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THE SERI SOLAR ENERGY STORAGE PROGRAM

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SUMMARY

The SERI Solar Energy Storage Program provides research on advanced technologies, systems analyses, and assessments of thermal energy storage for solar applications in support of the Thermal and Chemical Energy Storage Program of the DOE Division of Energy Storage Systems. Currently, research is in progress on direct contact latent heat storage and thermochemical energy storage and transport. Systems analyses are being performed of thermal energy storage for solar thermal applications, and surveys and assessments are being prepared of thermal energy storage in solar applications.

INTRODUCTION

As part of the Thermal and Chemical Energy Storage Program of the DOE Division of Energy Storage Systems, thermal energy storage technologies are developed for identified application areas by the laboratories designated with the appropriate lead responsibility. The SERI Solar Energy Storage Program supports the Thermal Energy Storage Program by researching advanced technologies and performing systems analyses and assessments.

The general objectives of the SERI Solar Energy Storage Program are to develop a better understanding of advanced thermal energy storage technologies for solar applications and to obtain information that allows storage developers to select promising thermal storage technologies for solar applications. To accomplish this objective, research and development are performed on advanced thermal storage options in an attempt to resolve technical and economic uncertainties that hinder development. New thermal storage concepts are also explored as part of this effort. Systems analyses are conducted for defined solar applications to determine thermal storage requirements and to aid in selecting thermal storage concepts. Surveys and assessments also are performed to examine the match between thermal energy storage technologies and solar application areas. For FY80, the emphasis of these activities is to support the joint plan between the DOE Division of Energy Storage Systems and the Division of Central Solar Technology for developing thermal energy storage for solar thermal applications (ref. 1). The SERI FY80 solar energy storage activities are discussed in the following narrative, with two areas discussed in some detail and the other two summarized briefly.

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ADVANCED TECHNOLOGY RESEARCH AND DEVELOPMENT

Thermochemical Storage and Transport Research

A new area in the SERI Solar Energy Storage Program for FY80 is thermochemical storage and transport research. Previous studies have raised questions as to the efficiency and cost capabilities of reversible thermochemical reactions for energy storage and transport (ref. 2). However, reversible reactions show significant technical promise because of their ability to store large quantities of heat at ambient conditions, an attribute which makes them appear particularly promising for long duration storage and transport. Therefore, an effort is in progress to define the efficiency and cost constraints for thermochemical storage and transport and to assess quantitatively the performance of such systems. The information developed will also be used to determine whether there are research opportunities that could make thermochemical energy storage and transport cost effective. If the cost and efficiency constraints are not prohibitive, laboratory research will be performed to understand the actual behavior of reaction systems.

Latent Heat Storage Research

The objective of latent heat storage research at SERI is to provide a quantitative understanding of advanced latent heat storage systems which can be used to assess their technical and economic potential. This section summarizes the results of an economic analysis of latent and sensible heat storage for home heating, a heat transfer analysis of a direct contact heat storage system, and a brief description of experiments to be undertaken to validate models and determine key mechanisms.

A comparative analysis of sensible and latent heat storage for home heating was carried out to define any performance or economic advantages attributable to the use of latent heat storage. Air/rock, air/salt hydrate, water, and water/salt hydrate systems were compared for a range of storage and collector sizes for locations of Albuquerque, N. Mex., and Madison, Wis. For a given load and size of collector array, increases in storage mass increase the amount of solar energy delivered until all the energy collected is used, the load is fully supplied, or losses from storage exceed the gains. Results describing the energy delivered to the load as a function of the storage mass for fixed collector areas, heating loads, and locations were obtained from a previous study (ref. 3). The cost of the solar system may be defined as a function of collector area and storage size. Dividing the cost of the system by the annual delivered energy yields a criterion for judging the relative economics of latent and sensible heat storage.

In this analysis no allowance was made for subcooling or degradation of the phase change material performance. Therefore, the conclusions drawn from the analysis are optimistic projections for latent heat storage. The major conclusions for home heating use include:

- Air-based salt-hydrate latent heat storage offers a four to one reduction in storage volume over rock bed systems, while liquid-based salt hydrate systems offer a two to one reduction over hydronic storage.
- Constant temperature operation during the phase change provides no operational advantage.
- The distinction between air- and liquid-based systems is far more important than that between sensible and latent heat systems.

