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**Low-Temperature Thermal Energy Storage
Program Annual Progress Report for
Period October 1977-September 1978**

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MASTER

OAK RIDGE NATIONAL LABORATORY
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LOW-TEMPERATURE THERMAL ENERGY STORAGE PROGRAM
ANNUAL PROGRESS REPORT FOR PERIOD
OCTOBER 1977-SEPTEMBER 1978

G. D. Brunton
D. M. Eissenberg R. J. Kedl

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SUMMARY

This is the fourth technical progress report in a series covering the activities of the Low-Temperature Thermal Energy Storage (LTTES) Program. The projects have been grouped into seven principal areas. Focus is on (1) seasonal storage of waste or natural hot and cold waters in aquifers, (2) short-term and diurnal storage of solar or off-peak electricity-derived heat in building materials containing phase-change materials (PCMs) or in modular configurations with bulk or macroencapsulated PCMs, and (3) identification and feasibility determination of industrial energy conservation opportunities requiring heat storage.

Seasonal Storage in Aquifers. The first cycle of heated water injection and recovery in an aquifer at Mobile, Alabama, was completed (Auburn University). The cooling pond for chilled water was constructed, and the injection wells were completed for the chilled-water-storage field experiment (Texas A&M). The feasibility cost analysis of winter chill storage at Kennedy International Airport was completed (Desert Reclamation Industries). A study of the applicability of aquifer storage in the Minneapolis-St. Paul area (to a district heating system) was funded late in the fiscal year (G. E. TEMPO).

Short-Term/Diurnal Storage with PCMs. The study of the encapsulation of PCMs in polymer concrete blocks continued (Brookhaven National Laboratory), and a project to support the development of a rolling drum storage system was initiated [General Electric (GE) Corporate Research and Development (R&D)]. The regenerated desiccant drying concept has been significantly improved (Lockheed).

A direct-contact latent heat storage system was found to be feasible and to have excellent storage efficiencies (Clemson University). "Chubs" may meet the handling and other requirements for packaged PCMs (University of Delaware). A series of materials having solid-state phase transitions in the temperature range 335 to 400 K has been identified (Villanova University).

Industrial Applications. Rocket Research investigators completed preliminary studies of a waste-heat district-heating system at Bellingham, Washington. The studies show that a detailed techno-economic analysis of the system is warranted.

Waste heat recovery from certain food processes has been found feasible and can be performed economically using available, off-the-shelf hardware (Westinghouse).

Support R&D. The salt hydrate heat storage system studies were completed (Desert Research Institute). The determination of the thermophysical properties of PCMs and the analytical modeling related to the use of PCMs for energy storage systems continued as support R&D this year [Oak Ridge National Laboratory (ORNL)]. The U.S. Geological Survey is providing field support for anticipated geological work at Kennedy International Airport.

LOW-TEMPERATURE THERMAL ENERGY STORAGE PROGRAM
ANNUAL PROGRESS REPORT FOR PERIOD
OCTOBER 1977-SEPTEMBER 1978

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ABSTRACT

The Low-Temperature Thermal Energy Storage (LTTES) Program is part of a national effort to develop means for reducing United States dependence on oil and natural gas as primary energy sources. To this end, LTTES addresses the development of advanced sensible and latent heat storage technologies that permit substitution by solar or off-peak electrical energies or permit conservation by recovery and reuse of waste heat. Emphasis is on applying these technologies to heating and cooling of buildings.

As the LTTES program continued to mature, a number of technologies were identified for development emphasis, including (1) seasonal storage of hot and cold water from waste or natural sources in aquifers, (2) short-term or daily storage of heat or coolness from solar or off-peak electrical sources in phase-change materials, and (3) recovery and reuse of rejected industrial heat through thermal storage. These areas have been further divided into three major and four minor activities; significant accomplishments are reported for each.

1. INTRODUCTION

A major focus of energy conservation is the development of technologies permitting the substitution of natural energy sources (e.g., solar, wind, and winter chill) and waste heat sources (e.g., power cycle and chemical and manufacturing processes) that are in plentiful supply for the more expensive, exhaustible, and politically sensitive fossil and nuclear fuels. Cycles based on such alternate energy sources generally require a storage element to accommodate discrepancies in availability time between the energy source and its utilization. Thermal energy storage (TES) — as distinguished from mechanical, electrochemical, magnetic, and other types of storage — provides one means for accomplishing this necessary function.

Thermal energy storage can be attained through the sensible heat characteristic of solids and fluids, through latent heat phase transformations, or through reversible chemical reactions. Because of this wide breadth of storage mode and the equally broad extent of storage application, the Department of Energy (DOE), through the Chemical and Thermal Storage Branch of its Division of Energy Storage Systems (STOR), has subdivided the TES technology development activity into three subprograms:

1. The LTTES program using sensible and latent heat storage at temperatures up to ~ 523 K, under the direction of ORNL.
2. High-temperature thermal energy storage (HTTES) using sensible and latent heat storage at temperatures over ~ 523 K, under the direction of National Aeronautics and Space Administration-Lewis Research Center (NASA-LcRC).
3. Thermochemical energy storage and transport (TEST) using reversible chemical reactions, under the direction of Sandia Laboratories-Livermore (SLL).

As managers of these subprograms, the several national laboratories have responsibility (with DOE-STOR) for planning, implementing, and controlling the technical effort for disseminating the results obtained and for assisting in the transfer of developed technologies for demonstration and eventual commercialization.

The LTTES program is national in scope, and the various development efforts are being carried out by industries, universities, research laboratories (private and national), and individuals. The general guideline in this area is that supporting research and technology will be the province of universities and research laboratories, whereas specific concept development (that could lead to a marketable product or service) will be the responsibility of industry. LTTES efforts are directed toward applications such as building heating and cooling (residential, commercial, and industrial), agriculture (drying, greenhouses, and animal shelters), and industrial processes (drying, preheating, and batch operations). The energy sources may be solar, waste or cogenerated heat, off-peak electrical, or others (e.g., water chilled in winter for summer cooling). Development efforts will, in general, carry TES concepts through the system prototype stage.

This progress report — the fourth in a continuing series,¹⁻³ reports activities within the LTTES program for the period October 1977 through September 1978.

References

1. *Thermal Energy Storage for Building Heating and Cooling Applications, Quart. Prog. Rep. April-June 1976*, ORNL/TM-5700 (November 1976).
2. *Low-Temperature Thermal Energy Storage Quart. Prog. Rep. July-September 1976*, ORNL/TM-5795 (February 1977).
3. *Low-Temperature Energy Storage Program Ann. Prog. Rep. October 1976-September 1977*, ORNL/TM-6509 (August 1978).

2. PROGRAM OBJECTIVES

The objectives of the LTTEs program are to (1) develop sensible and latent heat storage technologies capable of effectively accepting, storing, and discharging thermal energy supplied at temperatures up to 523 K and (2) define the potential of these technologies in the conservation of energy and natural resources. Technologies will be proved through the prototype system development stage. Both the economic and technical feasibilities of the concepts under development will be established sufficiently to recommend their viability for demonstration and ultimate commercialization. These technologies will be considered in the context of both new and retrofit applications for centralized or decentralized systems.

Development of sensible heat storage technologies under the LTTEs program is restricted to advanced concepts. Thus, the uses of fluids such as water and oils in atmospheric or pressurized tanks and rocks, sand, or gravel beds with energy transport by gases or liquids are considered existing practices requiring only optimization in respect to specific designs, containment materials, and costs. In contrast, the program will consider technologies for which feasibility has not yet been demonstrated and ability to predict performance is limited. Currently included in this category are aquifers, surface ponds, earth, and fluidized beds.

Latent heat storage offers the advantages over sensible heat storage of reduced volume requirements and essentially constant temperature storage. However, the use of storage utilizing phase-change materials (PCMs) is still in the research and development stage, with problems identified relating to costs, stability, corrosion, heat transfer, volumetric changes, supercooling, toxicity, and containment. Although emphasis has generally been on heat-of-fusion systems, technologies based on heats of transition (solid state) and heats of solution also warrant examination. Categorization within this area is in terms of form rather than technique as with sensible heat storage; thus, it is on macroencapsulated, bulk, and dispersed storage.

The objectives of the LTTES program are consistent with the national TES program and are to be accomplished within the framework of the national plan. Specific national TES goals supported by the LTTES program are indicated in Table 2.1. This table, organized into four general application sectors, relates the national TES program goals with the application areas. As shown, the LTTES program provides support to the TES program in two of these application sectors: household and commercial (H/C) and industrial and agricultural (I/A).

Table 2.1. National TES program goals supported by the LTTES program

Application area	TES program goals	LTTES primary support
H/C	Improve energy management	Yes
	Improve economics of solar systems	Yes
	Use waste heat from industry and utilities	Yes
Utilities	Use base load generating system for peak load following	No
	Improve economics of solar electric power generation	No
I/A	Improve process efficiency and waste heat utilization	Yes
	Improve economics of solar-generated process heat	Yes
	Improve energy management	Yes
Transportation	Use vehicle heat storage for propulsion system	No

3. TECHNICAL PROGRAM

During this report period (FY-1978), the purposes and directions of the LTTEs program — along with the other elements of the national TES program — were examined. This introspection has led to a definition of principal thrusts (Table 3.1) as a means for focusing efforts and assuring appropriate allocation of resources. In this chapter, the 16 separate efforts now comprising the LTTEs program have been organized within the thrust areas as shown in Table 3.2, and each of these efforts is described in the following sections. It is anticipated that in FY-1979, as the program matures, many of these efforts will be completed and phased out and will be replaced by others directed to specific goals (thrusts).

3.1 Seasonal Storage of Waste Heat/Winter Cold

A significant amount of heat is annually wasted to the atmosphere or hydrosphere in consequence of electricity generation, manufacturing processes, or chemical conversion; recovery and reuse of this energy through seasonal storage appear to be both technically feasible and worthwhile as an energy conservation goal. Further, conserving winter cold to accomplish summer cooling also appears promising. Because storage of large volumes of water is required in either case, the use of artificial or natural geologic structures is indicated. Current progress on efforts relative to adapting aquifers to this purpose is given below; however, no work is planned at present for the surface pond alternate.

3.1.1 Experimental study of the storage of thermal energy in confined aquifers (Auburn University — Water Resources Research Institute; Fred J. Molz and James C. Warman, principal investigators; Union Carbide Subcontract 7338)

The objectives of the experiment, which is contracted for the period July 1, 1977, to Feb. 28, 1979, are to test the heat storage well concept and to provide data for calibration of mathematical models designed to simulate the effects of storage of thermal energy in aquifers.

The test facility is located in a cleared soil dump area at the Barry Steam Plant of the Alabama Power Company in northeast Mobile County,

Table 3.1. Proposed LTTEs program thrusts

LTTEs program thrusts		Concept	TES	
			Material	Mechanism
<u>Major</u>				
1	Seasonal storage of waste heat/winter cold	Primary — aquifers Alternate — ponds	Water Water	Sensible Sensible
2	Short-term storage of solar energy for heating	Primary — building materials with PCMs Alternate — compact units involving PCMs	PCM PCM	Latent Latent
3	Storage for specific industrial applications ^a			
<u>Minor</u>				
4	Seasonal storage of solar energy for heating	Primary — earth storage Alternate — ponds	Earth Water	Sensible Sensible
5	Seasonal storage of ice for cooling	Primary — natural generation in winter with storage until summer	Ice	Latent
6	Diurnal storage for off-peak electricity (heating/cooling)	Primary — compact units involving PCMs Alternate — "existing technology"	PCM Bricks/ water	Latent Sensible
7	Short-term storage of solar energy for cooling	Primary — compact units involving PCMs Alternate — "existing technology"	PCM Bricks/ water	Latent Sensible

^aThis thrust, although major, does not fit well into the taxonomic structure of this table. It consists of identifying industrial waste heat sources that can be recovered, stored, and subsequently used for some other application, and encouraging its implementation by that industry. Generally, the TES mechanisms are based on existing technology for near-term implementation.

Table 3.2. Summary of technical efforts under LTIES program

Contractor	Objective	Contract	
		Term	Amount (\$)
1. <u>Seasonal storage of waste heat/winter cold</u>			
Auburn University	Determine hydraulic and thermal parameters in a test aquifer (warm water)	7/1/77-2/28/79	296,867
Texas A&M University	Determine hydraulic and thermal parameters in a test aquifer (winter-chilled water)	—9/1/77-9/30/78	79,512
Desert Reclamation Industries	Establish feasibility of storing winter-chilled water in an aquifer for summer cooling of Kennedy International Airport	10/4/77-6/30/78	102,180
Lawrence Berkeley Laboratory	Prediction of thermal-hydraulic behavior of hot/cold waters in aquifers	5/15/77-9/30/78	150,000
General Electric Co. - TEMPO	Feasibility study of aquifer storage in the Twin Cities, Minnesota	8/14/78-6/30/79	132,141
2. <u>Short-term storage of solar energy for heating</u>			
Brookhaven National Laboratory	Establish feasibility of containing PCMs within matrix of polymer concretes	7/1/77-9/30/78	152,000
3. <u>Storage for specific industrial applications</u>			
Lockheed-Huntsville Research & Engineering Center	Determine feasibility of regenerated desiccant concept for use in crop drying	4/1/77-10/31/77	98,849
Rocket Research Corporation	Assess potential for energy recovery and reuse through storage in aluminum manufacture	10/1/77-5/30/78	89,428
Westinghouse Electric Corporation	Assess potential for energy recovery and reuse through storage in food processing	8/31/77-9/30/78	105,326
4. <u>Seasonal storage for solar energy heating</u>			
No activity			

Table 3.2 (continued)

Contractor	Objective	Contract	
		Term	Amount (\$)
5. <u>Seasonal storage of ice for cooling</u>			
No activity			
6. <u>Diurnal storage for off-peak electricity (heating/cooling)</u>			
Clemson University	Develop immiscible-fluid, direct-contact heat transfer concept utilizing a hydrated salt	7/1/76-5/31/78	139,000
University of Delaware	Assess macroencapsulated Glauber's salt for TES applications	7/1/76-10/31/77	121,000 ^a
Villanova University	Identify/characterize materials exhibiting solid-state transitions useful for TES	6/1/77-5/31/78	26,205
G.E. Corporate R&D	Develop rolling drum concept	8/78-10/80	350,000
7. <u>Short-term storage of solar energy for cooling</u>			
See item 3			
8. <u>Systems studies</u>			
No activity			
9. <u>Support R&D</u>			
Desert Research Institute	Develop techniques for nucleating PCMs so as to minimize adherence to heat exchange surfaces	7/1/75-6/30/77	176,000
ORNL	Identify/characterize PCMs suitable for application in absorption air conditioning temperature range	10/1/76-9/30/78	100,000
ORNL	Develop analytic models describing freeze-melt boundary movement in PCMs	10/1/76-9/30/78	50,000

^aTotal contract for \$161,550 includes work on HTTES.

