A WORKSHOP ON THE ADVANCED THERMAL ENERGY STORAGE TECHNOLOGIES FOR SOLAR APPLICATIONS

Baton Rouge , LA.
April 23-24, 1976

Energy Research and Development Administration

Prepared by
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Editor

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PREFACE

A WORKSHOP on the ADVANCED THERMAL ENERGY STORAGE TECHNOLOGIES FOR SOLAR APPLICATIONS was held in Baton Rouge, Louisiana, on April 23-24, 1976, with 46 invited participants, the list of which is included at the end of this document. This activity was coordinated by C. J. Swet of ERDA, P. J. Graf of TRW, Inc., Washington, and O. A. Arnas of Louisiana State University with funding from ERDA.

In the following pages, documentation of the discussion held as a group and subsequently, in three subsections of SOLAR AND CONVENTIONAL POWER GENERATION, INDUSTRIAL/AGRICULTURAL PROCESS HEAT, and BUILDING HEATING AND COOLING is presented. Finally, in each section, the discussions are summarized in the form of ISSUE AND/OR STORAGE CONCEPT-CONCERN-RECOMMENDATION to bring together the common aspects of the problems arising in these three subsections. It is hoped that this will enhance researchers' appreciation for thermal energy storage, in general, and give some insight as to what seems to be the direction for future work. (However, this document should not be misconstrued as a commitment by ERDA to any of the activities discussed within.)

As the editor of this document, I would like to thank C. J. Swet, P. J. Graf, T. Bramlette, J. L. Butler, R. J. Kedl, J. A. Bowden, B. H. Holmes, A. Bruckner II, T. M. McQueen, and A. M. Barnett for their contributions to the material presented here. All the shortcomings, however belong to the author.

This documentation does not indicate an "in depth" assessment of the issues; rather, it consists of an informal discussion of them by technologists knowledgeable in the area.

er A. Arnas
Baton Rouge, Louisiana
March 1977

ADVANCED THERMAL ENERGY TECHNOLOGIES FOR SOLAR APPLICATIONS

The general group discussions started on the morning of April 23, 1976, in which C. J. Swet of ERDA made a presentation outlining the activities of the Thermal Energy Storage Program within ERDA as of March 1976. It should be noted that some reorganization at ERDA headquarters has occurred since then, but the context of the TES program and its direction are still generally as presented in this document. The stated goals and milestones were tentative.

The ERDA administrative organization in relation to thermal energy storage is:

Administrator
Robert C. Seamans, Jr.

Assistant Administrator for Conservation
Austin N. Heller

Division of Conservation Research and Technology
John A. Belding

Assistant Director for Energy Storage
George Pezdirt

Thermal Energy Storage Branch
Phillip Lowe

Thermal Energy Storage Program
C. J. Swet

Solar Electric Applications
Ray Mar--Sandia-Livermore Labs

Utility Electric Power Plant Application
W. Masica--NASA-LEWIS

Transportation Applications
W. W. Schertz--Argonne National Laboratory

Industrial Applications
C. J. Swet--ERDA

Building Heating-Cooling Applications
H. W. Hoffman--Oak Ridge National Laboratory

Applications/Commercialization Investigation
C. J. Swet--ERDA

The objective of the thermal energy storage program is to "ASSESS, DEVELOP AND DEMONSTRATE THERMAL ENERGY STORAGE TECHNOLOGIES FOR RESIDENTIAL, COMMERCIAL, INDUSTRIAL, TRANSPORTATION, AND ELECTRIC UTILITY APPLICATIONS." Within this objective, the scope of this program can be expanded upon as:

- I. The program includes the thermal energy storage technologies of sensible, latent, and reversible chemical reactions.
- II. The program is related to specific applications in the areas of residential, commercial, industrial, transportation, and electric utilities.
- III. The program goals are directed at demonstrated technology achievements within the next ten years.
- IV. The program does not limit itself to projects sponsored by the ERDA, but takes into account the technology advancements of projects sponsored by other government agencies, industry, universities, and other countries.

The thermal energy storage program can be separated into various application areas, each area having specific goals. These can be summarized as:

A. BUILDING HEATING AND COOLING

1. Develop to proof-of-concept thermal energy storage for use in conventional heating/cooling of buildings by early 1978.

2. Develop to proof-of-concept thermal energy storage for use in solar powered heating/cooling of buildings by early 1980.
3. Develop to proof-of-concept thermal energy storage for use in seasonal heating/cooling of buildings by late 1980.

B. CONVENTIONAL POWER GENERATION

4. Develop to proof-of-concept thermal energy storage for retrofit to conventional systems for meeting peak-power requirements by mid 1980.
5. Develop to proof-of-concept thermal energy storage for incorporation into center power stations for peak-power requirements by late 1980.

C. SOLAR POWER GENERATION

6. Develop to proof-of-concept thermal energy storage for use in solar thermal electric generating stations by late 1984.

D. INDUSTRY

7. Develop to proof-of-concept thermal energy storage for use in industrial batch process systems - by mid 1983.
8. Develop to proof-of-concept thermal energy storage for use in recapturing and subsequent use of industrial waste heat by mid 1983.
9. Develop to proof-of-concept thermal energy storage for use in solar generated process heat by late 1980.

E. TRANSPORTATION

10. Develop to proof-of-concept thermal energy storage for use in transportation by late 1986.

The milestones to be reached in each of the above include decisions on which technologies to investigate; which should proceed into feasibility studies; which thermal storage technology to carry into the next development phase; and completion of proof-of-concept tests in the technology/technologies.

A number of projects under the subheading of thermal energy storage by sensible heat, by latent heat, by reversible chemical reactions and general thermal energy storage systems studies have been initiated and are being performed. Projects with TES subsystems which have been funded by other ERDA organizations are also presented. They can be categorized as:

I. THERMAL ENERGY BY SENSIBLE HEAT PROJECTS

A. Assess feasibility of steam storage in underground man-made caverns

R & D Associates -- Hammond

ERDA-TES -- \$72,500.00

Support program goal #3

B. Develop immiscible fluid thermal storage for solar heating systems

Clemson University--

ERDA-TES -- \$139,000.00

Supports program goal #2

C. Assess the feasibility of prestressed cast iron vessels for storage of steam in conventional and solar/thermal electric power systems

Institute of Thermal Power and Nuclear Engineering

Graz University of Technology

Graz, Austria -- P. V. Gilli

ERDA-TES -- \$30,000.00

Supports program goals #4, 5, 6

- D. Complete economic and technical feasibility studies of retrofitted feedwater for steam electric power

Bechtel Corporation --T. R. Fick

ERDA TES--

Support program goal #4

- E. Complete economic and technical feasibility study of retrofitted feedwater heat storage for steam electric power with solar thermal augmentation

Franklin Institute -- H. Lorsch

ERDA-TES -- \$36,000.00

Supports program goals #4, 6

- F. Develop rock bed heat accumulators for applications to solar thermal electric power production

University of Minnesota--M. Riaz

ERDA-TES -- \$160,000.00

Supports program goal #5

- G. Heat storage for adiabatic compressed air systems compared to steam systems

Massachusetts Institute of Technology --

ERDA-TES --

Supports program goal #5

- H. Investigate the feasibility of hot water storage in aquifers

Auburn University -- Warman

ERDA-TES and USGS -- \$185,000.00

Support program goal #3

- I. Research and concept of solar energy storage in the earth and its subsequent reclamation.

