27
6/4/79

MASTER

**Low-Temperature Thermal
Energy Storage Program
Progress Report for Period
October 1978-March 1979**

D. M. Eissenberg
H. W. Hoffman

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

~~ALL~~ DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.50; Microfiche \$3.00

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, contractors, subcontractors, or their employees, makes any warranty, express or implied, nor assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, nor represents that its use by such third party would not infringe privately owned rights.

Contract No. W-7405-eng-26

Engineering Technology Division

LOW-TEMPERATURE THERMAL ENERGY STORAGE PROGRAM
PROGRESS REPORT FOR PERIOD
OCTOBER 1978 - MARCH 1979

D. M. Eissenberg H. W. Hoffman

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does represent a final report.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

	<u>Page</u>
ABSTRACT	v
1. INTRODUCTION	1
2. SEASONAL STORAGE	3
Objective and Scope.....	3
Background	3
Status of Projects	4
Hot-Water Storage (Auburn University)	4
Cold-Water Storage (Texas A&M University)	6
Cold-Water Storage (JFK Airport Project)	6
Hot-Water Storage (Bellingham Project)	8
Aquifer Storage Value (GE-TEMPO)	8
Mathematical Modeling (LBL)	9
Aquifer Availability (TVA)	10
Environmental Impact (ORNL)	10
Aquifer Storage Economics (ORNL)	10
References	12
3. SHORT-TERM/DIURNAL STORAGE	13
Objective and Scope	13
Background	14
Status of Projects	16
Rolling Cylinder TES System (GE)	16
Chub TES System (IEC)	17
Intermediate Temperature TES System (University of Delaware)	18

	<u>Page</u>
Direct Contact TES System (Clemson University).....	19
Polyethylene TES System (University of Dayton)	21
Mathematical Modeling (ORNL)	21
Physical Modeling (ORNL)	24
Thermal Cycling Facility (ORNL)	25
References	26
4. STORAGE FOR INDUSTRIAL HEAT REUSE	27
Objective and Scope.....	27
Background.....	27
Status of Projects	28
Bellingham Project	28
H. J. Heinz Project	30

ABSTRACT

Use of low-temperature heat can result in significant conservation in building heating and cooling through replacing oil and gas with energy from alternate sources such as direct solar, environmental chill, waste heat, and off-peak electricity. Developing technologies for storing this heat for subsequent consumption is the responsibility of the ORNL Low-Temperature Thermal Energy Storage (LTTES) Program. The effort is focussed in three thrust areas: seasonal storage of hot/cold water principally in aquifers, short-term/diurnal storage for space conditioning principally in phase-change materials, and short-term storage of industrial waste heat. The first of these is receiving primary emphasis. The objective and status of projects in each of these areas is reviewed.

1. INTRODUCTION

D. M. Eissenberg

The use of low-temperature (less than 250°C) thermal energy storage can result in significant conservation by making technically and economically feasible the increased substitution of natural energy sources (solar, winter chill), waste heat (utility, industrial), and off-peak electricity (generated by coal and nuclear) for oil and gas in such applications as residential or commercial building heating/cooling and industrial or agricultural process heat. The responsibility for developing this technology has been assigned by DOE - Division of Energy Storage Systems (STOR) to the ORNL Low-Temperature Thermal Energy Storage (LTTES) Program. Responsibilities include developing long-range and annual implementation plans, subcontracting and monitoring concept development efforts, and carrying out supporting analysis and research (inhouse or by subcontract). The LTTES effort is one of several sponsored by DOE-STOR to develop thermal storage based on sensible heat, on latent heat of phase change, and on reversible thermochemical reactions.

The LTTES Program during the reporting period October 1978 to March 1979 has focussed on three elements or thrust areas. The primary element has been seasonal storage of waste heat or winter cold utilizing aquifers. Other elements with work in progress are short-term/diurnal storage of heat or cold for residential and commercial space conditioning and short-term storage of industrial

waste heat. In each case, the work is a continuation or extension of tasks carried out in prior reporting periods.

Emphasis during the past six months was directed towards aquifer technology development and seasonal storage economic analysis in anticipation of a greatly expanded effort in this thrust area. Thus, during the latter part of the period, DOE-STOR initiated a new program, the Aquifer Thermal Energy Storage (ATES) Program, aimed at designing and constructing multiple demonstrations of aquifer thermal storage. Battelle Pacific Northwest Laboratories was designated lead laboratory for that program, which will include the supporting aquifer technology development now being carried out under the LTTES Program. Accordingly, that thrust of the LTTES Program is being phased out.

Coincidental with the phase-out of the aquifer storage element, DOE-STOR has requested ORNL to plan a greatly expanded effort in the area of short-term/diurnal thermal storage for residential/commercial building heating and cooling. Although not appearing in the discussions of the program that follow, planning for that expansion was active in this period.

2. SEASONAL STORAGE

G. D. Brunton, E. C. Fox

Objective and Scope

Seasonal storage investigates the technology and applicability of cyclical annual storage of industrial waste heat, environmental chill, utility cogenerated heat, and solar heat in geological structures (principally aquifers) for such uses as district heating and cooling.