Alabama. At the end of summer 1977, bids were requested and contracts granted for the construction of supply, injection, and observation wells and for the assembly of a temperature recording system.

During fall 1977, a leak in the storage formation was repaired, and construction of a supply well, observation well, and new injection well was completed. During winter 1978, the boiler and injection pipeline were installed (Fig. 3.1) along with the data acquisition system (DAS). The injection of warm (328 K) water began in March and continued until June 1978. The storage phase lasted from June through July, at which time production began and continued until September 1978.

The experiment is still under way and consists of two injection-storage-recovery cycles. The first cycle is now completed. Water from an aquifer above the storage formation (Fig. 3.1) was pumped through an oil-fired boiler that warmed the water from 293 to ~ 328 K. The warm water was then injected into the storage formation for later recovery.

ORNL-DWG 79-4927 ETD

Fig. 3.1. Diagram showing supply well, pipeline to boiler, and injection well. Water is pumped from supply well to boiler, heated from 20 to 55°C, and injected into the storage formation ($K = ^\circ C + 273$).

The water injection began on March 18, 1978, and continued until June 5, 1978. During this time, 54,784 m³ of water heated to an average temperature of 328 K was pumped into the storage aquifer (Fig. 3.2). Some clogging in the production well was observed, reducing the injection rate from the planned 0.0126 m³/sec to as low as 0.0063 m³/sec. Injection was 95% continuous, however, with short stops due to power failures.

The storage phase lasted from June 5, 1978, to July 26, 1978 (51 days). Water was then withdrawn from the storage aquifer at a constant rate of 0.016 m³/sec (Fig. 3.3). The temperature of recovered water was 328 K initially and diminished at an average rate of 0.5°/day. On September 5, 1978, recovery was terminated after 55,345 m³ of water had been withdrawn. At that time, the temperature of the recovered water was 306 K. (Native groundwater temperature is 293 K.) The energy recovery factor (energy out/energy in) was calculated to be 0.65 (Fig. 3.4).

The permeability decrease appears to have been due to clay particle swelling, dispersion, and migration in the storage formation, where the migrating particles gradually clogged the pores. This clogging was controlled during the 80-day injection period by surging the injection pump and by pumping water out of the formation for short periods of time.

Fig. 3.2. Cumulative volume of heated water injected into storage formation as a function of time.

ORNL-DWG 79-4929 ETD

Fig. 3.3. Cumulative volume of heated water produced from storage formation as a function of time.

ORNL-DWG 79-4930 ETD

Fig. 3.4. Ratio of thermal energy recovered to total thermal energy injected as a function of production water temperature. Production was stopped when water temperature reached 33°C ($K = ^\circ\text{C} + 273$).

Another important observation was that convection in the wells initially resulted in erroneous temperature readings in the wells. This was corrected by backfilling the wells with coarse sand. Also, throughout the experiment, temperatures of injected and recovered water, temperatures at various depths and locations within the storage aquifer, and head elevations in observation wells were recorded at regular intervals. These data are currently being compiled and analyzed by Auburn University project personnel.

The second injection-storage-recovery cycle is now under way. During this cycle, the subsidence of the land surface when water is removed from storage and the rebound of the land surface when water is injected will be measured by precise leveling instruments. The temperature and hydraulic head data, which were collected during the first injection-storage-recovery cycle, are still being studied. When data analysis is complete, the results will be published.

3.1.2 Storage of cold water in groundwater aquifers for cooling purposes (Texas A&M University - Research Foundation; D. L. Reddell and R. R. Davison, principal investigators)

The objectives of this project, which is contracted for the period Sept. 1, 1977, to Sept. 30, 1978, are to:

1. design, construct, and operate a cooling pond to chill water from 294 to <283 K and to evaluate the operation of the cooling pond when interfaced with an injection well;
2. evaluate in detail the transmissivity, storability, heat transfer coefficients, and heat storage properties of a groundwater aquifer located near Texas A&M University in Burleson County, Texas;
3. perform a field test in which cold water produced by the cooling pond is injected into the aquifer, stored for several months, and then pumped out for air conditioning purposes;
4. monitor the resulting water movement and temperature profiles in a system of observation wells, use the results to verify available numerical models, and evaluate the concept of storing cold water in groundwater aquifers during the winter for use in air conditioning buildings during the summer.

A 465-m² cooling pond has been constructed that is capable of chilling 0.063 m³/sec from 294 to 277 K during periods of low outdoor temperature. The pond is lined with a butyl rubber liner to prevent seepage. Water will be pumped from a well into the pond, where a 0.0378-m³/sec pump will circulate it through a series of spray nozzles during periods when the wet-bulb temperature is less than 283 K. When the pond water temperature is sufficiently low, 0.0063 m³/sec will be taken from the pond and injected into a second well. The water will be chlorinated and passed through a sand filter prior to injection.

Two wells have been drilled at the research site and are located in the shallowest groundwater aquifer in the area, the flood-plain alluvium which exists extensively along the Brazos River. The right side of Fig. 3.5 shows a log of the well. The clay and dense clay from depths of 6.7 to 11.6 m apparently form a slightly permeable caprock for the sand and gravel aquifer. Thus, the aquifer must be analyzed as a leaky-roof, confined aquifer. The water level in the sand and gravel is about 7.6 m deep. Both of the wells were constructed in an identical manner; the well design is shown in Fig. 3.5. The well was drilled using a reverse-circulation rotary drilling rig. Surface casing was set and grouted to a depth of 5.5 m. A fiberglass casing and well screen was used to prevent corrosion and allow strong chemicals to be used to remove any incrustations or plugging material and to allow hot water to be injected without loss of strength. Stainless steel could have been used, but it would have been more expensive.

A short-term pumping test (24 hr) was conducted for both wells. The injection well was capable of yielding 0.0116 m³/sec with a 4.26-m drawdown, and the pumping well yielded 0.027 m³/sec with a 2.44-m drawdown. Preliminary values of hydraulic conductivity are 0.00212 m/sec at the injection well and 0.00255 m/sec at the pumping well. The storage coefficient was 7.9×10^{-4} and 1.05×10^{-2} at the injection and pumping wells, respectively. The hydraulic conductivity values are large but are typical of the values expected for this aquifer. The storage coefficient values indicate that the aquifer in the vicinity of the injection well is confined, while that in the vicinity of the pumping well responds more like an unconfined aquifer. A more detailed pumping test analysis using "leaky

Fig. 3.5. Log of well site and well construction for both injection and pumped wells (1 m = 3.28 ft = 39.37 in.).

aquifer" techniques will be required to determine final values for hydraulic conductivity and storage coefficient.

Observation wells have also been drilled near both the pumped and injection wells. Locations of these observation wells with respect to the injection and pumped wells are shown in Fig. 3.6, a schematic of

Fig. 3.6. Schematic of cold water injection site showing relationship between injection well, pumping well, observation wells, and cooling pond (1 m = 3.28 ft).

the wells completed to date. Additional observation wells will be added, particularly around the injection well.

Phase I of this project was for construction of the project and aquifer evaluation only. No data have been collected to date, except those for the pumping test to evaluate aquifer parameters. These results were described in the previous section. No problems were encountered except those caused by weather and by failure of well drillers and manufacturers to supply goods and services on time.

The construction of the project is now essentially complete. Water injection (without chilling or aerating) will begin early in November at the rate of $0.0126 \text{ m}^3/\text{sec}$ for 15 days; water will then be pumped out for 15 days. This will provide experience with injecting nonaerated water and some background on potential plugging problems using nonaerated water.

During November, the chilling pond will be operated and the chemical changes which take place during the cooling operation will be evaluated.

If there has been enough cold weather to collect a substantial amount of cold water by the latter part of November or first of December, the injection of chilled water will begin. This injection will continue until the latter part of March or the first of April. The water will be stored for a few weeks and pumped out of the ground, and the thermal losses will be evaluated.

3.1.3 Aquifer storage at Kennedy International Airport
(Desert Reclamation Industries; H. J. Hibshman,
principal investigator)

The objective of this project, which was contracted for the period October 1977 to August 1978, is to assess the technical and economic feasibility of capturing winter chill as cold water and storing it for subsequent use in summer air conditioning of terminal buildings at Kennedy International Airport in New York City. This activity was funded in response to the Program Research and Development Announcement (PRDA) issued by DOE-STOR (then ERDA) on industrial waste heat recovery and reuse through thermal energy storage. The effort was carried out with the cooperation of the Port Authority of New York and New Jersey (operators of Kennedy International Airport) and with the support of Dames and Moore (subsurface engineering) through subcontract to Desert Reclamation Industries. Winter chill may be captured as cold water either through heat exchange with neighboring Jamaica Bay or by means of existing cooling towers operating in a lower temperature reject mode. This cold water will be stored in a fairly well-known aquifer located under the airport.

A preliminary study, limited to published information, has been completed on the technical and economic feasibility of storing winter cold in an aquifer for summer air conditioning. The study showed that aquifer storage of winter cold for summer air conditioning may be both technically and economically feasible. Payout periods of 4.5 to 8.5 years may be possible for similar sites with 4¢/kWhr electric power. The study also showed that the technology is site-specific to a variety of factors such as cold source, hydrogeology, air conditioning requirements, energy costs, and space limitations.

One technical factor at Kennedy International that has a "go/no-go" impact and that can only be resolved by field investigations is whether

there is serious risk of aquifer storage aggravating existing subsidence problems. These problems arise because a filled-in swamp under the site continues to compact. There are other unanswered questions posing technical problems that can have a significant impact on the design and cost of any demonstration at Kennedy International. Two of these (the thickness of the aquifer under the site and the uniformity and permeability of the aquifer) involve aquifer characterization, which can only be resolved by field work. A drilling program is under way to provide an answer to the first question, and one or more hydrological tests will be required to answer the second. The results of these programs will provide data to assist in analyzing the subsidence issue.

Another problem that should be addressed is the significance of estimated costs to allow for site-specific problems at Kennedy International, such as (1) laying over a mile of insulated pipe among the labyrinth of existing underground utility lines, (2) building a bay water pumping station, and (3) possibly tunneling under runways if Jamaica Bay water is used for winter cooling instead of cooling towers. The use of bay water may result in significantly lower operating costs than the use of cooling towers.

Overall, Kennedy International Airport remains a promising site for a prototype demonstration. It is highly visible to air travelers from around the world and has 24,000 tons of air conditioning, enough to centrally air condition every home in a city of about 25,000 people.

3.1.4 Analytic modeling of the aquifer thermal energy storage concepts (Lawrence Berkeley Laboratory; C. F. Tsang, principal investigator)

The objective of the study, which is contracted through FY-79, is to use numerical models and other methods to (1) study and understand the hydrodynamic and thermal behavior of an aquifer under a variety of possible situations when used for storage of hot or chilled water, (2) estimate the efficiency of storage and retrieval, and (3) model field experiments.

A numerical model developed at the Lawrence Berkeley Laboratory (LBL) is used to investigate hot- and chilled-water storage. The model, called

"CCC" for conduction, convection, and compaction, is based on the integrated finite-difference method. It computes heat and mass flow in three-dimensional, water-saturated, porous systems while concurrently simulating the vertical deformation of the system using the one-dimensional consolidation theory of Terzaghi. Thus, the following physical effects are included in the calculations: (1) effects of temperature on fluid heat capacity, viscosity, and density; (2) heat convection and conduction in the aquifer; (3) effects of regional groundwater flow; (4) spatial variations in aquifer properties; and (5) gravitational effects. The numerical model has been validated for examples for which analytical or semianalytical solutions are available (e.g., Theis, 1935; Avdonin, 1964; Gringarten and Sauty, 1975).

The following hypothetical cases have been modeled:

1. Annual cycle - seasonal storage. In this example, hot water is stored in the aquifer for 90 days in summer and is produced for heating during 90 days in winter. No injection or production was postulated during spring or fall. The model predicts that for successive cycles, the recovery temperature increases as the aquifer is heated, making it a more efficient hot-water storage system. The predicted percentage of energy recovered was >80% after only three or four injection-production cycles.

2. Different cycle periods. In addition to annual cycle storage, the semiannual cycle was also investigated (i.e., fall storage and winter production for space heating and spring storage and summer production for air conditioning). Results very similar to those for annual cycle storage were obtained. The percentage of energy recovered for successive cycles is shown in Fig. 3.7.

3. Well partially penetrating the aquifer. Figure 3.8 shows the results of calculations that assume the well is open only for the upper half of the aquifer. The temperature contours in the aquifer after 90 days of injection and 90 days of subsequent production are plotted; the buoyancy effect of low-density hot water is clearly evident. The percentage of energy recovered for successive cycles is similar on each cycle.

4. Storage of water of different temperatures. Storage of water at 393, 413, and 593 K was evaluated. The results of calculations of the hydrodynamic and thermal behavior of the aquifer appear to scale as

Fig. 3.7. Calculated energy recovery from aquifer storage ($K = ^\circ\text{C} + 273$).

Fig. 3.8. Calculated isotherms in aquifers with partial penetration ($K = ^\circ\text{C} + 273$).

$(T_s - T_o)$, where T_s is the temperature of water stored and T_o is the original aquifer temperature.

5. Effect of a clay lens in the aquifer. The aquifer is divided into two parts by a clay lens with a radius of 20 m for the model. If a well is open only below the lens, the results of calculations of hot-water injection and production are shown in Fig. 3.9, which displays the temperature contours after 90 days of injection and 90 days of subsequent production. The effect of the clay lens on these temperature contours is clearly demonstrated; however, the percentage of energy recovered is only affected slightly (Fig. 3.7).