George Washington University -- S. W. Yuan

ERDA (originally NSF) -- \$157,000.00

Supports program goals #2, 3

- J. Develop transient thermal energy storage model for prediction of sensible heat storage and perform experiments for calibration

Pennsylvania State University -- F. W. Schmidt

ERDA (original NSF) -- \$114,000.00

Supports program goal #1

- K. Assess feasibility of hot and cold water storage for solar and electric heat pump building heating/cooling

Potomac Electric Power Company--

ERDA-TES -- \$23,500.00

Supports program goals #1, 2

- L. Feasibility of heating and cooling of schools by using storage tanks for water and water-glycol solutions

The Heating and Cooling Branch

ERDA-DIVISION OF SOLAR ENERGY -

Supports program goal #2

- M. Design and test a 5 MWH storage system using a fuel oil and crushed granite storage media

Solar Thermal Branch, McDonald-Douglas Corp.-- R. W. Hallet

ERDA-DIVISION OF SOLAR ENERGY -

Supports program goal #6

- N. Design and test a 5 MWH storage system using thermal 55 and HITEC

Note: HITEC ($T_{\text{melt}} = 288^{\circ}\text{F}$), $\text{NaNO}_2 + \text{NaNO}_3 + \text{KNO}_3$

Martin Marietta Corporation and Engineering Experiment Station

Georgia Institute of Technology -- F. Blake

ERDA - DIVISION OF SOLAR ENERGY--

Supports program goal #6

- O. Investigate the feasibility of using wind power for space heating, considering resistance heating, mechanical means, and in combination with flat plate solar

University of Massachusetts -- W. E. Heronemus

NSF--

Supports program goal #2

- P. Develop and evaluate solar heated water storage for brooding poultry

USDA South Central and Southeast Research Laboratories --

P. N. Pierce and L. N. Drury

USDA--

Supports program goal #9

- Q. Develop solar heated water storage tanks for peanut drying

ARS --J. L. Butler

USDA-ARS--

Supports program goal #9

- R. Investigate use of controlled salt concentration to make solar ponds capable of storing energy up to 180°F for use in green-houses and small residences

Ohio Agricultural Research and Development Center, Wooster,

OH--T. H. Short

USDA--

Supports program goals #2, 9

- S. Evaluate solar energy storage system for use in milking parlors

USDA Genetic and Management Laboratory -- P. D. Thompson

USDA --

Supports program goals #2, 9

- T. Develop and evaluate thermal storage in structural walls for space heating of a swine farrowing house

Kansas State University -- C. K. Spillman

USDA --

Supports program goals #1, 2

- U. Determine feasibility and techniques for waste treatment systems for overnight storage of heat for livestock shelters

Virginia Polytechnic and State University -- D. H. Vaughn

USDA --

Supports program goal #8

- V. Develop simulation model to analytically determine energy storage size for minimum equipment and operating costs in combination with solar energy

Lockheed Missiles and Space Company -- P. McCormick

ARS-USDA --

Supports program goal #6

- W. Evaluate operational feasibility, solar thermal storage energy requirements and poultry performance for maintaining temperature for rearing broiler chickens

University of Maryland -- J. L. Cain

USDA -- \$37,500.00

Supports program goal #9

II. THERMAL ENERGY STORAGE BY LATENT HEAT PROJECTS

- A. Containment material compatibility with NaCl, KCl, $MgCl_2$ eutectics will be measured and engineering model of thermal storage device

Will be built and tested

Naval Research Laboratory -- T. Chubb

ERDA-TES -- \$150,000.00

Supports program goals #4, 5

- B. Select a liquid/solid phase change carbonate system, construct an engineering scale system and evaluate the performance for central power, inclusive of the prototype and full scale unit

Institute of Gas Technology -- L. Marianowski

ERDA-TES -- \$1,927,000.00

Supports program goal #6

- C. Engineering assessment of the phase change thermal energy storage process, utility stations (three phase project)

Sandia-Livermore Laboratories -- T. Bramlette

ERDA-TES -- \$230,000.00

Supports program goals #4.5

- D. Develop dispersed phase change storage in construction materials for heating and cooling application

Suntek Research Associates -- Day Chahroudi

ERDA-TES -- \$54,000.00

Supports program goals #1, 2

- E. Optimize the phase change storage media for use in the Honeywell Solar Thermal Project

Honeywell Corporation --

ERDA-TES -- \$55,000.00

Supports program goal #6

- F. Develop polyethelene polymers for paced-bed thermal energy storage for solar heating

Monsanto --

ERDA-TES -- \$173,000.00

Support program goal #2

- II. G. Macroencapsulation of phase change material in plastics and metals for residential buildings

Dow Chemical Company -- G. A. Lane

ERDA-TES -- \$162,000.00

Supports program goals #1, 2, 3

- H. Study and select a potentially viable phase change system and a preferred chemical system for solar/Brayton power systems (also represents chemical heat storage)

Boeing and Rocket Research Corporation -- J. R. Gintz

ERDA-TES coordination with EPRI -- \$75,000.00

Supports program goal #6

- I. Develop thermal energy storage for vehicular power systems, with emphasis on the Stirling cycle engine

Argonne National Laboratory -- W. Schertz

ERDA-TES and ERDA-DIVISION OF TRANSPORTATION ENERGY STORAGE --
\$661,000.00

Supports program goal #10

- J. Feasibility of energy storage in building materials for space heating, concept involves incorporation of phase change material into construction material.

Brookhaven National Laboratory -- F. Salzano

ERDA-TES and ERDA-DIVISION OF BUILDINGS AND INDUSTRY -- \$243,000.00

Supports program goals #1, 2

- K. Theoretical and experimental program to establish viability of phase change fluorides for buildings, residential or industrial

Philips Laboratories -- A. Daniels

ERDA (NSF Transferred Contract #AER 75-20605) -- \$150,000.00

Supports program goal #1, 2, 7

- L. Study nucleation, growth and habit of salt hydrates in a liquid/solid phase change storage system, three year program

Desert Research Institute -- J. Hallett

ERDA (NSF contract transferred #AER 75-19501) -- \$338,000.00

Supports program goal #2

- M. Acquisition of performance data on eutectic salt (Glauber's salt with 3-5% borax) for energy storage for building heating and cooling.

University of Delaware, Institute of Energy Conservation --

ERDA-DIVISION OF SOLAR ENERGY --

Supports program goals #1, 2

- N. Design and test a 5 MWH storage unit using eutectic salts

Honeywell Corporation -- R. Schmidt

ERDA-SOLAR THERMAL BRANCH --]

Support program goal #6

- O. Study of eutectic phase change processes with water transporting the solar energy to the salt

Univeristy of Minnesota and Honeywell Corporation -- R. Jordan

ERDA-SOLAR THERMAL BRANCH --

Supports program goal #6

- P. Research on microencapsulation of paraffin phase change material

General Electric Company -- A. Tweedie

ERDA-DIVISION OF SOLAR HEATING AND COOLING BRANCH -- \$106,000.00

Supports program goals #1, 2

- Q. Identify latent heat thermal energy storage heater exchanger

concepts; evaluate their technical and economic characteristics
in utilities

TBD --

NASA -- \$150,000.00

Supports program goals #4, 5, 6

- R. Purchase and evaluation of anhydrous phase change "therm-bank"
water heater thermal storage unit with 100 KW windmill

Comstock and Westcock -- R. Rice

NASA -- \$30,000.00

Supports program goal #6

- S. Test latent heat thermal storage units, and evaluate heat exchange
concepts, e.g., reflux tubes, conductivity exchangers

NASA -- E. Furman

NASA -- \$100,000.00

Supports program goals #4, 5

III. THERMAL ENERGY STORAGE BY REVERSIBLE CHEMICAL REACTION PROJECTS

- A. Develop MgO and CaO heat of hydration storage systems for solar
application

Atomics International --

ERDA-TES -- \$240,000.00

Supports program goals #7, 8, 9

- B. Expand a DSE/USDA program on the use of desiccant thermal energy
storage for crop drying

Lockheed Missiles and Space Company --

ERDA-TES --

Supports program goal #2

- C. Evaluate eight (8) ammoniated salt pairs, select three (3) for
utility power plants and build/test bench scale model

