melting occurs when the anhydrous salt is completely soluble in its waters of hydration at the melting temperature. Incongruent melting occurs when the salt is not entirely soluble at its melting point. Semicongruent melting defines salt hydrates which are first transformed to a lower hydrated form or a partially dissolved mixture that subsequently melts and dissolves completely at a higher temperature. The most attractive PCM salts and some physical parameters are listed in Table 1-1. None of the congruent melting salt hydrates were judged suitable for use in thermal storage

Table 1-1. PHYSICAL PROPERTIES OF PHASE CHANGE MATERIALS

Salt	Moles of Water	Melting Point ¼F	Heat of Fussion (Btu/lb)	Specific Heat (Btu/lb/¼F)	Specific Density	Melting Behavior
$CaCl_2$	6.2	84-102	75	0.35	1.68	Semicongruent
Na_2PO_4	12.2	97	114	0.37	1.52	Semicongruent
Na_2SO_4	10	88-90	108	0.42	1.45	Incongruent
$Na_2S_2O_3$	5	118-120	90	0.35	1.66	Semicongruent

because of cost or safety considerations [17]. (However, calcium chloride hexahydrate, a semicongruent material which is inexpensive and safe, behaves almost like a congruent substance because it completely dissolves at a temperature only slightly above the melting point.) Recent work (see Section 3.2.3) suggests new congruently melting PCM may be available at reasonable (<10¢/lb) costs.

1.3.1.2. Problems

Use of PCM for thermal storage is beset by a number of interrelated but solvable problems, the most difficult of which involve material segregation in incongruent and semicongruent substances. Following melting, the insoluble portion of salt tends to settle and remain at the bottom of the container. Within a few freezing/melting cycles, significant amounts of salt have accumulated at the bottom of the container. In subsequent cycles this material will not hydrate effectively and, thus, may seriously impair performance. The severity of this problem depends on container design and on the salt used. For example, settling is a serious concern with Glauber's salt; settling is minimal and tolerable with calcium chloride, resulting in only a slight performance loss. A number of solutions to this problem have been advanced. Use of various thixotropic agents maintains the anhydrous salt in a gel that inhibits settling. Different container designs can minimize the problem by constantly agitating the stored material or using extremely small storage volumes. The University of Pennsylvania concluded that, with repeated use of a Glauber's salt storage device, extremely poor performance is unavoidable [18]. Recent work indicates that this conclusion is not necessarily correct. For example, the Cabot Corporation's eutectic salt mixture used in the MIT solar house has been cycled 3500 times with no measurable change in performance (see Section 3.3). However, PCM systems using thixotropic agents must be demonstrated over system lifetime to guarantee system behavior. Some degradation of performance may be acceptable if initial cost is reasonably low.

Three recently suggested solutions to the salt-settling problem appear promising. Herrick at General Electric is testing the behavior of PCM in a rolling drum designed to maintain a uniform mixture of insoluble salt in the PCM melt [19, 20]. Telkes has devised a technique to embed salt hydrate crystals in a binding agent in order to maintain their microintegrity upon melting [21]. Calmac Corporation is developing and will market a PCM storage unit that has a small stirring motor in the lid (see Fig. 3-3); vortex action minimizes salt segregation. Other more traditional systems may also prove to be commercially feasible (see Section 3.3).

Salt hydrates may cool below their normal freezing points without solidifying. Such behavior interferes with normal functioning of the storage system and must be avoided. The use of solid crystals that are completely or partially isomorphous with PCM (for example, borax in $Na_2SO_4 \cdot 10H_2O$) effectively minimizes supercooling, Physical nucleating methods (such as "cold freeze" in which a solid hydrate crystal is injected) are also used to promote nucleation.

Corrosion of the container or water losses can introduce further difficulties. Corrosion problems can be overcome but doing so introduces new costs into the PCM storage

system. Rapid cycling tests may mask effects due to water loss and settling of salt both of which occur in the real time frame, although standard ASTM testing procedures probably give a good indication of vapor permeability. Loss of water will cause a decrease in performance, shorten lifetime, and raise lifetime costs.

In spite of such difficulties (see also Section 1.3.4), a number of PCM thermal storage devices, either under development or commercially available, appear to offer promise (see Section 3.3 for more details).

1.3.2 Organic Compounds

Organic compounds of lower molecular weight are theoretically the most promising PCM for use in thermal storage systems because of high transition energies [17]. However, many such substances are unstable, costly, highly flammable, or fall outside the desired temperature range. Paraffins are the most attractive because they are relatively inexpensive and safe and have reasonably high heats of transition compared to other organic compounds. The least expensive waxes melt over a range of temperatures from approximately 115°F to 118°F but cost more than 16¢/lb.*

Because all of these substances melt congruently, the only major limitation to performance is heat transfer across a solid boundary. However, cost of the storage material is high compared to salt hydrates. In addition, storage devices using paraffin incur costs associated with containers and heat transfer methods, especially since the heat transfer within paraffin is relatively low.

1.3.3 Water/Ice Systems

Freezing water releases 144 Btu for each pound of material. Water is a good candidate for use as a PCM storage medium for space cooling systems. It is safe and inexpensive. In most designs, water is frozen either by exposure for winter chill or by use of heat pumps, icemaking machines. At present, a disadvantage to using water/ice systems arises because commercially available heat pumps do not perform well at source temperatures as low as 32°F. However, larger scale machines that are specially designed to make ice are obtainable.

Two notable systems have been proposed that use water/ice systems as both a heat source and storage. The Annual Cycle Energy System uses an electrically driven, unidirectional heat pump to extract energy from an insulated tank of water for space heating and potable hot water [22,23]. During this process ice is formed for water use in summer cooling. Provisions are made to balance heating and cooling loads by use of auxiliary radiant/convector panels and/or external fan coils.

*FOD Tulsa 1979 price, SunOil Company.

The Community Annual Energy Storage System (CASES) uses similar technology but also directs thermal energy between buildings that have different load profiles [24].

1.3.4 Containment

Three techniques for containing PCM are employed: bulk, macroencapsulation, and building materials. Bulk refers to enclosure within large containers with heat exchange effected by either a novel method or by coils immersed within the PCM. In macroencapsulation, PCM is packaged in a nonpermeable membrane that also functions as a heat exchange surface. The cross-linked, high-density polyethylene pellets developed by Monsanto can also be considered a macroencapsulated PCM (see Section 3.3) because, upon melting, they retain their integrity and thus have a large heat transfer surface. Finally, building materials can simultaneously provide structural support and thermal storage capacity.

Chemical interaction of PCM with concrete followed by concrete fracture has proven to be a difficulty when building materials are used as containers for PCM. Recent developments in packaging PCM before enclosure in building blocks (see Section 3.2) may solve this problem. Water loss and subsequent decreases in performance also remain problems, except in systems which store PCM in bulk metal or glass containers. Although plastic packages with low permeability to water seem to be effective in some cases, long lifetime performance has not been observed. Heat transfer between the storage bin and the collector field or load poses another major problem. Unlike water, solid salt hydrates or paraffins are poor heat transfer agents, especially at the low temperatures under consideration. In order to facilitate heat transfer, packing schemes are often employed to maintain a high heat-transfer-surface-area to storage-material-volume ratio. In most devices, crystallization first occurs near the outer, cooler storage boundary and inhibits subsequent heat transfer to the interior material. However, the problem can be reduced by using a high internal heat transfer area such as in the Calmac device or by internal stirring. Macroencapsulation is the most efficient configuration for improving heat transfer because of the high surface-to-volume ratio. Even so, formation of a solid layer of hydrated salt at the boundary still somewhat impedes heat transfer.

1.3.5 Summary

PCM are attractive storage materials because of their high energy storage density and isothermal behavior. In particular, retrofit applications are candidates for PCM storage because space is often at a premium. However, a recent system simulation [25] of hot water collection and storage versus hot air collection and PCM storage found no space saving advantage (see also Shelpuk et al. [17]). The same study showed a four:one saving of space when this PCM system was compared to an air-to-rockbin storage system. The actual space saving of PCM is dependent upon system configuration and collector operating temperatures. The often quoted large storage volume savings derived by theoretical calculations [28] are, in practice, not fully attainable.

All of the technical problems mentioned in Section 1.3 are solvable at a cost, although the lifetime performance of cost-effective PCM storage devices is uncertain. PCM storage is presently offered commercially but economic competitiveness remains to be determined.

1.4 REVERSIBLE THERMOCHEMICAL REACTIONS

Thermal energy can be stored for indefinite periods of time by reversible chemical reactions. Thermal energy from a solar collector, utility waste heat, or any other source is used to drive an endothermic chemical reaction. This energy can be released by the reverse exothermic reaction between the products. This technology is discussed in detail by Wyman [1].

The chemical heat pump (CHP) is the primary application for reversible chemical reactions in low temperature TES. The reaction products are chosen so that the forward endothermic reaction is driven by temperatures produced by higher temperature solar collectors. In general, these systems consist of two interconnected vessels, each of which contains a liquid or a solid; one of the reaction products moves in vapor or gaseous form between the vessels. When energy is required from storage, outside ambient temperature heat aids in driving the lower temperature reaction in the second container. The product of this low temperature reaction moves back into the first container where the exothermic reaction occurs. This pumping of heat is maximized by choosing optimal temperatures of reactions and optimal vessel pressures. Because a combination of solar energy and environmental heat drives the CHP, coefficients of performance (COP) are greater than 1.0 in heating applications—COPs of 1.6 are expected. In cooling applications COPs are less than 1.0—COPs in the range of 0.6 to 0.7 are expected. The operation of this storage device in both heating and cooling applications is illustrated by the ammoniated salt CHP in Fig. 1-3 and 1-4 (for more details see Wyman [1]).

Reactants to be used in CHP must be minimally corrosive, inexpensive, stable, and safe. Chemicals must be chosen such that operating temperatures and pressures are suitable for solar collector output temperatures and ambient thermal source temperatures. In addition, the higher the heat of vaporization the more effectively heat can be stored and pumped to the load. Reactions which produce two distinct phases minimize chemical carryover from one tank to the other.

Six systems are presently being developed (see Section 3.6): ammoniated salts, hydrated salts, methanolated salts, dilute/concentrated sulfuric acid, hydrated zeolites, and hydrogenated metals. The dangers associated with use of ammonia are minimized by use of reactive salts in both tanks. Hydrated salts are not generally considered for use in heating systems because of the possibility of water freezing during operation although, at a cost, various design options may be used to overcome this problem. Use of concentrated sulfuric acid has obvious safety problems which can be minimized with careful design. The hydrogenated metal CHP (the HYCSOS system) uses expensive components but may find excellent applications as a rapidly cycled CHP without storage.

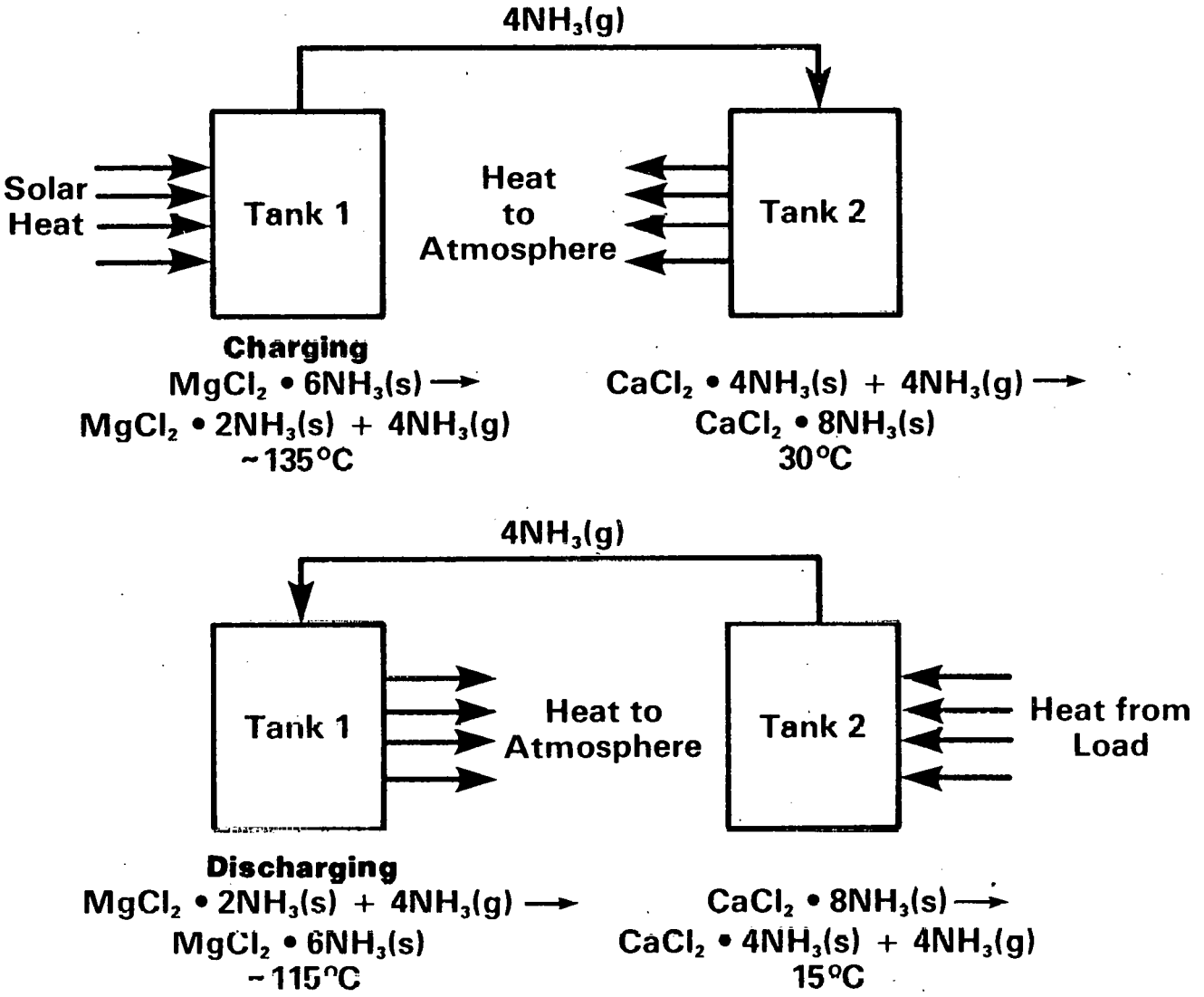


Figure 1-3. COOLING OPERATION OF AMMONIATED SALT CHP—SCHEMATIC

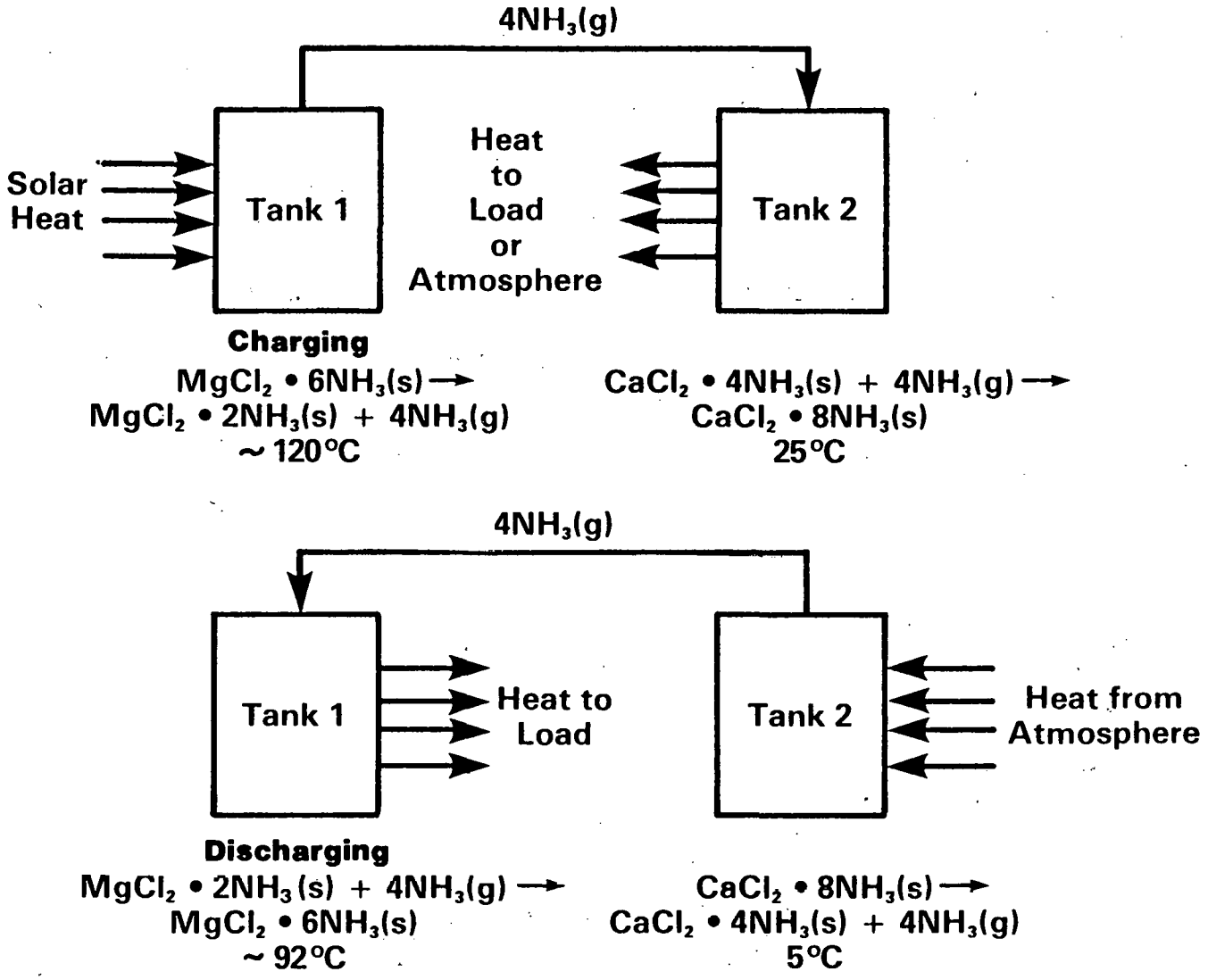


Figure 1-4. HEATING OPERATION OF AMMONIATED SALT CHP—SCHEMATIC

CHP storage systems have a number of distinct advantages over other low temperature TES systems. Energy storage density is generally higher than for both sensible heat and PCM devices. Thermal energy can be stored at ambient temperatures allowing indefinite storage in situ or transportation with minimal thermal losses. However, heat exchange between reactants and products must be carefully arranged so as to maximize efficiency and minimize sensible heat loss [1]. Energy collection and storage are part of an integral process. The system also has few moving parts so that maintenance should be minimal. Most reactions presently being considered use inexpensive and abundant materials. Large-scale implementation, therefore, will not be restricted by material availability if such systems prove commercially viable. Furthermore, if the coefficient of performance is greater than 1.0 as currently expected, the CHP allows a reduction in collector area for a given storage cost. Such devices may be competitive with water storage systems.

CHP are still in research or development stages. Full-scale demonstrations will probably be constructed and tested within the next five years. However, a number of developmental problems remain to be solved. The process must show that it is repeatedly reversible with minimal degradation of the reactants by side reactions. Corrosion must not be excessive. Adequate energy storage densities and efficiencies must be demonstrated in cost-effective systems having acceptable heat transfer rates.

1.5 STORAGE APPLICATIONS

Low temperature TES techologies have a diverse range of applications. This section outlines them briefly.

Thermal energy at temperatures either above or below ambient levels is necessary for maintaining comfortable temperatures in buildings or for use in many industrial and agricultural processes. TES devices are incorporated into energy delivery systems to match energy supply and demand by storing either coolness or heat.

The gamut of TES technologies discussed in the previous sections can be used to store heat. Coolness can be stored either as "cold" material (sensible or PCM storage) or as higher temperature thermal energy which subsequently powers an absorption air conditioner or chemical heat pump. Heating and cooling of buildings is defined as either active or passive. Passive TES systems usually incorporate either sensible or PCM storage. Active systems use a wide range of TES devices, energy supplies, and heat transfer methods such as heat pumps, heat pipes, or other heat exchangers. Agricultural and industrial systems often require more power or higher temperatures and are accordingly somewhat more sophisticated in design.

The applicability of each TES technology is limited by the physical laws that determine temperature ranges over which roundtrip storage efficiencies are optimized or by economic laws that require use of cost-effective devices. A number of examples follow. The cost of pressurized tanks makes the storage of heat in water, at temperatures substantially over 100°C, expensive and in many cases uneconomical. Coolness storage in water is limited by the 0°C (or close to 0°C) freezing point. Cooling a

building with 0°C ice or water requires larger heat exchangers than heating the same structure because of the smaller temperature differential (20°-0°) between storage and load.

In many cases a particular TES device is very well suited to a particular application. Aquifer storage is appropriate for community thermal utilities because of the large storage volumes available at relatively low cost. Solar ponds, which store energy year-round, can be discharged in a period of a month and are well matched to applications such as crop drying which are "one-shot" affairs. Solar ponds, as well as other storage devices which store thermal energy reasonably, can be used both for generation of small amounts of electrical power and for heating of buildings (see the ORMAT Turbines project in Section 3.2). PCMs store and release thermal energy isothermally and are ideal materials for integration into building structures.

SERI

SECTION 2.0

LOW TEMPERATURE THERMAL STORAGE ACTIVITIES: PROGRAMS

A comprehensive overview of low temperature TES programs is presented in this section. An attempt was made to describe all programs designed to aid in the development and commercialization of low temperature TES technologies. Those discussed include DOE programs, the International Energy Agency, foreign programs, and privately funded industrial programs. Programs are classified either as DOE, privately funded (I), or foreign (IEA or F). Tables 2-1 and 2-2 summarize the information contained in Section 2.0. Abbreviations describing DOE programs used in these tables are defined in the Table of Nomenclature.

2.1 DOE PROGRAMS

The Department of Energy has responsibilities for various solar functions subdivided primarily between two Assistant Secretaries: the Assistant Secretary for Energy Technology (ET); and the Assistant Secretary for Conservation and Solar Applications (CS). IT is mandated to develop mid- or far-term solar and other advanced technlogies (see Fig. 2-1). ET has no formally delegated responsibility for commercialization activities. CS has responsibility for developing and commercializing near-term solar energy supply and conservation technologies. As solar technologies approach maturity, the plan is to transfer them from ET to CS. In reality, some overlap of functions has occurred. As indicated in Fig. 2-1, some responsibilities are also delegated to two other secretaries.

Storage technologies for applications in solar systems are under development primarily in the Division of Energy Storage (STOR) in ET and the Thermal Storage/Heat Exchange subprogram (SA-S) in the Solar Applications Branch of Cs. The responsibility is divided between these two entities as between their respective divisions; simply stated, these are technology development and commercialization activities. A number of other subprograms in Solar Applications are engaged either in applying TES technologies in systems or in refining near-term TES devices. In addition, the Offices of Buildings and Community Systems (BCS), and Agricultural and Industrial Process Heat (AIPH), and Small Scale Technology (Fig. 2-5) are end-users of storage components. To a certain extent BCS develops TES technologies.