6. Aquifer inhomogeneity. If the aquifer is composed of two layers, one more permeable than the other, the flow and the temperature contours will be changed. The results of calculations on an example in which one region is twice as permeable as the other are shown in Fig. 3.10. The water appears to flow into the higher permeable region as would be expected; however, the calculated percentage of annual recovery is only affected slightly (Fig. 3.7).

7. Chilled-water storage. In addition to the modeling of hot-water storage, the concept of storage of winter-chilled water to be used in summer for air conditioning was investigated. Storage of 277 K water for 90 days in winter and production for 90 days in summer was assumed for the model, and the production temperature after a few cycles was expected to stay below 283 K for the entire production period.

8. Two-well system. In this example, a system of two wells was modeled with one well supplying the water that is heated and injected into the other. In models described above, the thermal front moves radially from the single well; however, in this case, the presence of the second well will distort the thermal front. Figure 3.11 shows the thermal fronts as a function of the separation between the storage well and the supplying well. If the two wells are reasonably far apart, the results are similar to those of a single well. A three-dimensional numerical modeling of the two-well system was developed. A fine mesh was used near the storage well to ensure an adequate description of the temperature changes in that region. Results of the calculations are shown in Fig. 3.12, where the effects of the supplying well and the

Fig. 3.9. Calculated isotherms in an aquifer with a clay lens ($K = ^{\circ}\text{C} + 273$).

Fig. 3.10. Calculated isotherms in aquifers with simulated inhomogeneities ($K = ^{\circ}\text{C} + 273$).

Fig. 3.11. Calculated thermal fronts for two-well systems.

Fig. 3.12. Calculated isotherms for a two-well system ($K = ^\circ\text{C} + 273$).

gravitational buoyancy effect are clearly indicated. A plot of the production temperature as a function of the production period in the first cycle is shown in Fig. 3.13, along with the corresponding single-well curve for comparison.

9. Possibility of consolidation or uplift. To demonstrate the capability of the model to calculate the consolidation or uplift effect, calculations were made based on two sets of arbitrarily chosen parameters. Results indicate that consolidation and uplift are strongly parameter dependent (i.e., site-specific).

Fig. 3.13. Calculated production temperatures for an aquifer storage system ($K = ^\circ\text{C} + 273$).

10. Natural regional flow. The effect of natural regional flow has been calculated using both a two-dimensional, steady-state, fluid-flow model and a three-dimensional model. Results of the calculations indicate that a natural flow rate on the order of 1 m/year will not adversely affect storage capabilities; however, appreciable effects may occur if the flow is unusually large (~ 100 m/year). In addition to the above model studies of various effects and possible situations that might occur in the field, the following work was done during FY-1978.

Workshop on Thermal Energy Storage in Aquifers — LBL organized and hosted the Workshop on Thermal Energy Storage in Aquifers held May 10-12, 1978, to provide an exchange of ideas and technical information. More specifically, workshop participants reviewed the potential for thermal energy storage in aquifers; addressed possible technical, environmental, and institutional problems; and examined storage projects currently under way. There were 76 participants, including 6 foreign speakers who discussed aquifer storage projects in their countries. Proceedings from the workshop will be published soon.

Aquifer Thermal Energy Storage Newsletter — At the request of DOE, ORNL, and foreign participants at the Aquifer Workshop, LBL will publish a bimonthly Aquifer Thermal Energy Storage Newsletter. The newsletter will keep workers in this field informed of the major results and current status of aquifer storage projects throughout the world. The first issue, compiled during August and September, consists of brief descriptions of storage projects discussed at the workshop.

Simulation of Auburn University Field Experiments — Data from field experiments being conducted at Auburn University have been stored on the LBL computer, and a mathematical analysis of the data has been initiated to model aquifer parameters and geometry. By using a variable-flow well-test analysis method, we hope to calculate the properties of the aquifer and its nearby barriers. Once aquifer parameters have been calculated, the aquifer will be modeled for hot-water storage.

A simulation study will be made of the Auburn University field experiments in an effort to understand the hydrodynamics and heat flow processes in these experiments and to calibrate and validate our numerical

model. The results of this study may be useful to other demonstration projects.

LBL will continue to publish the Aquifer Thermal Energy Storage Newsletter, and articles will be solicited from researchers throughout the world. The first issue was distributed to 116 persons, including 33 foreign recipients in 10 different countries.

Typical situations in thermal energy storage will be modeled, and these studies will include a calculation of daily cycle storage. A program will be written that will include the effect of heat loss along the well bore as water is injected into or produced from the aquifer. If the calculated percentage of heat recovery is large, this type of storage may have application for solar power systems.

3.1.5 Heat storage well application to Twin Cities District Heating (General Electric Company - TEMPO; C. F. Meyer, principal investigator)

The objective of this project, which is contracted for the period Aug. 14, 1978, to June 30, 1979, is to evaluate the technical and economic feasibility of adding thermal energy storage components (primarily based on the annual cycle) to an existing Twin Cities District Heating Project (TCDHP).

The project began seven weeks before the end of FY-1978, and a number of documents describing the proposed TCDH system were acquired and reviewed.

After correspondence and discussions with representatives of the Swedish firm Studsvik Energiteknik AB, a subcontractor to TEMPO on this project, tasks were assigned to Studsvik to (1) characterize the long-, medium-, and short-term variations in DH and electricity loads for the Twin Cities area and their relevant degree of correlation; and (2) analyze the influence of short-term TES on required DH production capacity, co-generation plant capacity factor, load split between coal- and oil-fired generation, and system economics. The major activity in progress by September 30, 1978, was the development of correlation functions that convert Swedish DH systems to Twin City conditions.

Arrangements were also made with representatives of GE's Electric Utility System Engineering Department to review briefly the new system

dispatch and control problems involved in Northern States Power (NSP) converting to cogeneration.

The descriptions of the DH system configurations should be received from Studsvik in October 1979 with the company's final report on its initial effort. This report will be reviewed in mid-November 1979 at a St. Paul meeting of the various sponsors and participants involved in the Twin Cities DH project.

Once the reference system has been defined, TEMPO will study the system and postulate that TES is added. (An explicit assumption will be that suitable aquifers for annual-cycle storage are available.) The expected effects will be to (1) reduce or eliminate the auxiliary peaking and backup boiler capacity needed without TES; (2) reduce the size of pipelines; (3) conserve fuel energy required without TES, with accompanying savings in fuel cost and environmental impact; (4) decrease system investment cost; (5) substitute coal burned in central plants for oil that would be burned in auxiliary boilers; and (6) increase the flexibility for siting future cogeneration plants, if elimination of cooling towers or water for condenser cooling will do so.

The results of the NSP study of the effects on the electric system of the proposed DH system without TES will be reviewed and applied to estimate and compare similar effects to be expected from the alternative DH system(s) with TES. Studsvik researchers will also complete their characterization of heat load fluctuation with time and will work with TEMPO to establish a common ground for estimating and comparing the performance and cost of Twin Cities DH systems with and without TES.

The final product will be not only an analysis of the value of TES to this prototype DH system, but also a draft of a general methodology for describing and evaluating TES as a part of DH systems.

3.2 Short-Term Storage of Solar Energy for Heating: Encapsulation of Phase-Change Materials in Concrete Masonry Construction
(Department of Energy and Environment, Brookhaven National Laboratory; M. J. Sansone, principal investigator)

The solar source has long been recognized as a potentially significant alternative for building heating, but one whose implementation requires the development of an efficient and cost-effective system involving elements of energy collection, heat transport, and thermal storage. Of these three elements, the TES component is, at present, probably the least proven as to technical and economic feasibility. Ongoing work under the LTTEs program is described in this section relative to the development of building materials containing PCMs for storage capacity enhancement. The alternative of modular units containing PCMs in bulk or macroencapsulated form is considered in Section 3.6.

The main objective of the project, which is contracted for the period August 1977 to September 1978, is to develop building materials with large heat capacities that can be used economically for LTTEs. The objective is to be achieved by developing the method for incorporation of large amounts (15 to 50%) of PCMs that undergo phase transition in the temperature interval 293 to 305 K into a supporting matrix such as concrete, polymer concrete, polymer-impregnated concrete, gypsum wallboard, etc.

The project has been organized into the following tasks: (1) identification and selection of PCMs, (2) encapsulation techniques, (3) thermal and physical properties measurements, (4) economic studies, (5) technology transfer, and (6) administrative. The bulk of the work to date has been focused on tasks 1, 2, 3, and 6.

Task 1. The preliminary screening for potential PCMs was performed by the Dow Chemical Company (Contract NSF-C906, Report No. NSF/RANN/SE/C906/FR/76/1). A number of PCMs have been selected from the list in the Dow report, and further work has been done under tasks 2 and 3.

Task 2. Efforts to encapsulate PCMs in various supporting matrices have begun. Inorganic and organic PCMs have been incorporated into concrete, polymer concrete, and gypsum matrices. Polymer concrete shells

have been made and filled with inorganic and organic PCMs. Porous aggregate has been impregnated with PCM, and several different coatings have been applied to the aggregate.

Task 3. The goal of this task was to establish the capabilities in thermal and physical properties measurements and to apply these methods to PCMs and composite systems containing PCMs in various supporting matrices.

Task 4. Economic studies to date have only involved the calculation of composite material costs and have excluded fabrication costs and total systems analysis.

Task 5. Some cooperation with the National Concrete Masonry Association has been initiated, but, in general, the work has not reached the stage of development where technology transfer can be realized.

Task 6. Ten monthly administrative letters and three quarterly reports were issued during the year, and two program plans and one technical status report were written.

All PCMs tested are incompatible with concrete and prevent it from setting. Table 3.3 summarizes some typical results. Samples have also been made incorporating $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$, and decanoic acid into cement with similar poor results. Incorporating PCMs into concrete without prior encapsulation of the PCM does not appear to be feasible.

The results of encapsulation of PCMs in polymer and polymer concrete are summarized in Table 3.4. In general, the samples require an external coating to retain the PCM. Most samples develop leaks during thermal cycling as a result of the solid-to-liquid volume expansion of the PCMs (8 to 15%). Supercooling of PCMs is also a frequently encountered problem, as demonstrated by the cooling curve of Fig. 3.14. The results of experiments that blend PCMs as liquids directly with monomer before subsequent monomer polymerization are summarized in Table 3.5. The resulting materials lack strength and require an excessive amount of expensive monomer (25 to 50% by weight).

Work has begun on the encapsulation of PCMs in cylindrical polymer concrete shells. Since none of the 25 samples made to date have leaked, this method may offer good prospects for success in the near future.

Table 3.3. Composition of systems with cement matrix^a

Binder	Aggregate	Foamed glass beads	PCM	Comments
Portland cement #1, 22.0%	Sand, ^b 37.9%	40.1% SSD, ^c 22.0% dry	0	Control samples; cured to acceptable strength; polymer impregnated showed high strength
Portland cement #1, 21.2%	Sand, 36.5%	21.2% dry	Decanoic acid, 16.5%	All samples were unacceptable; polymer impregnation did not produce strength or impermeability
Portland cement #1, 18.5%	Sand, 31.8%	24.2% dry	PEG 600, 25.5%	Samples never set
Portland cement #1, 17.6%	Sand, 30.3%	22.9% dry	CaCl ₂ ·6H ₂ O, 29.0%	Samples cracked and fell apart

^aThe water:cement ratio for all samples was 0.4.

^bSand ratios in all cases were 2:1:1 (16 mesh, 30 mesh, 100 mesh).

^cSaturated surface dry basis.

Table 3.4. Composition of polymer concrete systems^a

Binder	Initiator/ promoter ^b	Sand aggregate ^c	Foamed glass beads	PCM	Comments
PES, 12% of total	MEKP, 1%; CoN, 1/2%	88% of total	0	0	Controls
MMA/TMPTMA (90/10), 15% of total	BPO, 1%; DMA, 1/2%; DMT, 1/2%	85% of total	0	0	Controls
PES, 12% of total	MEKP, 1%; CoN, 1/2%	78% of total	0	CaCl ₂ ·6H ₂ O, 10% of total	Samples required over two months to cure
PES, 12% of total	MEKP, 1%; CoN, 1/2%	0	0	Na ₂ S ₂ O ₃ ·5H ₂ O, 88% of total	Sample requires outside coating to retain PCM; no strength above transition temperature
PES, 12% of total	MEKP, 1%; CoN, 1/2%	44% of total	0	Na ₂ S ₂ O ₃ ·5H ₂ O, 44% of total	Sample requires outside coating to retain PCM
MMA/TMPTMA (90/10), 12% of total	BPO, 1%; DMA, 1/2%; DMT, 1/2%	0	0	Na ₂ S ₂ O ₃ ·5H ₂ O, 88% of total	Sample requires outside coating; not as good as PES system
MMA/TMPTMA (95/5), 12% of total	BPO, 2%; DMA, 1%; DMT, 1%	66% of total	0	Decanoic acid, 22% of total	Large amount of catalyst used in attempt to avoid dissolution as above; PCM ran to walls of sam- ple through the fiberglass
MMA/TMPTMA (90/10), 12% of total	BPO, 1 1/2%; DMA, 1%	44% of total	0	Na ₂ S ₂ O ₃ ·5H ₂ O, 44% of total	Excellent samples made by re- casting with PES to cover exterior
MMA/TMPTMA (90/10), 15% of total	BPO, 1%; DMA, 1%	22.5% of total	0	Na ₂ S ₂ O ₃ ·5H ₂ O, 62.5% of total	Mold surfaces lined with fiber- glass; excellent, nonleaking samples resulted
PES, 11.3% of total	MEKP, 1%; CoN, 1/2%	34.6% of total	24.2% of total	PEG 600, 25.5% of total	Samples cured but require ex- ternal coating
PES, 38.1% of total	MEKP, 1%; CoN, 1/2%	0	38.9% of total	Decanoic acid, 23% of total	Samples prepared by pouring resin over beads in large test tube; cured, but require further coating
MMA/TMPTMA (90/10), 33.5% of total	BPO, 1%; DMA, 1/2%	0	41.8% of total	Decanoic acid, 24.7% of total	Same as above

Table 3.4 (continued)

Binder	Initiator/ promoter ^b	Sand aggregate ^c	Foamed glass beads	PCM	Comments
MMA/TMPTMA (95/5)	BPO, 1%; DMA, 1%	66% of total	0	Decanoic acid, 22% of total	Decanoic acid added to mix as pellets; all ingredients chilled; dissolution of large amount of PCM prior to cure
MMA/TMPTMA (95/5)	BPO, 1 1/2%; DMA, 1%	38.5% of total	26.9% of total	Decanoic acid, 17.7% of total	Attempt to retain PCM in foamed glass bead until gelation; PCM ran to walls of sample through the fiberglass

^aAbbreviations: PES - polyester/styrene 50/50 LB183-13, MMA/TMPTMA - methyl methacrylate/trimethylolpropane trimethacrylate, MEKP - methyl ethyl ketone peroxide, CoN - cobalt napthenate, BPO - benzoyl peroxide, DMA - dimethylaniline, DMT - dimethyltoluidene.