Background

The seasonal storage component of thermal energy storage technology development evolved from planning efforts initiated by the Energy Research and Development Administration (ERDA) early in its existence. The responsibility for managing seasonal storage projects was subsequently assigned to the ORNL Low-Temperature Thermal Energy Storage (LTTEs) Program by the Division of Energy Storage Systems. Initial projects in this category included the field study on aquifer storage by Auburn University (originally funded by the U.S. Geological Survey) and two projects (Bellingham, and J. F. Kennedy (NY) Airport) funded under an ERDA-PRDA (Program Research and Development Announcement) on conservation opportunities associated with industrial waste heat recovery and reuse. Over the past several years, aquifer seasonal storage activity was expanded to include a field study by Texas A&M University, an opportunities survey by the Tennessee Valley

Authority (TVA), and limited inhouse examination of environmental and cost-benefit issues. In addition, a study of the feasibility of earth storage for solar energy was completed by George Washington University.

Seasonal storage is being studied in Sweden, Belgium, Japan, France, and West Germany; to date, these studies have been limited to small-scale field experiments and mathematical modeling.

Status of Projects

Hot-Water Storage (Auburn University)

Auburn University is conducting a hot-water storage field test in a Mobile River flood-plain aquifer north of Mobile, Alabama, to determine the storage efficiency of an aquifer in-situ.^{1,2} The results will also be used to test mathematical models for predicting aquifer performance. The scope of the experiment covers two or three cycles of injection of water heated to 55°C into a shallow aquifer with subsequent recovery of the water after a storage period of six to eight weeks.

This project was jointly funded in 1975 by ERDA and the U.S. Geological Survey. The experiment was sited near the Barry Steam Plant of the Alabama Power Company north of Mobile, Alabama, to take advantage of a source of warm water from the condenser/cooling-water discharge canal. Plugging problems in the injection well were ascribed to unfilterable particulate material in the canal water; eventually, excessively high injection pressures ruined the injection

well. The results of this experiment were published by Warman, Molz, and Jones (June 1977).^{1,2}

Subsequently, the injection/storage well was reconstructed; and the experiment was redesigned to use water extracted from a well drilled into a sand-gravel aquifer 25-m to 34-m subsurface. The storage aquifer is 40-m to 61-m subsurface. This water was heated in an oil-fired boiler from ambient (20°C) to 55°C and injected into the storage aquifer. Ultimately, 54784 m³ of water were pumped into the storage aquifer over a period of 6 weeks. Clogging of the formation surrounding the injection well reduced the injection rate from the planned 200 gal/min (757 liters/min) to as low as 100 gal/min (378 liters/min). Injection was continuous, except for short stops due to power failures. During the injection period, and throughout the entire experiment, ground water temperatures were recorded at six depths in each of ten observation wells; and hydraulic heads were recorded in five observation wells. The observation wells used to measure temperatures were backfilled with sand to prevent significant thermal convection.

After a 51-day storage period, during which time there was only a small amount of regional ground water drift, pumping of water from the storage aquifer began at a nearly constant rate of 250 gal/min (946 liters/m). The temperature of the recovered water started at 55°C and diminished at an average rate of 0.5 degree per day. Very little heat was lost from the storage formation through the confining layers. Hydrodynamic thermal dispersion within the storage aquifer was probably the most important dissipation process, though additional mixing

due to clogging and unclogging of the formation could have been an important factor also. On September 5, 1978, recovery ceased after a total of 55,345 m³ of water had been withdrawn. By this time, the water temperature had dropped to 33°C (13° above ambient); and 65 percent of the injected thermal energy had been recovered.

A second storage/withdrawal cycle has now been completed, but the results have not been completely analyzed to date.

Cold-Water Storage (Texas A&M University)

The Agricultural Engineering Department, Texas A&M University, is conducting a field experiment at College Station, Texas, to test the efficiency of storing winter-chilled water in an aquifer in the Brazos River flood plain. The scope of the experiment covers three cycles of injection and withdrawal each during the winters of 1978, 1979, and 1980.

By the end of March 1979, approximately 8.5×10^6 gals of water with an average temperature of 50°F had been injected in the first cycle. This water will be stored for the first storage cycle.

Cold-Water Storage (JFK Airport Project)

Desert Reclamation Industries (DRI) is evaluating the technical and economic feasibility of storing winter-chilled water in the aquifers underlying J.F. Kennedy (NY) Airport for subsequent reuse in summer air conditioning of the airport terminal buildings. This effort developed from the 1977 ERDA-PRDA on industrial waste heat.

Based on limited data on the geology of the aquifers, the DRI evaluation of the storage potential and economics of chilled water storage and use at the airport was optimistic.

New York State Energy Research and Development Authority (NY-ERDA) cofunded with ORNL the drilling by DRI of four boreholes at the JFK Airport to determine the geology and distribution of the underlying aquifers. These holes were cored and sampled to evaluate the integrity and permeability of the Gardner Clay aquitard and to estimate the hydrological properties of the Jameco-Magothy aquifers. The results of these tests (separately evaluated by the U.S. Geological Survey, Water Resources Branch) indicate that aquifers of adequate capacity and transmissibility for chilled water storage exist under the airport site. The problem of possible subsidence of the ground as a result of the cyclic pumping pressures developed in the aquifer and aquitard was not resolved; it remains an item of major concern to the Port Authority of New York and New Jersey (PA-NY/NJ), operators of the airport.

An independent economic analysis of aquifer storage at the airport by ORNL staff, Engineering Technology Division, indicates that DRI underestimated many of the costs (e.g., piping and pumping) critical to economic success of the project. Further, without the active involvement of the PA-NY/NJ in the project to the extent of cost sharing and accepting management responsibility, it is unlikely that the project can be advanced.