2.1.1 Thermal Storage Section (TS) and Technical and Economic Analysis Section (TEA) in STOR

STOR is one of five divisions in the Office of Solar, Geothermal, Electric, and Storage Systems (see Fig. 2-2). This division has a diverse set of customers for emerging storage technologies (Fig. 2-3). Projects relevant to this document are located in the Physical Systems Program. Stated objectives [29] of this program are to:

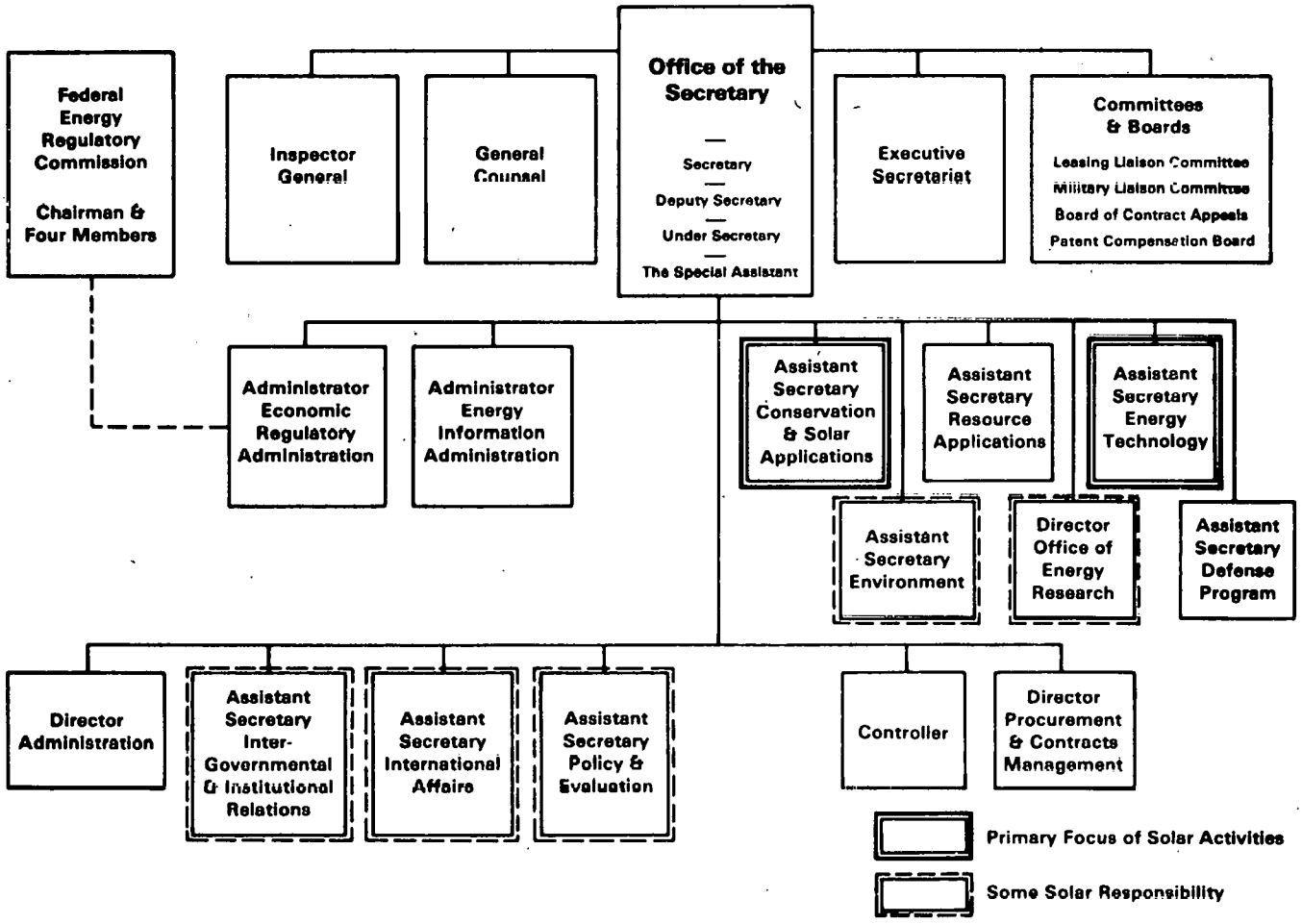


Figure 2-1. ORGANIZATION OF DOE'S SOLAR-RELATED ACTIVITIES

Table 2-1. SUMMARY OF RECENTLY COMPLETED PROGRAMS AND PROJECTS

Topic	Contractor	Agent
Short-Term Sensible Heat	None	
Annual Cycle Sensible Heat	Desert Reclamation Industries	TS
	George Washington Univ.	TS
	U. of Virginia	SA-S
PCM	BNL	TS
	Desert Research Inst.	TS
	Dow Chemical	TS
	Franklin Research Inst.	TS
	General Electric U.	SA-S
	Monsanto Research Corp.	TS
	N. Carolina State U.	SA-S
	ORNL	TS
	Penn State U.	TS
	Suntek	TS
	Villanova U.	TS
Heat Transfer and Exchange	Altas Corp.	SA-S
Industrial Heat Recovery and Storage	Lockheed	TS
	TRW (2)	TS
	Westinghouse Electric Corp.	TS
CHP	Chemical Energy Specialists	TS
Models, Economic Analyses, and Support	EIC	SA-S
	Hittman Associates	SA-S

Table 2-2. SUMMARY OF ONGOING PROGRAMS AND PROJECTS

Topic	Contractor	Agent
Short-Term Sensible Heat	Altas	SA-S
	U. of Alabama	SA-S
	ANL	SA-S
	Rockwell	SA-S
	Colorado State U.	SA-S
	Dynatech	SA-S
	Independent Living	SA-S
	U. of Nebraska	SA-S
	Westinghouse	SA-S
	Heliodyne	SST
	Window Rock School	SST
	Energietechnik	IEA
	Toyo Netsu Kogyo	IEA
	Bouwcentrum	IEA
	Ecole Polytechnique	IEA
Annual Cycle Sensible Heat	George Washington U.	TS
	Auburn U.	TS
	LBL	TS
	ORNL	TS
	Texas A&M	TS
	G.E. Tempo	TS
	TVA	TS
	ANL	SA-S
	U. of Toronto	SA-S
	Iowa State U.	SA-P
	Center for Environment and Man	SA-C
	Miamisburg	SA-C
	U. of New Mexico	SA-C
	Ohio State U.	SA-C
	Delft Soil Mechanics Lab	IEA
	Eindhoven U. of Technologie	IEA
	Technical U. of Denmark	F
	Ecole National Superieure des Mines	F
	Federal Republic of Germany	F
	Weizmann Institute of Technology	F
	University of Yamagata	F
	Lund Institute of Technology	F
	Neuchatel	F
PCM	Clemson U.	TS
	U. of Dayton	TS
	U. of Delaware, IEC	TS
	ORNL	TS
	ORNL	BCS

Table 2-2. SUMMARY OF ONGOING PROGRAMS AND PROJECTS (continued)

Topic	Contractor	Agent
	Calmac	SA-S
	U. of Delaware, Dept. Mech. Eng.	SA-S
	General Electric Co.	SA-S
	Suntec	SA-S
	Eikonix	SA-P
	Artech	SA-D
	Garrett	SST
	J. Horton	SST
	Addison Corporation	I
	Anheuser Busch Inc.	I
	Architectural Research Corp.	I
	Arizona State U.	I
	Brown U.	I
	Dow Chemical	I
	Michigan Tech. U.	I
	Ramco	I
	Solar, Inc.	I
	Solar Marketing	I
	Solarmatik	I
	Valmont Industries	I
	Thermal Insulation Lab.	IEA
	Ishikawajima-Harima	IEA
	Mitsubishi Electric Corp.	IEA
	Delft U.	IEA
	Philips	IEA
	Institute of Applied Physics TNO	IEA
	Studsvik Energiteknik	IEA
	Royal Institute of Sweden	IEA
	Ecole Polytechnique, Switzerland	IEA
CHP	EIC	TS
	Martin Marietta	TS
	Rocket Research Corp.	TS
	Sandia	TS
	ANL[a]	TS
	Martin Marietta	SA-S
	Faculte Polytechnique des Mons	IEA
	Philips	IEA
	Institute of Applied Physics TNO	IEA
Heat Transfer and Exchange	California State U.	SA-S
	Colorado State U.	SA-S
	Franklin Research Institute	SA-S
	Sigma Research	SA-D
	Zia Associates	SA-S

Table 2-2. SUMMARY OF ONGOING PROGRAMS AND PROJECTS (continued)

Topic	Contractor	Agent
Industrial Heat Recovery and Storage		
	Heinz Co.	TS
	Rocket Research Co.	TS
Models, Economic Analyses, and Support		
	A.D. Little	TMA
	ANL	TS
	ANL	TMA
	ANL (2)	SA-S
	Boeing Computer	SA-S
	National Bureau of Standards	SA-S

[a]This work is not funded by TS but is funded by the chemical element of the Thermal Storage Branch.

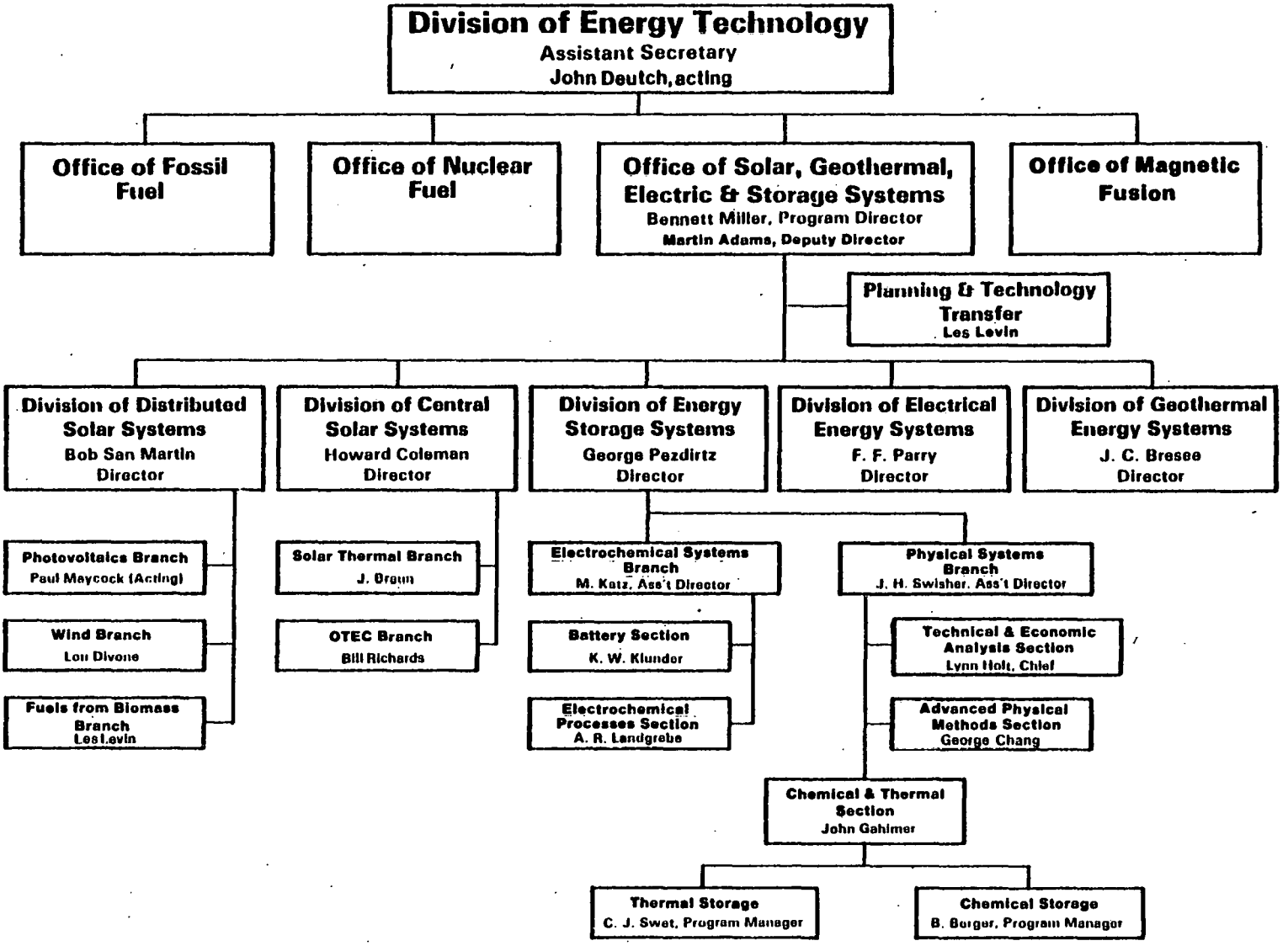


Figure 2-2. ORGANIZATION STRUCTURE OF THE DIVISION OF ENERGY TECHNOLOGY

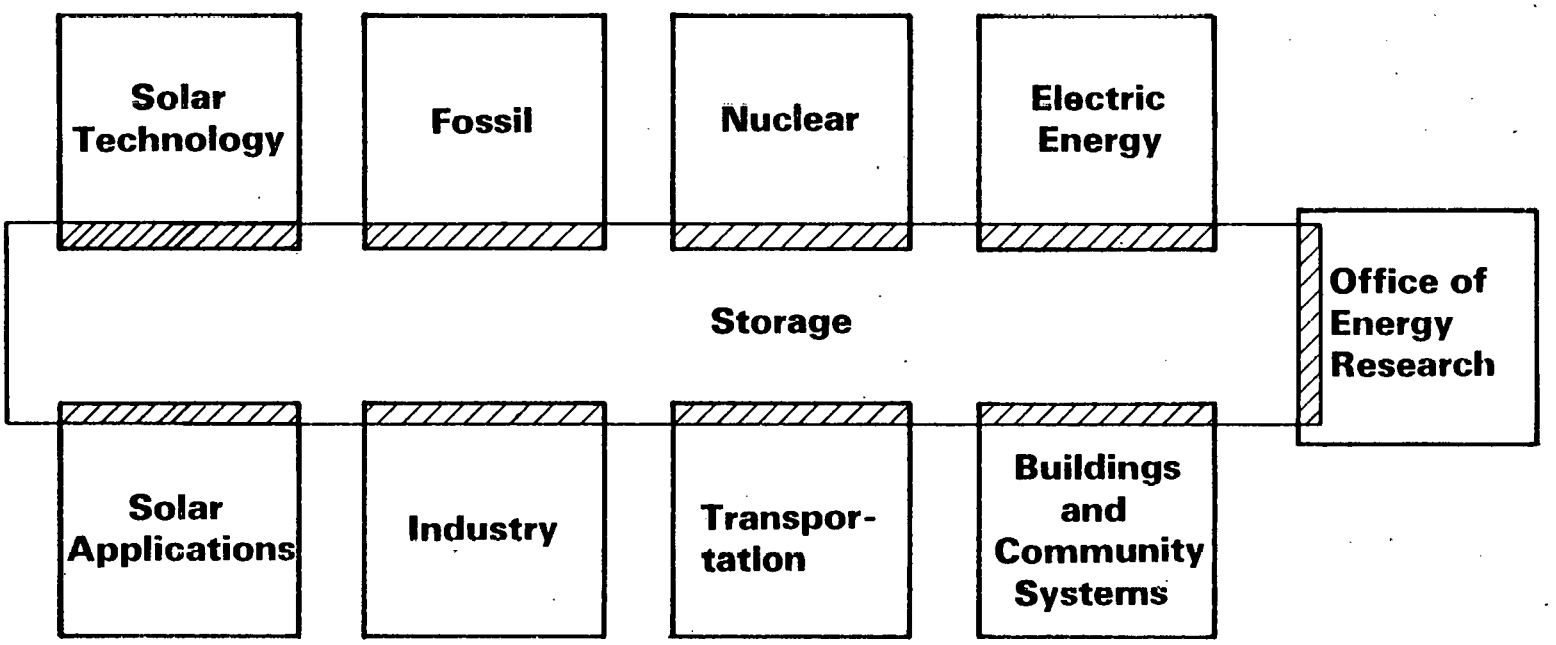


Figure 2-3. END-USERS OF STORAGE TECHNOLOGIES

- displace the use of coal, nuclear, and natural gas by inclusion of physical storage devices in energy systems;
- enable solar, wind, and other intermittent energy systems to provide continuous service for dispersed applications; and
- promote conservation by recovering waste heat from utilities and industries and by improving process efficiency.

The strategy of this program [29] is to:

- identify energy storage technologies for physical systems having the greatest market potential;
- conduct analytical and experimental programs to select the best options for further development;
- conduct analytical and experimental programs to select the best options for further development;
- determine which systems have significant technical and economic potential for buildings, industry, transportation, utilities, and residential/commercial applications;
- perform proof-of-concept tests to validate laboratory test results on a pilot-plant scale in cooperation with other DOE divisions and private industry; and
- encourage rapid commercialization of storage technologies by giving financial incentives, participating in joint programs with other doe divisions, and disseminating technology through seminars and publications.

The thermal storage component (TS) of the Chemical and Thermal Storage Section and the Technical and Economic Analysis Section (TEA) are funding numerous organizations to develop low temperature TES.

Thermal storage projects include High Temperature Thermal Energy Storage (HTTES), Low Temperature Thermal Energy Storage (LTTES), and Thermochemical Energy Storage and Transport (TEST). (See Hoffman et al. and Wilson for program descriptions [26,27].) In the past most projects were funded directly from DOE headquarters in response to unsolicited proposals. Management support was provided by Oak Ridge National Labs (ORNL) in LTTES, NASA-Lewis in HTTES, and Sandia Livermore Labs (SLL) in TEST. Recent strategy has been to shift nearly all subcontracting responsibility to these supporting laboratories. For example, in FY79 ORNL has received approximately $1.8 million, of which $0.5 million will fund in-house research. In addition, future subcontracts will be initiated mainly by government request. Program managers in these laboratories have authority to grant and terminate subcontracts. Close contact is maintained with DOE headquarters by monthly written progress reports. In addition, contractor information exchange conferences were held in September 1977 [26] and December 1978 [27] to educate all parties involved and to aid in program planning. The national laboratories that manage these programs also publish yearly operating plans [30,31].

Low temperature TES projects having applications in solar energy systems are included both in the LTTES and TEST programs. In this document, both types of projects are subsumed under the category of low temperature TES programs in STOR (TS) (see Tab. 2-3).

Four thrust areas have been identified in the LTTES program: seasonal storage of heat and cold; short-term storage in modular units; industrial applications; and short-term storage in building materials. Specific objectives for the near-term include: (1) field testing hot and cold water storage in aquifers for building heating and cooling by FY80; (2) proving commercial feasibility of customer-owned components for storing off-peak electrical energy by FY81; and (3) completing retrofit thermal storage installation in food and paper plants having payback periods of three years or less by FY83.

The test program at SLL has made progress toward developing a number of new technologies. Only one, the chemical heat pump (CHP), has applications in low temperature TES.

TEA provides information to evaluate the energy storage program objectives. Two general objectives have been outlined [29] for the FY80 through FY84 period: (1) define the specific role of energy storage in solar energy systems; and (2) compare centralized and dispersed energy storage systems. TEA projects are listed in Table 2-5b.

Recently, in order to consolidate and streamline TES programs in STOR responsibilities for managing the various components of the TES programs has been changed. It should be noted that the category TS used in this report is not altered by this reorganization. The new structure is defined as follows:

Lead Center	Managing Laboratory	Program
NASA-Lewis	ORNL	-Short-term TES for building heating and cooling
	SLL	-TES for the Solar Thermal Program
	NASA-Lewis	-TES for AIPH
SAN	Battelle Pacific NW	-ATES demonstration program
CHIC	BNL	-Chemical and Thermochemical Energy Storage

The major changes in this reorganization which is effective Oct. 1, 1979 include: (1) transfer of the ATES program from ORNL to Battelle NW; (2) transfer of the TEST program from SLL to BNL; and (3) emphasizing the SLL role in TES for the Solar Thermal Program (which includes technologies such as the Solar Power Tower, total energy systems, etc.).

Table 2-4 lists TS projects by generic type. Although a few of these projects fit reasonably well into two or more categories, this breakdown is fairly accurate. Fig. 2-4 complements Table 2-4 by presenting this generic project information by name of subcontracting organization. Tables 2-5a and 2-5b and 2-6 provide detailed project listings (descriptive details are presented in Section 3.0). Finally, Table 2-7 outlines this information by type of contractor.

Table 2-3. TS FUNDING[a]
(BA, $M)

	Actual FY77	Estimate FY78	Estimate FY79
Total solar budget in ET		280.4	288.4
Division of energy storage systems	33.5	50.2	58.0
Chemical and thermal branch	10.44	13.03	15.2
Thermal energy storage	3.73	4.45	9.3[b]
Low temperature	1.32	2.64	1.30[c]
High temperature	2.41	1.81	--
Reversible chemical reaction storage	2.07	2.27	2.40
Chemical heat pump	0.85	0.85	1.00
Chemical/hydrogen storage	4.64	6.31	7.40

[a]Many budget figures in these and subsequent tables have been derived from the DOE Solar, Geothermal, Electric and Storage Systems Program Summary Document, DOE/ET-0041(78), March 1978.

[b]The 9.3M$ Budget Authority is broken down as follows [26]:

Aquifers for district heating and cooling	2.7
Industrial retrofits	1.4
Solar and conventional power	1.7
PCM for building heating & cooling	1.5
Chemical Heat Pumps	1.2
Thermochemical heat transport	0.6
Total capital equipment	0.2

[c]As additional projects are funded in FY79 this figure will probably increase. The requested funding for FY80 for the entire Thermal Storage program is 19.6M$ (BA) (FY80 Congressional Budget Request).

Table 2-4. FUNDING OF TS PROJECTS BY GENERIC TYPE[a]

Code	Project	$K/% Total Funding/Number of Projects FY77	FY78	FY79
A	Sensible heat	126.7/9.7/4	511.4/19.3/5	476.7/37.2/5
A1	Short-term storage	--	--	--
A1a	Water	--	--	--
A1b	Rocks	--	--	--
A2	Annual storage	126.4/9.4/4	511.4/9.3/5	476.7/37.2/5
A2a	Aquifers	101.7/7.8/3	486.4/18.4/4	476.7/37.2/5
A2b	Solar ponds	--	--	--
A2c	Large tanks/beds	25.0/1.9/1	25.0/0.9/1	--
B	Phase change materials	643.4/48.5/13	1105.3/41.9/12	95.5/7.5/14
B1	Building material	143.5/10.8/2	209.8/7.9/2	--
B2	Macroencapsulation	156.5/11.8/3	268.1/10.2/3	39.9/3.1/3
B3	Bulk	343.4/25.9/8	627.4/23.8/7	55.6/4.3/1
C	Reversible chemical reactions	392.1/29.6/4	444.5/16.8/4	416.1/32.5/3
	Heat pumps	392.1/29.6/4	444.5/16.8/4	416.1/32.5/3
D	Industrial waste heat recovery	161.8/12.2/4	204.8/7.8/3	9.1/0.7/1
E	Heat transport and exchange	--	--	--
F	Models and support	--	300.0/14.2/1	285/22.2/1
	Total	1324.0/100/24	2566.0/100/24	1282.4/100/13

[a]Projects listed here also include investigations of PCM properties and crystal structures.