^bPercentages of initiators and promoters refer to polymer weights.

^cSand aggregate is proportioned 2:1:1 (16 mesh, 30 mesh, 100 mesh).

Table 3.5. Composition of systems of PCM/polymer blends

Binder	Initiator/ promoter	PCM	Comments
MMA/TMPTMA (95/5)	BPO, 2%; DMA, 1%	Decanoic acid, 50% of total	Sample cured and was coated with PES; activity of PCM not yet established
Derakane, 50% of total	MEKP, 1%; CoN, 1/2%	MEG 600, 50% of total	Sample cured to hard solid; re- quires further encapsulation
PES, 50% of total	BPO, 1 1/2%; DMA, 1/2%	CaCl ₂ ·6H ₂ O, 50% of total	Sample cured to hard rubberlike mass; requires further encapsu- lation
PES, 25% of total	BPO, 1 1/2%; DMA, 1/2%	CaCl ₂ ·6H ₂ O, 75% of total	Sample did not cure; soft, spongy mass with pockets of free PCM
Corezyn 158-5, 50% of total	MEKP, 1%; CoN, 1/2%, DMA, 1/10%	CaCl ₂ ·6H ₂ O, 50% of total	Blended in Waring blender and catalyzed; cured to a soft, rubbery material

Fig. 3.14. Plot of temperature vs time for 60% $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ in polymer concrete matrix. Cooling curve shows high degree of supercooling (down to 28°C) ($K = ^\circ\text{C} + 273$).

Differential scanning calorimetry (DSC) for small samples and a Thermometrics heat flow calorimeter for large samples are available to the project (see Fig. 3.15 and Table 3.6). Thermal conductivity measurements are made with a Lafayette TC 1000 thermal comparator.

Fig. 3.15. Plot of heat flow vs time for polymer concrete in Thermometrics calorimeter. Total heat capacity between T_0 and T_f is proportional to area under curve. ($K = ^\circ\text{C} + 273$; $\text{m}^2 = 10^4 \text{ cm}^2$; $\text{m/sec} = 2.78 \times 10^{-2} \text{ cm/hr.}$)

Table 3.6. Heat capacity measurements with heat flow calorimeter

Sample description	Temperature range ($^\circ\text{C}$) ^a	Heat capacity [cal/(g- $^\circ\text{C}$)] ^b	Charging time (hr)
Polymer concrete; 15% MMA/TMPTMA and 85% sand; ratio of No. 16 to No. 30 to No. 100 sand, 2:1:1	24.3-35.3	0.234	1.54
Polyester styrene resin	24.3-35.25	0.411	1.82
Mortar; sand to cement ratio, 3:1; ratio of No. 16 to No. 30 to No. 100 sand, 1:2:1; water to cement ratio, 0.45:1	24.4-34.9	0.264	1.4
Porous aggregate (foamed glass beads)	25.05-35.1	0.193	NA ^c
Polymer (PMMA) with foamed glass aggregate impregnated with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	24.1-35.4	2.17	6.1
Decanoic acid	24.3-35.15	4.36 ^d	NA ^c

^a $K = ^\circ\text{C} + 273$.

^b $\text{J/kg-K} = 0.2389 \times 10^3 \text{ cal/g-}^\circ\text{C}$.

^cNot available

^dIncludes heat of fusion at 31°C .

3.3 Storage for Specific Industrial Applications

Manufacturing and process industries (whether involving mechanical manipulation or chemical conversion) not only account for a significant amount of the total U.S. energy consumption, but also reject equally significant amounts of heat (or cold) at temperatures of potential interest for other applications. The recovery and reuse of this waste energy is important to the national efforts for energy conservation. This aspect of the LTTEs program identifies promising industrial waste energy sources to establish feasibility for recovery and storage and then carries out technical demonstrations (in consort with other DOE elements) to show economic viability as a guide for pervasive implementation.

3.3.1 Analysis and development of a solar energy regenerated desiccant drying facility (Lockheed Missiles and Space Company - Huntsville Research and Engineering Center; D. V. Merrifield, principal investigator)

The major objectives of the study, which was contracted for the period Aug. 1, 1977, to Dec. 31, 1977, were to improve the cost effectiveness of the desiccant regeneration system and to establish significant design improvements over the regenerated desiccant drying concept developed in the previous study phases.¹⁻³ This goal was achieved by using a straightforward evaporative technique instead of a packed-column technique for regenerating (reconcentrating) the lithium chloride desiccant solution and by using a steam condenser for heat recovery. Additional objectives were to establish the technical and economic characteristics of a baseline desiccant drying system and to identify promising applications of the system.

The project was an R&D effort to further develop and improve the design of a regenerated desiccant drying and dehumidification system that requires less than half the energy input of conventional warm air dryers. The baseline application is for large-scale commercial grain drying, although several other applications have been identified, such as space air conditioning and kiln drying of lumber. The system has excellent potential for providing a significant degree of industrial energy conservation with payback periods of two to eight years to recover the added capital

investment over conventional less-efficient drying methods. Although the intended energy source for the system is solar, the basic energy-saving technique is the liquid desiccant drying process itself, which allows virtually any thermal energy input to be used. The use of solar energy permits further energy conservation if the additional capital investment is justified.

Major tasks carried out in the study were (1) analysis and evaluation of improved regeneration techniques; (2) laboratory tests and evaluation of an evaporative regeneration subsystem; (3) development of performance prediction methods; (4) definition, design analysis, and economic analysis of a commercial-size baseline drying system; and (5) analysis of specific applications. The final study report was published in December 1977.⁴

The initial study task — to identify the most promising approach to an improved desiccant regeneration system — resulted in the selection of an evaporator/condenser concept in which water evaporated from the desiccant is condensed in a water- or air-cooled condenser from which useful heat is recovered to provide additional drying capacity. This concept was then evaluated through a combined laboratory test program and mathematical modeling analysis. A 2.27-kg/hr-capacity laboratory-scale system was built and successfully tested. A specific energy input of approximately 459×10^3 J/kg of water was obtained,^{*} which is less than 50% of the energy requirement of conventional warm air dryers. The laboratory system also demonstrated the operating flexibility of the concept and its superior heat recovery capability.

The mathematical modeling effort developed models for predicting the system performance under various conditions and for determining principal design and operating parameters. An optimized specific energy input value of 4.31×10^5 J/kg, including thermal losses, is achievable with the evaporation technique. This value is 45% of the energy requirement of a conventional system. A baseline system, shown in Fig. 3.16, was defined and sized to meet the requirements of a large commercial grain dryer. For this system, with 2722 kg/hr of moisture removal capacity, optimum design parameters were determined, and a cost estimate was made

^{*}This is 15% better than that obtained from the previous laboratory system which used a packed column for regeneration.^{1,5}

Fig. 3.16. Regenerated desiccant grain dryer with evaporative re-generation.

and compared with the estimated cost of an equivalent system using the previous packed-column regeneration concept. The total cost of the system depicted in Fig. 3.17, including an absorption column, is 31% less than for the previous system. The major reason for the lower cost is that the total required heat transfer surface is considerably less. Using the estimated cost of \$385,000, an economic analysis (see Fig. 3.18) was made to show the payback and return-on-investment characteristics of the system considering its fuel cost saving capability over a typical conventional system. For a use factor greater than about 20% (continuous operation during 20% of the year), acceptable economics are obtained. For high use factors (exceeding 75%), the payback period is less than three

TOP VIEW

ELEVATION VIEW

Fig. 3.17. Conceptual layout of regenerated desiccant grain drying installation showing major components (1 m = 3.28 ft).

Fig. 3.18. Economic characteristics of regenerated desiccant drying system with 6000 lb/hr moisture-removal capacity. ($kg = 2.204 \text{ lb}$; $J = 9.48 \times 10^{-4} \text{ Btu.}$)

years with a return-on-investment of >30%. For use factors >40 to 50%, the use of solar energy is economically feasible. In addition to the baseline grain drying application, three other representative applications were analyzed — lumber drying, soybean processing, and space air conditioning — all with good economic potential.

Kiln drying of lumber is a promising application, because drying is required virtually year round. Also, the steam from the desiccant evaporator can be used within a conventional steam-heated kiln (see Fig. 3.19). Use of desiccant drying would permit the lumber to be dried at a lower temperature with better control of relative humidity and temperature than

Fig. 3.19. Block diagram of lumber drying application.

is possible with current kiln systems, thus resulting in better quality wood. The major components required for the drying system would be an evaporator, a heat exchanger, and an absorption column. The condenser normally used to condense steam from the desiccant evaporator will be an extra cost item, since the fin-pipe heat exchanger normally used for steam heating of the kiln can be used for this purpose. Special attention must be given to the design and sizing of the absorption column to ensure that it is matched to the drying conditions needed for the lumber. As indicated from the previous economic analysis, the desiccant equipment should pay for itself within two to four years, depending upon the specific size requirement. For this application, because the use factor will exceed 80%, it may be quite feasible to use solar collectors to provide for additional fuel savings.

Soybean processing represents a grain drying situation in which the drying equipment is operated over a large fraction of the year, thus resulting in a favorable economic situation for the use of a regenerated desiccant system. Large plants, such as those operated by the Gold Kist

Corporation, require that the soybeans be partially dried when received and further dried during later processing. A system such as the baseline design analyzed in the previous section of this report could be applied to soybean drying. As in the lumber drying case, the absorption column must be designed to meet the specific drying requirements (of moisture, flow rate, etc.). Solar energy should also be considered for this application because of the favorable use factor.

For space air conditioning, the regenerated desiccant process differs from the others in that the evaporator, heat exchanger, and absorption column would be combined with a standard lithium bromide absorption chiller to obtain an air conditioning process with a high coefficient of performance (COP). A block diagram of this concept is shown in Fig. 3.20. The key feature of this process is that the steam from the evaporator, at ~ 366 to 377 K, contains $\sim 75\%$ of the energy input to the desiccant evaporator and is used to drive the absorption chiller (specifically, to drive the lithium bromide vapor generator). Thus, the latent load (air dehumidification) is handled by the desiccant equipment while the sensible load (cooling) is handled by the conventional absorption cooling equipment.

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Fig. 3.20. Block diagram of regenerated desiccant air conditioning concept.

If the air conditioning load is such that all the steam (recovered heat) is utilized, the COP can be increased by >60%, with energy savings of >40% compared to those obtained using a conventional absorption chiller alone. This concept, which represents a hybrid absorption air conditioning machine, appears well suited for use in solar air conditioning applications, where a lithium bromide absorption chiller normally is used. In this case, there would be a substantial decrease in solar collector investment.

The major conclusion of the study is that the regenerated desiccant drying concept has been significantly improved, in both cost and performance potential, through the use of the evaporative regeneration technique. The overall concept shows excellent potential as a major means of industrial energy conservation with a wide range of applications and exhibits promising economic characteristics, particularly for high-use applications.

References

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3.3.2 Application of thermal energy storage to process heat and waste heat recovery in the aluminum industry (Rocket Research Corporation; L. B. Katter and R. L. Hoskins, principal investigators)

The objective of this project, which was contracted for the period Oct. 1, 1977, to May 30, 1978, is to determine the technical feasibility and economic incentive for capturing reject heat (as hot water) from the Intalco Aluminum Company primary aluminum plant in Ferndale, Washington; storing this heat appropriately; and subsequently using this energy for district heating in Bellingham, Washington.

The results of the first phase of this program show that waste heat recovery from aluminum smelting operations is technically feasible and economically viable. A ready demand for this energy exists for comfort conditioning for human habitation. Energy stored in the form of hot water improves the utilization of the continuously available source by the strongly time-variant demand.

A specific aluminum plant site has been analyzed during the study, resulting in a preliminary design from which the system performance may be estimated. This site, the Intalco Aluminum plant that is coupled to the cities of Bellingham and Ferndale, shows the prospect for displacing 1445×10^{12} J/year of fossil fuel energy (assumed heating efficiency of 70%). Thus, the fossil fuel displaced is 49.4% of the total energy contained above 294 K (2922×10^{12} J/year) in the Intalco fume flow. The site is a reasonably typical aluminum plant, allowing an estimate of the national fossil fuel savings from the example savings fraction at 374×10^{14} J/year. These are equivalent to 0.04×10^6 m³ of oil per year (one site) and 1.03×10^6 m³/year (national).

The system analyzed during the program provides the space heating and hot-water heating requirements for a mix of large commercial, small commercial, and single-family residential users equivalent to 12,000 single-family residences. A storage tank of 3.79×10^5 m³ emerges as the most cost-competitive storage volume for aboveground, insulated, non-pressurized steel tanks. The maturation of aquifer thermal storage technology is expected to result in less expense associated with storage of

heated water and higher energy savings and lower costs, thus resulting in even better economic parameters.

The system, as designed, incorporates mainly existing proven technology. The only element that presents a potential technology gap is the use of polymer-lined prestressed concrete pipe in the required diameter. However, such development is currently in progress in Europe, and discussions indicate that the development is proceeding rapidly. The maturation of polymer-lined prestressed pipe technology appears to be totally feasible by 1985. It is thus estimated that the system could be implemented and proved by 1985.

