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Review and Assessment of Thermal Energy Storage Systems Based upon Reversible Chemical Reactions

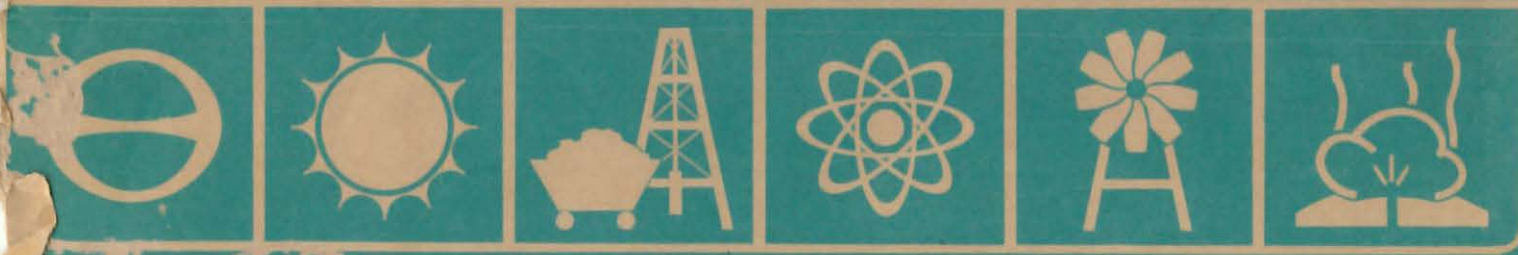
J. J. Iannucci, J. D. Fish, T. T. Bramlette

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789.

Printed August 1979



Sandia Laboratories
energy report



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

SAND79-8239
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REVIEW AND ASSESSMENT OF THERMAL ENERGY STORAGE SYSTEMS
BASED UPON REVERSIBLE CHEMICAL REACTIONS

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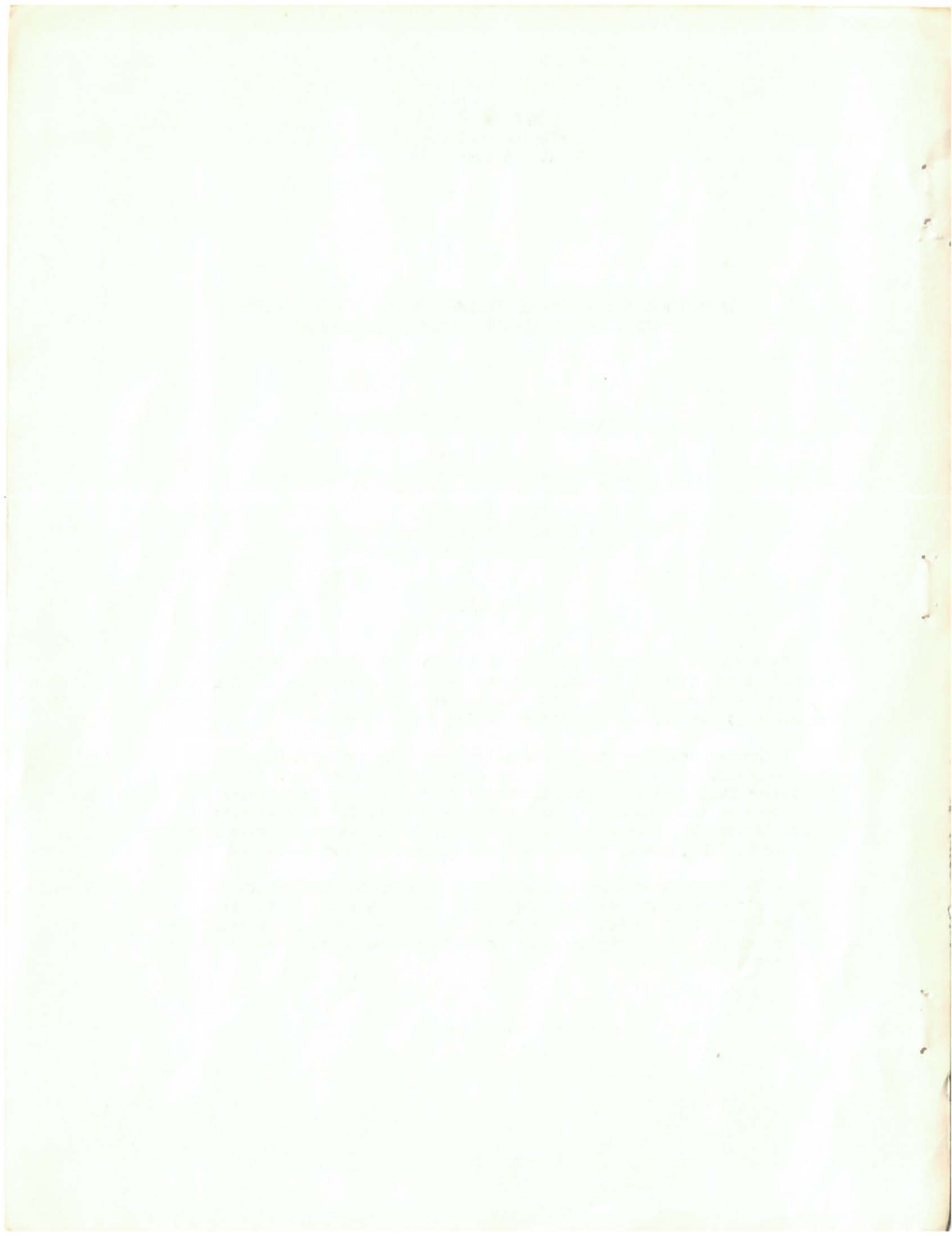
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ABSTRACT