Low Temperature Thermal Storage Projects

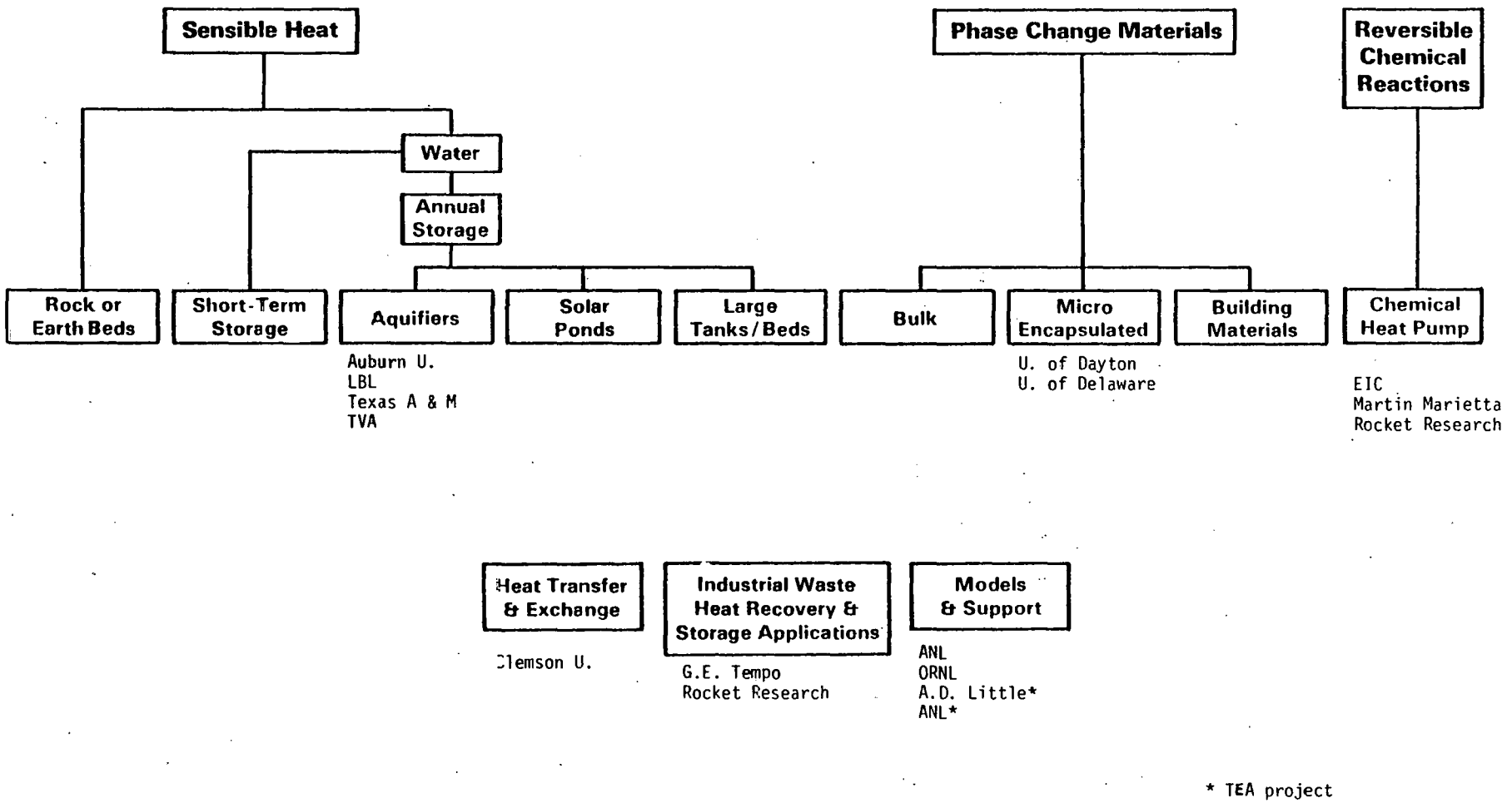


Figure 2-4. ORGANIZATIONS PRESENTLY SUBCONTRACTING TO TS—LISTING BY GENERIC PROJECT TYPE

Table 2-5a. ONGOING TS PROJECTS

Title	Code	Institution	Funding ($)	Period
Commercial Feasibility of Thermal Energy Storage	F	Argonne National Laboratory Chicago, IL	300,000	10/77-07/78
Aquifer Hot Water Storage, Experimental Study	A2a	Auburn University, Auburn, TX (Water Resources Research Inst.)	479,000	07/77-01/80
Immiscible Fluid-Heat of Fusion Heat Storage System	B3	Clemson University Clemson, SC	139,000	06/76-11/78
Manufacturing Cost of Form Stable Polyethylene	B2	University of Dayton Dayton, OH	20,000	01/79-05/79
Methanol-Based Single Substrate Heat Pump for Solar Thermal Storage	C	EIC Corporation 55 Chapel St. Newton, MA	119,498 278,212	05/77-06/78 06/78-06/79
Aquifer Storage of Cogenerated Heat for District Heating	A2a	G. E. Tempo Santa Barbara, CA	131,244	08/78-06/79
Thermal Energy Storage in Underground Aquifers	A2a	Lawrence Berkeley Laboratory Berkeley, CA	140,000	05/77-09/78
Thermal Storage for Solar Cooling Using Paired Ammoniated Salt Reactions	C	Martin Marietta Corp. Denver, CO	70,000 112,000	07/77-06/78 07/78-06/79
Mathematical Modeling of Moving Boundary Problems	F	Oak Ridge National Laboratory Oak Ridge, TN	100,000	10/76-09/78
Sulfuric-Acid-Water Integrated Chemical Energy Storage System	C	Rocket Research Company Redmond, WA	54,000 287,000 150,000	12/75-06/76 10/76-12/77 01/78-09/78
Applications of Thermal Energy Storage to Waste Heat Recovery in the Aluminum Industry	D	Rocket Research Company Redmond, WA	89,428	10/77-07/78
Storage of Cold Water in Ground-water Aquifers, Experimental Study	A2a	Texas A&M Research Foundation College Station, TX	16,800 300,000	08/09/ 10/78-09/81

Table 2-5a. ONGOING TS PROJECTS (continued)

Title	Code	Institution	Funding ($)	Period
Application of Low Temperature TES in the TVA Region	A2a	Tennessee Valley Authority 1360 Commerce Union Bank Bldg. Chattanooga, TN 37401	90,000	12/78-09/79

Table 2-5b. ONGOING TEA PROJECTS

Title	Code	Institution	Funding ($)	Period
Commercial Feasibility of TES	F	Argonne National Laboratory Chicago, IL	75,000	FY78
Cost Assessment of TES Technologies	F	A. D. Little Boston, MA	140,000	12/77-08/79

Table 2-6. RECENTLY COMPLETED TS PROJECTS

Title	Code	Institution	Funding ($)	Period
Encapsulation of Phase-Change Materials in Concrete Masonry Construction	B1	Brookhaven Nat'l Laboratory Upton, NY	152,000	07/77-10/78
The Chemical Heat Pump	C	Chemical Energy Specialists Costa Mesa, CA	112,395	09/76-07/78
Sodium Sulfate Decahydrate ($Na_2 SO_4$ 10 H_2O--Glauber Salt) As a Low Medium Temperature Phase-Change Thermal Storage Material	B2	University of Delaware Institute of Energy Conversion Newark, DE	146,000	09/78-10/79
Feasibility Study for Aquifer Coolness Storage at JFK	A2a	Desert Reclamation Industries	102,000	10/77-07/78
Studies of a Salt Hydrate Heat Storage System	B3	Desert Research Institute, Reno, NV (Atmospheric Sciences Center)	176,000	07/75-08/78
Microencapsulation of Heat Storage Phase-Change Materials	B2	Dow Chemical Co. Midland, MI	175,000	09/76-09/78
Thermal Energy Storage by Means of Heat of Solution	B3	Franklin Institute Research Labs Philadelphia, PA	107,000	06/76-11/77
Long-Duration Earth Storage of of Solar Energy	A2c	George Washington University Washington, DC	50,000	06/77-01/78
Analysis and Development of a Solar Energy Regenerated Desiccant Crop-Drying Facility	D	Lockheed Missiles & Company, Inc., Huntsville, AL	90,000 98,849	07/76-04/77 05/77-12/77
Form-Stable Crystalline Polymer Pellets for Thermal Energy Storage	B2	Monsanto Research Corporation Dayton, OH	172,737 38,500	07/76-05/77 09/77-01/78
Crystal Structures of Salt Hydrates and Nucleators	B3	Oak Ridge National Laboratory Oak Ridge, TN	60,000	10/76-04/78
Thermophysical Properties and havioral Characteristics of ase-Change Materials	B3	Oak Ridge National Laboratory Oak Ridge, TN	180,000	10/76-09/78

Table 2-6. RECENTLY COMPLETED TS PROJECTS (continued)

Title	Code	Institution	Funding ($)	Period
Prediction of the Performance of Solid Sensible Heat Thermal Storage Units	B3	Pennsylvania State University University Park, PA	114,000	07/75-12/77
Thermocrete & Thermotile Building Components with Isothermal Heat Storage	B1	Suntek Research Associates Corte Madeva, CA	230,000	08/76-07/78
Evaluation of Heat Recovery Methods	D	TRW Energy System Planning Division, McLean, VA	15,000	04/77-09/77
Fossil Fueled Home Heating Furnace Efficiency Improvement Using Thermal Energy Storage	D	TRW Energy System Planning Division, McLean, VA	7,200	04/77-09/77
The Use of Solid-State Phase Transitions for Thermal Energy Storage	B3	Villanova University Villanova, PA	26,205	06/77-08/78
Applications of TES to Waste Heat Recovery in the Food Processing Industry	D	Westinghouse Electric Corp. Pittsburg, PA	96,195 9,131	08/77-09/78 10/78-11/78

Table 2-7. FUNDING BY TYPE OF TS SUBCONTRACTOR

Code	Project	$K/% Total Funding/Number of Projects FY78	FY79
	Large business	590.2/27/7	306.4/22.3/5
	Small business	446.0/20.4/6	235.0/17.2/1
	Universities	570.9/23.3/6	371.4/27.1/5
	National labs	559.7/29.0/4	459.5/33.4/4
	Nonprofit organizations	7.6/0.3/1	--
	Total	2114.4/100/24	1372.3/100/15

2.1.2 Thermal Storage/Heat Exchanger Subprogram (SA-S) in SA

SA-S is responsible for the engineering development and commercialization of storage components for heating and cooling applications in buildings and agricultural and industrial processes. SA-S is one component of the Solar Applications Program (SA) in CS (see Section 2.1.3 and Fig. 2-5 and Fig. 2-6). The emphasis in this subprogram is on development of storage components that have near-term market potential and provide optimal solar system performance. Design and testing procedures are being created also as a quantitative basis for integration of TES into various solar systems.

A breakdown of FY77 through FY78 funding is presented in Table 2-8. It should be noted that the solar applications budget is a component of the total solar budget in CS. By contrast, the budget for the Division of Energy Storage systems is separate from the ET solar budget (see Table 2-3).

Table 2-9 presents a more detailed research breakdown by generic project classification. This breakdown is reasonably accurate although in some cases subjective judgments were used to group projects. Fig. 2-7 displays this generic project listing by organization. Tables 2-10 and 2-11 present detailed project listings including titles, locations, and funding levels (further information is included in Section 3.0). Funding by type of contractor is listed in Table 2-12.

The SA-S subprogram is managed by ANL. Close contact is maintained between DOE headquarters and ANL by verbal and written reports. A few projects funded by SA-S are managed at ORNL part of the TS Subprogram (see Section 2.1.6). Close liaison is maintained between ANL and ORNL on related TES programs.

The National Plan for Solar Heating and Cooling outlined a comprehensive set of technical requirements and goals necessary for successful commercialization fo solar heating and cooling [32]. SA-S Subprogram management at DOE has written a detailed program status report and plan using these guidelines to judge program efficacy [33]. Based on this internal evaluation, program deficiencies and suggested remedial actions were outlined. This plan is the most comprehensive encountered in low temperature TES and provides a valuable guide in commercialization of storage technologies.

2.1.3 Office of Solar Applications (SA) in CS

The Solar Applications Program is responsible for developing heating and cooling systems with near-term commercialization potential. The general objective of the Solar Applicatins program is:

> To assist in creating a viable solar energy industry by improving the performance and reliability of solar energy components and systems, and by reducing their costs. Specific objectives are to identify potentially cost-effective systems for building, agricultural, and industrial process heating and cooling applications, and to provide the emerging solar energy industry and other users with the materials, components, information, and methodology needed for designing, producing, and installing these systems [34].

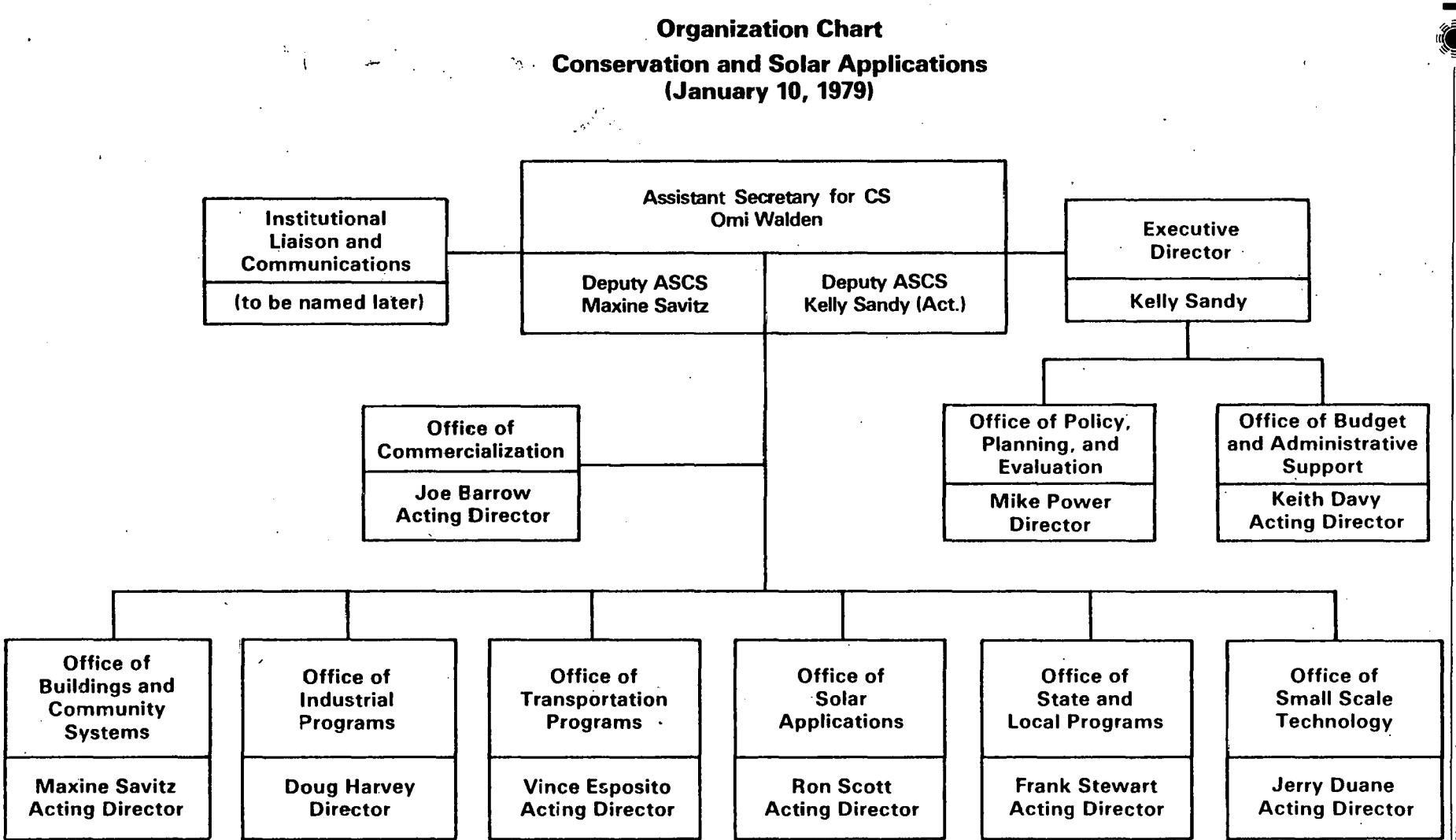


Figure 2-5. ORGANIZATIONAL STRUCTURE OF THE DIVISION OF CONSERVATION AND SOLAR APPLICATIONS

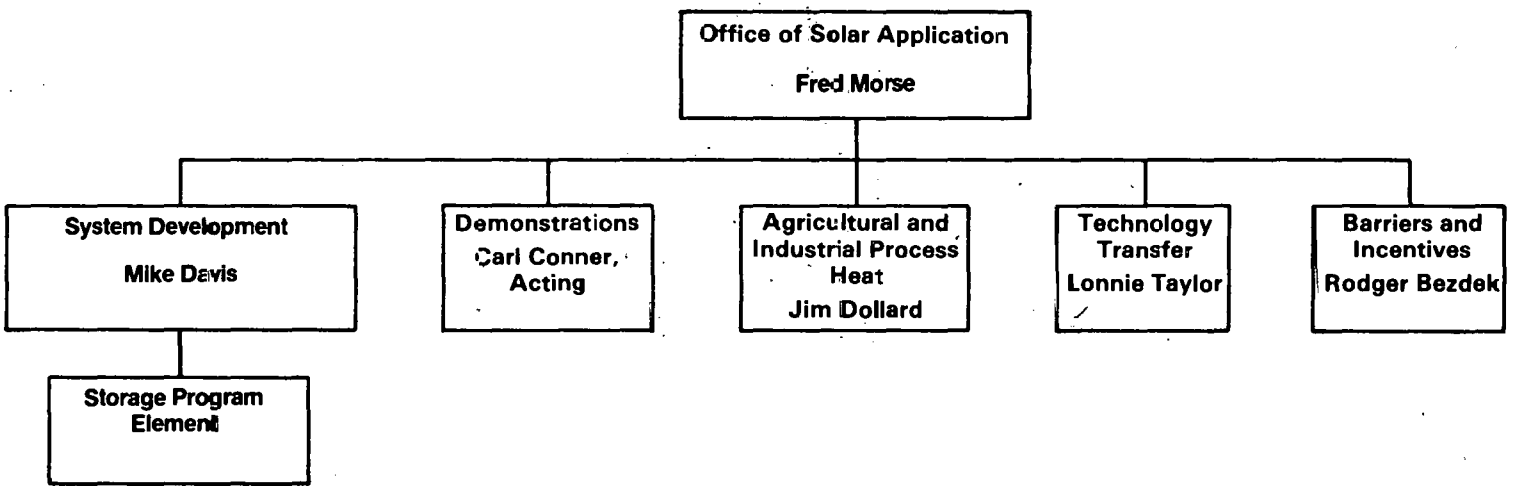


Figure 2-6. ORGANIZATIONAL STRUCTURE OF THE OFFICE OF SOLAR APPLICATIONS IN CS

Table 2-8. SA-S FUNDING
(BA, $M)

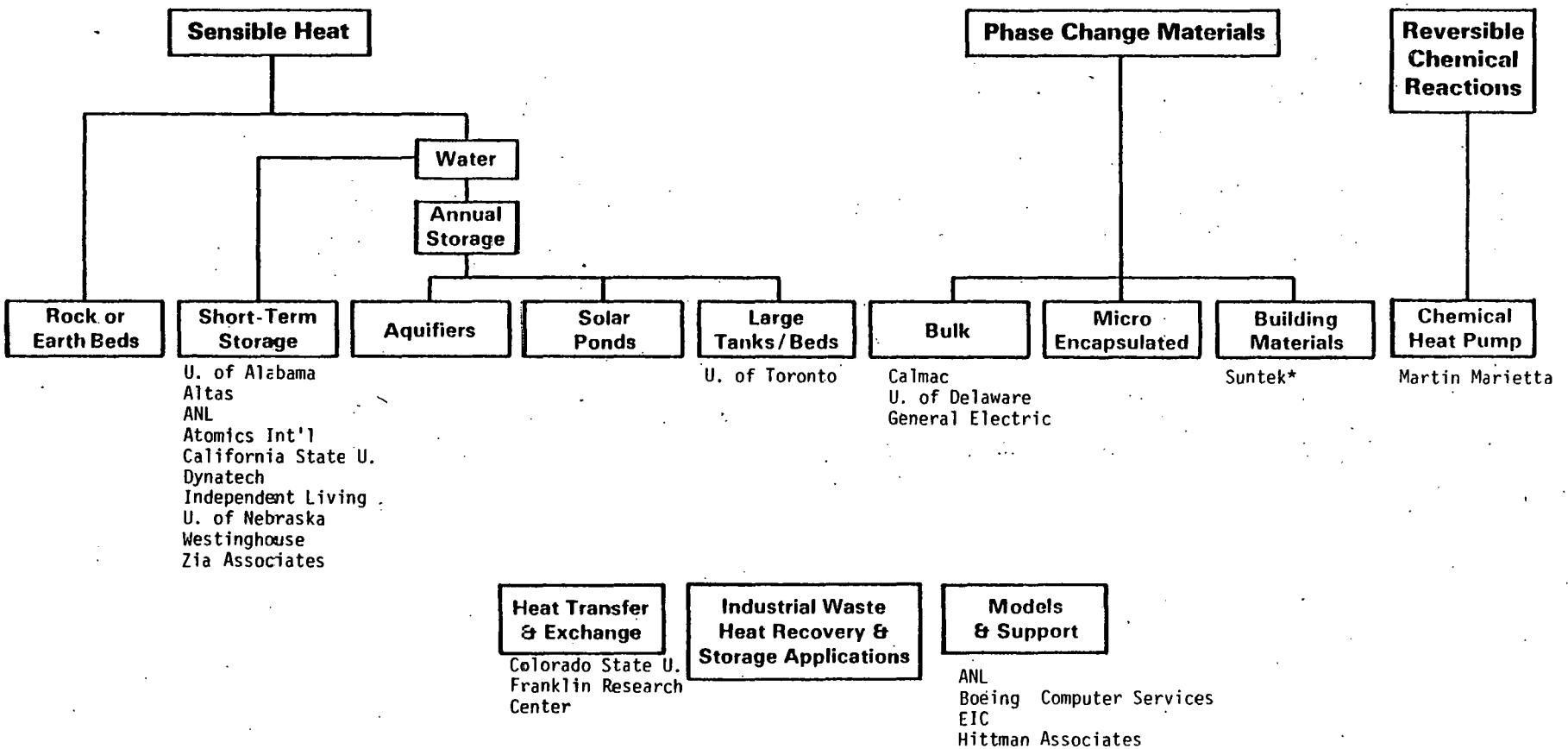
	Actual FY77	Estimated FY78	Estimated FY79
Total solar budget in CS		120.6	
System Development	15.0	18.5	
SA--storage component	0.6	2.34	2.12

Table 2-9. FUNDING OF SA-S PROJECTS BY GENERIC TYPE

Code	Project	$K/% Total Funding/Number of Projects FY78	FY79[a]
A	Sensible heat	1142/48.7/11	1268/59.8/7
A1	Short-term storage	1013/43.2/8	678/32.0/5
A1a	Water	682/29.1/6	646/30.5/4
A1b	Rocks	331/14.2/2	32/1.5/1
A2	Annual storage	129/5.5/3	230/10.9/2
A2a	Aquifers	--	--
A2b	Solar ponds	--	--
A2c	Large tanks/bed	129/5.5/3	230/10.9/2
B	Phase change materials	567/24.2/5	430/20.3/3
B1	Building materials	133/5.7/1	--
B2	Macroencapsulation	--	--
B3	Bulk	434/18.5/4	430/20.3/3
C	Reversible chemical reactions	152/6.5/1	210/9.9/1
	Heat pumps	152/6.5/1	210/9.9/1
E	Heat transfer and exchange	129/5.5/5	212/10.0/2
F	Models and support	354/15.6/6	360/17.0/4
	Total	2344/100/28	2120/100/17

[a]These are the Fiscal Operation Plan figures; a portion of this money is not being released in the initial funding.