The projected cost of the proposed system is \$63.2 million (1977). Escalating this cost to the assumed 1985 system start yields a value of \$93.3 million (1985). The system "present value" (1985 dollars) is \$349.3 million, yielding a system net present value of \$256 million (1985). Other economic indicators are as follows: (1) internal rate of return — 20.8%, (2) return on investment — 86%, (3) system lifetime (assumed) — 30 years, and (4) averaged energy cost/averaged cost of replaced fossil fuel — 0.255.

No technological breakthroughs are required before the system can be implemented, but the overall system will require a full-scale demonstration before a significant investment of private capital will be forthcoming.

3.3.3 Conservation of waste heat in the food processing industry utilizing thermal energy storage (Westinghouse Electric Corporation — Advanced Energy Systems Division; W. L. Lundberg, principal investigator)

The objective of this project, which was contracted for the period Aug. 31, 1977, to Sept. 30, 1978, is to assess the potential for economical waste heat recovery in the food processing industry and to evaluate prospective waste heat recovery systems. It is being conducted by Westinghouse with the cooperation of the H. J. Heinz Company. Heinz officials arranged access to two of their manufacturing plants within the Heinz U.S. Division and permitted Westinghouse personnel to analyze factory and food system operations. Besides the selection of the two

survey sites, a waste heat availability study was also performed at each site, and recovery system concepts were developed and evaluated.

Survey site description and selection rationale. The Heinz U.S. Division operates 11 factories engaged in a variety of thermal food processes. Two of those factories, located in Pittsburgh and Lake City, Pennsylvania, were selected as survey sites for the project. The Pittsburgh factory, a large multibuilding facility employing over 2000 production people, specializes in foods processed with steam and hot water. The factory's main products are baby foods and juices, canned soups, and canned bean products. At the Lake City factory, approximately 150 employees are employed in the preparation of frozen desserts. Lake City operations are conducted in a modern single-story building having a total floor area of 6503 m². These factories were selected as survey sites because their products and processes are common to a large segment of the food industry — nearly 13% on the basis of total energy consumption. This fact would lend attractiveness to any recovery system concept stemming from the project, because the potential for significant industry impact would be correspondingly great.

Waste heat availability study. The Pittsburgh factory operates several food systems that produce hot waste water. To eliminate the possibility of product contamination, waste water from the processes is not recycled nor is waste heat recovery currently attempted. Instead, the waste water streams are collected by a drain system that transports them from the factory via clear water and sanitary sewer systems.

The various waste water sources evaluated at the Pittsburgh factory and waste water conditions for individual units are identified in Table 3.7. To assess total waste heat availability, the unit data from Table 3.7 were combined by shift and on a building-by-building basis and are summarized in Table 3.8. The table entries apply to those systems selected for waste heat recovery. Systems not represented in Table 3.8 were neglected because of low temperature and/or low volume reasons and high fouling potential in the case of the blowdown heat source. As an indication of waste heat availability at the factory, the Table 3.8 waste water streams could yield 7278×10^{10} J annually if their temperatures were reduced to 297 K by heat exchange with incoming fresh water.

Table 3.7. Individual unit waste water conditions — Pittsburgh factory

Source	Flow rate (gpm) ^a	Temperature (°F) ^b
Continuous can washer	12	175
Continuous bottle washer	7	175
Continuous cooker/cooler	60	140
Horizontal stationary retorts		
Canned products	100	100
Glass products	100	140
Continuous pasteurizer	80	170
Continuous cooler	55	120
Horizontal rotary retorts		
Type 1	10	135
Type 2	30	125
Continuous boiler blowdown	12	212

$$^a_{\text{m}^3/\text{sec}} = 6.31 \times 10^{-5} \text{ gpm.}$$

$$^b_K = (^\circ\text{F} - 32)5/9 + 273.$$

Table 3.8. Waste water summary — Pittsburgh factory

Source	Average flow rate (gpm) ^a / temperature (°F) ^b	
	First shift	Second shift
Power building		
Continuous cooker/coolers	120/140	60/140
Can washers	37/175	12/175
Meat products building		
Horizontal stationary retorts (glass products)	316/140	316/140
Can washers	25/175	12/175
Bottle washers	7/175	7/175
Continuous pasteurizer	80/170	80/170
Bean building		
Can washers	25/175	12/175
Continuous coolers	110/120	55/120
Total flow rate and average temperature	720/145	554/145

$$^a_{\text{m}^3/\text{sec}} = 6.31 \times 10^{-5} \text{ gpm.}$$

$$^b_K = (^\circ\text{F} - 32)5/9 + 273.$$

This recovery potential is significant, representing nearly 6% of the factory's current energy demand.

The Lake City factory has two independent refrigeration requirements — blast freezing and cold storage. The refrigeration effect is provided by an ammonia system driven by ten rotary and reciprocating compressors. On the discharge side of the compressors, the condensers are arranged in two separate groups. One group primarily serves the blast freezer and its heat rejection; therefore, it peaks during production hours and subsides to a relatively low level during off-production periods. The second group, however, serves a storage freezer, and its heat rejection rate is more uniform over the entire day. Thus, the factory actually has two independent sources of refrigeration waste heat that behave differently with time and could therefore be linked with two independent waste heat applications whose energy demands also follow different time patterns. Waste heat availability estimates were performed for the Lake City factory using assumed ammonia vapor conditions, factory electrical consumption data, and compressor nameplate information. The estimates show an annual waste heat availability at the condensers of 4219×10^{10} J, which is ~50% larger than the factory's total energy consumption (gas and electricity combined).

Waste heat applications. Three separate energy demands that could be met by using the available waste heat were selected for study at the Pittsburgh factory. They involve the heating of boiler makeup water, fresh water for food processes, and factory cleanup water. Thermal storage would be required in the latter case and conventional heat exchange in the makeup and process water cases. A cleanup water application involving thermal storage also exists at the Lake City factory and could be supplied by the blast freezer refrigeration system. In addition, a continuous demand (in cold weather) also exists for heated air, which is blown beneath the freezer floors to prevent soil freezing. This demand represents an ideal application of waste heat from the storage freezer system.

Waste heat recovery system design and evaluation. Several recovery system concepts to satisfy the waste heat applications identified above are being considered for use at the Pittsburgh factory. Features of

the reference system, shown schematically in Fig. 3.21, will be noted. In this concept, waste water streams at various temperatures are collected from processes occurring in three production buildings. The high-temperature streams (i.e., those above 333 K) are collected in the high-temperature accumulator (HTA), while all low-temperature streams are channeled to a low-temperature accumulator (LTA). The LTA and HTA will be insulated and will serve as surge tanks between the waste water source and application points. From the HTA, waste water flows on demand to the high-temperature heat exchanger (HTHX) located in the Power Building. At the HTHX, heat is transferred to incoming fresh water as it flows to various food processes. When those demands diminish while hot waste water is still available at the HTA, the system will automatically divert the flow of heated fresh water to storage. Water that accumulates in storage during the production period would then be used during third shift for cleanup purposes.

Waste water collected in the LTA will flow to two low-temperature heat exchangers (LTHX) also located in the Power Building and mounted in parallel. Waste heat will be applied at that location to preheat fresh water for food processing and for boiler makeup. The parallel heat exchanger arrangement is necessary because the food processing and makeup applications require water from two different sources — on-site wells and the city water main, respectively.

Estimated materials and installation costs for the reference waste heat recovery system are identified in Table 3.9. Allowing an additional 15% for engineering brings the total system cost to \$413,300. At current fuel prices, the system would return that investment at the rate of 34%/year and reduce factory energy consumption by 5 to 6%.

Two independent systems have been evaluated for the Lake City factory. The first system, shown schematically in Fig. 3.22, will apply refrigeration waste heat from the blast freezer compressors to heat fresh water for later use during third-shift cleanup operations. The system will be located in an existing water distribution system at a point between the softener exit and the first cleanup station takeoff. The system heat exchanger will operate as a desuperheater and, under normal conditions, vapor will exit the unit with 3 to 6 K of superheat still remaining.

Fig. 3.21. Waste heat recovery system - Pittsburgh factor. $[K = (\text{°F} - 32)5/9 + 273; \text{m}^3 = 264.173 \text{ gal.}]$

Fig. 3.22. Waste heat recovery system for water heating - Lake City factory. [$\text{m}^3/\text{sec} = 4.4 \text{ gpm}$; $K = (\text{°F} - 32)5/9 + 273$; $\text{kg/sec} = 0.00061 \text{ lb/hr.}$]

Table 3.9. Estimated costs (\$) —
Pittsburgh factory system

Item	Materials	Installation
Tanks	90,000	
Heat exchangers	44,400	6,700
Pumps	13,400	6,000
Strainers	10,000	4,000
Valves	15,500	12,800
Piping	27,300	92,200
Instrumentation/controls	17,800	19,300
Total ^a	218,400	141,000

^aTotal materials and installation — \$359,400.

The vapor will then flow to the existing condensers to complete the heat-rejection process. For low thermal storage temperatures, the circulation pump will energize, sending water from storage to the heat exchanger and back to storage. During production hours, heated fresh water at 339 K will accumulate in storage to be available for local cleanup during production and for the general plant cleanup that occurs daily when production ends.

Materials and installation cost estimates for the water heating system are presented in Table 3.10. The total system cost, including engineering, is \$36,900; the system would reduce the factory's natural gas consumption by 7% — a savings of nearly \$3,900 based upon current fuel prices. The annual return on investment (ROI) for the water heating system is ~8%.

A second waste heat recovery system for the Lake City factory, shown schematically in Fig. 3.23, would apply refrigeration waste heat to warm freezer floor air. As the figure indicates, outdoor air is presently warmed by an existing gas-fired heater and distributed to floor ducts by a fan. The fan operates continuously and air temperature control is achieved by regulating the flow of natural gas to the heater. Waste heat from a storage freezer system could be utilized to preheat or completely heat floor air by installing an air-cooled condenser at the heater inlet.

Fig. 3.23: Waste heat recovery system for air heating — Lake City factory. $[K = (^{\circ}\text{F} - 32)5/9 + 273; \text{kg/sec} = 0.00061 \text{ lb/hr.}]$

Table 3.10. Estimated costs (\$) —
Lake City water heating system

Item	Materials	Installation
Thermal storage tank (6000 gal) ^a	8,300	3,000
Heat exchanger	3,500	1,200
Pump	500	500
Water flow control valve	1,100	200
Temperature sensor and transmitter	3,500	400
Piping	2,300	5,000
Total ^b	19,200	10,300

^a m³ = 3.79×10^{-3} gal.

^b Total materials and installation — \$29,500.

Refrigerant vapor from the freezer system would be routed through the condenser on its way to the existing evaporative condenser. The system control would cause the incoming air to bypass the new condenser in any proportion to maintain the gas heater inlet temperature at a setpoint value. Any portion of the air heating load not satisfied by waste heat will be supplied automatically by the gas heater, which will continue to operate with its own control system independently of the waste heat recovery system. Costs to procure and install the air heating system are identified in Table 3.11, and the total estimated cost, including engineering, is \$17,700. The system will reduce the factory's natural gas consumption by 10%, and its annual ROI is estimated at 14%.

Based on the study, waste heat recovery from certain food processes apparently is feasible and can be performed economically using available, off-the-shelf hardware. It was also concluded that demonstration projects should be implemented to evaluate and optimize recovery system design and to determine actual costs and benefits.

Work is currently under way to evaluate a decentralized version of the Pittsburgh factory system. The purpose of that study is to determine the feasibility of equipping each production building with its own waste heat recovery system. A parallel study is evaluating the ROI distribution between the high- and low-temperature parts of the reference system (Fig. 3.21). These projects are scheduled for completion early in FY-1979.

Table 3.11. Estimated costs (\$) --
Lake City air heating system

Item	Materials	Installation
Condenser	2,800	1,800
Piping	600	1,100
Air ducting	3,000	1,200
Controls	3,000	800
Fan motor	500	
Total ^a	6,900	4,900

^aTotal materials and installation --
\$11,800.

3.4 Seasonal Storage for Solar Energy Heating

Seasonal storage to accomplish winter heating of buildings from the summer solar energy source is clearly an element of importance in energy conservation. The "temporal transfer" could be achieved by heating water in solar collectors and storing it in aquifers (see Sect. 3.1). This concept best accommodates large installations (single-residence housing developments and apartment complexes) where district heating (DH) schemes can be justified. For situations involving small numbers of dwellings (one to perhaps six), the use of earth storage or surface ponds is indicated. There are no active LTIES efforts in this area at present.

3.5 Seasonal Storage of Ice for Cooling

Production of ice during the winter with storage for use in air cooling during the following summer is an intriguing possibility. The Annual Cycle Energy System (ACES) currently being developed by DOE Building and Community Systems Division with ORNL management uses the reject side of a heat pump during winter heating to create a large pool of ice. Another possibility is to use winter cold to generate ice. Several proposals addressed to this latter concept are being reviewed; however, at present, there are no active LTES program efforts in this area.

3.6 Diurnal Storage for Off-Peak Electricity (Heating/Cooling)

Sensible heat storage in conjunction with an off-peak electricity energy supply is being extensively used in Europe today. The effectiveness, and possibly the efficiency, of this application could be improved by using latent heat storage. As noted previously, storage in phase-change materials (PCMs) is also a viable option in harnessing solar energy for building heating and cooling applications. The PCM storage can be accomplished by (1) incorporation in building materials, as considered in Sect. 3.2, or (2) containment in compact (modular) units, as emphasized here. In turn, modular units can be configured either as bulk storage (a pool of PCM contained by a shell with heat exchange tubing traversing the space) or as macroencapsulated storage (discrete small envelopes of PCM arranged within a duct carrying the heat exchange fluid). This category has been the object of numerous, innovative proposals; concepts currently funded under the LTTEs program are described below.

3.6.1 Immiscible fluid — heat of fusion heat storage system (Clemson University; D. D. Edit, principal investigator)

The primary objective of this project, which is contracted for the period June 1, 1976, to Nov. 30, 1978, is to evaluate the feasibility of direct-contact heat transfer in phase-change energy storage using aqueous salt systems. This concept may alleviate the heat transfer and phase segregation problems encountered in earlier heat-of-fusion energy storage systems, yielding a practical, compact energy storage unit. A secondary objective is improved knowledge and understanding of heat and mass transfer in direct-contact aqueous crystallizing systems.