These conclusions apply only for the home heating application analyzed, and more advantages are anticipated for latent heat materials used for storage in hot or cold side air conditioning or in solar thermal steam generation.

These results show that latent heat storage must be economically competitive with sensible heat storage for home heating unless space is at a premium. One of the major impediments to successful use of latent heat storage is the expense of providing sufficient heat transfer surface to overcome solid phase resistance during heat extraction. This problem possibly may be avoided by the use of inexpensive containment materials. Direct contact heat exchangers as suggested originally by Etherington and recently researched by workers at Clemson University and the Desert Research Institute (refs. 4,5) also show potential for cost reduction. Research at SERI has been directed at the latter approach since the results may be useful for higher temperature operation as well.

To date, heat transfer in macroscopic direct contact latent heat storage systems has been analyzed in terms of volumetric heat transfer coefficients. This method is convenient for reporting experimental results but, because the fundamental physical processes governing heat transfer do not appear explicitly, it is of limited value in scaling up or in designing a system with a different geometry, phase change material, or immiscible fluid. Experiments are being conducted on salt hydrate/oil systems (Figure 1) such as would be used for space heating. This temperature range was chosen to simplify the experimental portion of the work and because of the previous experimental results available. As the models are developed further, it is expected that effort will shift to higher temperature applications where constant temperature operation and volume reduction are more critical and latent heat storage may be more beneficial.

Although heat transfer in direct contact systems may be calculated from a knowledge of the heat transfer coefficient U, the heat transfer area A, and the temperature differential, the calculation is not as straightforward as in systems with fixed heat transfer areas where each term has an easily identifiable mechanism and meaning. The heat transfer area A is equal to the surface area per drop of oil multiplied by the number of drops in the system. Surface area per drop is a function of drop diameter, which is itself a function of flow rate, distributor geometry, and fluid properties. The number of drops in the system is a function of dispersed phase flow rate, drop size, and physical properties of both phases.

If fluid flows slowly through a nozzle, drops will form at the surface, grow, detach, and rise. When the flow rate increases to a critical velocity, a jet forms and the drop diameter suddenly decreases. As flow rate increases the jet lengthens. When the jet length is a maximum, the surface area per unit volume of fluid also goes through a maximum. This critical flow rate and the drop size at this velocity may be determined from theory. The drop size at other flow rates must be found by empirical correlations with limited ranges of applicability (refs. 6-8).

If single drops rise through an infinite, quiet, continuous phase, their terminal velocities may be predicted from a force balance. When many drops rise simultaneously, they decrease the effective free area through which the drop rises. This reduction in free area compresses the streamlines around the drop, producing additional drag and dramatically reducing the rise velocity. This interaction may be described quantitatively and used to predict the number of drops in a storage unit (ref. 9).

Defining a heat transfer coefficient is a difficult process. Drops with diameters greater than 0.7 cm or rising with $N_{Re} > 200$ are often classified as large. They periodically shed their wakes, setting up oscillations within the drop which provide internal mixing. Such drops have resistance to heat transfer only at the surface, and heat transfer is relatively rapid. The fractional approach to thermal equilibrium is given by

$$Em = 1 - e^{-\frac{Ah}{V \rho C_p} t} \tag{1}$$

where Em = fractional approach to equilibrium $[(T - T_i)/(T_c - T_i)$, with c referring to the continuous phase and i to the interior of the drop]; h = heat transfer coefficient (J/s °C cm^2); V = volume (cm^3); ρ = density (g/cm^3); C_p = specific heat (J/g °C); and t = time (s).

In drops with diameters less than 0.3 cm and rising at low velocities, surface tension is considered strong enough to stop all movement within the drop. These small drops behave as rigid spheres in which internal conduction is the rate limiting mechanism. The fractional approach to equilibrium is much slower than that of mixed drops and is given by

$$Em = 1 - \frac{6}{\pi} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-\pi^2 n^2 \alpha_d}{a^2} t\right), \tag{2}$$

where α = thermal diffusivity (cm^2/s) and a = drop radius (cm).

For drops of intermediate size toroidal internal circulation patterns are set up. The dominant resistance is again internal but the characteristic distance for conduction is approximately half the radius. The fractional approach to equilibrium may be approximated as

$$Em = 1 \frac{6}{\pi} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-\pi^2 n^2 2.5 \alpha_d}{a^2} t\right). \qquad (3)$$

Effective heat transfer coefficients may be defined for circulating and rigid drops, but they are simply a mathematical convenience (ref. 10).