Low Temperature Thermal Storage Projects



* Funded initially for PCM storage investigation. Alternative project presently underway.

Figure 2-7. ORGANIZATIONS PRESENTLY SUBCONTRACTING TO SA-S—LISTING BY GENERIC PROJECT TYPE

Table 2-10. ONGOING SA-S PROJECTS

Title	Code	Institution	Funding ($)	Period
Experimental & Computer Studies of Thermal Stratification in Water Tanks	A1a	University of Alabama in Huntsville, School of Science and Engineering, P.O. Box 1247 Huntsville, AL 35807	65,035	09/29/77-11/15/78
The Development of a Gas Backup Heating Water Tank Properly Integrated with Solar Heated Domestic Water Storage Tanks	A1a	Altas Corporation 500 Chestnut Street Santa Cruz, CA 95060	195,810	04/01/78-03/30/80
Mathematical Modeling of Flow Stratification in Thermocline Storage Tanks	A1	Argonne National Laboratory 9700 South Cass Avenue Argonne, IL 60439	70,000 100,000	10/01/77-09/30/78 10/01/78-09/30/79
Handbook and Guide for Thermal Energy Storage Applications in Solar Heating and Cooling Systems	F	Argonne National Laboratory 9700 South Cass Avenue Argonne, IL 60439	110,000 100,000	10/01/77-09/30/78 10/01/78-09/30/79
Hybrid Thermal Storage with Water	A1	Atomics International Division Rockwell International 8900 De Soto Avenue Canoga Park, CA 91304	108,827	09/01/77-11/10/78
Developing and Upgrading of Solar System Thermal Energy Storage Simulation Models	F	Boeing Computer Services, Inc. Energy Technology Applications Division, P.O. Box 24346 Seattle, WA 98124	476,973	09/01/77-08/31/80
Series-Parallel Solar Augmented Rock Bed Heat Pump	E	California State University Fullerton, CA 92634	95,000	02/01/78-06/30/79
Salt Hydrate Thermal Energy Storage System for Space Heating nd Air Conditioning	B3	Calmac Manufacturing Corp. 150 South Van Brunt Street Englewood, NJ 07631	455,090	12/01/77-02/28/80
Direct Contact Liquid-Liquid Heat Exchangers for Solar Heated and Cooled Buildings	E	Colorado State University Solar Energy Applications Lab. Engineering Research Center Fort Collins, CO 80523	87,466 85,819 92,600	02/01/76-01/31/77 06/01/77-09/30/78 10/01/78-11/30/79

Table 2-10. ONGOING SA-S PROJECTS (continued)

Title	Code	Institution	Funding ($)	Period
Heat Transfer Properties of Soil	A2c	Colorado State University Solar Energy Application Lab. Engineering Research Center Fort Collins, CO 80523	59,400[a]	
Development of Intermediate Temperature Thermal Energy Storage Systems	B3	University of Delaware Department of Mechanical and Aerospace Engineering Newark, DE 19711	286,500	04/01/78-03/31/80
Rock Bed Storage for Cooling	A1b	Dynatech R/D Company 99 Erie Street Cambridge, MA 02139	104,241	08/01/77-09/30/78
Evaluation of Self-Driven Heat Transport Schemes	E	Franklin Research Center 20th and Race Streets Philadelphia, PA 19103	102,600	08/01/77-07/31/78
Prototype Design, Construction and Testing of the Rolling Cylinder Thermal Storage System	B3	General Electric Company Corporate Research & Development Power Systems Laboratory P. O. Box 8 Schenectady, NY 12301	375,000	08/19/78-10/31/80
Development of an Improved Water Tank for Thermal Energy Storage	A1a	Independent Living, Inc. 5965 Peachtree Corners Norcross, GA 30071	129,953	07/15/78-07/14/79
TES for Solar Cooling Using Paired Ammoniated Salt Reactors	C	Martin Marietta Corporation Aerospace Division P. O. Box 179 Denver, CO 80201	363,563	05/15/78-04/30/80
Membrane-Lined Foundation Systems for Liquid Thermal Energy Storage	A1a	University of Nebraska Engineering Research Center W181 Nebraska Hall Lincoln, NE 68588	110,000	05/01/78-12/31/79
Engineering Design for Thermocrete Central Storage Units for Low-Temperature Solar Application	B1	Suntek Research Associates[b] 500 Tamal Vista, #506 Corte Madera, CA 94925	133,990	04/01/78-03/31/79

Table 2-10. ONGOING SA-S PROJECTS (continued)

Title	Code	Institution	Funding ($)	Period
Solar Space Heating Systems Using Annual Heat Storage	A2c	University of Toronto Mechanical Engineering Toronto, Ontario, Canada M5S1A4	137,413 75,612	07/01/76-09/30/78 10/01/78-09/30/79
Lightweight Concrete Materials and Structural Systems for Water Tanks for Thermal Energy Storage	A1a	Westinghouse Electric Corp. Advanced Energy Systems Division P. O. Box 10864 Pittsburgh, PA 15236	359,006	03/01/78-01/29/80
Rock Bed Storage with Heat Pump	E	Zia Associates, Inc. 5590 Arapahoe Road P. O. Box 1466 Boulder, CO 80306	106,557	04/01/78-03/31/79

[a]In Fiscal Operating Plan but funds held back at DOE headquarters.
[b]Thermocrete work has been terminated. Balance of funds redirected to work on improved windows and skylights for passive heating.

Table 2-11. RECENTLY COMPLETED SA-S PROJECTS

Title	Code	Institution	Funding ($)	Period
Investigation of Methods to Transfer Heat from Solar Liquid-Heating Collectors to Heat Storage Tanks	E	Altas Corporation 500 Chestnut Street Santa Cruz, CA 95060	60,085	03/15/76-06/01/78
Analysis of Advanced Thermal Energy Storage Subsystems for Solar Heating and Cooling	F	EIC Corporation 55 Chapel Street Newton, MA 02158	77,456	09/01/77-08/31/78
Two Component Thermal Storage Material Study	B2	General Electric Company Valley Forge Space Center P. O. Box 8661 Philadelphia, PA 19101	105,144	02/23/76-03/30/78
Solar Applications TES	F	Hittman Associates 9190 Red Branch Road Columbia, MD 21045	55,242	06/01/78-10/31/78
Research on Solar Energy Storage Subsystems Utilizing the Latent Heat of Phase Change of Certain Organic Materials, Phase II	B3	North Carolina State Univ. Dept. of Mechanical and Aerospace Engineering, Raleigh, NC 27607	94,408	05/15/76-04/30/78
Annual Collection and Storage of Solar Energy for Heating of Buildings	A2c	University of Virginia Department of Mech. Eng. Charlottesville, VA 22901	165,666	05/01/76-07/31/78

Table 2-12. FUNDING BY TYPE OF SA-S SUBCONTRACTOR

	$K/% Total Funding/Number of Projects	
	FY78	FY79
Large business	695/29.6/5	629/ 31.8/5
Small business	746/31.8/8	315/116.0/5
Universities	480/20.5/8	482/ 24.4/7
National labs	360/15.4/1	550/ 27.8/1
Nonprofit organizations	64/ 2.7/1	0/0/0
Total	2344/100/23	1976/100/18

The objective includes performing engineering tests and marketing surveys and assessing the requirements for and capability of the industry to enter full production phases.

Originally transferred from the NSF-Research Applied to National Needs Program, this program has concentrated on developing components and systems for heating and cooling buildings. Although the main technical effort in developing AIPH and photovoltaic systems and components remains in other program areas (compare Fig. 2-2 and 2-5), a number of hybrid and single technology designs are ready for commercialization. The emphasis in the period from 1979 through to 1985 will be on developing marketable systems, products and designs. Funding levels for FY75 through FY80 are shown in Table 2-13.

The storage program element, SA-S, is a rather small component of the overall program in spite of the rapid growth in funding directed solely toward development of storage components. However, in all the systems' study areas a substantial number of projects include storage component integration and, thus, provide feedback to the development of storage components. Some projects are specifically addressed to storage component R&D. For example, two projects, one in the Collector and one in the Passive program element, are funded to investigate the MIT Thermic Diode Solar Panels, which have an integral storage component. The Kalwall Passive Solar Furnace, funded as a passive heating project, is a direct-gain storage device. A subjective estimate of the projects directly related to storage components and systems is provided in Table 2-14. These data are considered to be accurae within 10%. Detailed project listings are provided in DOE's 1978 report (soon-to-be updated) [34]. SA projects (excluding SA-S projects) directly related to development of storage components are listed in Table 2-15. In this report solar ponds are considered to be storage devices, although they are justifiably included in the collector program element. (The NBS Project is devoting half of th funding to developing acceptble test procedures for storage components.)

2.1.4 Agricultural and Industrial Process Heat Program in SA

The Agricultural and Industrial Process Heat Program in SA is engaged in funding RD&D solar applications for both agricultural and industrial processes. In general, state-of-the-art components are being used in these solar energy systems. Low temperature TES devices find applications in many of these projects.

Agricultural projects or food processing, grain drying, crop drying, heating of livestock shelters, and heating and cooling of greenhouses are being jointly managed by DOE and USDA. In FY79, 57 agricultural projects are underway. Industrial process hear projects in low temperature ($<176°$ ranges include dehydration of foods, curing of concrete blocks, production of hot water for car washing, productin of low pressure steam for industrial uses, and various drying operations such as those employed in the food processing, textile, and pulp and paper industries. In FY79, 11 projects are funded in industrial process heat.

The technical performances of many sensible heat storage technologies are being tested in such systems. Data from these projects will be useful in defining their operational characteristics and in determining the need for TES in AIPH applications. A complete program and project summary has recently been issued [35].

Table 2-13. FUNDING IN SA[a]

Program Element	Funding - $M					
	FY75	FY76	FY77	FY78	FY79	FY80 (Estimated)
Components						
Collectors	2.0	1.9	3.8	6.9	5.6	--
Storage	0.5	0.5	0.6	2.2	2.1	--
Controls	0.5	0.5	0.6	0.2	--	--
Active heating	0.3	0.4	0.6	2.1	3.4	--
Active cooling	1.0	0.8	4.9[b]	1.0[b]	6.6	--
Passive systems	c	c	c	c	3.9	16.2[d]
Active systems						16.5
Testing	1.4	1.4	3.7	3.5	2.7	
Development	0.9	11.3	12.0	11.0	11.0	
AIPH systems	--	--	--	--	2.5	14.3
Program support	0.8	0.6	1.4	2.6	1.1	--
Total	6.9	16.9	27.0	29.5	40.0	47.0
Projects	58	73	141	160		250

[a]Does not include $5.0M design competition and $3.0M Passive Demonstration.
[b]NASA/MSFC funding not included.
[c]Funding previously included under systems element ($2.1M in FY78).
[d]Additional funds are included.

Table 2-14. STORAGE-RELATED PROJECTS IN THE CS SA PROGRAM IN FY78

Program Element	Number of Projects	
	Storage Projects	Total Projects
Collectors	5	84
Thermal storage/heat exchangers	27	27
Heat pumps	3	6
Cooling	9	26
Passive systems	31	31
Advanced system development	26	27
Systems analysis	0	15
Controls	0	15
Support projects	0	24

Table 2-15. SOLAR APPLICATIONS PROGRAM: STORAGE-RELATED PROJECTS

Title	Code	Institution	Funding ($)	Period
Experiment and Theoretical Study of the Thermal Performance of a Hybrid Solar Residence	A2b	Ames Design Collaborative 208 5th Street Ames, Iowa 50010	54,500	09/77-10/78
Development of Thermal Energy Storage Using Phase Change Salts	B2	Artech Corporation 2901 Telestar Court Falls Church, VA 22042	151,306	10/76-12/79
Viscosity Stabilized Solar Ponds, Phase II, Segment 1	A2b	Center for Environment and Man 275 Windsor Street Hartford, CT 06120	82,466	05/76-11/76
The Application of PCM on Passive Solar Systems	B2	University of Delaware Institute of Energy Conversion Newark, DE 19711	59,130	10/77-11/78
Passive Solar Collector/Concentrator Incorporating Energy Storage	B2	Eikonix Corporation 103 Terrace Hall Avenue Burlington, MA 01803	40,000	09/77-08/78
Evaluation of the Miamisburg, Ohio, Solar Pond	A2b	Monsanto Res. Corp. P.O. Box 32 Miamisburg, OH 45342	38,000 57,000	FY78 FY79
Development of Methods for Evaluation and Test Procedures for Solar Collectors and Thermal Storage Devices, Phase III	F	National Bureau of Standards Washington, DC 20234	320,000	10/77-10/79
Salt Gradient Solar Pond Development	A2b	Ohio State University Research Foundation, Dept. of Physics, Ohio State University Columbus, OH 43210	184,945	09/77-04/79
A Demonstration Salt Gradient Solar Pond	A2b	University of New Mexico Depart. of Physics & Astronomy 800 Yale Boulevard Albuquerque, NM 87131	55,952 50,000	04/77-04/78 06/78-04/79
Development of a Thermosyphon Heat Exchange for Residential Solar Heating Systems	E	Sigma Research, Inc. 2952 George Washington Way Richland, WA 99352	91,831	10/76-06/78

2.1.5 Offices of Small Scale Technologies Program (SST), and Buildings and Community Systems (BCS)

The Office of Small Scale Technology (see Fig. 2-5) funds small-scale, community-level projects. Maximum grants are $50,000. Though most projects are not novel concepts, this effort is expected to aid in demonstrating the feasibility of participation by parties using low technology methods in energy-related projects. Ten regional DOE offices have complete responsibility for allocating funds. The first series of storage-related projects, funded in April 1978, is listed in Table 2-16.

The Office of Buildings and Community Systems manages as a component of its total program applied RD&D and promotes commercialization of (1) energy efficient processes, systems, and products in the built environment and (2) community systems to foster integrated energy conserving and renewable resource concepts and planning methodologies. BCS is therefore a direct user of low temperature TES. In particular, the ACES program managed by ORNL is involved in developing an integrated energy supply/PCM storage system.

2.1.6 Coordination among DOE Programs

Coordination among the various DOE programs involved in developing and commercializing both solar and storage technologies is critical. The division between R&D and commercialization activities increases the likelihood of program redundancy.

In the past, formal mechanisms for coordination between SA-S and TS included the transfer of management responibility for projects (Table 2-17 lists those projects) and the joint sponsorship of conferences. For example, a recent conference and workshop on Solar Enewrgy Storage Options (March 19-21, 1979) was jointly funded.

SA-S is engaged in defining low temperature TES requirements for solar applications, but is only one of a wide range of customers to which TS must respond. Efforts are now underway to strenghthen the link between TS and SA-S program plans.

Various informal mechanisms have been established for communicating between TS and SA-S requirements for and developments in TES. Operating plans and monthly written reports from the managing national labs are interchanged regularly. Conferences and workshops often are attended by all parties.

Lines of communication between TS and other DOE programs and subprograms in CS and ET were not judged to be so clearly established. However, STOR is beginning a process of formalizing and coordinating activities between itself and the various elements of the solar program.

2.1.7 Other DOE Programs

TES is widely applicable to many energy supply technologies and systems. Therefore, other divisions of DOE, especially in ET, are using and developing such devices. Although

Table 2-16. ONGOING OFFICE OF SMALL-SCALE TECHNOLOGY PROJECTS

Title	Code	Institution	Funding ($)	Period
Thermal Pile, Salt Hydrate Heat Storage System	B3	J. Horton Marina Del Ray, CA	14,700	
PCM Thermal Storage System	B3	Garrett Energy Reseach and Engineering Claremont, CA	10,000	
Thermal Energy Storage in Copper-Embedded Concrete Blocks	Alb	Heliodyne, Inc. and North Bay Research Richmond, CA	7,000	
Stratified Liquid Thermal Storage Bed	Ala	Marvin L. Stacy Claremont, CA	4,500	
Community Based Solar Storage Project	Alb	Window Rock School District #8 Fort Defiance, AZ	46,800	

Table 2-17. SA-S FUNDED, TS-MANAGED PROJECTS

Martin Marietta--CHP (Ammoniated Salts)
University of Delaware--PCM (Elevated Temperature Storage) Dept. of Mechanical Engineering
General Electric--PCM (Rolling Drum)

it would be a job beyond the intent of this report to chronicle all the uses for TES throughout DOE, one example of such activities is presented here. The Division of Electrical Energy Systems in ET (see Fig. 2-2) surveys utility load management and energy conservation projects [36]. One major component of this technology involves using after-the-meter sensible heat or ACES TES systems. Approximately 71 projects are being conducted. ORNL's Survey of Utility Load Management and Energy Conservation Projects lists details of these projects as well as equipment manufacturers in the United States [36].

2.2. OTHER PROGRAMS

Several programs of the International Energy Agency, other foreign programs, and privately funded industrial programs are described in addition to DOE programs.

2.2.1 International Energy Agency

The International Energy Agency (IEA) was established by member countries from the Organization for Economic Cooperation as an autonomous agency to foster cooperation in energy R&D. Participants include Austria, Belgium, Canada, Denmark, Federal Republic of Germany, Great Britain, Greece, Ireland, Italy, Japan, Luxembourg, the Netherlands, Spain, Sweden, Switzerland, Turkey, and the United States. Solar heating and cooling of buildings and solar radiation measurement and analysis were identified as fruitful areas for cooperation. One of the five solar tasks identified is R&D on system components. Forty-five projects (including 11 U.S. projects) concentrating on development of thermal storage devices have been identified and catalogued. See IEA's 1978 survey of component R&D projects report [37] for more details. Nine IEA countries are engaged in storage component R&D. Table 2-18 lists these projects by country.

2.2.2 Commission of the European Communities

In early 1975 The commission of the European Communities (including Belgium, Denmark, France, Germany, Great Britian, Ireland, Italy, and the Netherlands) established a five-part program in energy RD&D [38]. This program began a second phase on July 1, 1979 [39]. Program structure and funding are outlined below:

	7/1/75-6/30/79	7/1/79-12/31/79	1980	1981	1982	1/1/83-6/30/83
Energy Conservation	15.14	2.00	13.3	13.3	3.99	0.67
Production & Use of Hydrogen	17.61	1.33	7.98	6.65	2.66	1.33
Solar Energy	23.28	3.99	34.58	21.28	13.3	3.99
Geothermal Energy	17.29	1.33	10.64	7.98	5.32	1.33
Systems Analysis/Energy Modelling	5.16	0.67	3.33	3.33	1.33	0.67
Total Funding (M$)[a]	78.48	7.0	69.83	52.54	26.6	7.98

[a] A conversion of $1.33 per EVA, the standard European currency unit, was used.

Table 2-18. IEA PROJECTS IN LOW TEMPERATURE TES

Country	Title	Organization	Funding (US$)	Period	Type[a]
Austria	Domestic Heating with Solar Energy	Arbeitsgemeinschaft Sonnenenergie	52,000	01/76-01/78	Sys
Austria	Solar Energy Test Stations in Austria	Austrian Solar and Space Agency	375,000	01.76-onward	Sys
Austria	Development of Prototype Plastic Storage Tank for Low Temperature TES	University of Technology	2,000	1977	Sens
Austria	Compact Solar System for Domestic Water Heating	Vereinigte Metallwerke Ranshofen-Berndorf	15,000	05/77-11/77	Sys
Belgium[b]	Reversible Chemical Reaction Storage	Faculte Polytechnique de Mons		3 years	Chem
Denmark[b]	Salt Hydrate Low Temperature TES	Thermal Insulation Laboratory	93,000 567,000	11/76-08/77 1/78-1/80	PCM Sens PCM Chem
Federal Republic of Germany	Investigation of Low Temperature TES	Energietechnik, GmbH	162,000	06/75-06/78	Sens
Federal Republic of Germany	Modular Solar House Heating System, Phase I	Messerschmitt-Bolkow-Blohm GmbH	478,500	11/74-12/76	Sys
Federal Republic of Germany	Modular Solar House Heating System, Phase II	Messerschmitt-Bolkow-Blohm GmbH	562,300	01/76-06/77	Sys
Federal Republic of Germany	Rational Use of Energy and Utilization of Solar Energy in Buildings	Philips GmbH	3,935,882	06/74-12/77	Sys
Japan[b]	Salt Hydrate and Paraffin Phase Change Low Temperature TES Systems	Ishikawajima-Harima Heavy Industries, Co., Ltd.	55,300 (FY78)	01/74-01/81	PCM
Japan[b]	PCM Storage for Rankin-Cycle Engine Applications	Mitsubishi Electric Corporation	56,800 (FY76-FY78)	07/74-03/81	PCM

Table 2-18. IEA PROJECTS IN LOW TEMPERATURE TES (continued)

Country	Title	Organization	Funding (US$)	Period	Type[a]
Japan[b]	Solar Heating, Cooling and Hot Water Supply System for Large Buildings	Toyo Netsu Kogyo Kaisha, Ltd.		07/74-03/80	Sens
Netherlands[b]	Development of a Concrete Heat Storage System	Bouwcentrum			Sens
Netherlands[b]	Development of an Integrated Collector Heat-Storage System for Low-Cost Housing Projects	Bouwcentrum			Sens
Netherlands	Solar Heating for Swimming Pools	Bronswerk, BV			Sys
Netherlands	Development of an Integrated Solar Boiler System	Calcol BV			Sys
Netherlands[b]	Seasonal Soil Storage of Solar Energy	Delft Soil Mechanics Laboratory	320,000	01/78-09/79	Sens
Netherlands[b]	Heat Storage in PCM	Delft University of Technology	100,000	08/77-08/80	PCM
Netherlands	Integration of Water Tank Storage, Hot Water Boiler and Auxiliary Heater	Eindhoven University of Technology	60,000	01/76-01/80	Sys
Netherlands[b]	Seasonal Storage of Solar Heat in the Ground	Eindhoven University of Technology	250,000	01/76-01/81	Sens
Netherlands[b]	R&D on Solar Thermal Components	Philips Gloeilampen Fabrieken			Chem PCM
Netherlands	Simulation of Solar Heat Pump Heating System	Central Technical Institute TNO	2,000	01/75-01/77	Sys
Netherlands	Soil as Source for Heat Pump	Central Technical Institute TNO	60,000		Sys

Table 2-18. PROJECTS IN LOW TEMPERATURE TES (continued)

Country	Title	Organization	Funding (US$)	Period	Type[a]
Netherlands[b]	Low Temperature TES System Based on Encapsulation of PCM	Institute of Applied Physics TNO-TH	350,000	01/77-01/80	PCM
Netherlands[b]	Development of a Reaction Vessel of a Thermal Storage Using Heat of Adhesion	Institute of Applied Physics TNO	200,000	01/78-07/79	Chem
Netherlands[b]	Photochemical Storage of Solar Energy for Heating of Houses and Buildings	Institute for Organic Chemistry TNO	460,000	01/77-01/81	Chem
Netherlands	Solar System for Domestic Heating and Hot Water Supply Using Concrete Structure for Storage	Veg-Gasinstituut	15,000	3 years	Sys
New Zealand	Packaged Solar Water Heater	Pel, DSIR		01/76-01/78	Sys
New Zealand	Solar Space Heating Using Passive Storage	University of Auckland	3,500 (NZ$)		Sys
Sweden[b]	Energy Storage by Use of PCM	Studsvik Energiteknik AB	48,000	04/76-09/77	PCM
Sweden[b]	Low Temperature TES in Salt Hydrates	The Royal Institute of Technology, Dept. 8 Physical Chem.	299,775	01/74-01/79	PCM Chem
Switzerland[b]	Hybrid Fluid Heat Storage Unit	Ecole Polytechnique Federale de Lausanne	12,500	10/77-04/78	Sens
Switzerland[b]	PCM Thermal Storage	Ecole Polytechnique Federale	110,000	01/77-01/79	PCM

[a]Chem = Reversible chemical reaction or photochemical; PCM = Phase change materials; Sens = Sensible heat; Sys = Systems studies on low-temperature TES (not directed toward development of basic storage technique).
[b]Project detailed in Section 3.0.