The essence of the direct-contact/heat-of-fusion energy storage technique is that a fluid (lower in density and immiscible with the salt solution) is used as the primary heat transfer agent. It is introduced at the bottom of the storage vessel as a dispersed phase. As bubbles of the fluid rise through the vessel, heat is transferred to or from the salt solution and the fluid agitates the vessel contents. Finally, the heat transfer fluid is pumped through the remainder of the primary heat transfer loop (e.g., solar collectors or heat pump exchanger and the air heating

units of a residential heating system). Figure 3.24 is a schematic of the immiscible-fluid/heat-of-fusion storage system.

In order to facilitate study of this energy storage device, the research effort was divided into four major areas: (1) crystal growth velocity study on selected salts, (2) selection of salt solutions, (3) selection of immiscible fluids, and (4) studies of heat transfer and system geometry. Studies 2 and 4 were completed this year and studies 1 and 3 are nearly complete.

Fig. 3.24. Immiscible-fluid/heat-of-fusion storage system.

Crystal growth velocity study. This investigation was perhaps the most fundamental of the four major areas of study. Before this study, no one had measured the interfacial growth kinetics (how solid growth rate varies with solution temperature or concentration) for the salt hydrates proposed for energy storage. A crystal growth apparatus was designed and built in order to provide these data. The dependence of crystal growth rate V on undercooling ΔT was determined for $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$, $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$, and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. The dependence of growth velocity on undercooling for $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ was also measured, and these data are shown in Fig. 3.25. This study is providing basic interfacial growth data on energy storage materials that can be used directly to accurately model both the performance of direct-contact storage devices as well as contained systems.

Selection of Salt Solutions. An apparatus similar to the schematic shown in Fig. 3.24 was constructed to determine quantitatively the storage potential of the various salt hydrate candidates. The cylindrical plexi-glass tank held $1.25 \times 10^{-3} \text{ m}^3$ of salt melt with an additional $0.25 \times 10^{-3} \text{ m}^3$ reserved for coalescence of the immiscible fluid. Varsol was

Fig. 3.25. Crystal growth velocity vs undercooling ($K = ^\circ\text{C} + 273$).

pumped from a storage reservoir through an auxiliary heat exchanger and circulated through the salt solution to simulate heating or cooling. The heat flux was calculated as a function of time, and the total heat transferred between the Varsol and the PCM material is an integration of this flux over the duration of the cycle. Disodium phosphate, calcium chloride, sodium sulfate, sodium thiosulfate, sodium carbonate, and calcium nitrate were compared over an identical temperature cycle. Table 3.12 gives a comparison of average storage efficiency values for these salts. The value for this efficiency is calculated by dividing the amount of actual heat removed or stored in the PCM by the amount of energy that could have been removed or stored at equilibrium.

Table 3.12. Comparison of the average storage efficiency of various salt hydrates

Salt	Efficiency (%)
$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	76.9
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	62.4
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	51.2
$\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$	95.1

Sodium carbonate is not an efficient PCM because of poor crystal nucleation and inverse solubility in water. Calcium nitrate is not suitable, either, because of excessive carryover in Varsol. Because of their various crystallization temperatures, each of the other four PCMs might be suitable, depending on the final use application of the storage device. Most of the energy transition for disodium hydrogen phosphate occurs above 307 K; for calcium chloride, above 300 K; for sodium sulfate, above 300 K; and, for sodium thiosulfate, above 320 K. Thus, sodium sulfate and calcium chloride may be useful in heat pump or solar-assisted heat pump applications, whereas disodium hydrogen phosphate and sodium thiosulfate may be applicable to direct solar energy storage.

Selection of immiscible fluids. More than 160 potential immiscible fluids have been identified for potential use in the direct-contact storage system. However, high costs, toxicity, or high density eliminate the use of many fluids. Bench-scale tests show that high fluid viscosity (greater than 4 to 5 cP) could increase carryover of salt solution during cycling of the storage system. Properly placed and sized screens within the immiscible fluid may permit the use of fluids with viscosities as high as ~ 10 cP; thus, 12 fluids are being tested with disodium hydrogen phosphate as the PCM. These fluids are listed in Table 3.13.

Studies of heat transfer and system geometry. Heat transfer and system geometry effects were studied in a fourth phase of the research to provide design data for a prototype storage unit. A modular storage tank was constructed with a volume of $\sim 4.7 \times 10^{-3}$ to 14.3×10^{-3} m³ (depending on the desirable tank height), and the system operated similarly to the smaller unit used to select feasible salt solutions. Calcium chloride, disodium hydrogen phosphate, and sodium sulfate were tested in this apparatus. Average storage efficiencies of 68.2% for disodium hydrogen phosphate, 61.4% for calcium chloride, and 47.8% for sodium sulfate were measured using a 0.30-m column height. These values agree closely with those found in similar measurements from the smaller unit. Reducing the number of diffusers from four to one did not lower the value of the storage efficiency, and an increase of the column height from 0.30 to 0.50 m increased storage efficiency by 6 to 17%, depending on the salt used (see Table 3.14). Table 3.15 gives typical volumetric heat transfer rate data.

The remaining 12 potential immiscible fluids are to be tested for salt carryover. The growth kinetics of $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ are also being determined. The four studies have shown that the direct-contact latent-heat storage system is feasible and has excellent storage efficiencies. A 200×10^{-3} m³ prototype unit is under construction using the results of these studies. It will have six inlet diffusers for the immiscible fluid (comparable to the intermediate-scale unit using a single diffuser), and it will be 0.95 m high. The unit will be automatically controlled by a Data General Nova 1220 minicomputer system to cycle

Table 3.13. Feasible immiscible fluids

Fluid	Melting point (°C)	Boiling point (°C)	Flash point (°C)	Density (g/cm ³)	Viscosity (cP)	Solubility	Cost (\$/liter) ^a	Manufacturers
Butyl oleate	-27		180	0.865	8.2 @ 20°C	Insoluble	0.50	Ashland Chemical, CP Hall, Harwick
Di (2-ethyl hexyl) adipate		214 @ 5 mm	199	0.921-0.927	8.2 @ 38°C	Insoluble		Ashland Chemical, W. R. Grace and Company, Pfizer Chemical
Di (2-ethyl hexyl) azelate		237 @ 5 mm	227	0.917	10.0	Insoluble		Emery Industries, Pfizer Chemical
Di (n-hexyl) azelate		215 @ 5 mm	205	0.927 @ 20°C	7.8	Insoluble	1.81	CP Hall, Emery Industries, Pfizer Chemical
Diisobutyl adipate	-38	183 @ 14 mm	175	0.961	5-6 @ 20°C	Insoluble	1.61	CPS Chemical, CP Hall, W. R. Grace and Company
Dow-Corning Silicone Oil Q2-1132	-83	>350	232	0.946	18.9 @ 25°C	Insoluble	5.30	Dow-Corning
Exxon Marcol 72	-9		185	0.859	11.4 @ 38°C	Insoluble	0.32	Exxon
Isopropyl myristate (EMEREST 2314)	-5		152		6 (est) @ 38°C	Insoluble	2.27	Emery Industries
Methyl oleate (EMEREST 2801)	-16	228	177	0.879	5 (est) @ 38°C	Insoluble	1.14	Emery Industries
Therminol 44	Pour point -62 to -68	10% 337; 50% 390	207	0.919	8.08 @ 38°C		2.22	Monsanto
Therminol 60	Pour point -67.8	10% 288; 50% 394	154	0.998	4.89 @ 38°C		1.93	Monsanto
Transcal LT	-46	309 (IBP)	160	0.864 @ 18°C	6.91 @ 40°C			British Petroleum

^am³ = 999.973 liter.

Table 3.14. Effect of solution height on efficiency of salt systems^a

Cycle No.	Solution height (cm)	Superficial velocity (cm/sec)	Efficiency (%)	
			Cooling	Heating
Na ₂ HPO ₄ •12H ₂ O				
P1	30	0.10	74.4	61.0
P2	30	0.12	73.2	60.1
P3	30	0.15	74.3	66.1
P4	50	0.11	84.4	79.6
P5	50	0.13	76.9	73.1
CaCl ₂ •6H ₂ O				
C1	30	0.11	60.5	62.0
C2	30	0.15	58.9	64.3
C3	50	0.11	73.9	77.5
C4	50	0.15	71.4	71.9

^aDiffusers: 4.Table 3.15. Effect of superficial velocity on average heat transfer coefficient^a

Cycle No.	Storage material	Superficial velocity (cm/sec)	Heat transfer coefficient (W/liter=°C) ^b	
			Cooling	Heating
P1	Na ₂ HPO ₄ ·12H ₂ O	0.10	9.7	6.4
P2	Na ₂ HPO ₄ ·12H ₂ O	0.12	11.1	6.4
P3	Na ₂ HPO ₄ ·12H ₂ O	0.15	11.8	11.6
C1	CaCl ₂ ·6H ₂ O	0.11	8.8	7.8
C2	CaCl ₂ ·6H ₂ O	0.15	11.1	13.2
S1	Na ₂ SO ₄ ·10H ₂ O	0.11	8.5	7.9
S2	Na ₂ SO ₄ ·10H ₂ O	0.15	6.9	9.7
S3	Na ₂ SO ₄ ·10H ₂ O	0.19	9.8	10.7

^aSolution height: 30 cm; diffusers: 4.^bm³ = 999.973 liter.

over a prolonged period and yield long-term performance data. A minicomputer has already been programmed to provide on-line system monitoring and data reduction.

3.6.2 Life and stability testing of packaged low-cost energy storage materials (University of Delaware - Institute of Energy Conversion; G. R. Frysinger, principal investigator)

The objective of this project, which is contracted for the period Sept. 1, 1978, to Oct. 31, 1979, is to test the package integrity of the "CHUB" packaged materials and to experimentally verify the ability of the package to retain the moisture within the salt mixture. The life and stability of the packaged material will be verified by thermal cycle and performance measurement. The "CHUB" packages are prepared by DuPont for mechanical and temperature stability tests, and the immediate goal is a qualified "CHUB" for performance life testing. Precontract work indicates excellent weight retention by "CHUB" package laminates and the ability of the "CHUB" to meet handling and mechanical requirements. During future work, verification of weight retention and mechanical integrity will be determined with larger "CHUB" lots, and thermal cycling and performance testing will continue through the contract period.

3.6.3 The use of solid-state phase transitions for thermal energy storage (Villanova University; A. J. Leffler, principal investigator)

The objective of this project was to investigate new materials with high heats of transition in the temperature range up to 523 K and to briefly investigate the engineering problems involved in designing a heat exchanger. The project began with a survey of all classes of compounds that were potentially useful as phase-transition materials. Because the desirable phase transitions should occur at above-ambient temperatures, the melting points of the compounds to be studied were required to be above 473 K. In addition, since certain classes of compounds are at least potentially carcinogenic, these were omitted. The classes of compounds examined were benzene derivatives, naphthalene derivatives, anthracene derivatives, heterocyclic compounds, cyclohexane derivatives,

phosphazene derivatives, miscellaneous ring structure, adamantane derivatives, diamantane derivatives, oxaadamantane derivatives, azaadamantane derivatives, thiaadamantane derivatives, bicyclo derivatives, and camphor derivatives.

Based on the above survey, many compounds were obtained from commercial sources and tested for phase transitions using the Perkin-Elmer DSC-1 Differential Scanning Calorimeter. Approximately one in eight compounds tested showed a solid-state phase transition. Very small differences in structure cause the substances to behave totally differently; for example, while a certain structure containing an anhydride linkage shows a solid-state transition, the same structure containing an imide group does not. The difference in behavior appears to be quantitative rather than qualitative and is correlated with the relative heights of potential wells resulting from intermolecular interactions. If the wells have the proper height difference, a phase transition will result, but if the difference is too large, no phase transition occurs.

A synthesis program was undertaken to prepare compounds that have structures similar to the best types of compounds found in the testing work. This program led to the synthesis of a series of related derivatives that, in many cases, show phase transitions with energies similar to the original compounds. Table 3.16 lists those compounds showing solid-state phase transitions and the temperatures and energies of transition.

An engineering study was conducted to define the problems that would be encountered in constructing a heat exchanger using solid-state PCMs. The volume change at the phase change varies from 4 to 8% of the volume for the tested materials, and thermal conductivities were similar to those of most organic compounds. A hysteresis effect was measured in which the transition temperature was lowest during the cooling cycle, and the amount of hysteresis appears to be a function of the packing density of the pellets (i.e., well-packed pellets show a much smaller hysteresis effect). The PCM is also slightly volatile in a stream of hot air. Finally, there is an increase in size of the pellet with a concomitant increase in voids during the cycling process. The experimental data are listed in Table 3.17.

Table 3.16. Compounds showing solid-state phase transitions

Compound	Transition temperature (K)	Heat of transition (cal/g) ^a	Entropy of transition (cal/mole-K) ^b	Fusion temperature (K)	Heat of fusion (cal/g)	Entropy of fusion (cal/mole-K)
Trans-w,3-dicyano-5-norbornene	335.5	27.97	12.01	369.8	3.97	1.55
dl-Camphoric anhydride	375.2	25.15	12.19	498.5	8.05	2.94
Bicyclo(2,2,2)-oct-5-ene-2,3-dicarboxylic acid anhydride	383.3	22.89	10.63	420.5	4.15	1.76
5-Norbornene-2,3-dicarboxylic acid anhydride	365.5	22.59	10.13	432.25	3.65	1.38
d-Camphoric anhydride	405.3	22.79	10.24	498.8	7.64	2.79
d-Camphoric oxime	384.25	20.19	8.77	392.8	2.90	1.23
2,3-Dichloro-5-norbornene-2,3,-dicarboxylic acid anhydride	398.88	18.93	11.92	457.70d	4.09	2.24
2-Imidazolidone	344.0	9.07	2.27	394.3	14.20	3.10
Triethanolamine borate	469.3	5.60	1.87	499.4	10.79	3.39

^aJ/kg = 4.186×10^{-3} cal/g.^bJ/mole-K = 4.186 cal/mole-K.