Hot-Water Storage (Bellingham Project)

A study of the recovery and reuse of waste heat from the Intalco Aluminum plant in Bellingham, WA, was funded under the industrial ERDA-PRDA. The status of this effort is described in this report under the heading of Storage for Industrial Heat Reuse. The first phase of this study suggested the desirability of including aquifer storage; and in late FY 1978, a separate project to build and operate an aquifer storage prototype double well system at Bellingham was originated. The initial objectives of this new project were to locate and determine the hydrological properties of a local aquifer and to delineate the engineering and economic factors relevant to constructing and testing a full-scale double-well aquifer-storage module. This module would be the smallest unit of an aquifer storage system for a proposed district heating system.

The project was advertised, and a subcontractor was selected to manage and construct the prototype module. Battelle Pacific Northwest Laboratory has now been assigned overall responsibility for this thrust area and will complete contract negotiations with the subcontractor.

Aquifer Storage Value (GE-TEMPO)

At the beginning of FY 1979, GE-TEMPO contracted with the LTES Program to determine the value of aquifer storage to the proposed Twin Cities district heating system (TCDHS) at Minneapolis-St. Paul, Minnesota. This proposed TCDHS, whose feasibility is being evaluated by a consortium headed by Northern States Power Company in a

separately funded DOE study, would use cogenerated heat for seasonal heating without storage.

A substantial portion of this project has been sub-subcontracted in turn by GE-TEMPO to the Swedish firm of Studsvik Energiteknik AB which has experience with district heating systems in Sweden. Studsvik has completed some of the assigned tasks, but substantive results have not yet been made available. Some delays have resulted from corresponding delays in the progress of the TCDHS project.

The study is scheduled for completion by June 30, 1979.

Mathematical Modeling (LBL)

The Lawrence Berkeley Laboratory has provided mathematical modeling service to the LTTEs Program throughout the life of the program. The level of this service has varied from year to year depending upon programmatic needs and funding availability.

The scope of the FY 1979 work includes (1) continued development of models for daily aquifer storage and (2) analyses of data from the Auburn University field experiment at Mobile, Alabama.

Model calculations were made assuming two hot-water storage-retrieval schemes for daily storage in a "typical aquifer." The first scheme involved 12 hours of injection of hot water into the aquifer followed by 12 hours of production. The second scheme was eight hours of injection, four hours of production, eight hours of storage, and four hours of production. The calculated storage efficiencies for these scenarios were >75%.

From the Auburn field data, the presence of a barrier in the aquifer 250 to 306 m northwest of the injection well can be inferred; this conforms with reality. Other models with different mesh densities are also being calculated.

Aquifer Availability (TVA)

The Tennessee Valley Authority (TVA) has initiated a study for the LTTES Program through interagency agreement with DOE-ORO. The objective of this project is two-fold: (1) to identify potential sources and users of low-temperature thermal energy, such as institutional heating and cooling and industrial processes in addition to TVA facilities in the TVA service area; and (2) to identify appropriate aquifer storage sites with particular emphasis on the definition of aquifer storage criteria.

The interagency agreement was approved in March 1979 by the TVA Board of Directors, and work is to begin shortly.

Environmental Impact (ORNL)

A generic aquifer storage environmental impact assessment is being prepared by the ORNL Energy Division. This impact assessment will document the institutional and environmental concerns that must be addressed for siting and construction of an aquifer storage system. The report should be available in June 1979.

Aquifer Storage Economics (ORNL)

Storing low-temperature thermal energy in aquifers is thought to be one of the more economic methods for energy storage. ORNL (Engineering Technology Division) is examining this belief in a study

to evaluate the economics of aquifer TES, to determine the chances of specific systems for commercial success, and to indicate the market potential for aquifer TES.

A specific initial task has been the evaluation of the economics for capturing winter-chill at JFK Airport and storing the cold water in a confined aquifer for subsequent summer cooling of the airport terminal buildings. Prior work (started in 1977) included a conceptual design of the system and a preliminary cost estimate by Desert Reclamation Industries. As noted above, this work is currently being extended into the drilling of test wells to determine the aquifer characteristics. The data from this well drilling program were factored into updated cost estimates, and an economic analysis was performed. The results indicate that there are insufficient economic incentives to justify a demonstration of aquifer storage economic viability at this site. Specifically, there is not enough potential savings of fuel to pay for the required capital expenditure over the 20 year life of the project. However, it is misleading to draw general conclusions from these site-specific results. One consideration is the retrofit nature of the project. The location of taxiways, runways, and presently installed utilities drives the costs of system installation upward. Further, the labor cost, and specifically the cost of well drilling in the Long Island area, is much higher than in other regions of the country. When all these factors are considered, other sites could provide stronger incentives.

A generic assessment of thermal aquifer storage is planned. This will include an analysis of both cold and hot water storage for a

number of applications. The National Water Well Association will supply a well cost model which will be incorporated in an aquifer storage cost model. This model will then be used to evaluate specific concepts.

References

1. J. C. Warman, F. J. Molz, and T. E. Jones, "Subsurface Waste-Heat Storage: Experimental Study," ORO/5003-1, June 1977.
2. F. J. Molz, J. C. Warman and T. E. Jones, "Aquifer Storage of Heated Water: Part I - A Field Experiment," Ground Water, 15, 324, 1978.

3. SHORT-TERM/DIURNAL STORAGE

R. J. Kedl, R. M. Deal, A. D. Solomon

Objective and Scope

This thrust of the LTTEs Program is directed to developing advanced thermal energy storage systems for use in the residential and commercial energy-use sector. Energy sources to be exploited are primarily solar and off-peak electricity; applications are principally in building heating and cooling, although some industrial and agricultural utilization is possible.