Thermal, electrochemical, and mechanical energy storage are integral components of these programs. For example, the projects were funded in energy storage as part of the Energy Conservation element in the first phase. Detailed descriptions of these programs are found in the Commission's publications [38,39]. Of particular interest is the Pilot Test Facility established to perform validation testing of complete solar systems (collectors, storage controls, piping) using simulated weather and load data.

Projects are funded by the commission at universities and at industrial and private laboratories. It should be noted that many projects listed under the IEA receive monies from this program.

2.2.3 Other Foreign Programs

Projects outside the IEA umbrella in countries participating in the IEA and projects in non-IEA countries have been identified from various sources. For example, the ATES Newsletter [40] outlines seven countries engaged in studying aquifers for low temperature thermal storage. Solar ponds are being investigated in a number of countries by both private and public organizations. Section 3.0 describes many of these efforts.

2.2.4 Privately Funded Industrial Programs

A number of storage technologies are being developed independently of DOE. The reasons for such activities are numerous but stem from a perception that the potential markets and rate of return for this new technology are promising.

SECTION 3.0

LOW TEMPERATURE THERMAL STORAGE ACTIVITIES: PROJECTS

Recently completed, ongoing, and new or planned projects in low-temperature thermal energy storage are listed in this section.* These projects are categorized into seven types. Projects are grouped as follows: short-term sensible heat storage; annual sensible heat storage; PCM storage; heat transfer and exchange; industrial waste heat recovery and storage; reversible chemical reaction storage; and models, economic analyses, and support studies. As expected, there is some overlap between different categories, although in general the subgroupings are reasonably well defined. The levels of funding are presented for FY76 through FY79 and, when possible, for FY80. In those cases in which detailed fund procurement information was not available, money was assumed to be spent linearly over the contract period in order to allow allocation between financial periods.

The project information has been gleaned from a variety of sources including published documents [26,27,30,33,34,41,42] and personal communications with contract managers, contractors, and industrial spokesmen.

A number of abbreviations are used in the tables in this section. See the Table of Nomenclature for a complete list of abbreviations.

3.1 SENSIBLE HEAT—SHORT-TERM STORAGE

TES Projects investigating short-term TES using sensible heat principles are listed in Table 3-1 and are described below.

3.1.1 Ongoing Projects

An experimental apparatus designed to make 22 simultaneous, two-dimensional temperature measurements in a rectangular water tank has also been built. Combined with weather and insolation data and load outputs, this apparatus will be capable of producing three-dimensional temperature profiles in an operating heat storage tank. Validation of the ANL two- and three-dimensional transient hydrodynamic temperature stratification codes is a goal of this project for use in optimizing overall system performance.

Altas Corporation. A gas backup heater for use with a solar hot water system is being developed (see Fig. 3-1). By minimizing standby heat losses and by using a heat pipe feeding line, firing efficiencies of 75% to 80% are expected (50% overall efficiencies are typical for current heaters).

*Recently completed is loosely defined as projects for which funding terminated within the last few years.

Table 3-1. SENSIBLE HEAT PROJECTS: SHORT-TERM STORAGE

Project	Source	Funding-$ FY76	FY77	FY78	FY79	FY80
Ongoing						
Univ. of Alabama	SA-S	--	25,000	40,035	--	--
Altas Corp.	SA-S	--	--	66,000	*	*
ANL	SA-S	--	--	70,000	100,000	--
Atomics Int'l, Rockwell	SA-S	--	41,500	67,327	--	--
Colorado State U.	SA-S	--	--	--	*	--
Dynatech	SA-S	--	37,500	66,741	--	--
Heliodyne	SST	--	--	7,000	--	--
Independent Living	SA-S	--	--	129,851	--	--
Univ. of Nebraska	SA-S	--	--	66,000	*	--
M. L. Stacy	SST	--	--	4,500	--	--
Westinghouse	SA-S	--	--	120,000	*	*
Window Rock School District	SST	--	--	46,800	--	--
Foreign						
Federal Republic of Germany						
Energietechnik, GmbH	IEA	54,000	54,000	36,000	--	--
Japan						
Toyo Netsu Kogyo Kaisha, Ltd.	IEA	7,000	7,000	7,000	7,000	3,000
Netherlands						
Bouwcentrum	IEA	--	--	--	--	--
Switzerland						
Ecole Polytechnique Federale de Lausanne	IEA	--	--	12,500	--	--

*Funding has been proposed.

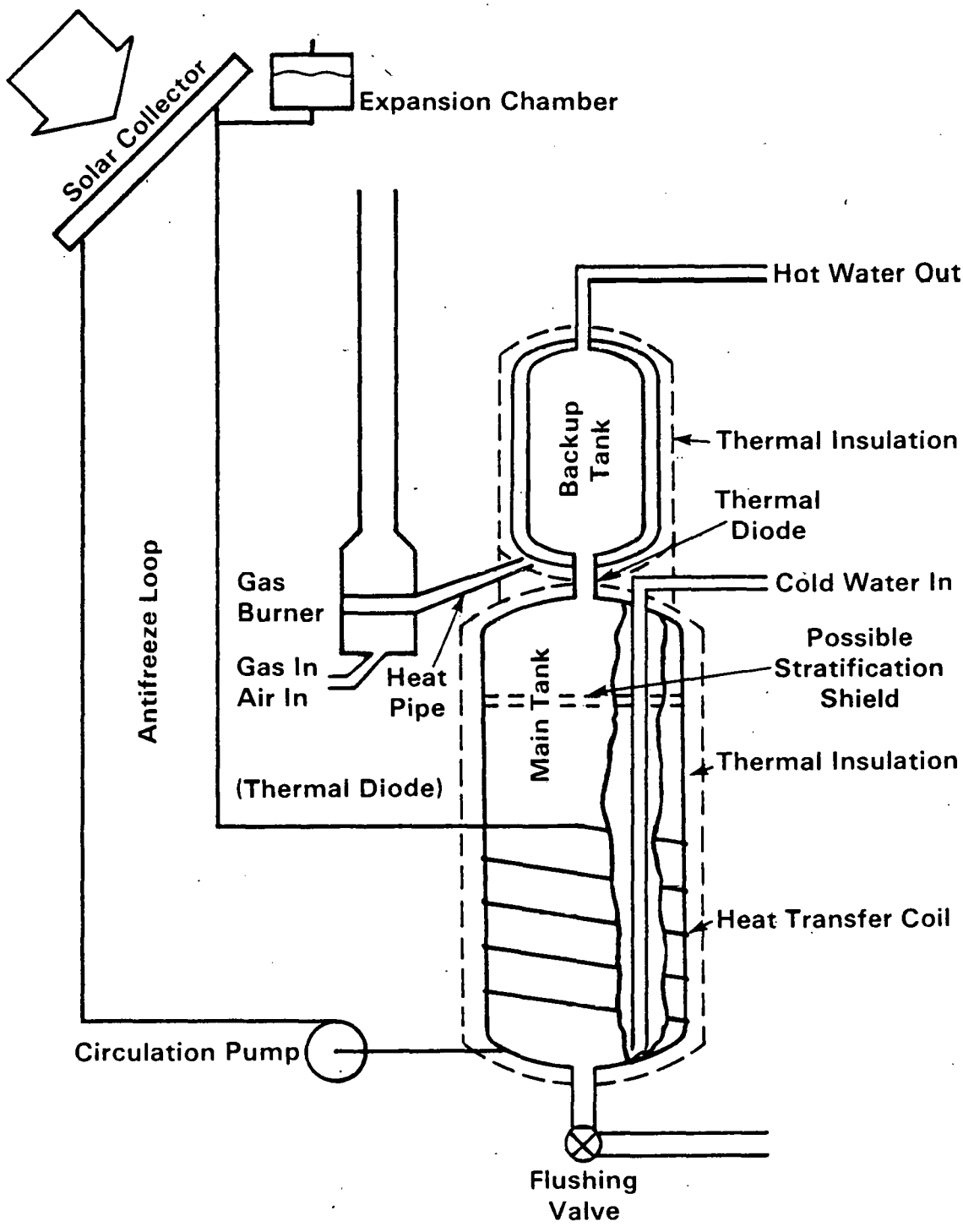


Figure 3-1. ALTAS CORPORATION—GAS BACKUP HEATER

ANL. A three-dimensional modeling of thermal stratificaton and flow dynamics in a single fluid tank has been developed. This model includes effects of turbulence, buoyancy, tank-wall thermal capacity, variable mesh, baffles, jetting, heat sources and sinks within the tank, and wall effects. A three-dimensional two-fluid code is planned. These models will be validated with data from the University of Alabama study.

Atomics International. A study has been conducted of engineering and cost data of hybrid water tanks and solid material thermal storage concepts. Five design concepts have been identified (see Fig. 3-2 describing four of them). Six existing regional hybrid storage projects have been identified and simulation models have been run.

Colorado State University. A small-scale experiment followed by a small-scale field study will investigate soil heat transfer properties including water migration and heat fluxes. Effects of moisture and barriers for controlling moisture will be detailed.

Dynatech. Costs and performances of rock beds chilled by night air or by air from an evaporative cooler have been studied in six different regions. Cost and performance models for rock bed cooling components have been assembled or developed, and regional data and rock properties have been acquired. Evaluation criteria have been established and simulation runs performed. The performance of rock-bed-storage cooling systems has been optimized to provide information on regional economic feasibility.

Heliodyne, Inc. (and North Bay Research). This joint effort is aimed at developing and testing a storage device consisting of concrete blocks embedded with copper tubes. The work is aimed at the retrofit market, which requires units that can be easily installed.

Independent Living. A novel water tank composed of a rigid fiberglass outer layer, a foam-insulated wall and a flexible water-impermeable inner layer is being developed. Candidate materials for the inner moisture boundary are being screened. The tank is composed of hemispherical modules that can be interlocked and sealed on-site. A life expectancy of greater than 30 years is expected from this lightweight tank. Mass production costs will be projected.

University of Nebraska. This project is studying performance and economic characteristics of membrane-lined storage tanks. Construction techniques and membrane materials are of central concern. Plans include studying alternative methods for heat transfer and exchange and evaluating designs which promote thermal stratification.

M. L. Stacy. This researcher is investigating a stratified liquid thermal storage bed composed of layers of round tubes filled with a high-heat-capacity fluid.

Westinghouse. Lightweight foamed concrete insulating and structural elements are being developed for water thermal storage tanks. Initially, 500-gallon tanks are being built. A 2,000-gallon prototype tank will be designed, constructed, and tested.

Window Rock School District. This local agency plans to build a "Navajo hogan" style model home which incorporates solar technology. Earth block walls will be employed to retain heat.

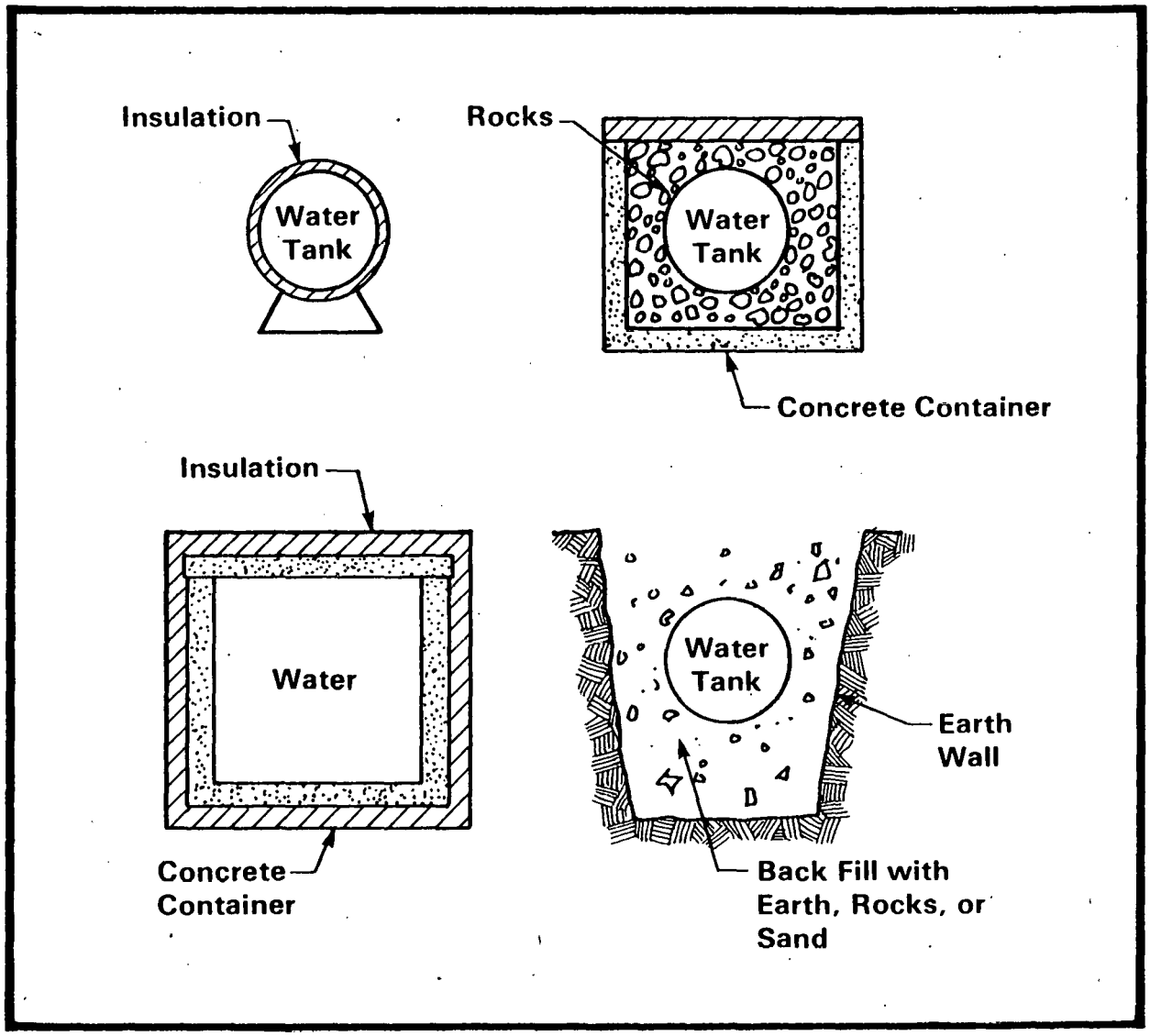


Figure 3-2. ATOMICS INTERNATIONAL—HYBRID SENSIBLE HEAT STORAGE SYSTEMS

3.1.2 Foreign Projects

Germany, Energietechnik, GmbH. A variety of containers using water are being investigated for low temperature TES. These include: (1) steel containers embedded with foam and welded on-site in cellars, (2) cellars lined with pressure-resistant thermal insulation and waterproof films, (3) underground insulated and waterproofed steel containers, (4) underground containers of reinforced insulating material and film, and (5) underground, double-walled, insulated steel containers.

Japan, Toyo Netsu Kogyo Kaisha, Ltd. Work is in progress on developing inexpensive thermal storage tanks (water as storage medium) for heating and cooling of buildings. Thermal stratification has been found to improve storage efficiency.

Netherlands, Bouwcentrum. An insulated, square concrete column (1m x 1m x 6m) with embedded air pipes is being studied for low temperature TES.

Switzerland, Ecole Polytechnique Federale de Lausanne. A hybrid heat storage system using air heat input and water heat output is being investigated.

3.2 SENSIBLE HEAT—ANNUAL STORAGE

TES projects studying annual storage which use sensible heat principles are listed in Table 3-2 and described below.

3.2.1 Recently Completed Projects

Desert Reclamation Industries. This study explored the feasibility of cooling JFK Airport in New York with cool winter water from neighboring Jamaica Bay. In winter, water just above freezing would be stored in an aquifer for use in summer cooling. A preliminary engineering and economic evaluation by Dames and Moore (an engineering consulting firm) concluded that a payback period of 3.5 to 8 years is likely for a system which supplied 100% of the 24,000-ton air conditioning load. Other methods of cooling the aquifer water were also investigated. New York State Energy Research and Development Authority (ERDA) has drilled four exploratory wells to provide detailed engineering data and to evaluate potential subsidence of soil over time. This is a major concern to the NY/NJ Port Authority, operating agents for JFK, since the airport is built over a landfill and some settling and damage to terminal buildings has already occurred. A large-scale demonstration was suggested. Organizations involved in this joint venture have included the Port Authorities of New York and New Jersey, the U.S. Geological Survey, New York ERDA, and Dames and Moore.

George Washington University. The technical and economic feasibility of long duration earth storage of solar energy was explored using computer modeling. The technical options were transportation of heat from solar collectors by heat or water pipes and

Table 3-2. SENSIBLE HEAT PROJECTS: ANNUAL STORAGE

Project	Source	Funding-$ FY76	FY77	FY78	FY79	FY80
Recently Completed						
Desert Reclamation Industries	TS	--	--	102,180	--	--
George Washington Univ.	TS	--	25,000	25,000	--	--
Univ. of Virginia	SA-S	78,181	40,000	47,485	--	--
Ongoing						
Ames Design Collaborative	SA-P	--	--	15,000[a]	--	--
ANL	SA-S	--	--	--	*	--
Auburn Univ.	TS	--	46,355	185,419	*	*
Center for Environment & Man	SA-C	58,905	23,562	--	--	--
G. E. Tempo	TS	--	--	--	*	*
Lawrence Berkeley Labs. (LBL)	TS	--	41,176	98,824	--	--
Monsanto Res. Corp., Miamisburg	SA-C	--	--	38,000	*	--
Univ. of New Mexico	SA-C	--	55,952	50,000	*	--
Ohio Agricultural Station	USDA	--	--	49,000	*	--
Ohio State Univ. Res. Found.	SA-C	--	--	184,945	--	--
ORNL	TS	--	--	--	*	--
Texas A&M Res. Found.	TS	2,585	14,215	100,000	*	--
Univ. of Toronto	SA-S	--	67,130	70,283	*	--
TVA	TS	--	--	--	*	--
Foreign						
Denmark						
Technical Univ. of Denmark	F	--	--	--	--	--
Thermal Insulation Laboratory	F	--	--	283,500	283,500	--
France						
Ecole Nationale Superieure des Mines de Paris	F	--	--	--	--	--
Commissariat a L'Energie Atomique	F	--	--	--	--	--
Federal Republic of Germany						
Federal Government	F	--	--	--	--	--

*Funding has been proposed.

Table 3-2. SENSIBLE HEAT PROJECTS: ANNUAL STORAGE (continued)

Project	Source	Funding-$ FY76	FY77	FY78	FY79	FY80
Israel						
Weizmann Inst. of Science	F	--	--	--	--	--
Ormat Turbines, Ltd.	F	--	--	--	--	--
Dead Sea Potash Works	F	--	--	--	--	--
Eilat, Red Sea	F	--	--	--	--	--
Japan						
Univ. of Yamagata	F	--	--	--	--	--
Netherlands						
Delft Soil Mech. Lab.	IEA	--	--	240,000	80,000	--
Eindhoven Inst. of Technology	IEA	36,885	49,180	49,180	49,180	49,180
Sweden						
Lund Inst. of Technology	F	--	--	--	--	--
Switzerland						
Centre d'Hydrogeologie de l'University, Neuchatel	F	--	--	--	--	--

[a]This cost is for construction of a solar pond and is a fraction of the total contract, a study of hybrid solar residences. The solar pond is being managed by Iowa State University.

extracting heat by water pipes. Storage material was undisturbed earth surrounded by insulation and covered by a plastic sheet. Direct absorption into storage by use of a black plastic cover was found to not be technically feasible. A storage area an acre 4 by 20 feet deep could supply annual heating for 12 homes. The earth storage system is claimed to be economically competitive today when it is used in conjunction with electric heating. The economic calculations assumed a 12% escalation in conventional energy costs, a $2,000 tax credit, and ignored property taxes.

University of Virginia. A 27,000-gallon water pond with plastic lined, uninsulated sloping walls and surface insulated by floating styrofoam beads was constructed and tested. After mid-August, heat losses greatly exceeded heat collected by the trickle collector mounted over the pool, and temperature dropped rapidly. Operational data compared well with analogue model predictions. The conclusion was that this design is inadequate for annual storage.

3.2.2 Ongoing Projects

Ames Design Collaborative (Iowa State Univ.). A solar pond (60 m^2) designed to heat an adjacent structure is under construction on the Living History Farm in Iowa. The walls are insulated with 10 in. of polyurethane. Initially, use of a transparent dome cover was planned; economic considerations led to abandoning this concept when it was learned that decrease in heat loss would be offset by a 5% transmission reduction. Funds are mostly from private sources, although SA-P provides some support to Ames Design Collaborative, the manager of this venture.

ANL. A project in long-term ice storage has been started. A one-way heat pipe freezes a large underground tank of water by pumping heat into cold winter air.

Auburn University. Injection into and withdrawal of heated water from an aquifer are being monitored. The data will be used to calibrate simulation models being developed at LBL. A preliminary experiment involved injecting 99°F water obtained from the effluent discharge canal of a power plant. Clogging of soil around the injection well, caused by a high level of suspended solids, was a major problem. In a subsequent experiment, 14.5 million gallons of water at 131°F were injected over a period of three months, stored for one and a half months, and then withdrawn. The efficiency of recovery was approximately 65%, and higher efficiencies are expected in the next injection/storage/withdrawal cycle. Clogging problems were reduced because aquifer water was used as an influent to the heating system. A short backwashing procedure repeated about once a week helped to minimize clogging. A second six-month injection/storage/withdrawal cycle is presently underway. A concern of these researchers is the effect of higher temperatures on hydraulic conductivity of aquifer formation soils.

Center for Environment and Man. Fundamentals in the operation of viscosity-stabilized solar ponds are being investigated. To be satisfactory, thickening agents must have high viscosity and optical clarity and low thermal degradation. Laboratory test and a bench-top model will be used to investigate feasibility.