Table 3.17. Thermal-physical properties of selected PCMs

Properties	dl-Camphoric anhydride	d-Camphoric anhydride	Triethanolamine borate	2-Imidazolidone
Density at 298 K, g/cm ^{3a}	1.11	1.16	1.36	1.37
Thermal expansion, 1/°C (volumetric coefficient) ^b				
Low-temperature phase	5.2×10^{-4}	3.3×10^{-4}	1.35×10^{-4}	1.33×10^{-4}
High-temperature phase	2.2×10^{-4}	2.2×10^{-4}		6.4×10^{-4}
Volume change of phase change, cm ³ /g ^a	0.060	0.046	>0.077	0.063
Volume change from 298 K through phase change, %	11	8.9	>13	9.2
Temperature of phase change, °C ^b				
Low to high	104	133	120-160?	66
High to low	81	124	120-160?	61
Thermal conductivity, cal/sec-cm-K ^c				
Low-temperature phase	3.6×10^{-4}	3.1×10^{-4}	6.1×10^{-4}	6.0×10^{-4}
High-temperature phase	2.2×10^{-4}	2.2×10^{-4}		3.4×10^{-4}
Heat capacity, cal/g-K ^d	0.341	0.341	0.378	0.414
Thermal diffusivity, cm ² /sec ^e	9.5×10^{-4}	7.8×10^{-4}	11.9×10^{-4}	11.7×10^{-4}

^akg/m³ = 10⁻⁹ g/cm³.^bK = °C + 273.^cJ/sec-m-K = 4.186 × 10⁻² cal/sec-cm-K.^dJ/kg-K = 4.136 × 10⁻³ cal/g-K.^em²/sec = 10⁻⁴ cm²/sec.

The major technical accomplishment of the study is the identification of a series of materials with solid-state phase transitions in the temperature range 335 to 400 K. The results of the engineering study indicate that a number of problems will have to be overcome for practical use of these substances in a heat exchanger. Two of these problems are volatilization of the material and physical weakening of the pellet during cycling. These problems may be overcome by placing the materials in containers.

3.6.4 Macroencapsulation of heat storage PCMs (Dow Chemical Company, Contract EY-76-C-05-5217)

Objectives of the project, which is contracted for the period Sept. 2, 1978, to Dec. 31, 1978, are to assess the technical and economic feasibility of encapsulated PCMs for storing heat in residential solar energy systems and to develop and evaluate such encapsulated PCMs. The project tasks are (1) materials selection, including a limited literature search, selection of candidate PCMs, and selection and characterization of encapsulating materials; (2) procurement of phase-change and encapsulating materials, encapsulation studies, and testing of the encapsulated materials; and (3) preliminary design and economic evaluation of a residence-size heat storage subsystem.

Table 3.18 lists the PCMs and encapsulants that were tested in a subscale thermal-storage unit. ASHRAE Standard 94-77, *Methods of Testing Thermal Storage Devices Based on Thermal Performance*, was used as a guide in the design of this thermal battery, and air was used as the heat transfer fluid. In addition to the four storage units of Table 3.18, a double-zone heat battery containing $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ encapsulated in steel aerosol cans and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} + \text{NH}_4\text{NO}_3$ eutectic encapsulated in R-2 re-tort film pouches was assembled and tested. The method used for calculating heat storage capacities was modified from that recommended in ASHRAE Standard 94-77 to give more realistic values. Using the latent heat of fusion of the PCM, its solid and liquid heat capacities, and the sensible storage capacity of the storage unit structure, theoretical heat storage capacities were calculated for each of the five thermal batteries.

Table 3.18. Encapsulated PCMs tested

PCM	Melting point ^a (°C)	ΔH (cal/g) ^b	Cost (¢/lb) ^c	ΔH , cost ^d (kcal/¢)	Encapsulant
Mg(NO ₃) ₂ ·6H ₂ O	89	36	15 (est.)	1.09	Drawn steel aerosol can
Urea + NH ₄ Br	76	36	30	0.54	Polyp:propylene bottle
Mg(NO ₃) ₂ ·6H ₂ O + NH ₄ NO ₃	52	30	10	1.36	R-2 retort film pouch
CaCl ₂ ·6H ₂ O	27	46	5	4.17	High-density polyethylene bottle

$$^a K = ^\circ C + 273.$$

$$^b J/kg = 4.186 \times 10^{-3} \text{ cal/g.}$$

$$^c \text{ ¢/kg} = (\text{¢/lb})/2.20\text{ ¢.}$$

$$^d J/\text{¢} = 4.186 \times 10^3 \text{ kcal/¢.}$$

Figures 3.26 and 3.27 give a comparison of charge and discharge data for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$.

Table 3.19 compares the results obtained with the different thermal batteries. After correction for heat losses, each test configuration stored and discharged a high percentage of the theoretical storage capacity. An exception to this is the urea/ NH_4Br battery, which was inferior

Fig. 3.26. Capacity (energy) vs air flow rate for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ in HDPE bottles ($\text{m}^3/\text{sec} = 0.589 \text{ CFM}$).

Fig. 3.27. Percentage of capacity (energy) vs air flow rate for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ in HDPE bottles.

Table 3.19. Storage test results for thermal batteries

PCM	PCM weight (kg)	Air flow (ft ³ /min) ^a	Capacity		Design rate, q _c , q _D (MJ/hr)
			MJ	Theory (%)	
CaCl ₂ •6H ₂ O in HDPE bottles, CC/DC	97/97	46/46	24.4/22.7	101/91	0.73/0.84
Mg(NO ₃) ₂ •6H ₂ O in aerosol cans, CC/DC	100/100	61/61	21.7/22.1	98/97	1.09/0.62
Mg(NO ₃) ₂ •6H ₂ O + NH ₄ NO ₃ in R-2 film pouches, CC/DC	86/86	59/59	17.1/17.7	98/99	0.91/1.01
Urea/NH ₄ Br in polypropylene bottles, CC/DC	93/93	55/54	18.7/14.6	93/72	0.82/0.76
Double zone, ^b CC/DC	81,29/81,29	91/90	28.6/27.1	90/85	1.80/1.04

^a m³/sec = 4.72 × 10⁻⁴ ft³/min.

^b CaCl₂•6H₂O in aerosol cans (81 kg) and Mg(NO₃)₂•6H₂O + NH₄NO₃ eutectic in R-2 retort film pouches (29 kg).

to the others in the number of heat transfer units. This PCM also showed partial segregation of the eutectic at the end of the test.

On the basis of our test results and further computer modeling of storage subsystems, six solar space heating concepts were evaluated for performance and economics in a northern midwest climate. Table 3.20 summarizes calculated projected capital and operating costs of these six concepts, along with comparable values for traditional heating schemes. The solar fraction of the heating load was estimated from available system modeling programs. Although these projections have considerable uncertainty, the following conclusions can be drawn: (1) oil- and gas-heated homes are less expensive to build and operate than solar homes in this climate, if all costs are considered; (2) solar homes with conservatory collectors are competitive with resistance-electric- or heat-pump-equipped houses; and (3) solar homes with flat plate collectors are considerably more expensive to build and operate.

The forced-air heating system with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ storage battery and conservatory collector was selected for system design work and solar house planning. The chosen plan incorporates solar collection into the living space, as in a passive system, yet maintains the comfort level better than active solar designs. Collected heat is transferred via an air stream to storage and on to the rest of the heated space. The vertical glazing system is covered with movable insulation to minimize heat loss at night and during cloudy periods. Insulation may also be used to control overheating when the rate of collection exceeds the storage rate and the load.

Figure 3.28 shows the selected storage battery design. High-density polyethylene pipe was chosen as encapsulant (1) to withstand the pressure variations caused by freeze-thaw cycling, (2) to offer a positive moisture vapor barrier to assure compositional stability of the PCM, and (3) to be compatible with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$. The storage battery contains 2368 kg of PCM, storing 3.80×10^8 J with a design heat exchange rate of 2.67×10^3 J/sec. The heating load was assumed to be 86 J/sec-K, and the collector area is assumed to be 60.4 m².

Figure 3.29 is a floor plan of the solar home. The house is a bi-level design, built ideally on a lot sloping from north to south. The

Table 3.20. Economics of various home heating systems

Heating system	Capital cost (\$)	Fraction of heating load solar	Utility costs [(\$/year) A]	Yearly mortgage, insurance, and maintenance [(\$/year) B]	Operating cost [(\$/year) A + B]
A. Passive solar $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ storage conservatory collector	7,606	0.66	479	939	1,418
B. Forced-air solar $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ storage conservatory collector	5,962	0.50	704	859	1,563
C. Hybrid solar $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ storage conservatory collector					
D. Forced-air solar $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ storage with parallel air-to-air heat pump conservatory collector	8,762	0.50	493	1,081	1,574
E. Forced-air solar $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ + NH_4NO_3 eutectic storage flat plate collectors	11,052	0.46	760	1,364	2,124
F. Forced-air solar double-zone storage with night setback flat plate collectors	10,819	0.54	583	1,335	1,918
G. Forced-air solar rock storage flat plate collectors	9,980	0.51	690	1,232	1,922
H. Air-to-air heat pump	4,200	0.0	986	518	1,504
I. Electric resistance heat	2,400	0.0	1,408	296	1,704
J. Oil-fired forced air	3,000	0.0	540	370	910
K. Natural gas	3,000	0.0	360	370	730

Fig. 3.28. Full-scale storage unit of calcium chloride hexahydrate encapsulated in HDPE cylinders (1 m = 3.28 ft = 39.37 in.).

ORNL-DWG 79-4955(PART A) ETD

UPPER FLOOR PLAN

1/8 IN = 1 FT

NORTH

LOWER FLOOR PLAN

1/8 IN = 1 FT

AREAS :

UPPER FLOOR PLAN :	850	
LOWER FLOOR PLAN :	1000	
	1850	LIVING AREA
	250	CARPORT
TOTAL :	2100	SQ. FT.

Fig. 3.29. Floor plan of a solar home (1 m = 3.28 ft = 39.37 in.).
Part A.

PROPOSED SOLAR HOME FOR
DOW CHEMICAL COMPANY
MIDLAND, MICHIGAN

Francis E. Warner, Architect
Midland, Michigan

Nov 1978

Fig. 3.29. Part B.

main entrance is at a stair landing midway between the first and second floors. The living room, which serves as the second stage of the collector, has a cathedral ceiling design. This attractive architectural feature also adds height to the hot-air collection duct to allow additional thermal stratification to the conservatory. The hot-air collection duct is used as the cold-air return for the heating system, and the hot-air ducts also act as the conservatory air supply for heat collection. An outside vent is used to avoid overheating early and late in the heating season. The entire south wall of the house is glazed vertically for solar collection, providing direct solar gain to the living area. This plan has the economic advantage of incorporating the collector glazing in the southern wall, coupled with the thermodynamic advantage of low-temperature collection. The energy storage material is conveniently located in the utility room, minimizing the architectural constraints of the system.

All tasks have been completed on this program, and no further efforts are planned under the present contract.

3.6.5 Thermal energy storage subsystem for solar heating and cooling applications (General Electric Corporate Research and Development, Contract EM-78-C-05-5759; C. S. Herrick, principal investigator)

The overall objective of this program, which is contracted for the period August 1978 to October 1980, is to develop the technology and engineering data required to implement rolling cylinder thermal energy storage in solar energy systems. The purpose of this contract is to design and build a large ($\sim 2.11 \times 10^8$ J) prototype in an instrumented calorimeter. During the first year of the contract, the thermal characteristics of the system will be carefully defined and designs developed for the prototype rolling cylinder device and its associated test equipment. During the second year of the contract, the prototype and test equipment will be constructed and preliminary checkout accomplished; a follow-on contract will be proposed the third year, during which the prototype will be tested for its performance characteristics.

A rolling cylinder thermal storage system using the latent heat of fusion of Glauber's salt would be considerably smaller and lighter in

weight than a sensible heat storage system using water or rocks and is essentially isothermal. A water system operated over a temperature range of 11 K could store 3.58 J/m^3 , and a rock bed system could store $\sim 2.09 \times 10^4 \text{ J/m}^3$; in contrast, a Glauber's salt system could store $2.99 \times 10^5 \text{ J/m}^3$. Thermal energy storage could be used with solar collectors, heat pumps, or air conditioners to reduce fuel and electrical bills and provide load leveling and fuel energy conservation.

Many of the problems with thermal energy storage systems using the latent heat of fusion of salts are solved by the rolling cylinder concept. A cylindrical container lying on its side, rotating slowly around its cylindrical axis, provides just enough stirring action to keep the internal temperature uniform and very close to the wall temperature. Under these conditions, crystallization occurs on nuclei in the liquid and not on the cylinder wall. The usual layer of solid does not build up on the cylinder wall, so heat transfer rates remain high as crystallization proceeds. Over 200 complete freeze-thaw cycles have been demonstrated prior to this contract on a laboratory-scale rolling cylinder charged with Glauber's salt. Figure 3.30 shows a schematic of the rolling cylinder thermal storage device. A nucleator that reliably initiates crystallization without significant supercooling has been developed.

Fig. 3.30. Rolling cylinder thermal energy store.

Glauber's salt (sodium sulfate decahydrate) has been used to illustrate the capabilities of the rolling cylinder apparatus. It was chosen because of its low cost and high latent heat of fusion; however, the rolling cylinder concept is broadly applicable to a wide range of materials.

This contract began on August 1, 1978. Work has begun on several tasks, but none were sufficiently close to completion by September 30, 1978, to warrant reporting the results. However, during the first few months of this contract, the internal heat transfer behavior of a rolling cylinder phase-change heat storage device will be studied analytically and experimentally. A design concept will be chosen based on these studies and on solar heating systems requirements. A detailed design of a prototype rolling cylinder thermal storage system will be prepared at the end of the first contract year. During the second year, the prototype will be built and instrumented and the mechanical and electrical operation of the prototype and its test equipment will be checked. Testing of the prototype, including freeze-thaw cycling and rate calorimetry, will be proposed as a third year follow-on to the present contract.