Martin Marietta Corporation --

ERDA-TES --

Supports program goals #4, 5

- D. Develop thermal storage using saturated aqueous solutions for application to solar heating and cooling (laboratory tests, prototype and full-scale phase)

Franklin Institute --

ERDA-TES -- \$107,000.00

Supports program goal #2

- E. Investigate use of metal hydride energy storage for residential and commercial use

Argonne National Laboratory -- D. M. Gruen

ERDA-CHEMICAL STORAGE BRANCH -- \$213,000.00

Supports program goals #1, 2

- F. Evaluate $\text{SO}_2 - \text{O}_2 - \text{SO}_3$ and $\text{CO} - \text{H}_2 - \text{CH}_4 - \text{H}_2\text{O}$ reversible chemical reactions for thermo-chemical storage

University of California, Lawrence Berkley Laboratories --

J. M. Hollander

ERDA-CHEMICAL STORAGE BRANCH -- \$80,000.00

Supports program goal #

IV. GENERAL SYSTEMS STUDY FOR THERMAL ENERGY STORAGE

- A. Assess overall technical and economic aspects of thermal energy storage for industrial applications

General Electric Company --

ERDA-TES -- \$294,400.00

Supports program goals #7, 8, 9

- B. Technical and economic assessment for power plant peaking

Public Service Electric and Gas of New Jersey --

ERDA-TES --

Supports program goals #4, 5, 6

- C. Examine commercial feasibility of customer owned off-peak electric energy storage and survey thermal energy storage test facilities

Argonne National Laboratories -- J. Asbury

ERDA-TES --

Supports program goals #1, 2, 3

- D. Develop initial thermal energy storage systems workshop

Louisiana State University -- O. A. Arnas

ERDA-TES -- \$10,000.00

Supports program goals #

- E. Determine cost/availability of fluoride salts

Pennwalt --

ERDA-TES --

Supports program goal #

- F. Define system requirements for seasonal thermal storage

Institute of Gas Technology --

ERDA-CHEMICAL STORAGE BRANCH -- \$18,000.00

Supports program goal #3

- G. Analytic study to define cost effectiveness comparisons for various thermal energy storage materials and systems

RCA --

ERDA-DIVISION OF SOLAR ENERGY --

Supports program goal #6

Upon completion of this presentation, the participants formed three working groups with a group leader and a rapporteur and considered the

areas of SOLAR AND CONVENTIONAL POWER GENERATION, INDUSTRIAL/AGRICULTURAL
PROCESS HEAT and BUILDING HEATING AND COOLING.

SOLAR AND CONVENTIONAL POWER GENERATION

The chairman of this group was Taz Bramlette of Sandia-Livermore Laboratories. The rapporteur was Joe A. Bowden assisted by Art Bruckner, II, both of Louisiana State University.

The results of the discussions of this group are written at three levels. The first is a narrative of the ideas that were brought out during the subsection workshop and are collected under the three headings as:

- I. Systems Considerations
- II. Heat Transfer and Fluid Mechanics Studies
- III. Materials

The second set of information is on a broad general base and could be applied to any of the three areas delineated in the first level. The third is a more specific collection of goals, ideals, state-of-art and aspirations.

Level One - Narrative of General Ideas

I. Systems Considerations

A. Specific questions and statements

1. What are the future solar thermal power generation systems with respect to energy storage - sensible, latent, reversible chemical reaction or other?
2. What types of systems analyses are required?
 - a. Engineering design
 - b. System control
 - c. System optimization with regard to storage
 - d. Source-system-load interaction

- e. The level of required detail
- 3. What are the allowable storage costs - cost calculated on energy in versus energy out?
- 4. Are there any institutional barriers?
 - a. Building codes - local, state or federal as well as one state versus another
 - b. Environmental considerations - considered very important for large systems
 - c. Safety considerations
 - d. Other
- 5. What operational experience exists with large thermal energy storage systems?
- 6. Are there related technologies that could provide guidance, such as the chemical process industry?
- 7. Are there established mechanical design procedures?
- 8. Are there established testing procedures?
- 9. What is the correct balance between basic thermal energy storage research and systems analyses?
- B. General discussion of systems
 - 1. Is there a need to develop new mechanical designs, or are the old existing systems to be fine-tuned or redesigned?
 - 2. Testing procedure must be uniform. There exists a question of whether it is even possible to test a large-scale system. There must be, however, a delicate balance between research, development, testing and actual systems applications.
 - 3. The system must be compatible with and integrable into current power-generating facilities, assuming that all stations will be on the power grid. If selected or perhaps

all, stations are not in the power grid, then many of these problems may be overcome. However, in such a case, the problems of storage or backup systems become even more important.

4. Energy costs of the total system and net energy analyses are important for lifetime costs versus lifetime benefits to the user.
5. Future systems appear to be cast into four temperature ranges: low, medium, high, and ultrahigh temperature. The temperature scale could actually be broken down into five scales and matched for the specific system. For example, 250-300°F could be a fluorocarbon system; 400-600°F, wet steam; 900-1000°F, superheated steam; 1000-1500°F, steam for a Rankine engine; and above 1500°F, helium can be heated to run an open or closed Brayton system.
6. It is important to define the temperature at which the system will work. This should be keyed to the collector system. Temperatures of less than 600°F could be obtained with the steam or the organic Rankine engine. It could also be a hybrid of the two; i.e., a high temperature and a secondary low temperature attached system. Temperatures of less than 750°F could run the steam or the organic Rankine engine using the central collector, the central receiver, the distributed receiver or the fixed mirror-curved ground system. Temperatures of about 1100°F, using sub or super critical systems could use the Rankine engine with central and distributed receivers. Temperatures of 1000-1500°F using the closed Brayton cycle could have central or distributed receivers.

Temperatures in the 1500-2000°F range would by necessity have to use the open Brayton cycle and the central receiver setup.

7. The specific type of storage would need to be matched to the rate of energy input and rate of energy output. Consideration should be given to a grid versus a stationary system with respect to the type of storage. There are problems with the utilization of solar energy in the electric power grid systems such as the length of cycling and short cycle versus long cycle storage. The type of system should also be matched to the cost of KWHR versus peak load considerations. Impact analysis from the utility point of view are required. Generation capacity can only be displaced by long duration storage.
What are the economic advantages of short cycle storage - generation cost efficiencies versus efficiencies of storage?
Are economic and fossil fuel benefits realizable?
8. How reliable is the system? A specific system must also be geared to the solar supply - Arizona versus Louisiana versus New England versus Iowa versus Chicago. All of these areas have different problems that would affect reliability - wind or salt in air, et cetera. Any new system development must be compatible with the power grid even if it may stand on its own. Reliability systems studies are needed.
9. The suggestion was made that thermal energy storage research be conducted in a problem solving mode - that specific systems considerations should guide the basic research.
10. Thermal energy storage technologies and systems face a degree of time credibility. A system must be operational very soon; the first system being tested, 5 MW, needs storage systems

on line relatively soon to promote general credibility.

11. All forms of thermal energy storage should be considered and that any one should not be developed exclusively or to the detriment of the others.

II. Heat Transfer and Fluid Mechanics Studies

A. Specific questions and statements

1. What is the state-of-art of thermal energy storage performance modelling at the steady state, transient and multidimensional systems? What models are available and have they been verified?
2. How well are the heat transfer processes understood? What is available from related technologies - NASA, ERDA(AEC), et cetera?
3. Do any special fluid mechanics problems - fluid mixing, multi-phase flow with chemical reactions - exist?
4. What advanced heat exchange techniques - direct contact, active heat of fusion systems, heat pipes, fluidized beds - are available?
5. Is energy transmission a problem?
6. Does thermal cycling, with regard to heat of fusion systems, pose any special problems?