Energy storage as sensible heat by hot or cold water in tanks or rockbeds is an existing technology. The emphasis in this program is on an advanced technology using the latent heat of phase change (melting/freezing, solid-state transition, etc.) as the storage mechanism. The principal advantages of phase change materials (PCM's) over sensible heat storage systems are the high energy storage densities attainable and the isothermal nature of the storage. The first of these — high energy storage densities — makes modular storage units utilizing active solar or off-peak electricity potentially more cost effective than the equivalent sensible heat storage systems. The second, isothermal storage, is of particular value in passive solar application. For example, if PCM's can be incorporated into building materials, building/room envelopes can be constructed that reduce the ambient temperature swings generally experienced with sensible heat systems.

Background

Projects under this technology development thrust can be classified into one of three technology areas:

- development of modular TES systems
- development of building materials containing PCM's
- supporting R&T

Early efforts focussed on development of modular storage for the active solar application and PCM's in building materials for the passive solar application. Much of this work has been completed and reported.^{1,2} Technical feasibility has been established for a number of the modular systems: e.g., form-stable polyethylene, hydrated salts in chub or rotating cylinder geometries, and direct-contact immiscible-fluid systems. In contrast, several concepts did not pan out; namely, heat of solution (cystallite precipitation) and solid-state heat of transition (material cost, toxicity, and low latent heat) systems. The economic feasibility of any of these concepts appears only marginally competitive at this time; more attention is needed in this area both to refine the economic analyses and to reduce system costs through hardware improvement.

Work on incorporating PCM's into concretes for use in passive solar systems was generally unsuccessful. In one study, the PCM occasioned catastrophic deterioration of the concrete matrix; in another, it was not possible to form the polymer concrete in the presence of the PCM. While future options were identified, a directed

shift of LTTES Program emphasis to aquifer seasonal storage resulted in a shutdown of both activities.

A limited amount of supporting R&T was also carried out. Much of this work developed from contracts transferred to LTTES Program management early in its life. These included general studies in such areas as PCM identification and evaluation, PCM structure and nucleation characteristics, analytical/physical modeling of thermal transport mechanisms in PCM's (melt/freeze process), and compatibility of PCM's and containment materials.

In addition to these studies under the direct aegis of the LTTES Program, work is being supported by other agencies, principal among these being:

1. DOE - Division of Solar Applications is developing TES components, largely sensible heat systems but also including some PCM systems.³
2. The International Energy Agency is sponsoring work.⁴
3. DOE - Solar Energy Research Institute (SERI) is becoming involved in TES system development; this is currently limited to a survey document to be published as SERI/RR-54-164D and program planning.
4. Commercial/industrial organizations who are developing and marketing TES units using private funding.

Emphasis in the future will be on moving promising concepts toward demonstration, particularly those finding application in offpeak electricity usage. This will involve testing and construction of prototypes, supported by only a limited R&T effort. For the solar heat

source, the focus will be on PCM's in building materials; an initial intensive effort on the concrete/PCM interactions is necessary.

Status of Projects

Rolling Cylinder TES System (General Electric Co.)

The rolling cylinder concept has inherent promise as a solution to the incongruent melting and phase segregation problems with Glauber's salt ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). This effort has as its objective the demonstration of initial technical and economic feasibility at up to prototype scale. The first phase involves laboratory-scale studies into the technical feasibility and identification of geometric and thermal scaling factors. The second phase proposes the design, construction, and testing of a full-scale prototype for the residential solar application. The project was funded by DOE-Solar Applications and transferred to the LTES Program for technical management.

In this concept, the PCM is contained in a horizontal cylinder rotating slowly around its longitudinal axis. The tumbling motion imparted to the crystallites prevents buildup on the heat transfer surface (cylinder wall) and helps to maintain a nearly uniform bulk temperature. Most importantly, as rehydration (melting) occurs, the anhydrous Na_2SO_4 crystals are closely exposed to the available water.

Calorimetric tests at laboratory scale have confirmed the viability of this concept. Initial and cycle life testing of commercial grades of sodium sulfate have shown that low-cost grades can be used;

over 70 cycles have been completed without performance degradation. Tests with various levels of excess anhydrous sodium sulfate, at several cylinder rotation rates and at heat fluxes over 200 btu/hr/ft² have helped define useful ranges of operation and have provided data for selection of larger scale designs. Preliminary evidence suggests that mild steel will be a suitable containment material. Analysis, using a computer model verified by initial test results, indicates that fins will be required on the outside cylinder surface in the full-size device to insure adequate heat transfer to air. Estimates of blower and rotating cylinder horsepower requirements are being made for several configurations. Stress analysis to determine cylinder wall thickness and roller spacing is also being done.

On completion of the first phase, the concept will be reviewed in regard to both its technical and economic aspects. Construction and testing of a full-size device will proceed only if this review indicates that the concept still holds significant promise.

Chub TES System (Institute of Energy Conversion)

This project is investigating the physical, chemical, and thermal stability of a PCM packaged in a sausage-shaped plastic module (chub) jointly developed by the University of Delaware - Institute of Energy Conversion (IEC) and du Pont. Tests include determinations of moisture retention, the effect of temperature extremes (high and low), mechanical behavior under physical handling (shock) and vibratory conditions, and deterioration in storage efficiency under both normal and accelerated thermal cycling. As a part of this project, IEC will

provide the LTTES Program sufficient chubs for independent performance assessment.