3.7 Short-Term Storage of Solar Energy for Cooling

The use of solar energy for cooling requires concentrating collectors in order to achieve the temperatures needed for absorption air conditioning cycles. The implementation of such systems requires, in turn, that these collectors be priced so that the total system costs are competitive with cooling alternatives. The thermal storage component of this system will be identical (except for the storage PCM) with those discussed in Sect. 3.6.

3.8 Systems Studies: Development of Intermediate Temperature Thermal Storage System (University of Delaware - Department of Mechanical and Aerospace Engineering; J. R. Moszynski, principal investigator)

The technology development efforts described in Sects. 3.1 through 3.7 are supported by studies considering the merit of thermal energy storage in conservation, the commercial feasibility (acceptance and economic viability) of TES units, and the identification and scoping of new areas for applying TES. A major outcome of these efforts (such as that currently funded and described below) is guidance for future technology development.

The objective of this research, which is contracted for the period April 1978 through March 1981, is to develop thermal storage systems in the temperature range 373 to 573 K. This range is important for solar-powered absorption and adsorption cooling as well as for some Rankine cycle systems. Suitable storage materials will be identified and their thermophysical properties pertinent to energy storage will be measured. The physical properties of the storage materials may be investigated in detail together with their compatibility with prospective containment schemes. A scale model of a storage system ultimately may be constructed and tested. Some storage systems considered under the present contract were (1) evaporating liquids, (2) salt hydrates, (3) eutectic mixtures, and (4) melting substances.

As a result of discussions with selected energy-storage-system developers, the following temperature ranges were selected for investigation: 383 to 403, 423 to 443, and ~573 K. Known substances were evaluated from the view point of transition temperature, associated enthalpy change, cost, and potential safety hazards. Preliminary selection criteria included (1) a cost limit of \$2/1000 kJ of storage capacity, (2) nonexplosiveness, and (3) nontoxicity of the storage material or its products of combustion or decomposition. A literature search yielded a limited group of candidate materials, satisfying the arbitrary cost and safety criteria. Large numbers of organic substances apparently are available in each temperature range of interest, and with very few exceptions, these organic substances pose problems of stability that would require substantial

experimental evaluation efforts. For this reason, they were excluded from consideration under the present contract.

DSC and DTA instruments cannot handle larger samples routinely; therefore, a special calorimeter capable of accommodating a 0.2- to 0.1-kg sample was designed and built. In the temperature range of interest (373 to 573 K), the transition temperature is determined with a precision of ± 0.1 K and the energy of transition with a precision of $\pm 5\%$. A second, less-precise instrument was built for multiple cycling tests in which the behavior of the transition temperature is of prime interest. A third cell was designed and built for the measurement of the thermal conductivity of the storage material, both in the solid and liquid states. This cell will be used only to determine the properties of the selected storage materials.

Substances whose latent heat of vaporization could be used for storage were surveyed. In the temperature range of interest, only two substances appear to be usable: water and ethylene glycol. The results of calculations described below indicate that the containment problems associated with either large volume changes or with high pressures make this storage mode unattractive.

The most promising storage materials identified to date are listed below.

1. Sodium-aluminum chloride (NaAlCl_4), which melts at 432 K and solidifies at 428 K, with a small amount of supercooling. Repeated thermal cycling (30 complete melting/solidification cycles) shows no detectable composition changes; in particular, there is no detectable evolution of chlorine.
2. Zinc chloride (ZnCl_2), which melts at 559 K. Repeated thermal cycling of ZnCl_2 shows no detectable physical change and no decomposition.
3. A eutectic mixture of NaOH and Na_2CO_3 , which melts at 556 K with no detectable physical change after 20 thermal cycles.
4. A eutectic mixture of FeCl_3 and NaCl , which melts at 425 K and solidifies at 415 K, with some reversible decomposition into Fe_2O_3 and HCl by hydrolysis with atmospheric moisture. Some chlorine may evolve as a decomposition product.

The following storage materials are less promising:

1. $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ melts at 341 K and dehydrates to $\text{FeSO}_4 \cdot \text{H}_2\text{O}$ at 363 K. The heptahydrate is not reformed upon cooling, but ferric sulfate and ferric oxide form with an evolution of SO_2 and SO_3 . This decomposition occurs even in an inert atmosphere where iron is present in the container walls.
2. $\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$ dehydrates to a dihydrate at 448 K but does not reform upon cooling.
3. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ dehydrates to $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ at 401 K and to CaSO_4 at 436 K. The CaSO_4 does not rehydrate easily upon cooling.

The results of this study lead to the conclusion that storage in hydrates at temperatures much above 373 K does not appear to be very promising. If water is to be maintained at high pressure, containment presents problems. If water is to be retained at atmospheric pressure, the large necessary volumes make latent heat storage in water preferable. Tests with urea have been similarly unsuccessful. After some 30 cycles at approximately atmospheric pressure, the material seems to have decomposed completely, leaving a white powder (possibly cyanuric acid). Under higher confining pressures, the decomposition was slower but still evident after some 10 cycles. KH_2PO_4 has an apparent variable heat of fusion that depends very strongly on the heating rate. The formation of a glassy substance instead of the original crystals depends on the cooling rate.

The storage potentials in water vapor and glycol were calculated assuming constant volume storage and constant pressure (isothermal) storage. In each case, these results were compared with storage potentials of rock, sand, brick, etc. Except for isothermal storage in water at 523 K or above with comparable rock-type storage limited to a 20 K temperature drop, a given volume of water or glycol stored substantially less energy than an equal volume of brick, sand, rock, or similar material.

It is proposed to continue the cycling tests of the four materials listed above, with special attention given their compatibility with prospective containment materials. Calorimetric studies will precisely determine the heat of fusion and the specific heats in the liquid and

solid phase of each compound; the density and the thermal conductivity of the liquid and solid will also be measured. Efforts will be made to identify suitable materials for use at higher temperatures (up to 773 K). A more extensive investigation of the safety aspects of the candidate materials will also be undertaken to determine if the preliminary safety criteria for industrial applications can be less severe than those for domestic applications. A scale model of a storage system will be constructed and tested to evaluate the expected performance of one or more of the materials ultimately selected.

3.9 Support R&D

The LTTEs program is engaged in limited R&D activities of a general nature in support of the technology development projects. Currently, most of this effort is directed to the properties of PCMs as chemical compounds or as heat carriers.

3.9.1 Studies of a salt hydrate heat storage system (Desert Research Institute; J. Hallett, principal investigator)

The objectives of this project, which was contracted for the period July 1, 1978, to Aug. 31, 1978, are to develop the physical criteria for crystal growth and secondary crystal production for salt hydrates and to design and operate a pilot system based on these criteria and utilizing continuous crystallization and sedimentation to give an essentially unencumbered heat transfer surface.

Crystallization of a one- and two-component system for thermal storage of salt hydrates by fusion heat has been investigated for sodium sulfate ($10 \text{ H}_2\text{O}$), sodium thiosulfate ($5 \text{ H}_2\text{O}$), and sodium acetate ($3 \text{ H}_2\text{O}$). In the one-component system, small crystals are continuously added to the salt solution. These crystals continue to grow in size and settle out. The objective of this procedure is to keep heat transfer surfaces crystal-free. The two-component system utilized kerosene as the heat transfer fluid, and it was circulated as millimeter-size drops rising by buoyancy through the salt solution. Under appropriate operating conditions, secondary crystals formed to replace those which grew and sedimented in both of these systems. The one-component system is unreliable because crystals occasionally nucleate and grow on the heat transfer surfaces during cooling. The two-component system functioned when crystal concentration was low enough (1 cm^{-3}) to permit sufficient growth for sedimentation; otherwise crystals remained in suspension throughout the cycle. The operating characteristics and thermal efficiency of these systems was investigated for two pilot units, and optimum operating conditions for constant power output are delineated.

Studies were made of solution nucleation, secondary crystal production, linear crystal growth velocity, habit and solution viscosity, refractive index, and density within the operating range of concentrations to be used in a storage system for both supersaturated and undersaturated solutions.

3.9.2 Identification and evaluation of phase-change materials for use as storage media (Oak Ridge National Laboratory; S. Cantor, principal investigator)

The objectives of this project, which was contracted for the period October 1977 to September 1978, are (1) to ascertain thermal performance of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ and other incongruently melting salt hydrates by calorimetric investigation of melting and freezing and (2) to select compounds and mixtures suitable for isothermal heat storage within the range 363 to 523 K (selection is to be based on laboratory evaluation as well as on economic and technical screening criteria).

Laboratory evaluation and measurements have been completed for the following groups:

Salt hydrates. By using differential scanning calorimetry, differences between ΔH of fusion and ΔH of solidification were determined for six salt hydrates. For $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ (Glauber's salt), a ΔH of solidification at or near the peritectic temperature is never greater than 60% of the ΔH of fusion; by cooling to lower temperatures, a second phase transition occurs at the temperature corresponding to the eutectic melting point of mixtures of ice and Glauber's salt. Sodium pyrophosphate decahydrate, $\text{Na}_4\text{P}_2\text{O}_7 \cdot 10\text{H}_2\text{O}$, a higher-temperature analog of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, exhibited less discrepancy between ΔH of fusion and of solidification; its higher transition temperature appears to permit a more rapid solidification reaction than is the case for $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. For $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, a congruently melting compound, and for $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, which melts almost congruently, the magnitude of ΔH of crystallization equaled ΔH of fusion. The $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ and $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ exhibited marked disparities between these two enthalpies. For incongruently melting hydrates in static systems, solidification can be viewed as a two-step process: crystallization from liquid solution and reaction of the lower hydrate (or anhydrate)

with the solution. Where ΔH of solidification appears to be less in magnitude than ΔH of fusion, the difference can be attributed to slower reaction rate between solution and the lower hydrate. For Glauber's salt, possible reasons for the slow reaction rate are inferred from an estimated diffusion constant and from the retrograde solubility of Na_2SO_4 .

PCMs for the range 363 to 523 K. Using economic as well as technical screening criteria, three compounds (urea, adipic acid, phthalic anhydride) were selected for evaluation by thermal cycling studies; at the melting point, only phthalic anhydride appeared to be thermally stable. Eutectic mixtures of urea with inorganic salts and with biuret were identified; the urea-biuret mixture was examined experimentally. Polyethylene and (isotactic) polypropylene in form-stable configurations may be potentially very useful storage materials. The screening criteria also narrowed the list of inorganic material candidates down to $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ and equimolar NaNO_3 - KNO_3 , which exhibit generally favorable thermal behavior.

3.9.3 Mathematical modeling of LHTES processes (Oak Ridge National Laboratory; A. Solomon, principal investigator)

The objectives of this project, which was contracted for the period October 1977 to September 1978, are to develop a computer model of the moving boundary phase-change mechanism in the context of a latent heat TES process and to provide analytical support of the LTTES program.

During FY-1978, the following results were obtained:

Computer modeling. The weak solution Stefan-problem computer program¹ has been applied to a number of test problems and debugged. Changes made have included a boundary condition discretization guaranteeing energy conservation in the system. Documentation and publication are awaiting the results of experiments being carried out for testing and calibration of the model.

Analytical modeling melting time of a simple body.² The formula

$$t_f = \frac{L^2}{2\alpha(1 + \omega)St} [1 + (0.25 + 0.17\omega^{0.7})St]$$

for the total melting time of a PCM body subject to constant boundary

temperature in any geometry was obtained. Comparison with numerical simulations and other data indicates a small relative error over the range of LHTES applications.

Numerical simulation of a PCM wall.^{3,4} The thermal behavior of a PCM wall subject to an external periodic input was simulated. It was found that the least inner surface temperature variation is obtained when the phase boundary is maintained within the wall. Conditions guaranteeing this were found, leading to trade-off criteria between objectives of storage and comfort.

Analytical rules of thumb.⁵ Simple closed-form approximations to the solution of the Stefan problem in the two-phase case were obtained for a semi-infinite slab. These can be calculated on a pocket calculator of the HP-45 class and have a small relative error over the range of LHTES applications.

Notation

c	PCM specific heat, cal/g-°C
H	PCM latent heat, cal/g
L	Slab length, cylinder, cm
t_f	Total melt time, sec
T_w	Imposed boundary temperature, °C
T_{cr}	Melting temperature, °C
ΔT	$T_w - T_{cr}$
St	$c\Delta T/H$
α	Thermal diffusivity, cm ² /sec
ω	Geometrical parameter (0 for slab, 1 for cylinder, 2 for sphere)

3.9.4 Cyclical storage and withdrawal of chilled water in aquifers beneath Kennedy International Airport, New York City (Department of the Interior, Geological Survey - Water Resources Division; J. Soren, principal investigator)

The objectives of the U.S. Geological Survey's participation in the project described below (which is contracted for the period June 21, 1978, to Sept. 30, 1979) are (1) the preliminary determination of the hydraulic

feasibility and consequences of large-scale withdrawal/recharge in a limited geographic area, in a system believed to be tightly confined, and (2) a description of the geology and hydrogeology of the proposed site and surrounding areas.

Under a separate contract with New York State Energy Research and Development Authority, Desert Reclamation Industries, Plainfield, New Jersey, is studying the feasibility of storing chilled groundwater beneath Kennedy International Airport. During the winter, groundwater will be withdrawn, chilled, and recharged; during the summer, the chilled water will be removed, used for cooling, and then recharged at approximately normal temperature. A pumping (and simultaneous recharge) rate of $2.90 \text{ m}^3/\text{sec}$ is currently estimated to be required for the airport's cooling needs. The feasibility of the project will largely be determined by the geometry and hydraulic parameters and conditions of the underlying aquifers and confining beds.

Kennedy International Airport has been considered a likely site for the cyclical storage of chilled water because of the suspected presence of the Jameco aquifer. The Jameco, a highly permeable fluvial sand and gravel aquifer, is believed to fill the ancestral Hudson River valley. In the absence of on-site data, the course of the buried valley was inferred by means of a study of the regional geology. Preliminary maps of the thickness and extent of the Jameco aquifer and the overlying Gardiners Clay were prepared. Based on these maps, four test drilling sites on the airport were chosen. The Geological Survey will collect and interpret geologic and hydrologic data from the four test wells. Based on these data, geologic and hydrologic maps of the airport will be prepared for use by project managers in determining the feasibility of the project.

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