B. General discussion of heat transfer and fluid mechanics

1. There needs to be the development of a thermal energy storage model. How well are the processes that are dealt with known? What are the problems with dimensional scaling of parameters from a pilot plant - to a prototype - to a real "on-line" situation? It was noted that scaling is system dependent.
2. Fluid dynamics problems, such as materials pulling away from

the surface on phase change, contact and heat transfer at the surface, need to be investigated. Potential technology transfer from casting industry should be explored.

Efficiencies may be increased with the addition of various additives; if so, what new methods must be developed?

3. Heat pipes for rapid use versus slow rate utilization should be investigated. The Office of Naval Research is working on such a problem with energy storage "boiler tanks" with mixed chloride salts using a steam and a solar loop. A secondary fluid for the transfer of the heat from the storage cans - encapsulation - is necessary. Concern for slow versus fast rates could be resolved by having two mixtures, one for rapid demand (1-2 seconds), the other for slow demand (lower minutes range).
4. The problem of heat diffusion - mixing of a cold and a hot system - must be addressed. Problems in thermal cycling of the system, of a specific container or of the materials must be resolved. Consideration must be given to the stress on the container and/or on the materials. Pressure effects - shrinking - and expansion effects of the storage materials must be considered. It is important to keep the operating temperature change small. At the same time, shutdown of the entire system for routine repair or maintenance is required.
5. Some advanced technology in heat transfer is needed in the areas of heat pipes, fluidized beds of liquid-solid, gas-liquid and gas/solid types as well as straight power
6. ~~beds~~ Advanced heat exchanger technologies --active, passive,

direct contact heat exchangers - must be developed.

Encapsulation storage of energy in exchangers, the "pull away" problem and the like must be solved with some technology transfer from the chemical industry. More work is needed, however.

7. Nucleation effects at high temperatures are to be considered.
8. Thermal cycling - hysteresis effects, structural problems, stability of particle size, morphological changes - are problems. Will there be any residual holdbacks in input-output of energy?
9. Problems associated with high temperature latent heat storage are those of the development of supercooled liquids. More thermodynamic data and research are needed.

III. Materials

A. Specific questions and statements

1. Are the corrosion processes understood? Storage media/containment materials need to be investigated. Dynamic, static and impurity effects are important. What developments are required for corrosion inhibitors and containment materials?
2. Does thermal cycling pose any unique problems with regard to corrosion?
3. What is known about the chemical stability of thermal energy storage materials - sensible, latent and reversible chemical reactions -, their mechanisms and prevention of their instabilities?
4. What basic thermophysical property measurements are required, in particular with respect to temperature dependence and

impurity effects?

5. What is known about the kinetics of heat of fusion materials and chemical systems?
6. What is the status of encapsulation research at high as well as low temperatures?
7. How thoroughly characterized are possible reversible chemical reaction thermal energy storage systems?
8. What is the status of in-situ monitoring ability for prediction of replacement, and what instrumentation development is required?
9. Reclamation of the storage media is necessary.
10. What catalyst, insulation and code case developments are required? Can existing ones be used?
11. How important is energy density and the magnitude of the container?

B. General discussion of materials

1. Corrosion will be a major problem, both in storage and in transfer. Although corrosion inhibitors are present, other materials from the containers will have to be contended with.
2. Impurities in materials from the supplier could become a major problem as the demand increases.
3. Encapsulation at high and low temperatures, each with specific problems, will have to be resolved.
4. The costs of production of the needed materials, the move from one geographical location to another, and the repurification or mixing of additives must be analyzed in the context of lifetime costs versus the cost of the materials. Availability of materials in the world and political availability

need investigation.

5. How will the problem of storage be accomplished? Will energy be stored at a general site and then transferred to the application and/or use site or will collection and storage occur at the same site? Can the storage material be processed at a collector, removed to a secondary site and used there to generate power and then be returned by pipeline, rail, et cetera? Multi-level storage should be considered having a very high internal, medium external temperature or even a cooler temperature on the outside as a third level. The effect of a central versus a diffuse system on the consumer must be investigated.
6. Major concerns were voiced with respect to environmental problems. These problems should be discussed and anticipated in advance of any application to minimize the problems of environmental impact studies, including the waste media. Possibly the Environmental Protection Agency could help overcome this problem by establishing guidelines in advance of the development of these systems. On-site safety problems should be resolved.
7. The exchange of heat between immiscible fluids was suggested.
8. How to contain corrosion is definitely a problem-oriented research and development area of study.
9. The monitoring problem was divided into three groups: monitoring of the corrosion - hydrochloric acid is a by-product of mixed chloride salt storage systems, monitoring other secondary and tertiary derivation products and monitoring the storage system energy content. Will these adversely

affect or enhance the efficiency of any storage system?

10. There is a need to know the long-term life of the chemicals involved. How many cycles can these chemicals undergo before degradation in the secondary and tertiary by-products occur? Currently, accelerated testing methods are used for these; however, it must be very closely watched how any type of accelerated testing is done and the effects of such testing on the material properties must be investigated. Is efficiency affected by aging?
11. For testing, the requirements of the system must be known. How are these obtained? Efforts should be made to obtain them now. Testing must be carried on for a long time - both real time and accelerated programs for short-term versus long-term.
12. More information on material properties must be ascertained. A test regime must be set up in advance of programs. These can help define the corrosion mechanisms since many of these mechanisms are unknown. Is the establishment of programs to study these necessary, or is putting these mechanisms in terms of acceptable parameters and working around them sufficient? Is corrosion a problem that is seen in an accelerated test, or will it show up only in the long term?
13. Accelerated testing should be done using the materials of the scale up design. Solder or weld around the connection of pipes should also be included. A specific metal may not have any problems of corrosion. When two metals are joined together in the welding process, certain subtle chemical changes that take place may be amenable to problems at that

specific site and may act as decomposition catalysts. Thus failure interaction analysis is required for the total test system.

14. Agreement was reached that there should be no work on catalysts and insulation materials unless they are "red hot" items. There should be a low priority for reclamation of the storage media; however, problems of disposal should be resolved.

Level Two - General Broad Based Discussion, Statements and Questions

1. How can exchange of information and transfer of technology be promoted to increase public awareness and acceptance of thermal energy storage? An education problem is at hand.
2. Five MW storage systems are available at a cost of \$1 - 2 million. The source of power, a closed Brayton cycle, with the gas cooled receiver using helium gas is available. Preliminary indications show that this system is 44% efficient with helium as compared to 38% efficiency with steam. In the 1000-1500°F range using helium, there are alloys which will contain the pressure and the temperature. In the 1500-2000°F range, adaptation and use of ceramic heat exchangers acquire importance.
3. It was brought out that there is thermal improvement using fluoride salts and refractive bricks. However, tremendous amounts are needed in any scale up and there must be some early identification of potential resource availability and assessment of production associated environmental problems.
4. It was noted that the need for establishing a known cycling period for any given system exists.
5. Matching of the temperature to the enthalpy, the capacity of the system

the duration of the storage (short versus long term), and the input versus output rates are required. These are the cycle definition and performance and are necessary for the game or system model. Additionally, the ranges of the capacity and the safety requirements are needed. The ΔT match with the storage is required along with subsystem interfacing; storage versus transmission versus control versus power generation.

6. Safety is of great concern. The operational safety of the system, the hookup with the utilities and the sources of the hookup, environmental safety problems, the stability of the system and the stability safety as a function of the system life (aging of the system), must be considered as problem areas. For the ultimate stability of the system, replacement costs are needed. Probably, in most cases, there is no information regarding stability at hand.
7. System monitoring includes performance and condition of storage medium and containment system. Reliability prediction requires the development of monitoring systems using acoustical techniques and analysis of secondary and tertiary decomposition products. For accelerated aging careful planning is required since the artificial environment may be more severe than that experienced by the system. Need for concurrent and extended real time tests exists. Tests should be checked by utilizing different cycling characteristics. The need to identify secondary and higher order effects were mentioned, and it was noted that these effects should be allowed to go to completion. There is also need for a normal testing program to identify mechanisms.
8. Any model requires a specification of a system. For this, technology assessment or pre-systems analysis for full scale of the type of required application and dimensional analysis - problems of designing

to scale - is needed. Scaling is a major problem area because of the presence of several modes of heat transfer, the effects on the phasing of the project planning, the difficulties in identifying the critical parameters and the fact that it is not a separate technology, but rather, a part of the maturation process of the system. The effects of the material property inaccuracies on performance prediction should also be considered. However, all parameters need not be scaled equally. The choice of the module size in advance is required.