The PCM is a modified Glauber's salt (a $\text{Na}_2\text{SO}_4 \cdot 10 \text{H}_2\text{O}$ eutectic with NaCl and NH_4Cl) having a melting temperature of $\sim 12^\circ\text{C}$. Borax is added as a nucleating agent; and Minugel, as a thickener. This mixture was "designed" for cold side storage in association with heat pumps and off-peak electricity use.

Moisture retention tests on the chub indicate a loss of possibly as much as 10% in storage capacity after 10 years at rated temperatures. Initial mechanical tests show acceptable ability of the chubs to withstand normal handling. Thermal cycling tests have been started. The results continue to support this concept as technically viable; current IEC estimates place installed costs in a residential unit at considerably less than \$1000.

Intermediate Temperature TES System (University of Delaware)

The objective of the project is the development of a PCM thermal energy storage system for application of solar energy in the 100-300°C temperature range to absorption, adsorption, and Rankine cycle air-conditioning systems. The study is organized into two phases: (1) identifying and evaluating appropriate PCM's, and (2) design, construction, and testing of a prototype TES unit. Funding for this project originates in DOE-Solar Applications; technical management is provided by the LTTES Program.

Phase 1 has been completed with the identification of the following four storage materials:

PCM	Melting Temperature (°C)	Heat of Fusion (cal/g)	Approximate Cost (¢/kg)
NaCl·AlCl ₃	159	16	60
ZnCl ₂	312	37	70
FeCl ₃ /NaCl Eutectic	152	28	14
NaOH/Na ₂ CO ₃ Eutectic	283	40	35

None of the above materials appear desirable as a TES medium by reason of high material cost, low heat of fusion, or both. It is recommended that the study be discontinued on final completion of Phase 1 contractual requirements.

Direct Contact TES System (Clemson University)

This study has been investigating the feasibility of an immiscible-fluid, direct contact TES concept. To accomplish this objective, the program was organized into four research tasks:

1. Crystal growth velocity studies with selected hydrated salts,
2. Selection of appropriate hydrated salts,
3. Selection of compatible immiscible fluids, and
4. Studies on heat transfer and system geometry.

A fifth task would build and operate a 55-gal demonstration unit based on PCM, immiscible fluid, heat transfer, and geometric characteristics delineated by the first 4 tasks.

In this concept, a fluid that is completely immiscible with the water solution of the hydrated salt functions as the primary heat carrier. As this fluid bubbles through the PCM-filled vessel, heat is transferred to (or from) the salt. This mode of operation not only eliminates the heat transfer surface (reducing costs) but also significantly alleviates, through mixing, problems associated with incongruent melting and phase separation.

Prior to this period, crystal growth studies were completed for $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, and $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$. Over 160 potential immiscible fluids were surveyed with only two — Exxon Marcol 22 and Monsanto Therminol 60 — appearing to satisfy criteria for the heat transport fluid (Task 3). In Task 4, direct contact heat exchange between several salts ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$, and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and the immiscible fluids was examined; the design of the 55-gal demonstration unit was initiated.

During the current reporting period, Task 1 studies (crystal growth) were extended to include $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$. Impurities in the latter salt resulted in scatter and unreliable data. Tests with Marcol 22 were completed (Task 3), and testing of Therminol 60 is underway. Atomic absorption spectrophotometry was proven to be an effective tool in determining salt carry-over by the immiscible fluid. Construction of the 55-gal demonstration unit was completed (Task 5); preliminary shakedown runs with Marcol 22 and water without PCM were initiated.

Two immiscible-fluid, direct-contact PCM storage systems are being developed in this country outside of the LTES Program: a U.S. Navy development, and a system funded privately.

Polyethylene TES System (University of Dayton)

In an earlier study,^{5,6} crosslinked, high-density polyethylene in pellet form was identified as a TES medium. Technical feasibility was established, but high raw material and processing costs indicated poor economic competitiveness. This project investigates the possibility of using electron-beam, rather than chemical, crosslinking as a means for improving the concept economics. Phase 1 of this effort determines the optimum electron-beam irradiation parameters for forming pellets; phase 2 will prepare 250-lb of this material for later evaluation in an existing test facility.

This study was funded at the end of 1978, and results are not yet available.

Mathematical Modeling (ORNL)

This study by ORNL (Computer Sciences Division) is directed to developing mathematical modeling tools for use in predicting the performance of phase-change materials as TES media. These tools are in the form of analytical approximation techniques and computer programs. The activities are limited in scope to those of simple, effective, and inexpensive applicability.

Prior to this reporting period, computer programs were prepared for phase change processes in slab, cylindrical, and spherical geometries subject to a variety of boundary conditions. These have been used for developing simple analytical expressions for the melt-time and thermal behavior of a simple body,⁷ the analysis of a PCM-filled wall,⁸ and other problems of this kind.^{9,10}

Additional analytical approximation techniques have been developed and studied¹¹ as means for verifying the computations.

During the reporting period, work was concentrated in three areas:

1. The development of simple analytical approximations for a phase-change process with a convective boundary condition;
2. The continued development and debugging of a multi-component simulation program; and
3. Comparison of mathematical models with experimental results.

The results obtained were as follows:

Area 1. The kind of problem examined consists of a melting (or solidification) process due to heat convecting into the PCM with a heat transfer coefficient h . We obtained:

- a) A relation between surface temperature and time which could be used as a source of verification of thermal parameters and heat transfer mechanisms.¹²
- b) A relation linking the surface temperature and extent of the phase change process.¹³
- c) A relation for the total heat stored in the PCM as a function of time and/or surface temperature.
- d) Estimates of the effect of experimental error upon the reliability of the model.