This report presents a summary of a number of projects related to thermal energy storage for solar thermal electric plants and carried out under DOE's Thermochemical Energy Storage and Transport Program. Technology projects, as well as analytical studies, are reviewed.

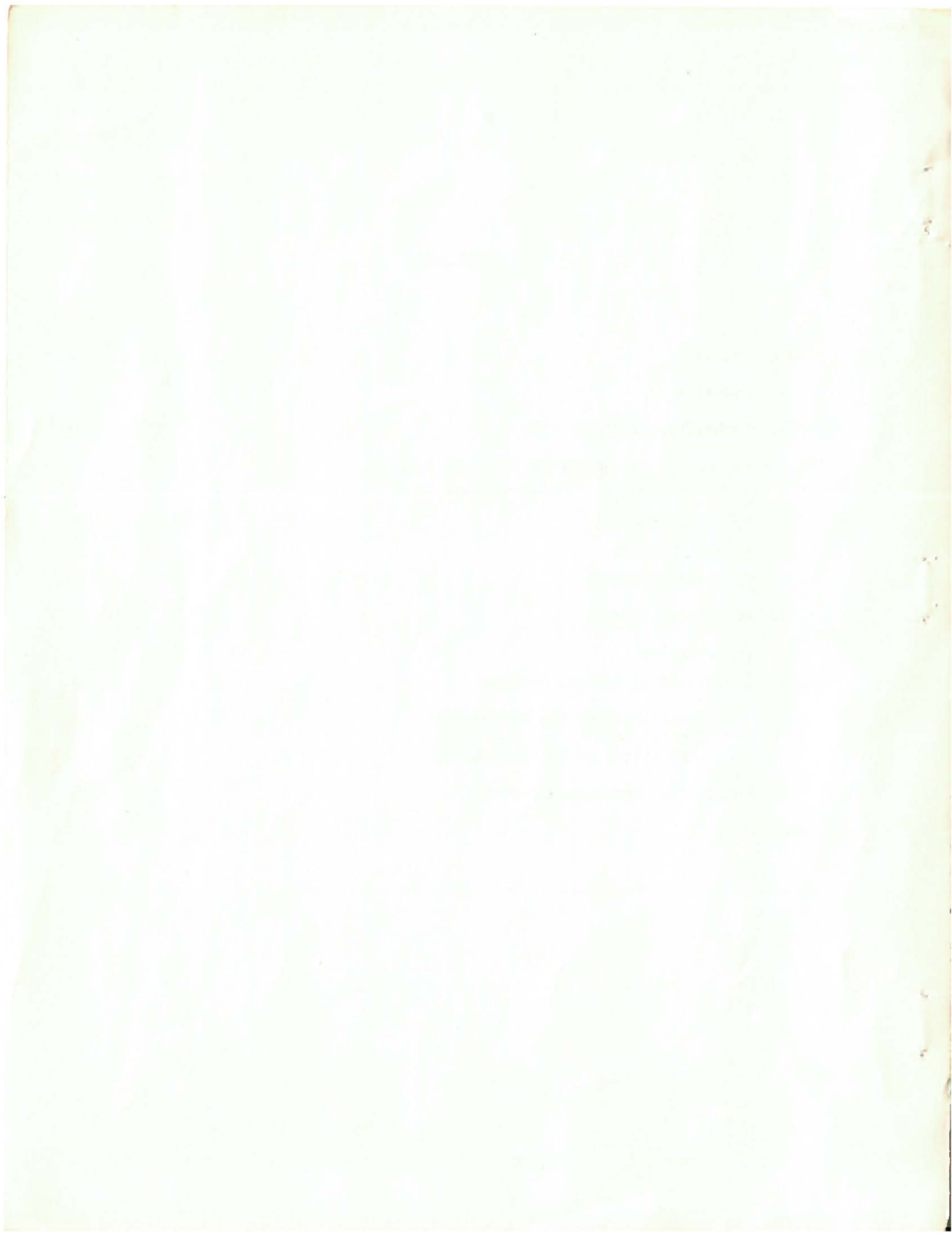
Technical problems remain for all of the reaction systems under consideration. More importantly, the analytical studies have led to the conclusion that long-duration (seasonal) storage of any type presently envisioned is not economically attractive and that, for short-duration (diurnal) storage, thermochemical systems would not be competitive with the advanced sensible energy storage systems currently being developed.