G. E. Tempo. Evaluation of thermal energy storage for the twin cities (Minneapolis/St. Paul) proposed district heating system was initiated recently. In concert with the Northern States Power Company, Minnesota Energy Agency, and the Swedish firm of Studsvik Energiteknik AB, this metropolis has studied use of hot water produced as a byproduct of electricity generation for district heating. G. E. Tempo will examine the value of aquifer storage to the entire system. Preliminary analysis suggests a 10% to 20% fuel savings and a 5% to 15% decreased investment cost by use of TES.

Lawrence Berkeley Laboratories (LBL). A model has been developed to investigate injection, storage, and withdrawal of hot (120° C, 220° C and 320° C) and cold (4° C) water from aquifers. Four cases have been studied: (1) hot water daily storage; (2) hot water seasonal storage, semi-annual cycle; (3) hot water seasonal storage, annual cycle; and (4) chilled water seasonal storage. In the future a two-well system will be investigated. This model is validated against a few semi-analytic solutions available in the literature. It has been used extensively in geothermal studies. Currently it is being validated against data from the Auburn aquifer. The model will be used to determine sensitivity of aquifer storage to variables such as flow rates, permeability, thickness, injection/withdrawal strategies, and boundary conditions.

Miamisburg. The city has recently completed a 3.5-m deep, 2090-m^2, 1.4 million gallon salt gradient solar pond which is the world's second largest one in operation. Salt concentration is 18% at the bottom, and a heat exchanger is located 4 feet below the surface. A heavy plastic liner (22,000 ft^2) prevents leakage. Accidental pond runoff could add substantial salt to the nearby river. It is estimated that 48,000/Btu/ft^2-year will be extracted to heat a municipal swimming pool and adjacent shower building. This pond was financed entirely by city funds and completely installed for $3.20 per ft^2. DOE has recently supported data collection and analysis.

Monsanto Research Corporation. This firm is presently evaluating the Miamisburg Solar Pond. Operational data will be collected and analyzed.

University of New Mexico [11]. A 2.5-m deep 175-m^2 solar pond which supplies the heat requirements of a 185-m^2 home has been in operation for over two years. Automated data collection equipment records heat input, losses, and extraction and temperature and salt concentration profiles in order to allow detection, understanding, and correction of convective instabilities. Corrosion of pond structural materials in hot brine is also being investigated. Thus far, the only major problem has been convective currents at the gradually sloping walls. Steeper walls are recommended. Wind and other factors have caused the surface convective layer to grow from 10 cm to 24 cm in depth. The maximum temperature attained to date is 93° C.

Ohio Agricultural Station. A partially above-ground solar pond (155 m^2 area; 3.6 m depth) is used for heating an adjacent greenhouse. Initially, a poor choice of pond liner resulted in serious leakage problems. The pond is now operational. Heat losses in winter are 60%, 21%, and 19% through the top, walls, and bottom of the pool, respectively. Heat will be transferred both by a tube and shell heat exchanger and by directly pumping pond brine from the convective layer. The pond will be monitored and modeled.

Ohio State University, Research Foundation. The longest continually operating solar pond (area 200 m^2, depth 2.5 m) is located at the university, and a second deeper pond with reflectors to increase solar gain is being constructed. Heat is removed at 72,000 Btu/hr ($\Delta T = 12°C$). Pond temperature varies from 18°C in February to 69°C in August. A surface ice layer causes upward movement of the gradient layer but protects the pond from the elements. Data indicate that the insulating layer thickness approaches a stable equilibrium determined by temperature and salt concentration profile. At equilibrium the surface mixing layer is also stable. Research issues include establishing a working model to understand the layer dynamics and maintenance of clarity. Future work will include construction of a grain drying facility powered by the solar pond.

ORNL. An environmental impact analysis of aquifer thermal storage is being performed. A literature survey will identify critical areas for site-specific analyses. In addition, an economic analysis of aquifer storage is underway.

Texas A&M Research Foundation. A field study is being done on a combination cooling pond/aquifer storage for cooling a building. Ten wells have been drilled: one for injection, one for withdrawal, and eight for observing groundwater movement and for measuring pressures and temperatures at various distances from the wells. In order to provide information about uplift and subsidence during injection and withdrawal, a precise-level network will be constructed. Field tests will continue for three years. Recently, an annual injection/storage/withdrawal cycle was begun in which water is chlorinated in the cooling pond to reduce biological activity. Problems with iron from the oxygenated water are anticipated and are being solved.

University of Toronto. Computer models designed for simulation and optimization of solar space heating systems using a large, insulated underground tank for seasonal storage suggest that a 100% solar system is competitive and feasible for larger, multiunit systems [40]. Overall performance and life cycle cost analyses at higher latitudes are being validated by operational data from the Provident House in Toronto and from a new multiunit annual storage solar heating project at Aylmer, Ontario. The model shows that use of annual storage in Toronto cuts the required solar collector area in half. Economics of scale are also a major cost factor. A simple, noncomputer design procedure is being prepared.

TVA. ORNL has contracted with the Tennessee Valley Authority hydrologists and engineers to survey potential market applications for thermal energy storage in the TVA service area. A parametric modeling of aquifers and aquifer storage will aid in determining a priori the suitability of various types of aquifers for TES.

3.2.3 Foreign Projects

Denmark, Technical University of Denmark. The 4.5-year Danish seasonal aquifer warm-water-storage program is proceeding in stages. At least three years are being spent in developing mathematical models, to be followed by design, construction, and operation of

a demonstration plant near a district heating load. Finally, a general, nationwide geological and hydrological survey will identify potential aquifer sites.

Denmark, Thermal Insulation Laboratory. TES technologies using water and rocks as sensible heat media, PCM, and reversible thermochemical reactions are being investigated in this Danish-government-financed program.

France, Ecole Nationale Superieure des Mines de Paris. An aquifer experiment was conducted and a mathematical model is being developed. Hot water was injected for 20 days and withdrawn after four months. Efficiency of storage was only 30%.

France, Commissariat a l'Energie Atomique. A number of community solar systems using annual storage of thermal energy in large water tanks have been designed and are being built.

Federal Republic of Germany, Federal Government. This German program has two foci, aquifer and pond thermal storage. Three lake storage projects are underway. One of these is a $5 million project to which DOE is contributing $250,000 through the IEA. A small-scale pilot aquifer project is presently generating test data. If successful, a full-scale aquifer will be completed in 1979 and operated in an actual heating district.

Israel, Weizmann Institute of Science. Use of an aquifer in a power station/agricultural dual service mode is under study. Cold water withdrawn from the aquifer would be used in the power station; during the cold season warm water would be withdrawn and delivered to users. Power generation is problematic in warm, arid regions.

Israel, Ormat Turbines, Ltd. This firm, which has manufactured low temperature closed-cycle vapor (usually Freon) turbogenerators for 14 years, has built two solar ponds. The first, a 15,000 ft^2 pond at Yavne, generates 6-kW of electric power. Water from the storage layer at 195°F drives the turbine. Cool surface water cools the condenser. The second, a 70,000 ft^2 pond at Ein Bokek on the Dead Sea, is used to provide electricity, absorption cooling, and hot water for a 200-room hotel.

Israel, Dead Sea Potash Works. A 12,000 ft^2 solar pond in operation for one year is being studied. The operating temperature of 218°F is obtainable because the high salt concentration and the location of the dead Sea at 1200 feet below sea level raise the boiling point of water.

Israel, Eilat, Red Sea. A 12,000 ft^2 solar pond is being used for desalination. Eventually, one million square feet of pond surface will be operational.

Japan, University of Yamagata. Experiments on TES in aquifers with applications in heating and cooling of buildings have led to a number of conclusions. Storage efficiency was 40%. With large well flow rates compared to natural rates, thermal diffusion is not a problem. No evidence of clogging was apparent.

Netherlands, Delft Soil Mechanics Lab. This group is investigating seasonal storage of solar energy in soil of different compositions with and without use of heat pumps. The

model will be compared to data from the Philips Veldhoven project and a number of technical and economic alternatives will be formulated.

Netherlands, Eindhoven Institute of Technology. Preliminary studies of seasonal storage of thermal energy in the ground suggest economic feasibility for systems having capacities larger than 10^5 kWh (half life of such a storage volume is approximately eight months). Following consolidation of technical results, the heat loss, characteristics, and control strategies will be verified experimentally. Subsequently, a full-scale unit will be built and tested.

Sweden, Lund Institute of Technology. Two TES projects are underway: storage of hot water in eskers (long and narrow glacial deposits of high permeability) and underground heat storage. Models of both of these systems are being developed.

Switzerland, Centre d' Hydrogiologie de L'University, Neuchatel. Different methods are being employed for calculating efficiency of thermal storage in aquifers. Major factors are permeability of geological formations and natural groundwater flow.

3.3 PCM STORAGE

PCM projects are listed in Table 3-3 and described here. The independently financed projects are grouped separately following government-funded projects.

3.3.1 Recently Completed Projects

Brookhaven National Laboratories (BNL). Efforts to encapsulate PCM in polymer concrete have met with difficulties. Hydrated calcium chloride interfered with curing. Attempts were made to pack this salt into partially sealed glass beads so that the concrete would cure. In recent efforts PCM has been blended in polymer concrete or in impregnated foamed-porous aggregate, loaded into coated cylindrical shells of polymer concrete, and then inserted into conventional concrete blocks [43]. Vapor permeability may still be a problem. Although these building materials may function well as low temperature TES devices, the whole issue of manufacturing costs must be addressed. A final report is being prepared to describe this work.

Desert Research Institute [26,30]. Attempts to develop methods to alleviate the problem of nucleation occurring on heat transfer surfaces were unsuccessful. A crystal fallout technique achieved by controlled supercooling and nucleation was studied.

Dow Chemical Company. A wide range of congruently melting PCM and their associated packaging for use in space heating (70 to 90°C), water heating (60 to 70°C), air heating (40 to 60°C), and heat pump applications (20 to 40°C) have been investigated. The materials listed below were identified as promising candidates:

Table 3-3. PCM PROJECTS

Project	Source	FY76	FY77	FY78	FY79	FY80
Recently Completed						
BNL	TS	--	28,500	114,000	*	--
Univ. of Delaware	TS	80,000	--	--	--	--
Desert Research Inst.	TS	55,579	55,579	50,947	--	--
Dow Chemical Co.	TS	7,000	84,000	84,000	--	--
Eikonix	SA-P	--	6,700	33,300	--	--
Franklin Research Inst.	TS	15,286	45,857	7,643	--	--
General Electric Co.	SA-S	30,667	52,592	21,905	--	--
Monsanto Research Corp.	TS	64,776	117,586	28,875	--	--
North Carolina State Univ.	SA-S	20,523	49,256	24,628	--	--
ORNL (1)	TS	23,226	23,226	13,548	--	--
(2)	TS	60,000	60,000	60,000	--	--
Penn. State Univ.						
Suntek	TS	19,167	115,000	95,833	--	--
Villanova Univ.	TS	--	3,855	22,350	--	--
Ongoing						
Artech	SA-D	--	106,804	44,502	**	--
Calmac	SA-S	--	--	200,000	*	*
Clemson Univ.	TS	--	18,533	55,600	*	*
Univ. of Dayton	TS	--	--	--	*	--
Univ. of Delaware						
IEC	SA-P	--	40,680	8,450	--	--
Mech Eng.	SA-S	--	--	84,000	*	*
Other	Sun Oil	--	--	--	--	--
Garrett Energy Res. & Eng.	SST	--	--	10,000	--	--
General Electric Corp.	SA-S	--	--	150,000	*	*
J. Horton	SST	--	--	14,700	--	--
ORNL	BCS	--	0.6	0.9	1.1	1.1M$
ORNL	TS	33,333	33,333	33,333	--	--
Penn State Univ.	TS	76,000	19,000	--	--	--

Table 3-3. PCM PROJECTS (continued)

Project	Source	FY76	FY77	FY78	FY79	FY80
Suntek	SA-S	--	--	33,085	*	--
Westec Services Inc.	Navy	--	--	--	--	--
Independent Projects						
Addison Corp.	I	--	--	--	--	--
Anheuser Busch, Inc.	I	--	--	--	--	--
Architectural Research Corp.	I	--	--	--	--	--
Arizona State Univ.	I	--	--	--	--	--
Brown Univ.	I	--	--	--	--	--
Dow Chemical	I	--	--	--	--	--
Michigan Tech. Univ.	I	--	--	--	--	--
Pipe systems Inc.	I	--	--	--	--	--
Ramco	I	--	--	--	--	--
Solar, Inc.	I	--	--	--	--	--
Solar Marketing	I	--	--	--	--	--
Solarmatic	I	--	--	--	--	--
Valmont Ind.	I	--	--	--	--	--
Foreign						
Denmark						
Thermal Insulation Laboratory	IEA	--	75,000	--	--	--
Japan						
I-H Heavy Industries	IEA	9,090	9,090	9,090	6,818	9,090
Mitsubishi Electric	IEA	18,200	21,700	16,900	*	*
Netherlands						
Delft Univ.	IEA	--	5,405	32,432	29,730	--
Philips	IEA	--	--	--	--	--
Inst. of Appl. Phys. TNO	IEA	--	90,000	120,000	120,000	40,000
Sweden						
Studsvik Energiteknik AB	IEA	16,000	32,000	--	--	--
Royal Institute	IEA	68,630	68,630	76,140	95,450	*
Switzerland						
Ecole Polytechnique	IEA	--	66,000	66,000	66,000	--

*Funding has been proposed.
**A no-cost extension has been granted until December 1979.

Phase Change Materials	Cost (¢/lb)	Encapsulating Medium
$CaCl_2 \cdot 6H_2O$	5	High density polyethylene bottle
$Mg(NO_3)_2 \cdot 6H_2O/NH_4NO_3$	10	R-2 retort film
Stearic acid	25	Sulfonated polyethylene bottle
Naphthalene/benzoic acid eutectic	15	Sulfonated polyethylene bottle
$Mg(NO_3)_2 \cdot 6H_2O$	15 (est.)	Drawn steel aerosol can

The major problem encountered was chemical incompatibility of PCM with container materials. A small-scale module using these macroencapsulated PCM and computer simulations are being studied. A final report will be issued in the near future.

Eikonix. A combined solar collector/storage system using paraffin encapsulated in 50 to 100 micron pores was designed for use as a passive heating device. This unit is expected to have an especially long lifetime.

Franklin Research Institute. Heat of solution systems was studied using a variety of heat exchanger types. Both a tube-in-shell exchanger and a tube-in-bath exchanger with stirring functioned poorly because of salt nucleation on the heat exchange surface. Problems also arose with a liquid-liquid heat exchanger because of formation of emulsions which carried salt from the storage container and clogged the system. The final report, which regards the outlook for heat of solution storage as unpromising, has been published.

General Electric Co., Space Division. A process to encapsulate congruently melting paraffin in spherical, 500- to 1,000-micron diameter pellets was studied. Pellets with a modified nylon coating (Penwalt Corporation) survived over 3,000 melt-freeze cycles but failed due to paraffin release and plugging of fluid flow channels after a few cycles in a liquid flow, packed-bed TES device. In addition, the packaging cost of 30¢/lb to 50¢/lb combined with paraffin cost of 11¢/lb renders this concept economically impractical unless lower cost materials and processes are developed.

Monsanto Research Corporation. Monsanto developed form-stable crystalline polymer pellets as a PCM for use in thermal storage units by controlled crosslinking of a high density polyethylene. The congruently melting material has been cycled 700 times with no decrease in heat of fusion. The excellent stability of form allows air passage for heat transfer. The melting temperature (120°C to 140°C) is ideal for absorption air conditioning applications. However, these pellets are petroleum byproducts and cost approximately 30-40¢/lb or about $4,000/MMBtu and $2,400/MMBtu for a liquid and air heat transfer system, respectively. System economics using nonpetroleum sources such as biomass which were demonstrated to be technically feasible were studied but did not appear promising. It has been argued that the petroleum saved in energy storage would more than offset petroleum used to manufacture the pellets. A final report has been issued.

North Carolina State University. An analytic study was conducted of PCM paraffin storage including modeling. Pure paraffin (normal eicosane) and Sonoco 3420 commercial wax were tested in three heat exchange configurations. An evaluation of commercialization potential was not included.

Oak Ridge National Laboratories (ORNL). Refer to following Ongoing Projects section.

Pennsylvania State University. An effort at modeling the dynamic behavior of PCM rectangular slab storage units was recently completed. The model was highly predictive in this particular case.

Suntek. Refer to following Ongoing Projects section.

Villanova University. A substance with a solid-solid phase transition was sought as a possible PCM storage candidate. An extensive literature search and testing program identified the most likely material to be an organic compound costing about 40¢/lb, too expensive for competitive applications. A draft of the final report is available.

3.3.2 Ongoing Projects

Artech. Artech has developed a storage system for both heating and cooling using PCM with melting points of 55°F, 90°F, and 120°F. The active material is packaged in rigid plastic trays. Results initially showed a 90% efficiency of energy storage with the material cycled through 500 meltings and freezings. However, problems were encountered with salt segregation. These may be solved by the use of thickeners. Also, the thinner portions of the special plastic trays designed for adequate heat exchange could not be produced without leaks. A no-cost extension of the contract has been granted to solve this latter problem.

Calmac. PCM storage systems are being developed for solar space cooling (240°F, magnesium chloride hexahydrate and 45°F, salt selection which is in process) and solar heating (115°F, sodium thiosulfate pentahydrate plus 2% sodium sulfate). A self-contained tubular mat, coiled into a spiral and inserted into a cylindrical tank contining PCM, serves as a heat exchanger. To date, a 1-gallon 115°F prototype has been successfully cycled 1,000 times. Recently, good results have been obtained by using a small circulating pump to agitate the storage material (see Fig. 3-3).

Clemson University. A direct contact liquid-liquid heat exchange system is being developed. $NA_2HPO_4 \cdot 12H_2O$ as a phase change storage medium is combined with an immiscible, nonfreezing, heat transfer fluid (see Fig. 3-4). Although Exxon Varsol 18 functions well as the heat-transfer fluid in bench-scale experiments, it has a low flash point and, thus, more appropriate fluids are being sought. Efficiency of energy storage in a 55-gallon test unit remains stable with cycling at about 75% (ten cycles). The system does not meet the expectation of completely reducing salt segregation, although performance has been adequate over a limited number of cycles. Problems also remain with salt carryover into other portions of the loop.

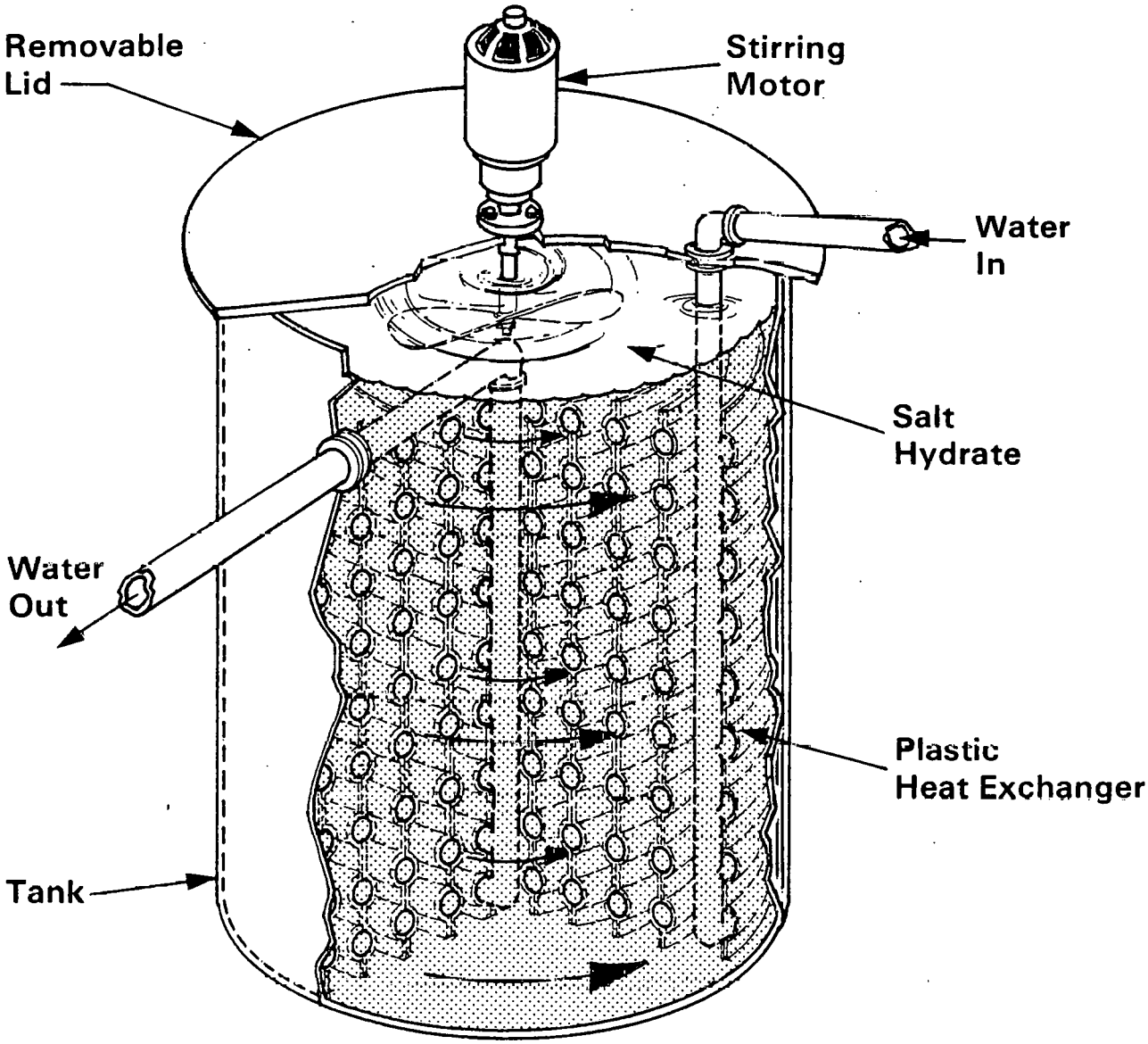


Figure 3-3. CALMAC CORPORATION—PCM STORAGE DEVICE

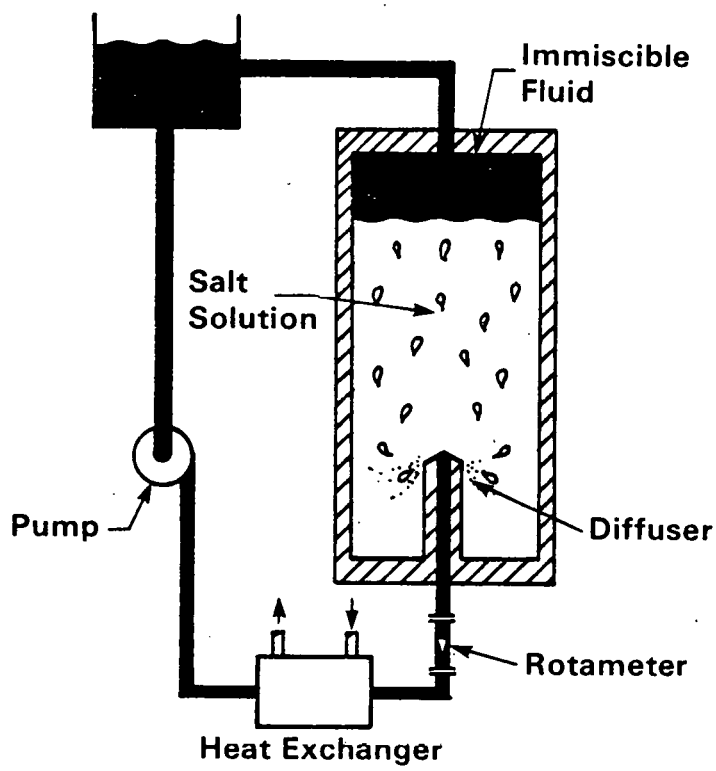


Figure 3-4. CLEMSON UNIVERSITY—IMMISCIBLE FLUID HEAT EXCHANGER

University of Dayton. Studies are being done on the feasibility of manufacturing the Monsanto form-stable polyethylene using radiation instead of chemical crosslinking to cut costs to 1¢/lb (the cost before crosslinking is 32¢/lb).