The predictions of the model have been compared with heat transfer data obtained on a system at Clemson University. The data compare reasonably well with results predicted from existing expressions for drop size, holdup, and heat transfer to a circulating drop, although a different heat transfer model is required at the end of the melting period. While this agreement is encouraging, it is not proof of model validity. As no experimental measurements were taken of the effect of drop size or holdup, the choice of heat transfer mechanism is simply an adjustable parameter in the model, since the drop size is such that any one of the three heat mechanisms could apply. Furthermore, several of the relations contain constants which were obtained experimentally at conditions considerably removed from those found in latent heat thermal storage units. Therefore, it is necessary to carry out experiments to independently validate or modify the equations for drop size, holdup, and heat transfer mechanism.

To test drop size predictions and to determine whether the rising drops behave as rigid spheres, circulating drops, or oscillating drops, a "single drop" experiment is being utilized. This experiment allows the measurement of drop size and heat transfer rate where flow rate, contact time, and continuous phase temperature can be closely controlled. To investigate holdup, a pilot-scale, "multi-drop" column is being constructed. This unit will also allow assessment of the total model and will be useful in studying continuous phase entrainment, phase segregation, and crystallization behavior.

SYSTEMS ANALYSES AND ASSESSMENTS

Thermal Storage Survey and Assessment

The thermal storage technologies under development must fit the intended solar applications. Therefore, continual communication is critical among researchers developing solar and storage technologies. In this area, SERI continually surveys the thermal storage technologies under development within the Division of Energy Storage Systems and elsewhere (ref. 11). Communications are then developed with the various solar application areas and their needs are identified through discussions and analyses. The goal of these activities is to arrive at a coordinated plan that will provide timely development of thermal storage technologies for defined solar applications.

Systems Analysis of Thermal Storage

The Systems Analysis of Thermal Storage is being conducted to support decision points in the Thermal Energy Storage for Solar Thermal Applications Program (ref. 1). In this program, second and third generation thermal storage technologies will be developed to provide lower cost and/or improved performance over the first generation technologies currently being deployed in Solar Thermal Large Scale Experiments (LSE). In each of the seven elements of the program, thermal storage technologies will be developed that are appropriate for different types of solar thermal systems:

- water/steam collector/receiver;
- molten salt collector/receiver;
- liquid metal collector/receiver;
- gas collector/receiver;
- organic fluid collector/receiver;
- liquid metal/salt collector/receiver; and
- advanced technologies (third generation).

For the first six elements, the second generation technologies developed will be verified through a retrofit of a solar thermal LSE (e.g., Barstow, repowering, Shenandoah, etc.). The last element develops advanced technologies for all types of solar thermal systems.

The objectives of the SERI systems analysis effort are to provide value data on thermal storage and rankings of thermal storage concepts. The value data are the basis for thermal storage cost goals which are then used to screen thermal storage concepts. Those concepts which pass this first screening are ranked on a delivered energy unit cost basis (busbar energy cost for electric power) within a specified program element. The process is then repeated as needed for other elements. In this manner, promising thermal storage concepts will be identified for development.

Value expresses quantitatively the price that a user is willing to pay for a system for a given application based on the cost of alternative systems, including capital, fuel, and operations and maintenance (O&M). The value of solar thermal systems thus depends on the energy supply alternatives (oil, gas, coal, nuclear, etc.), assumed future prices and escalation rates, and the performance of the solar thermal system. For electric power applications, Aerospace (ref. 12) and Westinghouse (ref. 13) have performed calculations of value for storage-coupled solar thermal systems.

For a given collector area, with all other parameters constant except storage capacity (H), the contribution to the total system value by thermal storage is calculated from the storage-coupled solar thermal system value as follows:

$$\left.\begin{matrix}\text{Total Thermal}\\ \text{Storage Value}\end{matrix}\right|_{H} = \left.\begin{matrix}\text{Solar Thermal}\\ \text{System Value}\end{matrix}\right|_{H} - \left.\begin{matrix}\text{Solar Thermal}\\ \text{System Value}\end{matrix}\right|_{H=0}, \qquad (4)$$

where the last term refers to the solar thermal system with no storage or only buffer storage. This calculation may be repeated to provide the thermal storage value as a function of both solar thermal collector area and location. To identify the appropriate combinations of storage and collector area, the ratio of system cost to system value must be minimized for that collector area.