It is recommended that future efforts related to thermochemical systems place more emphasis on fundamental research aimed at far-term applications and on systems analyses of other solar/chemical applications such as: energy transport, chemical production (including potential fuels), and chemical heat pumps.



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REVIEW AND ASSESSMENT OF THERMAL ENERGY STORAGE SYSTEMS BASED UPON REVERSIBLE CHEMICAL REACTIONS

Introduction

The Thermochemical Energy Storage and Transport (TEST) Program^{1,2} is part of the National Thermal Energy Storage Program of the DOE Division of Energy Storage Systems (STOR). The TEST program, under Sandia management for the past two and a half years, has been involved in examining a variety of chemical reaction systems and possible applications. Current projects relate to thermal energy storage for solar and non-solar utilities; energy transport for nuclear, fossil, and solar energy systems; heat pump storage systems for solar heating and cooling; and research generic to these applications.

Recent preliminary studies conducted on general, as well as specific, thermochemical systems for solar electric utility storage applications have provided a sufficient data base for reaching conclusions and making recommendations. Further, although based upon solar utility applications, the nature of the studies performed makes it possible to extend these conclusions and recommendations to the entire thermal energy storage portion of the TEST program.

I. Overview

The TEST program was initiated to identify and investigate thermochemical energy storage subsystems which might possess unique features that would make them attractive for solar thermal electric applications. The desirable features include: (1) long-term storage--reactants and products can be stored at ambient temperatures with consequent low energy losses; (2) compactness--energy is stored by breaking chemical bonds with resultant high energy density; (3) high efficiency--the storage subsystem can be integrated into the complete system, thereby minimizing waste heat losses; (4) low cost--the basic chemicals are inexpensive and readily available, and ambient temperature storage allows less expensive containment material and eliminates insulation; (5) the potential for use with baseload solar thermal electric power plants because of the long term storage capability; and (6) transportability--many of the possible chemical systems are composed of gaseous and liquid species that can be transported easily, and at ambient temperature. Other characteristics which have been identified recently include the potential for: (1) recombination of the endothermic reaction products in a fuel cell; and

(2) the use of the reaction products as the working fluid in a thermodynamic cycle which would incorporate a storage feature.

Two broad courses of investigation have been carried out under the TEST program. First, a number of experimental investigations were initiated to obtain basic technical data on the chemical reaction systems thought to be most promising. This information was used to determine the feasibility of the proposed chemical reactions and to develop cost and performance models of the energy storage subsystems. Second, a systems analysis of the thermal energy storage subsystem/solar thermal electric conversion plant combination was initiated to assess the value of the unique features of thermochemical systems. The specific objectives of this systems study (conducted jointly by Sandia and Rocket Research Corporation) were to: (1) develop cost and performance models for all of the various subsystems (heliostats, receivers, energy storage, equipment for electricity generation, etc.); (2) construct a cost and performance model for the complete system; and (3) exercise this total system model with data from various geographical locations to determine the tradeoffs possible between the various subsystems in the design of solar thermal electric conversion plants for baseload operation.

Section II of this report summarizes the results from the experimental investigations of energy storage systems based upon the reversible decomposition of ammonium hydrogen sulfate, calcium hydroxide, and sulfur trioxide. Also presented are the results of a reaction screening task to identify other promising chemical reactions. The results of the systems analysis tasks are presented in Section III. Included there are a discussion of the fundamental thermodynamic limitations of thermal energy storage subsystems based upon reversible chemical reactions, a description of the modelling employed in the systems analysis, and a summary of the major results obtained to date. The final section presents the conclusions reached and recommendations for future investigations.