Area 2. A computer program was developed for a body consisting of PCM and wall material layers; its use is anticipated for examining various PCM-container configurations. The program rests on the "weak-solution" approach,¹⁴ and the use of an implicit

scheme within each layer. Because of differences in material properties, different time and space meshes are used in each layer, with an iterative "linking" at the interface points. During the reporting period, changes in the linking procedure were carried out; and tests were made of their accuracy.

Area 3. In cooperation with the studies by Deal (see Physical Modeling), comparisons were made between experimental observations and model predictions for a paraffin-wax PCM. Agreement was noted when literature values of the liquid wax thermal parameters were used. The experimental observations led us to examine more deeply, such questions as: which of the "observable" quantities is most "reliable," and what are the expected observations from the thermocouple measurements?

The results obtained will be of general benefit. Thus, analytical results can be readily used by engineers interested in sizing equipment and using "rules of thumb" for preliminary estimation. The computer programs will be a reliable "last word" in predicting PCM behavior.

We plan in the future, to do the following:

1. Develop "rules of thumb" for radiation conditions.
2. Incorporate natural convection in the melt into the computer models.
3. Develop legitimate two dimensional computer models.
4. Utilize the models to predict the performance of prototypes to be tested by the LTTE Program.

Physical Modeling (ORNL)

The LTTES Program is developing experimental capability for studying PCM phase boundary (melt/freeze) phenomena as a means for testing various analytic and numerical models (see above) and for examining critical parameters in complex geometries. The understanding thus gained is important to the development of effective and efficient TES modular units.

At the beginning of this period, a simple test cell was made operational. This experimental system consists of a small Plexiglas cell containing a flat plate heat source and a corresponding sink, appropriate thermocouples for temperature measurement, camera equipment to record the movement of the solid-liquid interface, and a microcomputer system to control system cycling and to gather and process the data. The cell is charged with n-octadecane wax melting at 28°C. Principal additions during this reporting period included (1) a low-power laser that provides a measure of temperature gradient through the amount of beam displacement and (2) a dilatometer that enables an independent measure of the heat input.

Several sets of experiments have been carried out for both horizontal (conduction only) and vertical (conduction plus convection) orientations. In the conduction only mode, results in this simple geometry agree within experimental error with predictions from the analytical and mathematical models. In the conduction plus convection model, melt/freeze patterns were found to be much more complex; under cycling conditions, segregation into various solid and liquid regions was observed. Results to date suggest for PCM's having thermal conductivities near those of the paraffin waxes that the full potential

for the storage and release of the latent heat may not be realized unless the cycle time is several days, PCM thicknesses are less than 1-in., and/or effective use can be made of convection.

Present plans include accumulation of more data to corroborate the simpler mathematical models, experimentation in support of the multi-dimensional models being developed, and studies into the effects of gas inclusions.

Thermal Cycling Facility (ORNL)

Testing of various prototypical, PCM-based, TES devices developed by the LTTEs Program or available from commercial sources is necessary to the selection of "best" systems. This testing should be done under circumstances that allow ready comparison between concepts. To this end, ORNL is constructing a facility that will permit examination of full-scale, residential-capacity modules. Two recirculating loops are planned: one using a liquid as the heat transport medium; the other, air. Control of conditions by a microprocessor allows realistic modeling of cyclical heat input and demand loads.

Conceptual design of the liquid loop is complete; detailed design and construction are pending internal review and authorization of the project. Design parameters for this loop are:

Capacity: 500,000 Btu (max); 50,000 Btu (min)

Temperature: 150°C (max); - 5°C (min)

Heating Rate: 40 Kw (136,520 Btu/hr)

Cooling Rate: 6.7 tons (80,400 Btu/hr)

Flow Rate: 20 gpm (max); 1.5 gpm (min)

Construction completion is scheduled for the end of FY 1979.

References

1. Proceedings of Second Annual Thermal Energy Storage Contractors' Information Exchange Meeting, September 29-30, 1977, CONF-770955.
2. Third Annual Proceedings of Thermal Energy Storage Contractors' Information Exchange Meeting, Dec. 5-6, 1978, CONF-781231.
3. Proceedings of Third Annual Solar Heating and Cooling Research and Development Branch Contractors' Meeting, Sept. 24-27, 1978, CONF-780983.
4. Survey of Component R&D Projects for Solar Heating, Cooling and Hot Water Supply Systems, TID-28721.
5. R. A. Botham et al., "Form-Stable Crystalline Polyethylene Pellets for Thermal Energy Storage," ORO/5159-10
6. R. A. Botham et al., "Form-Stable Crystalline Polyethylene Pellets for Thermal Energy Storage - High Density Polyethylene Intermediate Products," ORNL/Sub-7398/4.
7. A. Solomon, Melt-time and Heat Flux For a Simple PCM Body, Solar Energy 22 (1979) 251-257.
8. A. Solomon, Design Criteria in PCM Wall Thermal Storage, Energy (1979) (to appear).
9. A. Solomon, An Easily Computable Solution to a Two-Phase Stefan Problem (submitted for publication).
10. A. Solomon, Heat Transfer in a PCM-Filled Wall, pp. 37-39 in the Proceedings of the Conference on Systems Simulation and Economic Analysis for Solar Heating and Cooling, San Diego, Ca., June 27-29, 1978.
11. A. Solomon, Mathematical Modeling of Phase Change Processes for Latent Heat Thermal Energy Storage, Union Carbide Corp., Report CSD-26 (to appear).
12. A. Solomon, A Relation Between Surface Temperature and Time For a Phase Change Process with a Convective Boundary Condition, Letters in Heat and Mass Transfer (1979) (to appear).
13. A. Solomon, On a Phase-Change Process with a Convective Boundary Condition (to be submitted for publication).
14. A. Solomon, Some Remarks on the Stefan Problem, Mathematics of Computation 20, 347-360 (1966).