The approach described by equation (4) has been followed to calculate the value of thermal storage for solar thermal electric power applications. Table I presents the results for stand-alone solar thermal plants based on the Westinghouse and Aerospace data. The values shown are for a plant startup in the late 1980s and a small solar thermal penetration in the utility grid (less than 10% of the peak generation capacity). The data were generated employing conservative to average fuel price assumptions and Barstow technology. For more efficient thermal storage concepts, a higher value and cost goal will result; for less efficient concepts the value and cost goal will be lower.

The cost goals in Table I are the total capitalized value of thermal storage, which include direct, nondirect, and O&M costs. Direct costs include equipment, materials, labor, installation, etc. Nondirect costs are generally calculated as a percentage of the direct costs. Based on similarities with conventional power plants, the following nondirect factors are employed unless better data are available:

- contingency and spares--15 %;
- indirects (licences, fees, studies, etc.)--10 %; and
- interest during construction--19 %.

The total is a 44 % increase in the direct costs.

Operations and maintenance (O&M) are annual costs. The capitalized equivalent is:

$$\text{Capitalized O\&M} = \frac{\begin{pmatrix}\text{Annual}\\ \text{O\&M Cost}\end{pmatrix} \begin{pmatrix}\text{Levelizing}\\ \text{Factor}\end{pmatrix}}{(\text{Fixed Charge Rate})} \qquad (5)$$

Typical data for electric utilities are:

- annual O&M cost--1-2 % direct cost;
- levelizing factor--1.88; and
- fixed charge rate--17 %.

When available, actual O&M data should be employed. The net effect is to increase the cost by an additional 11 % (O&M 1 %) to 22 % (O&M at 2 %) of the direct capital cost. Combining the nondirect and O&M factors, the total capitalized cost is 1.55 to 1.66 times the direct capital cost. This cost should be compared to the cost goals in Table I.

Once several thermal storage concepts are established to be within the cost goals for a program element, SERI will provide comparisons for DOE to identify promising candidates for development. For each program element a reference solar thermal system and thermal storage concept are defined. Then, the delivered energy costs are calculated when the reference thermal storage concept is replaced by an alternative, with all other parameters constant (i.e., storage capacity, collector area, location, dispatch strategy). Each of these parameters is then varied systematically over its expected range. This procedure is repeated for each alternative, and the delivered energy cost for all thermal storage concepts are then compared.

The calculation of the delivered energy cost depends strongly upon the cost and performance of the thermal storage concepts. This information will be supplied by a subcontractor with experience in this type of analysis. This subcontractor will rework the thermal storage developer's data to ensure that all data are consistently calculated for the cost and performance analysis.

In addition to the cost goals and the delivered energy cost of each concept, other factors will be considered in selecting storage concepts for development. These include:

- safety,
- development status and program schedules,
- applicability to several program elements,
- development cost,
- development risk, and
- program priorities.

The Department of Energy, NASA Lewis Research Center, Sandia Livermore Laboratories, and SERI will participate in the selection of the storage concepts for development.

CONCLUDING REMARKS

The SERI Solar Energy Storage Program summarized in this paper consists of activities in advanced technology research and development and in systems analyses and assessments. Summaries were given of the effort in latent heat storage research and the systems analysis of thermal storage. The intent of all these activities is to provide technical and economic information that will aid the rapid selection and development of thermal storage technologies for solar applications. At this time, particular emphasis is given to the definition of thermal energy storage for solar thermal applications because of the need to provide appropriate storage technologies for the solar thermal systems now under development. In the future, SERI's Solar Energy Storage Program will assist the rapid development of a variety of storage technologies which will augment the displacement of conventional fuels by renewable solar energy sources.

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Table I. RECOMMENDED COST GOALS[a] FOR THERMAL STORAGE IN SOLAR THERMAL ELECTRIC PLANTS

(1976$)

Storage Capacity (hours)	High Insolation (Barstow, CA)		Medium Insolation (Midland, TX)		Low Insolation (Seattle, WA)	
	($/kW$_e$)	($/kWh$_e$)[b]	($/kW$_e$)	($/kWh$_e$)[b]	($/kW$_e$)	($/kWh$_e$)[b]
3	255	85	120	40	60	20
6	300	50	180	30	90	15
9	--[c]	--[c]	225	25	110	12

[a] Total cost of a thermal storage concept (including power-related, energy-related, nondirects, and O&M) must be lower then the value-derived cost goal.