9. Studies into the hysteresis of thermal cycling - the effect of the size of the bed or the storage container - are necessary. The chemical problems with the various reactions and the physical problems with the salt require research.
10. The phases for progression of research were identified as:
 - a. Systems engineering studies assuming applications in the utilities
 - b. More information on efficiency and economies of the media and investigation of potential economies-of-scale for reversible chemical reaction systems
 - c. Investigations to see if storage can be used as an alternative standby reserve and also time length of storage
 - d. Establishment and maintenance of thermoclines
 - e. Desirability of hybrid storage system to match temperature-enthalpy characteristics of collection and conversion systems and for energy cascading
 - f. Integration between the source, the system and the load interaction
 - g. Obtaining of data on corrosion, cycling, monitoring, materials, heat transfer and containment.

Level Three - Summary

In this section, the final summary of the discussions of the group is presented. Included are the comments made by the members of the group and summarized in the ISSUE - CONCERN - RECOMMENDATIONS form as shown on the following three pages.

ISSUE	CONCERN	RECOMMENDATIONS
Systems Analyses	System Engineering	Perform engineering analyses to identify viable solar systems
	Source/System/Load Interaction	Develop "gaming" models to ascertain required storage characteristics (quantity, rates, economics, etc.) for specific applications, configurations, and sites. Develop detailed models for system optimization and control.
System Monitoring	Storage System Energy Content	Adapt existing technology to develop required systems. System specific and needs development for on-line and remote applications.
	Storage Medium Content	
	Containment System Condition	
Testing Program	Adequacy of accelerated testing method for predicting the response of a system over its life-time (30 years).	Adapt existing technology and develop new technology. The proposed testing program for any system development should include both real time and accelerated testing of actual hardware.
Thermal Storage	Performance - steady state and transient	Development should be oriented toward specific systems. Activities should be phased with storage system research program (i.e., models for lab, prototype, and demonstration scales developed, verified, and modified as required).
	System scaling	
	System process and process mechanisms	
	Verification of model	
	General assessment of technology	

ISSUE	CONCERN	RECOMMENDATIONS
Contamination-Corrosion	Mechanism	Programs must depend on specific systems. Contamination/corrosion studies should be conducted in conjunction with system monitoring and testing programs. After identification of time frames, either add interceptors - inhibitors or plan for replacement schedules.
	Corrosion resistance	
	Inhibitors	
	System Life	
	Thermal cycling	
Stability	Failure predictions	Development of new techniques and modification of existing ones. For most part, scaling effects are unknown. Because the purity of any given storage material is directly related to its cost, efforts must be directed toward determining the high acceptable impurity level for each proposed material.
	Thermal stability	
	Scaling effects	
	Effect of impurities in the prime materials	
	Purification of impurities, reclamation of media and development of finer purification technologies	
Heat Exchangers	Geometry	Advanced and unique heat exchanger development is necessary. Low, high, and ultrahigh temperature systems are needed. Program should be guided by specific systems to optimize the efficiency and cost.
	Mechanisms	
	Materials	
	Fouling	
	Efficiency of change	
	Rate of input-output, both with respect to the entire system	

ISSUE	CONCERN	RECOMMENDATIONS
Resource Availability	Cost - both current and predicted future	Consider during initial system studies.
	Reliability of supply - import and export	
Exploratory Research	Development of advanced storage system	Small grants should be given to universities and/or R&D concerns. University-industry interaction is needed.
	Reaction kinetic studies	
Testing of Materials	Short- and long-term monitoring	Careful attention is to be given to the testing methods. The material tests should be part of the total testing program and should begin after preliminary screening. Short- and long-term "real time" and accelerated aging testing are required. Realistic thermal cycles should be imposed.
	Accelerated aging	
	Compatibility of Materials	
	Similarity to duty cycle	
In-situ Monitoring and Measurement of Energy Content	Energy and system monitoring	Development oriented work. It should be a part of the initial model and then transferred to prototype.
	Scheduled maintenance profile	
	Containment and stability of storage medium	

INDUSTRIAL/AGRICULTURAL PROCESS HEAT

This group was chaired by J. L. Butler of USDA-ARS. The rapporteur was B. H. Holmes of Louisiana State University assisted by K. Overdyke of Louisiana Department of Conservation.

The chairman began the session by indicating that the first step was to have input as to where the concerns are in thermal energy storage, the main issue being what is being done now and what needs to be done in the future.

It was quickly established that there appears to be significant potential for reduced dependence on scarce petroleum resources through increased utilization of solar energy for industrial and agricultural applications in areas where solar energy is readily available. However, economical means of collecting and storing thermal energy must be developed. Heat is greatly wasted in the agricultural industry; therefore, recycling and conservation of heat is extremely important. Conservation and storage go hand in hand, and wasted heat used is energy saved. There are particular processes that are inherently involved in energy loss. Economy can be found in large-scale processes in which energy can be regained and used. Some quality value has to be placed on the energy, even though the wasted heat could be low quality. In industry, any steam saved may be worth something in some other process. An example of such conservation is evident in Berlin with the nuclear power plant. The hot water waste temperature is approximately 160°F. This water could possibly be used for space heating and would therefore be more economical. Even though this was discussed as a possibility, limitations were placed to applications that are strictly solar.

Although the industrial and agricultural heat requirements are somewhat different, an attempt was made to analyze the systems, whether industrial or agricultural, as long as the temperature requirements are identical. Some large-scale farm operations come close to the same quantity and quality of heat as industrial applications. It was noted, however, that space available was quite different with the two. Industry may have to manage with smaller space requirements for storage systems whereas the farm may use more space due to the availability. This could possibly change the storage material as well. Overlaps will still occur.

The need was found to define the applications in the agricultural and industrial areas. The following ten areas were listed as important concerns for thermal energy storage in the agricultural and industrial areas. Each area was given an economic, technical and social standing as to importance and is indicated on the chart listed below, 1 being most important.

	TECHNOLOGY	ECONOMICS	SOCIAL
a. Temperature	1	2	
b. Nature of Use	2	1	
c. Demand Frequency	1	1	
d. Demand Load	2	1	3
e. Distribution (Delivery)	1	1	3
f. Contingencies	2	1	2
g. Competition (Storage)	1	1	
h. Retrofit	2	1	1
i. Environmental Impact		2	1
j. Information Dissemination		1	1

Several different generic systems were discussed such as the hot water tank at approximately 250°F maximum, the phase change system with molten salts and the process steam.

The problem with these systems is that not enough information exists at this time and it is difficult to correlate. The potentials of such systems would be greater than the existing storage systems. The number of quads represented by the system would need to be determined and parameters would need to be set before the system is designed. The areas of concern would include the temperature, the load - can it be used steadily as it is stored, the time - how long can it stay, and the control - careful monitoring is necessary. Such factors would have to be considered before a storage concept could be developed. Industrial/agricultural needs for thermal storage cover a wide spectrum of engineering parameters such as temperature level, storage capacity and duration, charging-discharging rate and frequency, et cetera. The following chart shows the relationship of these parameters. The selection of a storage concept for a particular application will depend not only on the conditions imposed by the load, but also by the availability and collection of solar energy. Therefore, storage should be considered in total systems context and not as a separate entity.