University of Delaware [44]. Three projects in PCM thermal storage are underway. The Institute of Energy Conversion (IEC) has developed sausage-like, flexible packages called "chubs" which contain a eutectic PCM mixture (sodium sulfate; sodium chloride; ammonium chloride; borax, a nucleating agent; and Min-u-gel 200, a thickener). Coolness storage is being explored at phase change temperatures of 50°F to 55°F using the same technique. Current work includes subjecting the chubs to vibration to test the efficacy and lifetime of the gel and studying water losses. The IEC plans to install and test 20 units for use in storing off-peak electrical generated heat. These would be utility owned. IEC expects to be able to sell rights for this sytem within a year. The storage systems for a typical residence of 2,000 square feet would market for $600 per $270,000 Btu or $2,300 per MMBtu retail.

The Department of Mechanical Engineering is being funded to investigate isothermal energy storage systems in the 90°C to 300°C transition temperature range. Four promising candidate PCM materials have been identified: $NaAlCl_3$, 159°C; $ZnCl_2$, 286°C; $NaOH/NaCO_3$ (eutectic), 283°C; and $FeCl_3/NaCl$ (eutectic), 152°C. A full-scale model will ultimately be tested.

Sun Oil Company has recently funded a study of encapsulation of paraffin in beer cans. The rather high cost of 3¢/lb to 4¢/lb for encapsulation is offset somewhat by increased surface areas and better heat transfer.

Garrett Energy Research and Engineering [42]. A PCM (salt) system for storing heat and cold is being constructed.

General Electric Corporation. A prototype PCM device is being investigated consisting of a rotating drum which contains the salt hydrate. A number of potential advantages are apparent. The constant mixing prevents salt settling and minimizes crystallization of salt on the drum interior, the heat exchange surface. The constant motion of the drum might prove to be a troublesome operational requirement. Three PCM salts are being tested in a small prototype. A 200,000 Btu unit will be designed, built, and tested. Problems may stem from inadequate rates of heat transfer, corrosion, or system cost as in most other PCM storage devices.

J. Horton. PCM salt hydrate storage incorporated into a prototype collector, the thermal pile heat energy system, is being built and tested.

Oak Ridge National Laboratory (BCS). The BCS ACES program is managed from ORNL. A highly instrumented ACES house has operated at the University of Tennessee, Knoxville, since 1976. The main advantages this house has are (1) the carryover of ice from the winter into the summer cooling season and (2) the constant capacity performance of the heat pump. A design handbook is being prepared.

Oak Ridge National Laboratory (TS). Three studies have been undertaken at Oak Ridge. The first two listed are completed. First, PCM for use in 90° C to 250° C thermal storage systems have been identified and evaluated. This work complements work at Dow Chemical Company. Tools for measuring thermophysical properties and characteristics of thermal energy storage media have been developed. The following organic materials have been identified and evaluated:

Compound	Formula	Melting point (°C)	Cost (¢/lb)
Urea	NH_2CONH_2	133	1.5
Adipic acid	$HOOC(CH_2)_4COOH$	152	7.5
Phthalic anhydride	$C_6H_4(CO)_2O$	130	5.3
Acetanilide	$C_6H_5NHCOCH_3$	114	6.2
Phthalimide	$C_6H_4(CO)_2NH$	234	8.3
Anthracene	$C_{14}H_{10}$	218	8.8
O-Chlorobenzoic acid	$ClCl_6H_4COOH$	140	10.3

Second, crystal structures of PCM and nucleating agents were studied.

Third, a time-dependent analytic model of PCM moving boundaries in thermal storage devices is being developed. This model incorporates conduction phenomena. In the future thermal convection mechanisms will be incorporated, and the model will be validated.

Another ongoing activity is the use of a small bench-top water recirculating heat exchanger loop to collect fundamental data on heat transfer mechanisms. Two other large loops (one liquid-driven; one air-driven) will be constructed in accordance with the ASHRAE/NBS Thermal storage standards and used for developmental testing of large storage systems.

Suntek. This project sought to develop techniques for encapsulating PCM ($CaCl_2 \cdot 6H_2O$ at 27° C and $CaCl_2 \cdot 4H_2O$ at 45° C) into concrete building materials and to perform technical and economic evaluations. Planned applications included cold storage (7° C), space heating (45° C), and domestic hot water (70° C). After an aging period, the Thermocrete blocks experienced failure of the epoxy surface coating and destructive deterioration of the concrete matrix and popped open. This breakdown was caused by reaction of the salt with the free lime in the concrete. Before discovery of these failures, funding for this project was transferred from the Storage Program into the Heating and Cooling Program for the design and testing of a prototype central TES unit. Because of failure to solve the difficulties with Thermocrete, funding has been transferred into another project also at Suntek, the use of a heat mirror in window skylights. Following diagnosis of this problem Suntek proposed use of lime-free cementitious systems (such as rice-hull-ash cement) in Thermocrete to overcome degradation problems.

Westec Services Incorporated. International Thermal Instrument Company has designed, tested, and patented a PCM immiscible fluid device which uses an intermediate immiscible heat transfer fluid (see Fig. 3-5). No solid heat exchange surface is present for crystal deposition and no carryover problems are possible [45]. A 10,000 Btu unit using $BaOH \cdot 8H_2O$ having heat extraction rates from approximately 5,000 to 40,000 Btu/hr. A 100,000 Btu unit designed to operate in the 115°F to 135°F range using sodium acetate trihydrate and having heat transfer rate in the range of 50,000 to 80,000 Btu/hr has been tested at the Navy Civil Engineering Laboratory in Port Hueneme, California.

3.3.3 Independent Projects

Addison Corporation. Addison Corporation is marketing a PCM system using paraffin packaged in approximately one-gallon paint-can-size metal containers. One unit has successfully operated for three years with few problems.

Anheuser Busch, Inc. A solar system that uses evacuated tube collectors and PCM storage unit (Thermelt) has been built by Barry-Wehmiller Company at the Anheuser Busch Florida brewery [46]. The system maintains 500 gpm of water 146°F. PCM (transition temperature 250°F) is packaged in 216 vertical tubes. A second generation Thermelt capacitor is under development for future evaluation in this system.

Architectural Research Corporation. Ceiling tiles (2 ft x 2 ft x 1.25 in.) containing Cab-O-Sil packages purchased from Cabot Corporation will be offered for sale in the near future. The Glauber's salt is enclosed in plastic/foil packages as 3/8-inch layers separated by polyethylene dividers. A constant heat of fusion of 33 Btu/lb has been observed for 3,500 cycles. Heat transfer is by radiation and free convection from tiles.

Arizona State University. Laboratory-scale studies are being conducted on processes for creating concrete/paraffin composites. Thermal conductivity, structural strength, and flammability of this assembly remain to be determined.

Brown University. Laboratory tests using rigid packages of disodium hydrogen phosphate have demonstrated that this material suffers from no segregation problems (as does Glauber's salt) but there are concerns with water permeability. The material has been cycled for one year (365 cycles).

Dow Chemical. Work originally funded by TS is being continued. A storage unit containing $CaCl_2$ (82°F melting point) enclosed in high density polyethylene tubes (2 to 3 in. diameter) is being tested. Use of these rigid tubes is expected to eliminate problems associated with volumetric charges of the storage material. Four other salt hydrate PCM (melting points at 54°F, 94°F, 136°F, and 243°F) are being developed. The 54°F m.p. substance undergoes incongruent melting. The 94°F eutectic mixture and the 136°F salt hydrate are congruently melting. The fourth salt hydrate has transition temperatures close together and behaves like a congruent substance.

Michigan Technical University. Thermtech, a proprietary PCM licensed to Gateway Sporting Goods, is composed of congruently melting tetra-n-butyl ammonium fluoride hydrate. This material is relatively expensive.

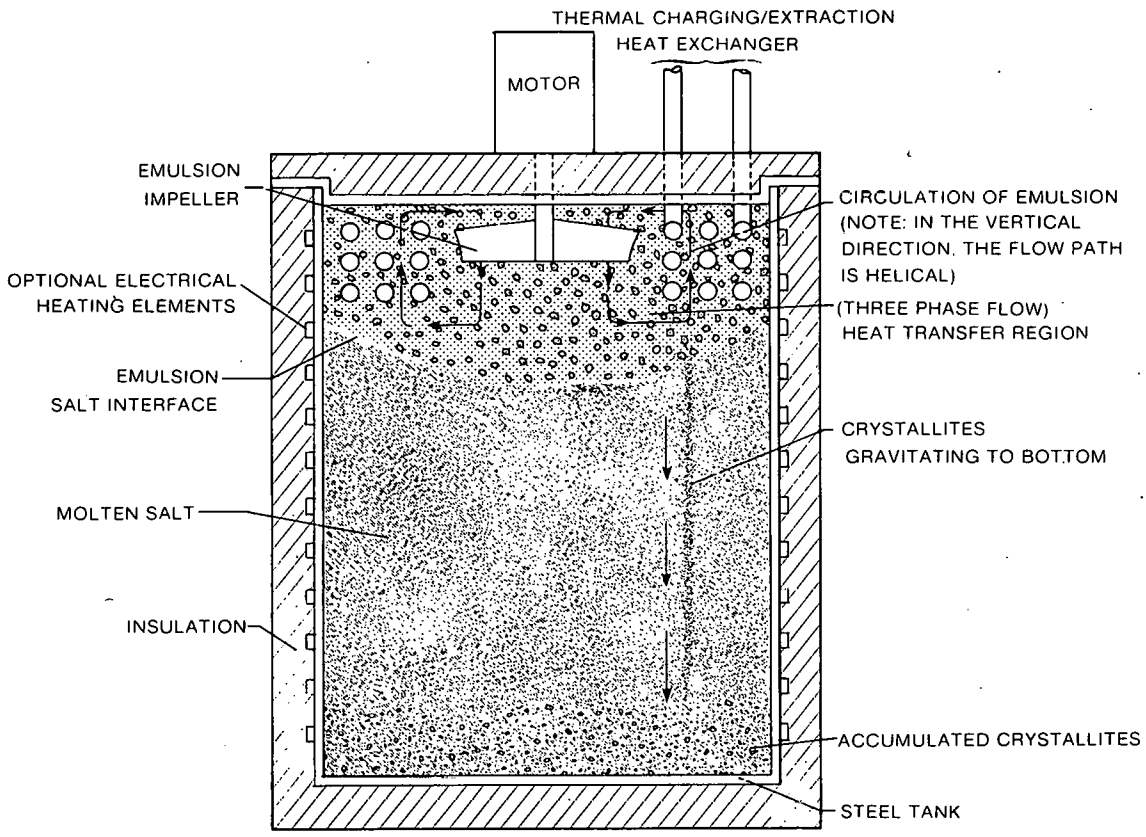


Figure 3-5. WESTERN SERVICES CORPORATION—PCM STORAGE DEVICES

Pipe Systems, Inc. Pipe Systems, Inc. in St. Louis, a distributor of Phillips Petroleum high density polyethylene tubes, manufactures a PCM system using Therminol 81 contained in blackened tubes (3" diameter, 6' height, $30 per tube). Therminol 81, an eutectic mixture containing calcium chloride hexahydrate and melting at 81°F, is manufactured by Dow Chemical Company. Textor Inc. of Omaha presently distributes these storages.

Ramco. Ramco is testing a PCM storage unit similar to that developed by Calmac (see Fig. 3-3). The unit uses several PCMs contained in a tank in which a heat exchanger is immersed.

Solar, Inc. The firm sells rigid polyethylene trays containing Glauber's salt PCM (1 ft^2 x 1/2 in.).

Solar Marketing. PCM storage systems using Glauber's salt packaged in rigid plastic containers were sold, but they performed poorly in a Michigan installation. A new system using the Dow Chemical product is being developed for use in a forced air heating system.

Solarmatic. The Solarmatic system is based on an immiscible fluid heat transfer device similar to the one being developed at Clemson University. In addition to using filters to solve the carryover problem, the unit has a heat exchanger placed in the immiscible fluid. The prototype has operated for one year but no efficiency tests have been conducted.

Valmont Industries. This firm has sole rights on M. Telkes' formulation of Glauber's salt crystals coated with 3% of an encapsulating material and packaged in rigid 2 in. x 24 in. x 24 in. trays. In essence the PCM is located in pockets in a plastic-like rigid crust. This system is now offered commercially.

3.3.4 Foreign Projects

Denmark, Thermal Insulation Laboratory. A PCM storage unit has been developed. Phase segregation problems were overcome by adding extra water to the salt hydrate mixture and stirring, by either bubbling air or oil through the slurry. The final reports were issued [43,44].

Japan, Ishikawajima Harima Heavy Industries Co., Ltd. Evaluation and development of PCM (salt hydrates and paraffins) thermal storage devices are underway. A shell-tube-type heater exchanger will be used in the prototype.

Japan, Mitsubishi Electric Corporation. The objective of this study is to store solar energy at 80°C to 100°C in a PCM device and deliver heat at 70°C to 90°C to a Rankine-cycle engine which powers a refrigeration unit. Ammonium alum is used as the storage medium. The PCM storage functions at a higher efficiency than a sensible heat storage used in the previous season.

Netherlands, Delft University. This group is studying PCM storage at 30° C to 150° C for space heating and solar-power absorption refrigeration. Emphasis is on encapsulated materials.

Netherlands, Philips. The firm is conducting research on a wide range of components for solar thermal systems including reversible chemical reactions for long-term energy storage (100° C to 400° C) and PCM storage for low-temperature heat.

Netherlands, Institute of Applied Physics, TNO. Encapsulation of PCM in a polymer for use in a storage device is being studied. Storage durations are a few days; storage temperatures are in the 35° C to 60° C range.

Sweden, Studsvik Energiteknik AB. A study of methods to overcome phase-separation problems experienced with Glauber's salt concluded that "Glauber's salt has a very limited technical and economical [sic] lifetime as a heat storage medium." Methods investigated included macroencapsulation, mechanical agitation, and use of ultrasound and magnetic fields.

Sweden, Royal Institute of Technology, Dept. Phys Chem. A variety of salt hydrates are studied both as media for phase change and thermochemical heat storage. Particular attention has been paid to calcium chloride hexahydrate as a heat-of-fusion storage medium [45]. Methods to overcome the problems of phase-segregation and heat-transfer are claimed to have been solved and a 200 kg air exchange PCM storage has been constructed and tested. Development of thermochemical systems for seasonal storage of heat is in progress.

Switzerland, Ecole Polytechnique. Evaluation of PCM storage units using paraffin and salt hydrates is in progress. A prototype using paraffin has worked satisfactorily in a solar hot water system since 1977. Pilot scale investigations of immiscible fluid salt hydrates devices continue.

3.4 HEAT TRANSFER AND EXCHANGE

Heat transfer and exchange projects are listed in Table 3-4 and are described below.

3.4.1 Recently Completed Project

Altas Corporation. This project was a comprehensive survey and analysis of liquid heat exchange methods focusing on freezing and corrosion problems, system modeling, and parameter optimization. Techniques studied were evaporative collector-condensing heat exchanger, double loop exchanger, liquid-liquid exchanger, and heat-exchanger-jacketed tank systems.

Table 3-4. HEAT TRANSFER AND EXCHANGE PROJECTS

Project	Source	FY76	FY77	FY78	FY79	FY80
Recently Completed						
Altas Corp.	SA-S	15,578	26,704	17,803	--	--
Ongoing						
California State Univ.	SA-S	--	--	95,000	--	--
Colorado State Univ.	SA-S	87,466	20,000	65,819	*	--
Franklin Research Lab.	SA-S	--	39,000	63,600	--	--
Sigma Research, Inc.	SA-D	--	50,288	41,543	--	--
Zia Associates, Inc.	SA-S	--	--	106,557	*	--

*Funding has been proposed.

3.4.2 Ongoing Projects

California State University. California State University is performing a systems study of a heat pump in parallel with a rock bed thermal storage system that acts as both heat source and sink. Feasibility of this concept depends on the time lag in heat transfer across the rock bed. Efficiency of energy storage can be increased by proper manipulation of operating conditions.

Colorado State University. A direct contact, liquid-liquid (water and diethyl phthalate) heat exchanger/TES device is being developed. A full-scale 1000-gallon prototype is under test on two CSU solar-heated houses.

Franklin Institute Research Laboratories. An evaluation of the technical feasibility of the following heat exchange systems has been completed: (1) external power cycles, (2) internal power cycles, (3) water-vapor bubble lift, (4) water/water-vapor heat transfer, (5) light ducts and guides, and (6) photovoltaic powered pumps. A cost evaluation and comparison of relative merit will be included in the final report.

Sigma Research, Inc. Sigma Research is designing and developing a thermosyphon heat exchanger for use with air heating collectors and water storage tanks. A completed unit has been delivered to NASA/MSFC for testing and marketing.

Zia Associates, Inc. Feasibility of mating a heat pump to rock bed storage and flat plate collectors is being studied. Following design optimization, cost effectiveness will be investigated.

3.5 INDUSTRIAL WASTE HEAT RECOVERY AND STORAGE

Industrial heat recovery and storage projects are listed in Table 3-5 and described below.

3.5.1 Recently Completed Projects

Lockheed. A solar-energy-regenerated desiccant drying system with a high energy efficiency and application in large-scale commercial grain drying has been studied.

TRW. Two projects were completed at the TRW Energy System Planning Division. First, gas-to-gas heat exchangers and air cleaning devices have been evaluated. It was found that such devices are available on an off-the-shelf basis. Second, a study is being done on a thermal energy storage-recovery system to recover sensible and latent heat lost through the flue of a home hot-air furnace (see Fig. 3-6). Use of such a system raises furnace efficiency from about 55% to 96% and is apparently a profitable investment.

Westinghouse Electric Corporation. In cooperation with the Heinz Company, Westinghouse evaluated current energy consumption and waste heat production patterns in the food industry. Conceptual designs and fuel savings have been published for waste heat recovery systems for plants utilizing short-term thermal energy storage. Heinz is carrying the project through to demonstration in two processing plants (see below).

Table 3-5. INDUSTRIAL WASTE HEAT RECOVERY AND STORAGE

Project	Source	FY76	FY77	FY78	FY79	FY80
Recently Completed						
Lockheed	TS	30,000	125,899	32,950	--	--
TRW	TS	--	15,000	--	--	--
TRW	TS	--	7,200	--	--	--
Westinghouse Electric Corp.	TS	--	13,742	82,453	*	--
Ongoing						
Heinz Co.	TS	--	--	--	--	--
Rocket Research Co.	TS	--	--	89,428	--	--

*Funding has been proposed.

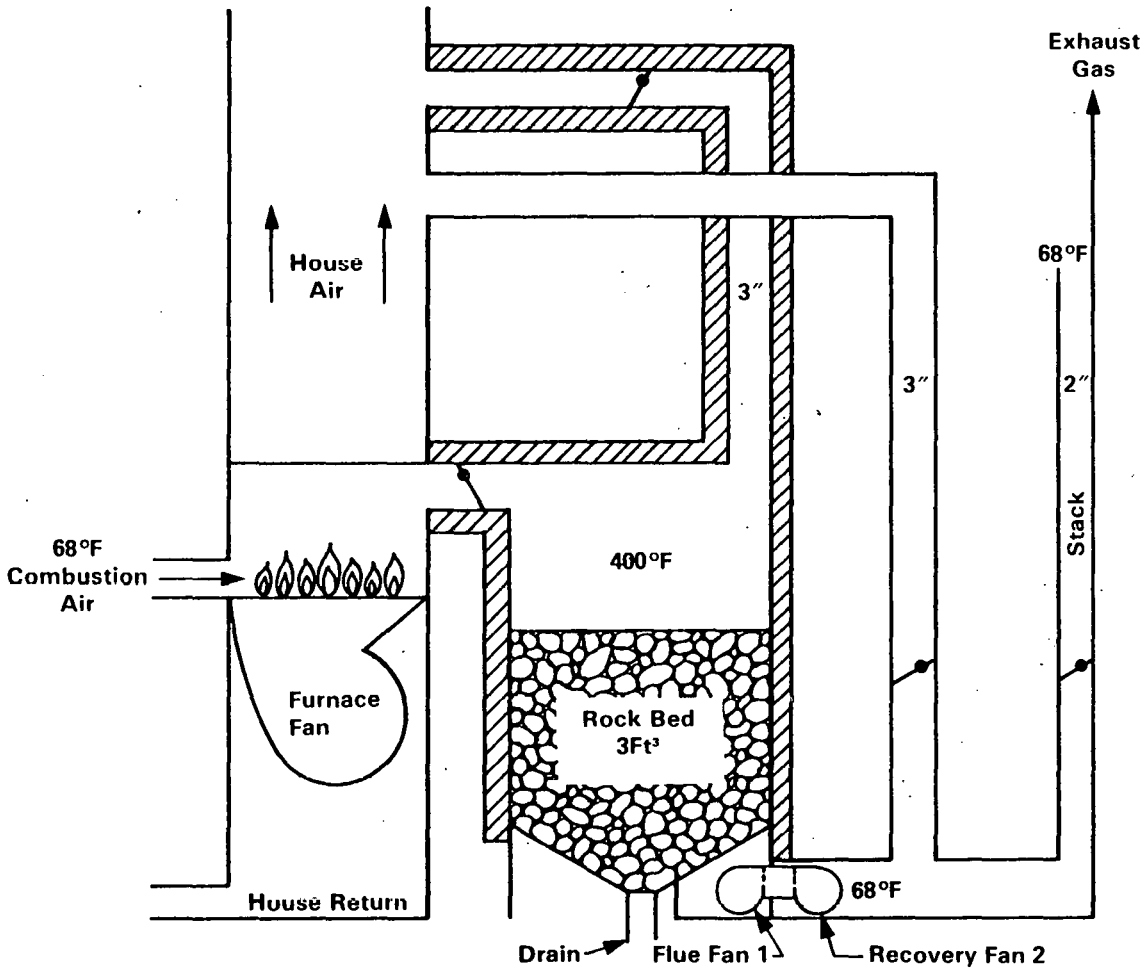


Figure 3-6. TRW—GAS FURNACE THERMAL ENERGY STORAGE—RECOVERY SYSTEM

3.5.2 Ongoing Projects

Heinz Company. Heinz, in cooperation with Westinghouse, is demonstrating the reuse of waste heat in its own facilities. These applications of short-term sensible heat storage are expected to have an attractive rate of return on invested capital. A ROI of 34% and a reduction in energy consumption by 5% to 6% is anticipated in one plant. Annual ROI in the second is 12% to 14%.