4. STORAGE FOR INDUSTRIAL HEAT REUSE

M. Olszewski

Objective and Scope

Industries annually reject about 13 quads (13×10^{15} Btu) of energy to the environment. Utilization of only a small fraction of this potential resource could represent a significant addition to the nation's energy supply and, at the same time, decrease the effect on the environment of this rejected heat.

Since the reject heat is generally available at constant rate, energy storage is required to utilize this constant energy source to meet energy demands that vary both diurnally and seasonally. This results in both long- and short-term storage techniques being applicable. Techniques that appear most promising are hot water storage in steel tanks and aquifers.

Background

Efforts in the LTTEs Program have focused on several industrial sectors in the past. These have included the food processing and aluminum production industries. The food processing study was directed at internal reuse of plant reject heat, while the aluminum plant study focused on external use of the plant's reject heat for district heating. Energy storage served different functions in these systems. For the food processing effort, storage permitted the waste

heat to be accumulated and subsequently reused when the waste heat was not being produced. Storage in this case involved a diurnal cycle. In the aluminum plant study, diurnal storage was used to balance daily loads; while seasonal storage (possibly using aquifers) was used to enable waste heat from the summer months to be utilized for district heating in the winter. Presently our efforts are concentrated on the aluminum plant/district heating system.

Status of Projects

Bellingham Project

The primary aluminum smelting industry is a large user of electrical energy. Waste energy streams are usually of low grade but high magnitude. The large amount of low-grade energy makes this an attractive candidate for conservation.

The objective of the study is to determine the technical and economic viability of the use of thermal energy storage techniques to process heat and waste heat recovery in the aluminum industry.

A preliminary feasibility study has been completed for the example site, Intalco Aluminum Corporation and the surrounding communities of Ferndale and Bellingham, Washington. In this study, a system was identified by which low-grade energy in the primary pollution control system gas stream could be recovered and utilized for comfort heating in the communities mentioned above. Energy is stored as hot water in conventional, insulated steel tanks, enabling more efficient use of the constant energy source by the cyclical energy

demand. Less expensive energy storage means (heated ponds or aquifers) could allow for even more cost-effective systems.

Extensive design tradeoff studies performed for the site indicate that a heating demand equivalent to 12,000 single-family residences can be supplied by the energy from the Intalco site. This system would include about 53% of the housing units and 75% of the commercial establishments in Bellingham.

Using a 30-year amortization (consistent with utility planning practice), energy can be supplied at a cost less than one-third that of a conventional system, averaged over the amortization period. The difference between the cost of supplying energy with the identified system and the cost of supplying identical energy service by conventional means represents potential for profit to the utility, savings to the customer, and perhaps compensation to the industry supplying the low-grade energy. The exact distribution of this difference between savings to the customers and profit to the utility was not within the scope of this engineering study; however, the study clearly shows that the utilization of waste energy from aluminum plants is both technically and economically attractive.

A detailed survey of all aluminum plants within the United States, allowing the site specific analyses to be extrapolated to national basis, was also performed. Should waste heat recovery systems be implemented by 1985, a national yearly savings of 6.5 million barrels of oil could be realized.

The economic results, although preliminary in nature, indicate that further analysis of the system is justified. The technical

assessment did not identify any significant problems that would impede implementation. However, prior to implementation on a national basis, full-scale demonstration of the technical and economic feasibility of the concept is required.

Future program activities should be directed toward demonstration of the concept at the study site. These activities would include the following steps: detailed assessment of the concept, conceptual design of a demonstration project, construction of the demonstration system, and operation of the system.

A detailed assessment of the concept will be completed within the next 1.5 years. This assessment will include analysis of the market potential, evaluation of institutional issues and financing arrangements, analysis of the technological risks associated with each component, and a detailed economic analysis of the system. If the economic analysis is favorable, the conceptual design effort will begin in FY-81.

H. J. Heinz Project

A study to assess the potential for waste heat recovery in the food industry and identify and evaluate practical heat recovery methods and systems was recently completed by Westinghouse. This study concentrated on two plants within the Heinz U.S.A. organization.

Waste heat availability and reuse applications surveys were conducted for low-temperature (freezing) and high-temperature (cooking, sterilizing, etc.) production systems. The surveys indicate usable waste heat is available in significant quantities; this heat could be

applied to satisfy existing, on-site energy demands resulting in sizable reduction in factory fuel and energy usage. At the high temperature plant, the energy demands involve the heating of fresh water for boiler make-up, for the food processes, and for the daily clean-up operation. Clean-up poses an opportunity for thermal energy storage, since waste heat is produced during the one or two production shifts of each working day; while the major clean-up effort does not occur until food production ends. At the frozen food facility, the clean-up water application again exists; and in addition, refrigeration waste heat could also be applied to warm the soil beneath the ground floor freezer space. Systems to recover and apply waste heat in these situations were developed conceptually and thermal/economic performance predictions were obtained. The results of those studies indicate the economics of waste heat recovery can be attractive for facilities with high energy demand levels. Small factories, however, with relatively low energy demands may find the economics marginal although, percentage-wise, the fuel and energy savings are appreciable.