Some of the specific problems discussed dealt with the question of long-range storage. Such long-term schemes as solar ponds - salty, and aquifer storage were discussed. In the agricultural field, long-term storage is not always necessary. An example of this would be the requirements for irrigation. The growing season - during high intensity sunlight - will have periods of cloudy weather, but the storage capabilities would not be considered long term. Irrigation requirements would be approximately two to eight months, 24 hours a day.

INDUSTRIAL/AGRICULTURAL PARAMETERS

	<u>INDUSTRIAL</u>	<u>AGRICULTURAL</u>
TEMPERATURE (°F)	0-1500°F (Extreme: greater than 1500°F)	0-350°F (Extreme: to 2000°F)
NATURE OF USE (supplied as)	Hot and cold water, steam, hot and cold air, other fluids	Hot and cold water, steam, hot and cold air, other fluids
DEMAND FREQUENCY (how often)	Less than hourly, maybe daily, seasonal, constant, batch	Daily, seasonal, constant, batch, intermittent
DEMAND LOAD (magnitude of BTU's)	_____ BTU's to _____ BTU's	_____ BTU's to _____ BTU's
DEMAND RATE (BTU/time)	_____ BTU's/hr.#storage to _____ BTU's/hr.#storage	_____ BTU's/hr.#storage to _____ BTU's/hr.#storage
CONTINGENCIES	Oil fired, natural gas, electric resistance, heat pumps, fossil fuel	Oil fired, natural gas, electric resistance, heat pumps, fossil fuel
COMPETITION	Compressed air storage, electro- chemical storage, hydraulic	Electrochemical storage, hydraulic
DISTRIBUTION	Local concentrated use	Local and dispersed use
RETROFIT	Space requirements, structural	Space and structural requirements
INFORMATION DISSEMINATION AND ACCEPTABILITY	Needs extensive dissemination, unions, acceptability dependent on economics	Needs extensive dissemination, acceptability dependent on social and economic acceptance

An example of another agricultural use would be crop drying, specifically corn. For the example, assume a harvest period of 25-30 days and a drying rate of 100 bushels per hour. If the initial moisture content is 24% and the final moisture is 14%, each 6 bushels of corn will require about 100,000 BTU's to dry. Drying air temperatures may range from 110-160°F. If a 3-day storage is assumed, the usable capacity must be 115×10^6 BTU. If the maximum storage temperature is 210°F and the minimum using temperature is 110°F, 115×10^4 pounds of water, or 18,400 cubic feet of storage will be required.

Some of the storage concepts discussed as possibilities were hot rocks, water, oils, salts, chemical reactions, desiccants, high pressure steam, hydrocarbons, and ammoniated salts. Some necessary areas of study would include packaging, heat transfer, and research into engineering demonstrations.

Many of the difficulties involved in these examples would simply be in the engineering design area. Using corn drying as an example, the most important goal to accomplish would be the establishment of the most reasonable system to get the job done. Therefore, the decision on this particular example would be to have further research and demonstration projects carried out. Many agricultural applications can be found in which storage concepts have already been developed that could provide the needed capabilities. The following charts approach the subject from a different concept. The two charts are divided into low temperature - less than 350°F, and high temperature - above 350°F. These charts indicate the major issues involved in several different storage concepts and a recommendation made by this group.

A need to develop methodology for matching the requirements for the applications to the most appropriate technologies was evident. An

LOW TEMPERATURE (< 350°F)

Industrial/Agricultural Process Heat

<u>STORAGE CONCEPT</u>	<u>CONCERN</u>	<u>RECOMMENDATION</u>
Sensible		
*Rocks-air as heat transfer	Heat transfer rates	Determine heat transfer characteristics for various flows
*Metals-air as heat transfer	Blower power requirements	Determine optimum storage medium size and shape to minimize blower requirements
Water and Steam	Cost of containment	Determine minimal cost of containment systems and corrosion
Oils	Cost of containment	Determine minimal cost of containment and establish corrosiveness of oils storage medium
	Toxicity and flammability	Establish candidate oil storage medium and perform basic engineering laboratory evaluation.

LOW TEMPERATURE (< 350°F)

STORAGE CONCEPT

CONCERN

RECOMMENDATION

Hot Water (400°F
in Aquifers

Energy density

Engineering optimization of
storage pressure

Heat loss

Establish porosity and
migration characteristics
of the specific aquifer

Size of Scale

Economic analysis of scale
versus capital investment

Social
(Environmental)

Identify and determine the
tradeoff requirements

Chemical Reaction

Reversibility

Selections, identification of
characteristics - kinetics,
life cycles, packing density

Materials of
construction

Engineering analysis

Heat transfer

Engineering analysis

Cost

Scale of operations defined

Environmental

Identify system studies
for trade-off

HIGH TEMPERATURE (> 350°F)

STORAGE CONCEPT

CONCERN

RECOMMENDATION

Hot water (400°F)
in Aquifers

Energy density

Engineering optimization of storage pressure

Heat loss

Establish porosity and migration characteristics of the specific aquifer

Size of scale

Economic analysis of scale versus capital investment

Social
(Environmental)

Identify and determine the trade-off requirements

Chemical Reaction

Reversibility

Selections, identification of characteristics - kinetics, life cycles, packing density

Materials of construction

Engineering analysis

Heat transfer

Engineering analysis

Cost

Scale of operations defined

Environmental

Identify system studies for trade-off

Application-Concepts matrix may be useful in this "matching" process. An example is attached. Such matrices could be developed for currently available, near term, and future "matches" with supplementary lists of problem areas and yet to be resolved issues.

There is also a need for a common basis for comparing alternatives. Not only would such a common methodology be useful for choosing from among alternative storage technologies, but also for comparing these systems with those using energy from other sources.

It was pointed out that one of the primary differences between industrial and agricultural energy storage would be the application of technology. With industrial applications the expertise for designing and the skill for constructing storage would probably be available on site. With agricultural applications, however, the information should be prepared for use by extension engineers. Many of the farmers would have the skill to handle plumbing, electrical and structural construction. They would, perhaps, need assistance from state extension engineers in designing for this storage. Thus, although the information required would be essentially the same, special effort is necessary to see that it is translated to the level that farmers could construct the storage-collector with input from the agricultural extension engineers. Behavior of systems can be matched to a storage system that is adequate.

When anticipating costs, the entire system should be discussed. The cost must also include any auxiliary fuel, cost of collectors versus storage capacity, et cetera. Therefore, what is needed to design a system becomes evident. A need is seen for the designer to find the proper storage system for each candidate. The areas of greatest need must be identified so that the system can be found that

EXAMPLE STORAGE CONCEPT/APPLICATION MATCHING MATRIX

NEAR TERM

STORAGE CONCEPT APPLICATION	SENSIBLE HEAT			PHASE CHANGE MATERIALS				CHEMICAL REACTIONS		
	ROCK	WATER	OTHER	INORGANIC	ORGANIC	PRESSURIZED STEAM	OTHER	DESICCANTS	DEHYDRATION	OTHER
I. AGRICULTURAL										
A. Crop Drying										
1. Corn										
2. Et cetera										
B. Space Heating										
1. Animals/ Poultry										
2. Crops										
3. Residential										
C. Process Water										
D. Other										
II. INDUSTRIAL										
A. Process Heat										
B. Lumber Processing										
C. Fabric Drying										
D. Other										

will produce some savings. After the system has been chosen, some of the problems and issues concerning the system could be exposed. Therefore, once the storage concept has been identified, the important issues can also be identified and necessary work be done.

Basically, the same characteristics would apply to farm applications as would apply to industrial applications. Therefore, the information should be collected and the problem addressed. The following chart indicates the problem issues in high temperature and low temperature storage concepts. The chart also includes recommendations for further development of such concepts in the agricultural and industrial areas.