[b] $/kW$_e$ = Total thermal storage value.

$/kWh$_e$ = Average thermal storage value; equal to total thermal storage value divided by h, the storage capacity.

[c] Data not available.

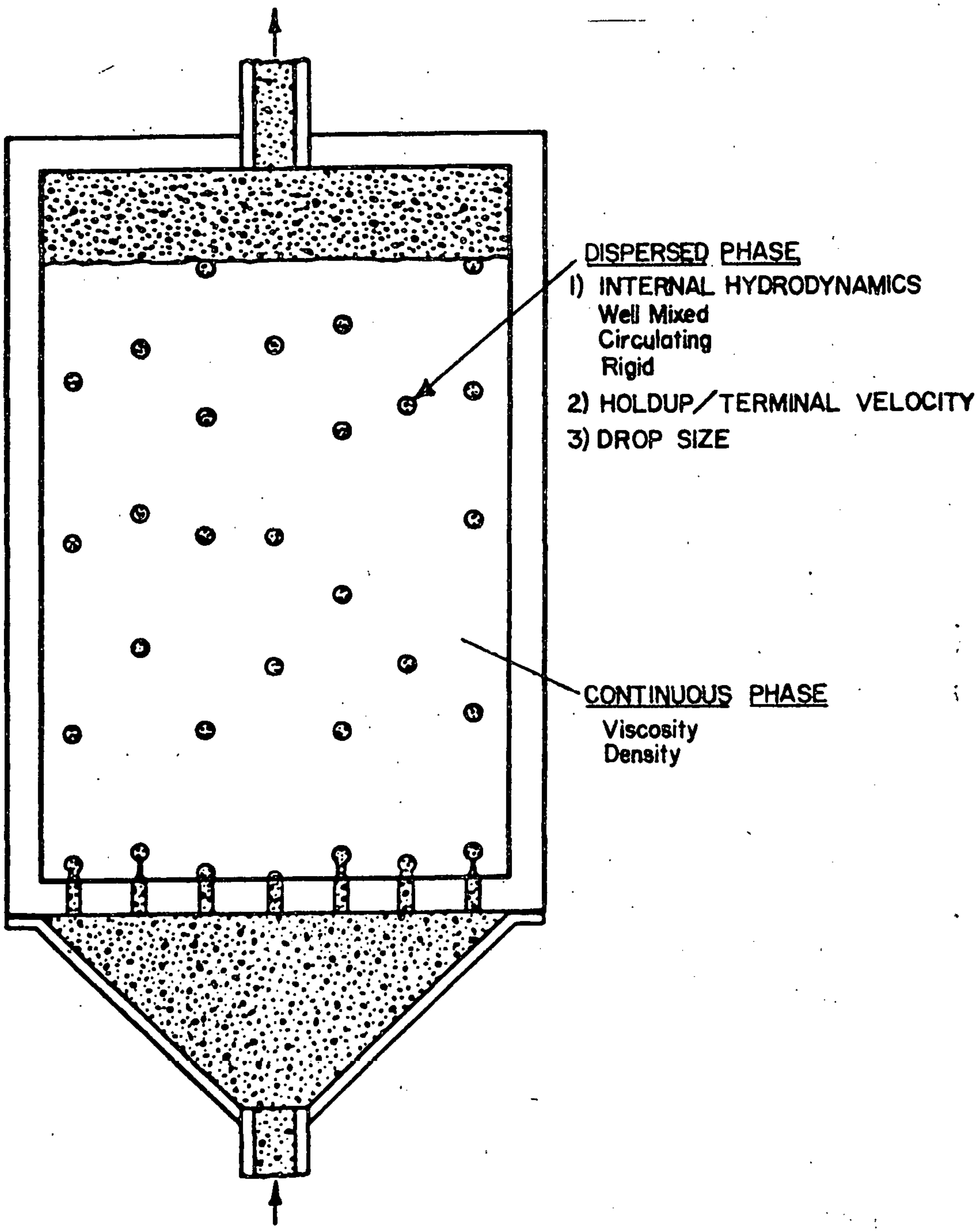

FIG. I MECHANISMS CONTROLLING HEAT TRANSFER

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