Analysis of these results indicated that a demonstration project involving only the Meat Products Building was justified. Therefore, negotiations for the Phase II effort, including design and installation of the demonstration system, were initiated. Program management responsibilities for this effort have been transferred to NASA-Lewis Research Center.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Internal Distribution

1. T. D. Anderson	34. W. R. Mixon
2. G. D. Brunton	35. M. Olszewski
3. R. S. Carlsmith	36. M. W. Rosenthal
4. W. B. Cottrell	37. T. H. Row
5. R. M. Deal	38. I. Spiewak
6-21. D. M. Eissenberg	39. A. D. Solomon
22. H. L. Falkenberry	40. W. Stockdale
23. M. H. Fontana	41. D. G. Thomas
24. E. C. Fox	42. H. E. Trammell
25. W. Fulkerson	43. D. B. Trauger
26. A. Golshani	44. E. K. Triegel
27. H. W. Hoffman	45. G. D. Whitman
28. A. S. Holman	46. ORNL Patent Office
29. R. J. Kedl	47-48. Central Research Library
30. M. A. Karnitz	49. Document Reference Section
31. R. E. MacPherson	50-52. Laboratory Records Department
32. W. C. McClain	53. Laboratory Records (RC)
33. J. Michel	

External Distribution

54. Robert D. Allen, Battelle Pacific Northwest Laboratory, c/o Department of Energy/STOR, 600 E. Street, Northwest, Washington, DC 2004
55. Frank Baylin, Solar Energy Research Institute, 1536 Cole Boulevard, Golden, CO 80401
56. Stanley N. Davis, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721
57. P. Donnelly, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
58. Dan D. Edie, Department of Chemical Engineering, Clemson University, Clemson, SC 29631
59. John A. Gahimer, Chief of Chemical and Thermal Branch, Division of Energy Storage Systems, Department of Energy, Washington, DC 20545

60. John Gibson, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
- 61-70. Robert Holliday, Division of Energy Storage Systems, U.S. Department of Energy, 600 E Street, Northwest, Room 416, Washington, DC 20545
71. Douglas Huxtable, Rocket Research Company, York Center, Redmond, WA 98052
72. Irving Kantrowitz, United States Geological Survey, Water Resources Division, 5 Aerial Way, Syosset, NY 11791
73. L. Kelso, Division of Industrial Energy Conservation, Department of Energy, Washington, DC 20545
74. Donald Langmuir, Department of Geochemistry, Colorado School of Mines, Golden, CO 80401
75. Walter Loscutoff, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
76. Wayne Lundberg, Westinghouse Electric Corporation, Advanced Energy Systems Division, P.O. Box 10864, Pittsburgh, PA 15236
77. Arnold Manaker, Tennessee Valley Authority, 1360 Commerce Union Bank, Chattanooga, TN 37401
78. W. Masica, NASA-Lewis Research Center, Cleveland, OH 44101
79. William McMaster, Tennessee Valley Authority, 160 Liberty Building, Knoxville, TN 37902
80. Charles F. Meyer, General Electric-TEMPO, Center for Advanced Studies, P.O. Drawer QQ, Santa Barbara, CA 93102
81. James Minor, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
82. Fred Molz, Water Resources Research Institute, Auburn University, Auburn, AL 36830
83. Jerzy R. Moszynski, Department of Mechanical and Aerospace Engineering, University of Delaware, Newark, DE 19711
84. G. C. Pezdirtz, Director for Division of Energy Storage Systems, Department of Energy, Washington, DC 20545
85. Henry J. Ramey, Jr., Petroleum Engineering Department, Stanford University, Stanford, CA 94305

86. Donald Reddell, Texas A&M Research Foundation, FE Box H,
College Station, TX 77843
87. Ival Salyer, University of Dayton, Research Institute, Dayton
OH 45469
88. Tom Schneider, Electric Power Research Institute, 3412
Millview Avenue, P.O. Box 10412, Palo Alto, CA 94303
89. R. Sheneman, Division of Industrial Energy Conservation,
Department of Energy, Washington, DC 20545
90. Melvin Singer, New York State Energy Research and Development
Authority, Empire State Plaza, Agency Building No. 2, Albany,
NY 12223
91. James A. Stottlemire, Battelle Pacific Northwest Laboratories,
P. O. Box 999, Richland, WA 99352
92. J. D. Swisher, Assistant Director for Physical Storage
Systems, Division of Energy Storage Systems, Department of
Energy, Washington, DC 20545
93. Roy Thornton, General Electric Company, Research and
Development Center, P.O. Box 8, Schenectady, NY 12301
94. Chin Fu Tsang, Lawrence Berkeley Laboratory, University of
California, Berkeley, CA 94720
95. Ronald Walter, Battelle Pacific Northwest Laboratories, P.O.
Box 999, Redmond, WA 99352
96. James Warman, Water Resources Research Institute, Auburn
University, Auburn, AL 36830
97. W. Wilson, Sandia Laboratories, Livermore, CA 94550
98. Charles Wyman, Solar Energy Research Institute, 1536 Cole
Boulevard, Golden, CO 80401
99. Director, Reactor Division, DOE, ORO
100. Office of Assistant Manager, Energy Research and Development,
DOE, ORO
- 101-127. Technical Information Center, DOE, ORO