Other topics that were considered briefly were the need for developing "packaged" systems for those with insufficient technical backgrounds. Some particular problems discussed were engineering design of the energy storage system and at what rate the heat can be moved. Engineering parameters would include the temperature, the load factor, the cost for BTU storage, and the time to maintain in storage. Further research is needed in phase change materials or storage capabilities. This would involve technological problems such as cycling. Solid desiccants are out if low temperatures are being used. Some research is being done, through the heating and cooling branch of ERDA, into the use of paraffin as a storage medium.

Emphasis was placed on the availability of information. An important need was expressed for an information retrieval system. The problems need to be exposed in order to deal with the issues properly.

General recommendations by this group included the following conclusions:

- 1) System engineering studies for agricultural application
- 2) Identify highest energy use by application area

- 3) Identify the chemical reaction candidates
- 4) Identify candidates for the thermal energy storage systems for process steam
- 5) Develop methodology for matching the requirements for the applications to most appropriate technologies
- 6) Establish criteria for comparing alternatives
- 7) Consider storage in total system concept.

In the following charts, the final summary of the discussions of the group is presented. Included are the comments made by the members of the group and summarized in the STORAGE CONCEPT - CONCERN RECOMMENDATION form.

BUILDING HEATING AND COOLING

This group was chaired by R. J. Kedl of Oak Ridge National Laboratory. The rapporteur was T. McQueen of Louisiana State University.

The participants in this subsection suggested quite a number of topics for discussion. Among those, the following selections were made and grouped according to their general problem areas as:

- I. ECONOMIC
 - A. Retrofitting
 - B. Cost parameters
 - II. TECHNICAL
 - A. Storage media
 - B. Applications - heating and cooling, conventional versus solar energy as a source
 - C. Duration of storage - short term versus seasonal
 - D. Heat pumps - second law of thermodynamics
 - E. Materials containment
 - F. Heat exchangers
 - G. Thermal energy storage systems
 - III. GENERAL
 - A. Building code requirements
 - B. Thermal energy storage system demonstration projects
- For lack of time, the two subjects under this heading were not discussed.

In discussing the first major topic, economics, relative to the question of retrofit of existing buildings, an apparent conflict between the national goals for solar energy and the potential for achievement

concerning the retrofit application was noted. The national goal is to conserve energy, and retrofitting existing buildings with solar equipment would conserve as much energy as solar equipment in new buildings. Thus, from this point of view, retrofitting should be actively pursued. Indeed, the retrofit application is defined as a major element in the National Program for Solar Heating and Cooling, (Energy Research and Development Administration-23A). On the other hand, most serious studies (i.e. the National Science Foundation-Phase 0) suggest that the retrofit application is not expected to capture a significant fraction of the total solar energy market. Thus, uncertainty exists as to what extent the development program should be influenced by the retrofit application.

During the discussion of the retrofit issue, the following points were made:

1. Solar domestic hot water heaters are commercially available on a limited scale today. Availability will increase in a natural manner as economic incentives develop. No significant development work is required in this area.
2. Energy loss from existing residences and buildings is substantial. In many cases 30 to 50 percent of energy consumption for space heating could be eliminated by energy conservation measures without affecting comfort or environmental quality for the occupants. This can be accomplished by adding insulation, by double glazing windows, by eliminating infiltration, by insulating air ducts, et cetera. At this time, it is felt that the thrust of retrofitting should be in the direction of minimizing these energy losses. It is likely that retrofitting an existing residence with a solar unit

would be uneconomical without first minimizing energy losses, (see for example National Bureau of Standards - Retrofitting Existing Houses for Energy Conservation: An Economic Analysis (NBS-BSS-64)).

3. Economic incentives should be developed to encourage home owners to minimize energy losses from their residences.
4. The normal course for thermal energy storage development should be directed toward new construction where the home can incorporate energy conserving methods and materials in its initial construction. It is important to note that new developments in thermal energy storage technology will generally be applicable to the retrofit application. Thus, if incentives change in the future, a rather minor redirection of the development program will be necessary to include the retrofit application.
5. None of the above opinions are intended to discourage the homeowner from retrofitting his residence with a solar heat source. Indeed, he should be encouraged to do so. The comments made here apply only to the overall thrust of federally storage units. This thrust should be directed toward the most massive market if significant reduction in residential energy requirements for heating-cooling is to be achieved in the near future.
6. Thermal energy storage directed toward load leveling, a nonsolar application, for an individual building should be examined. The economic incentives, lower cost for off-peak power, are not well developed yet but are expected to increase in the future. The possibility then exists to retrofit a

thermal energy storage unit which was installed for load leveling, for solar heating and cooling. An example was given where some churches operate a relatively small air-conditioning unit for a long-period of time, preconditioning the church to handle the short term but high load experienced on Sunday. Consideration should be given to the concept of the building mass acting as a loadleveling energy storage system.

These points were formulated into the following recommendations:

1. Solar heating for domestic hot water is commercially viable today. No significant research and development is required.
2. The thrust of the retrofit application in existing buildings should be directed toward minimizing energy losses - conservation.
3. The current thermal energy storage application of peak shaving by the customer, and other nonsolar applications, should be examined for future solar retrofitting.
4. The thermal energy storage development program should be focused on new construction. New developments in thermal energy storage technology will generally be applicable to retrofitting.

In the area of developing and reporting of cost parameters and costs of solar systems, in general, there exist certain inconsistencies. Different authors use different procedures to develop projected costs of their systems. The point was made that costs of different systems are meaningful only when they have been computed on a system level. The two components of the system cost that must be considered are:

1. Initial Capital Cost. This should include initial equipment costs and installation costs. The cost of flat plate solar

collectors was cited as an example. The initial cost of equipment and installation should be considered. In addition, any additional costs associated with supporting structures, since these panels may be heavier than a conventional roof, should be included. Credit may also be taken for the elimination of other structural materials not required, for example, shingles.

2. Annual Operating Cost. This should include the entire life cycle operating and maintenance costs. These are difficult to assess; nevertheless, for a meaningful economic analysis they must be included. It was noted that rocks and water, used as storage media, can become expensive. For example, consideration must be given to storage tank and heat exchangers required. Lifetime expectations of equipment are questionable. There is little knowledge about the reliability of storage systems in general.

In discussing this topic relating to cost parameters, the following additional points were made:

1. More demonstrations are needed to develop more realistic cost numbers.
2. When cost analyses are performed for a given solar concept, it is strongly recommended that a parameter sensitivity analysis be included. This will indicate where the high cost items are located and will assist in program planning directed toward minimizing these costs. Current studies in this area illustrate this.
3. Consideration should be given to any environmental impacts and associated costs.
4. In conducting a cost-benefit analysis, the researcher should

consider benefits from two points of view: the direct economic benefit to the consumer and the benefit to the nation in terms of energy conserved. Considerations like these may lead to more definitive reasons for developing economic incentives - tax benefits - for solar applications in the residential and commercial area.

The comments made above led to the recommendations below:

1. The entire net cost of solar collector/thermal energy storage/application system must be considered where net cost takes into account savings affected by the elimination of other materials.
2. The initial cost should include equipment and installation costs. Annual cost should include life cycle operating and maintenance costs.

To analyze the issues under the technical category, a somewhat different approach was used. A generic thermal energy storage unit was broken down into its basic components, which are generally common to all systems. The developmental status of each component, including costs and problem areas, was addressed. The components were identified as follows:

1. Media
2. Containment - overall tank
3. Heat exchanger - thermal energy storage material capsules
4. Insulation
5. Auxiliary equipment - pumps, et cetera
6. Integration with other components - solar collectors
7. Controls
8. Monitors

It was intended to evaluate the status of each component for each thermal

energy storage mechanism - sensible and latent heat, reversible chemical reaction - as well as each application - heating and cooling. This was an ambitious undertaking; nevertheless, a realistic one. Within the time limits and the mechanism of group dynamics, the sensible and latent heat mechanisms for the heating application were addressed in some detail. The reversible chemical reaction mechanism and the cooling applications were addressed only briefly.