Rocket Research Company. The continuous operation of the Intalco Aluminum Company generates 200°F waste heat at a rate of 4.6×10^8 Btu/hr. An initial study demonstrated the feasibility of using this wasted energy to provide heat for 12,000 residences in Bellingham, Washington. The average ROI of this investment is estimated to be 63%. Large-scale demonstration is planned by TS. RRC will perform market and technical analysis, review alternative heat source options, and provide a conceptual design and cost estimate. Although aquifer storage of thermal energy is the alternative of lowest cost, it is unproved; thus, it was decided to proceed with conventional unpressurized steel tanks. The storage option is covered by a separate contract.

3.6 REVERSIBLE CHEMICAL REACTION STORAGE

Chemical heat pump (CHP) projects are listed in Table 3-6 and are described below.

3.6.1 Recently Completed Project

Chemical Energy Specialists. Chemical Energy Specialists investigated the hydrated salt heat pump based on the reaction:

$$MgCl_2 \cdot 4H_2O \text{ (solid)} \quad MgCl_2 \cdot 2H_2O \text{ (solid)} + 2H_2O \text{ (gas)}$$

Equilibrium temperature for this reaction is 107°C, and energy density is approximately 360 Btu/lb. An approximate temperature of 300°F is required at the absorber to effect its recharge; the absorber chemical during discharge is at approximately 120°F. The absorption and desorption of water had a strong dependence on mechanical features of the system as is the case with other CHP. Understanding of the basic physicochemical properties was in a preliminary stage. Problems were encountered with formation of hydrochloric acid and subsequent corrosion. Overhydration of the salt led to solidification of the bed and difficulties in heat transfer and dehydration. These researchers have recently suggested a number of solutions to these difficulties.

3.6.2 Ongoing Projects

ANL. Studies are progressing on a CHP using hydrogen gas as a working fluid and metal hydrides as absorbers. Presently an alloy pair emitting H_2 at 212°F and 46°F is employed. A search for "lower temperature" metal hydrides continues. This system has

Table 3-6. CHP PROJECTS

Project	Source	FY76	FY77	FY78	FY79	FY80
Recently Completed						
Chemical Energy Specialists	TS	--	85,600	37,400	--	--
Ongoing						
ANL	**	163,000	200,000	20,000	*	--
EIC Corp.	TS	--	49,000	223,604	*	
EPRI	I	--	--	--	--	--
Exxon Res. & Eng.	I	--	--	250,000	*	--
Martin Marietta Corp.	TS	--	19,091	81,454	*	--
Martin Marietta Corp.	SA-S	--	--	152,000	*	*
Rocket Research Co.	TS	54,000	246,000	191,000	*	--
The Zeopower Co.	I					
Foreign						
Belgium						
Faculte Polytechnique de Mons	IEA	--	--	--	--	--
Netherlands						
Philips	IEA	--	--	--	--	--
Inst. of Appl. Phys. TNO	IEA	--	--	138,460	*	

*Funding has been proposed.
**Funded by Chemical Subprogram of Division of Energy Storage (ET).

the advantage of allowing rapid cycling since absorption and deabsorption occur within a minute.

EIC Corporation. This group is studying the methonalated salt heat pump:

$$CaCl_2 \cdot 2CH_3OH \text{ (solid)} \quad CaCl_2 \text{ (solid)} + 2CH_3OH \text{ (gas)}$$

$$2CH_3OH \text{ (liquid)} + CaCl_2 \text{ (solid)}$$

Other salts, including $MgCl_2$, FeBr, and $CoBr_2$ have been investigated, but $CaCl_2$ has been selected on the basis of reaction rates, cost, freedom from side reaction, and suitability of operating temperatures. Corrosion and cycling experiments with $CaCl_2$ have not identified any problems. Some difficulties in maintaining adequate reaction rates during cycling could stem from the tendency of $CaCl_2$ to form a crust.

EPRI. EPRI has contracted a study of the concentrated sulfuric acid CHP to be used in storing off-peak heat in electric utilities.

Exxon Research and Engineering. Exxon is investigating the CHP for residential solar heating and cooling applications using bench-scale fixed and agitated beds (rolling cylinders). Experimental results suggest that the CHP, in concert with an evacuated tube collector "may be the only route to economically viable active solar systems for space heating, cooling and hot water in the near term." A company publication claims that experimental results are promising and "economic analysis is very encouraging."

Martin Marietta Corp. Martin Marietta is examining five reactions of ammonia with salts (one with $CaCl_2$ and two each with $MgCl_2$ and $MnCl_2$) for use in a CHP (see Fig. 1-3 and 1-4). Pressures range from 0.5 to 3 atmospheres and possible decomposition temperatures from 25°C to 300°C. One steady state and two dynamic system models are operational. Chemical and physical properties of the reactants have been measured, and a small model is being cycled and tested. A subscale residential prototype is being built. Funding for this project is from both TS and SA-S.

Rocket Research Company. This group is developing the sulfuric acid CHP (see Fig. 3-7) which must be operated near 400°F (225°C). An advantage of this system is that liquid-phase heat exchangers overcome difficulties encountered by gas/solid systems. Use with single residential solar systems may be limited due to safety considerations. This project is entering its fourth year. Recent optimization tests on a 100,000 Btu model were completed. Multiple cyclical tests are in progress to determine the extent of acid carryover. Full-scale components such as valves and piping will be tested. A final report on the initial phases of development will be issued in the near future.

The Zeopower Company. This firm reports demonstration of the feasibility of using a natural zeolite system to provide domestic hot water, space heating, and space cooling, with overall efficiencies above 75% (see Fig. 3-8). Water vapor is used as the working fluid and a natural zeolite, which has extremely nonlinear absorption isotherms, is the solid absorber.

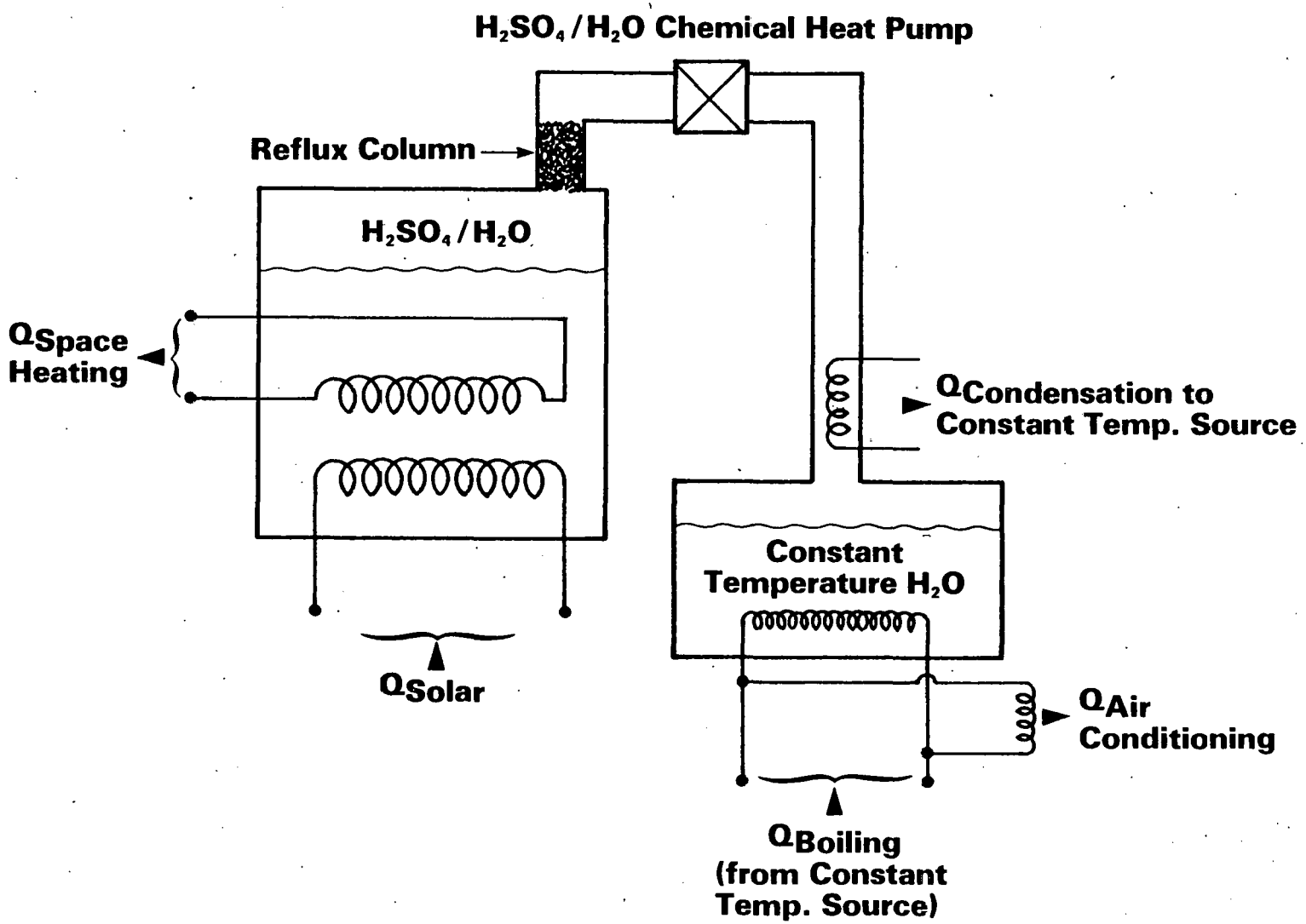


Figure 3-7. ROCKET RESEARCH COMPANY—SULFURIC ACID CHP

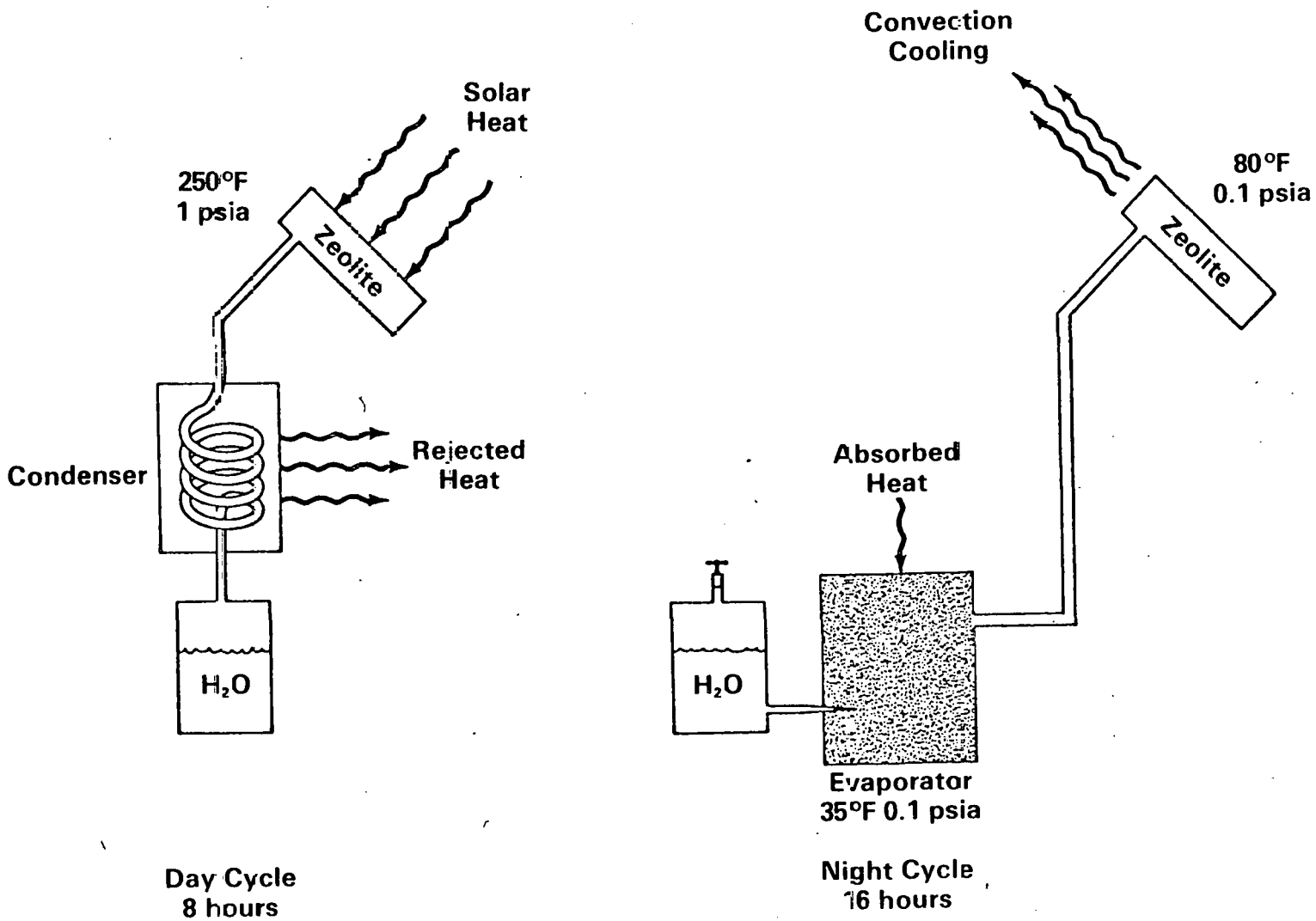


Figure 3-8. THE ZEOPOWER COMPANY—AIR CONDITIONING USING A NATURAL ZEOLITE CHP

3.6.3 Foreign Projects

Belgium, Faculte Polytechnique de Mons. A preliminary study of reversible chemical reaction storage suggests three candidate reactions: amine aqueous solutions, inorganic compound hydrates, and organic compound reactions. Following thermodynamic study, a pilot facility will be built and tested.

Netherlands, Philips. See Section 3.3.

Netherlands, Institute of Applied Physics, TNO. Studies of use of reversible absorption reactions of water with different porous substances are underway for TES devices.

3.7 MODELS, ECONOMIC ANALYSES, AND SUPPORT STUDIES

Model building, economic analysis, and support study projects are listed in Table 3-7 and are described below.

3.7.1 Recently Completed Projects

EIC Corporation. EIC Corporation has developed models for sensible heat, PCM, and reversible chemical reaction storage systems as well as for several other systems utilizing alternate energy storage (e.g., solar-assisted electric heat pumps). Full-year simulations have been performed on a number of systems including two using chemical storage.

Hittman Associates. This firm has completed an assessment of physical properties of commercially available storage devices and of the storage requirements for solar applications as outlined in the Solar Heating and Cooling R&D Plan [54].

3.7.2 Ongoing Projects

A. D. Little. A first step in developing a unified procedure for costing a TES system is nearing completion. A classification scheme and specifications for residential and commercial applications of TES were the first step. Expenses associated with transportation, installation, operation, maintenance, and equipment were estimated. Uncertainties associated with these estimates are being calculated.

ANL, Solar Group. Handbook, "Design and Installation Manual for Thermal Energy Storage," directed toward builders, HVAC contractors, and more sophisticated do-it-yourselfers is being prepared. Commercially available heat exchanger, water tank, and rock bed systems will be described. A series of public review seminars is planned prior to final editing and printing. A handbook on more advanced storage devices is contemplated.

Table 3-7. MODELS, ECONOMIC ANALYSES, AND SUPPORT STUDIES

Project	Source	FY76	FY77	FY78	FY79	FY80
Recently Completed						
EIC Corp.	SA-S	--	29,000	48,456	--	--
Hittman Associates	SA-S	--	--	55,242	--	--
Ongoing						
A. D. Little	TEA	--	--	70,000	70,000	--
ANL, Solar Group Program Support	SA-S	--	105,000	100,000	200,000**	--
ANL, Solar Group Handbook	SA-S	--	177,000	110,000	100,000	--
ANL, Solar Group Commercial	TEA	--	--	75,000	*	--
Feasibility	TS	--	--	300,000	285,000	--
Boeing Computer Services	SA-S	--	--	264,000	*	*
National Bureau of Standards	SA-S	--	200,000	160,000	100,000	--

*Funding has been proposed.
**Includes $50K for TES workshop.

Another group at ANL is evaluating the commercial feasibility of thermal energy storage. This program has two major thrusts. First, three after-the-meter thermal storage technologies (space heating, space cooling, and domestic hot water) and two before-the-meter mechanical storage systems have been compared for electric load leveling [50,51]. Field tests of customer-owned TES in Maine and Vermont utility markets are yielding information about baseline performance, load-leveling benefits, and customer acceptance. A second testing facility is being established at Purdue University. Beginning in FY79, some responsibility for component development will be transferred to ORNL. Second, several studies of TES for solar applications are underway. A theoretical study of the economics of annual storage, which compared seasonal storage with both daily storage solar systems and conventional heating systems, generated a range of seasonal break-even cost estimates [52]. A study of thermal stratification in storage tanks has suggested three advantages for such designs (see Section 1.2) [53]. A third study is investigating statistical aspects of solar insolation, such as variation of energy density with degree day heating requirements. Very preliminary conclusions using the Solmat weather tapes indicate that insolation may not be more reliable on colder, winter days.

Boeing Computer Service. A comprehensive approach to solar thermal energy storage system modeling is being developed. Code selection criteria have been designed, and component model standardization has begun. Models will be standardized, linked, upgraded, validated with field data and streamlined in order to develop this complete, user-driven system modeling tool.

National Bureau of Standards. Standard test methods for determining thermal performance of solar collectors and thermal storage devices for building applications have been developed and verified experimentally. In the final report, ASHRAE 94-77 test procedures were found to be less than adequate on a 500-gallon water tank. Tests on a 250 ft^3 rock bed storage unit and on a commercial PCM macroencapsulated device have been completed.

A new program has been started in FY79. It will analyze the interface (i.e., determine conflicts and means to resolve them) between the various advanced TES devices currently under development and the relevant state and local model building codes.

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SECTION 4.0

SUMMARY

Six groups within DOE are engaged in either developing technologies or providing support for low temperature TES systems. Table 4-1 summarizes storage-related funding levels in these programs for the last three fiscal years. Tables 4-2 and 4-3 show funding breakdown and number of projects by type of contracting institute and storage technology, respectively.

Table 4-1. OVERALL FUNDING OF LOW TEMPERATURE TES-RELATED PROGRAMS[a] (BA; $M)

	FY77	FY78	FY79
TS	1.32	2.73	1.30[b]
SA-S	0.6	2.34	2.12
SA	0.26	0.57	0.05
SST	—	0.05	0.05
USDA	—	0.05	0.05
TEA	—	0.15	—
Total	—	5.89	—

[a]Independently financed foreign projects are not included here.
[b]Further funding in FY79 will probably increase this value.

Table 4-2. FUNDING BY TYPE OF RESEARCH INSTITUTE: SUMMARY
(BA; $K--Number of Projects)

	Large Business	Small Business	University	National Lab	Nonprofit Organization	
A: FY78						
TS	590.2/7	446.0/6	510.9/6	634.7/4	7.6/1	2189.4/24
SA-S	695/5	746/8	480/8	360/1	64/1	2345/23
SA	38.0/1	77.8/2	297.9/5	160.0/1	573.7/9	1147.4/18
SST	--	46.5/6	--	--	--	46.5/6
USDA	--	--	--	49.0/1	--	49.0/1
TEA	70.0/1	--	--	75.0/1	--	145.0/2
Total	1393.2/14	1316.3/22	1288.8/19	1278.7/8	645.3/11	5922.3/74
B: FY79						
TS	306.4/5	235.0/1	371.4/5	174.5/4	--	1087.3/15
SA-S	629/5	315/5	482/7	550/1	--	1976/18
SA	37.0/1	--	--	160.0/1	--	197.0/2
SST	--	46.5/6	--	--	--	46.5/6
USDA	--	--	--	49.0/1	--	49.0/1
TEA	-- /1	--	--	-- /1	--	-- /2
Total	-- /12	596.5/12	853.4/12	-- /8	0/0	-- /44

Table 4-3. FUNDING BY PROJECT TYPES: SUMMARY
(BA; $K--Number of Projects)

	TS	SAS	SA	SST	USDA	TEA	Total
A: FY78							
Sensible Heat; Short-Term	--	1013/8	--	34.2/4	--	--	1047.2/12
Long-Term--Aquifers	486.4/4	--	--	--	--	--	486.4/4
Pond	--	--	305.9/4	--	49.0/1	--	334.9/5
Tanks/Bed	25.0/1	129/3	--	--	--	--	154.0/4
PCM	1105.3/12	567/5	86.3/3	12.3/2	--	--	1770.9/22
CHP	530.1/4	152/1	--	--	--	--	682.1/5
Heat Transfer & Exchange	--	129/5	41.5/1	--	--	--	170.5/6
Models & Support	--	354/6	160.0/1	--	--	145.0/2	659.0/9
Industrial Waste Heat Recovery	204.8/3	--	--	--	--	--	204.8/3
Total	2651.6/24	2344.0/28	593.7/9	46.5/6	49.0/1	145.0/2	5829.8/7
B: FY79							
Sensible Heat; Short-Term	--	678/5	--	34.2/4	--	--	712.2/9
Long-Term--Aquifers	476.7/5	--	--	--	--	--	476.7/5
Pond	--	--	67.0/2	--	49.0/1	--	116.0/3
Tanks/Bed	--	230/2	--	--	--	--	230.0/2
PCM	95.5/4	430/3	--	12.3/2	--	--	537.8/9
CHP	416.1/3	210/1		--	--	--	626.1/3
Heat Transfer & Exchange	--	212/2	--	--	--	--	212/2
Models & Support	285.0/1	360/4	160.0/1	--	--	--/2	-- /8
Industrial Waste Heat Recovery	9.1/1	--	--	--	--	--	9.1/1
Total	1282.4/13	2120.0/17	227.0/3	46.5/6	49.0/1	--/2	-- /42

SECTION 5.0

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SERI

Document Control Page	1. SERI Report No. RR-54-164	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle

Low Temperature Thermal Energy Storage, A State-of-the-Art Survey

5. Publication Date

July 1979

6.

7. Author(s)

Frank Baylin

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Solar Energy Research Institute
1536 Cole Boulevard
Golden, Colorado 80401

10. Project/Task/Work Unit No.

11. Contract (C) or Grant (G) No.

(C)

(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered

Research Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report is organized into the following sections. Section 2.0 is a generic description of low temperature thermal energy storage technologies and the associated technical and environmental problems. The three basic categories and support activities are subdivided as shown in Figure 2-1: sensible heat, phase change, and reversible chemical reaction storage. Also, a brief overview of low temperature TES applications is provided. This information is not intended to be a detailed technical description, but it does touch on critical areas. Section 1.0 is a prelude to a detailed and comprehensive description of programs and projects in low temperature TES which is presented in Section 2.0. Section 2.0 is an up-to-date detailed listing and brief description of ongoing and recently completed RD&D projects. This information has been compiled by first searching all available literature and then obtaining feedback from DOE program managers, DOE field managers, and the subcontractors listed in the survey.

17. Document Analysis

a. Descriptors

b. Identifiers/Open-Ended Terms

c. UC Categories

59, 59a, 59b, 59c

18. Availability Statement

National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

19. No. of Pages

117

20. Price

$6.50

*U.S. GOVERNMENT PRINTING OFFICE : 1979--O-677-083/44