I. Status of thermal energy storage based on sensible heat - heating application

- A. Media - is classically water or rocks. No further research and development is needed.
- B. Containment - is defined as the water tank or rock vault. This is one of the high cost items in a sensible heat system. Further work is required to reduce life cycle costs of this component. Aquifer storage falls under this heading. It was felt that this concept has potential, particularly for the long term, district heating application. Research and development is required to demonstrate concept.
- C. Heat exchanger - is another high cost item. Further work is required toward reducing its cost.
- D. Insulation - requires investigation with respect to long term stability of underground applications. Impact of the cost of insulation may be important. Although not specifically related to insulation, the heat loss phenomena - storage efficiency - of aquifers should be investigated for the various aquifer types with the greatest potential.
- E. Auxiliary equipment, integration, controls, monitors - are thought to be resolvable with existing technology and no major research

and development is required.

These points were formulated into the following recommendations:

1. Media - No further research and development is required.
2. Containment - Further work is required toward reducing life cycle costs. Research and development is required for aquifer storage.
3. Heat exchangers - Further work toward reducing life cycle costs is required.
4. Insulation - Long term stability of underground insulation requires investigation.

II. Status of thermal energy storage based on latent heat - heating application

- A. Media - is relatively available. Many attractive phase change materials are already known and involve a number of chemical species. Thermo-physical properties and behavior characteristics of these materials are generally available, to a greater or lesser degree, depending on the material, property or behavior parameter involved. There are some discrepancies in the literature concerning properties and behavior, particularly in thermal cycling. These discrepancies should be resolved. It was suggested that standardized testing procedures would be helpful in this area. Long term nucleation of phase change materials should be investigated, particularly when nucleating agents are added. Competent authorities disagree as to the expected lifetime of nucleating agents, or for that matter, even the lifetime of self nucleating materials. In general, researchers should be more professional in reporting properties and behavior of phase change materials. More attention should be given to describing their equipment,

materials and procedures used.

- B. Containment and heat exchangers cannot be separated because of the multiplexity of proposed thermal energy storage systems based on phase change materials - often these two components are the same. For example, the phase change materials may be encapsulated and the capsules then arranged in a holding tank - in this case the components are separable. However, the phase change materials may be contained as microcapsules in the building structural components or wall board and in these cases the components are not separable. Because of this multiplexity, it is difficult to make specific comments. The point was made that packaging of the phase change material is at least as important as the material itself. Accepting the idea that many attractive materials are already available (under A-Media), then the focus of research and development should be toward the engineering design of package systems. Of particular concern is the cost of the package system. According to some recent studies, active thermal energy storage systems charged with phase change materials may not be significantly cheaper than sensible heat thermal energy storage systems charged with water. One of the reasons for this is a high projected cost of the phase change material capsules rather than the phase change material itself.
- C. System evaluation is necessary. The general statement was made that thermal energy storage demonstration units for field engineering evaluation are necessary for phase change material concepts. One extension of this thought is that attractive thermal energy storage concepts charged with phase change

materials should generally be funded through the demonstration phase.

- D. Auxiliary equipment, insulation, and control are, in general, not considered to be serious problems. However, problems may be encountered on a specific system basis. These should be investigated as needed.
- E. Monitoring was argued as to its necessity for residential applications. Since a thermal energy storage system charged with phase change materials is essentially isothermal in operation, it will probably be difficult to devise a simple instrument to monitor the stored energy content.

Recommendations for use of phase change materials in thermal energy storage systems are

1. Media - Some materials require further development. Discrepancies in published results of cycling performance of phase change materials should be resolved. Standardized testing procedures should be developed for material properties.
2. Containment, heat exchanger - The packaging of the media is as important as the media itself. Emphasis should be focused on engineering design of phase change material packaged systems in future studies.
3. Systems evaluation - Thermal energy storage demonstration units for field engineering evaluation are necessary with phase change materials.

Due to the lack of time, the status of thermal energy storage based on the heat of reaction was addressed only superficially. Generally, this area is in a lesser state of development; indeed, it is considered by many to be embryonic. All the potential reactions have not yet

been identified. Research and development required to fully implement this concept may be substantial. Basic and fundamental research is needed before systems studies can be proposed. Containment of some chemical systems for energy storage may be difficult. Economical and technical feasibility and reliability must be shown. Control of the chemical reaction may be difficult. Getting the reaction to go completely to the correct end product with no undesirable by-products may be difficult. Although there are many problems, the concept of thermal energy storage by means of reversible chemical reactions has many attractive features, and its full potential should be explored.

Thermal energy storage for the cooling application could not receive enough attention either. However, many of the previous comments made concerning sensible and latent heat storage for the heating application are appropriate for cooling as well. It was felt that systems and materials studies should be initiated to determine feasibility and requirements for energy storage to support the solar cooling application.

In summary, the issues, concerns and recommendations for this group's discussion are shown on the following pages.

ISSUE	CONCERN	RECOMMENDATION
Retrofitting of thermal energy storage into existing buildings	Focus of development program	Solar heating for domestic hot water systems is viable today, no long range research and development is required. The thrust of the retrofit applications in existing buildings should be directed toward minimizing heat loss - energy conservation. Current thermal energy storage application for peak shaving should be examined for future solar retrofitting. Thermal energy storage development program should be focused on new construction. New developments in thermal energy storage will generally be applicable to retrofit.
System cost parameters	Standardization of costing procedures	Entire net cost of system must be considered, where the net cost includes savings effected by the elimination of other materials. Initial cost should include equipment and installation costs. Annual costs should include life cycle operating and maintenance costs.
Development status of thermal energy storage elements		
*Sensible heat (heating application)	Media	No further research and development is required.
	Containment	Further work required toward reducing life cycle costs. Research and development is required for aquifer storage.

ISSUE	CONCERN	RECOMMENDATION
*Latent heat (heating application)	Heat exchangers	Further work toward reducing life cycle costs is required.
	Insulation	Long term stability of underground insulation requires investigation.
	Media	Some materials require further development. Discrepancies in published results of cycling performance of phase change materials should be resolved. Standardized testing procedures should be developed for material properties.
	Containment-Heat Exchanger	The packaging of the media is as important as the media itself. Emphasis should be focused on engineering design of phase change material package systems in future studies.
	Systems evaluation	Thermal energy storage demonstration units for field engineering evaluation are necessary with phase change materials
*Reversible chemical reaction	Status	Generally, chemical energy storage is in a lesser state of development. Full potential of this technology must be explored.
*Thermal energy storage for cooling	Status	Systems and material studies should be initiated to determine feasibility and requirements for storage to support the solar cooling application.

SUMMARY

During the final general session of the workshop, each session chairman presented the summaries of their findings as given at the end of each section. After that, the floor was opened for general remarks pertaining to the discussions held. The two major issues evolving out of these were economics and public information programs in any phase of solar thermal energy storage. The entire system must be considered when looking at the cost of a solar system for cost analysis purposes. The capital cost of a solar unit would consist of the unit and the storage media.

It was felt that the success of any new technology lies within the transfer of knowledge to the general public. To do this effectively requires the efforts of all involved in the development of this technology. An educated public would be more receptive to the new developments and be more interested in implementing them. For this, all efforts should be focused in the general educational process.

It was the general consensus that future workshops are needed and should focus on the research and development of user need problems. Also, a narrower description of the workshop topic would be helpful. For all future workshops, it was recommended to start during one evening where preliminary and general discussions can be held in preparation to the full day's work. A common base of general and specific information would keep the participants in the correct directions. The length of one evening followed by a full day and a half was felt to be very satisfactory.

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AN INVITED WORKSHOP ON
ADVANCED ENERGY STORAGE TECHNOLOGIES
FOR SOLAR APPLICATIONS

April 23-24, 1976

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