II. Technology Projects

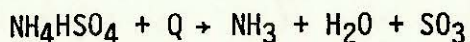
Summary of Current State of Technology

To date, a successful demonstration of a complete storage cycle based on a high temperature, reversible thermochemical reaction has not taken place. For each reaction system, at least one step of the cycle awaits definitive demonstration of technical feasibility. In addition to the technical breakthroughs required, fundamental thermodynamic properties of the reaction components and kinetics of the various reactions under a wide range of conditions need to be measured. Engineering studies to optimize system integration and to maximize overall efficiency also need to be continued as more, and more accurate, data become available.

The status of three experimental projects and one reaction screening activity are described below briefly. For additional details, References 3-7 should be consulted.

Ammonium Hydrogen Sulfate Decomposition⁴

The reaction



appears promising for several reasons: it possesses a high heat of reaction, which leads to high energy density; the reaction products are condensable, which facilitates storage; and the liquid and gas phases minimize the heat transfer problems associated with the reactor. The reaction, with a turning temperature* of 740 K (870°F), would be applicable to a storage subsystem interfacing with a central receiver steam, Rankine power plant⁶. Problems still to be resolved include: (1) development of a reaction mechanism which will allow satisfactory separation of SO₃ from NH₃ and H₂O during the thermal decomposition of ammonium hydrogen sulfate, AHS; (2) selection of materials of containment; and (3) development of efficient operational cycles.

Reaction screening via thermogravimetric and differential thermal analyses indicated that the Group IA metal sulfates and certain metal oxides would allow product separation through a two-step reaction sequence. Of the fifteen sulfates and six oxides selected for more detailed analysis, only Cs₂SO₄, Rb₂SO₄, K₂SO₄ and ZnO were found to be suitable as a means of providing energy storage with satisfactory product separation. Thermodynamic properties, reaction rate constants and optimum reaction conditions for mixtures of AHS and each of these compounds have been determined. At present, all the metal sulfate and metal oxide separation reactions tested require temperatures above 1125 K (1565°F) for completion. At this high a temperature, SO₃ decomposes and hence the catalyzed back-reaction, SO₂ + 1/2O₂ → SO₃, would have to be carried out prior to storage. Currently under investigation are mixtures of AHS and boron oxide compounds. A systematic study has begun to determine whether a mixture can be found which decomposes as desired and which is complete for temperatures below 1125 K.

Studies to identify metals suitable for construction of the high-pressure reactor required to separate NH₃ and H₂O from SO₃ by a condensation technique have revealed that all metals examined promote unidentified, but definitely undesirable, side reactions when exposed to NH₄HSO₄-metal sulfate mixtures at 675 K (755°F). Vicor glass, however, did not promote any observable side reactions, which suggests that any metal reactor system designed for use in NH₄HSO₄ decomposition might have to be glass-lined.

A bench-scale flow unit in which the decomposition reactions can be studied has been constructed. This system is to be used to determine the reaction characteristics and kinetics in a flow mode, the operating space velocities, and the operating heat flux values. Initial runs have been completed.

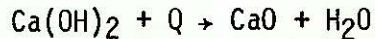
Several conceptual designs of solar thermal electric systems employing the ammonium hydrogen sulfate energy storage subsystem have been synthesized,

*The turning temperature is defined as the ratio of the enthalpy change for the reaction divided by the entropy change. It is the temperature at which equilibrium favors neither the products nor the reactants; i.e., the equilibrium constant is equal to unity.

and their technical and economic characteristics are being analyzed currently.

Calcium Hydroxide⁵

The reaction



is an attractive candidate for thermal energy storage because of high energy density and low materials costs. This reaction, with a turning temperature of 720 K (835°F), would have the same application as the ammonium hydrogen sulfate system discussed in the previous section⁶. The overall objective of the Reference 5 investigation was to establish the technical and economical feasibility of this application. The two major activities were: (1) a study of basic hydration/ dehydration properties, and (2) conceptual design and evaluation of fixed-bed, rotating drum, and fluidized bed reactors.

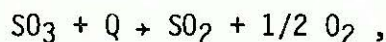
After characterizing the composition of the as-received Ca(OH)_2 , it was thermally cycled many times. It was found that cycling continually decreased the amount of water that could be reacted with the system (34% of the initial amount after 140 cycles). The reason for this decrease is not fully understood, although it has been postulated to be due to the presence of noncondensable gases (primarily H_2) on the surface of the reacting materials. An as yet unidentified corrosion mechanism is suspected to be responsible for the H_2 generation.⁵

Conceptual designs of three methods for transferring energy into and out of the system showed the economics of fixed and fluidized bed systems to be about equal and both to be superior to a rotating drum.

While there is a possibility that this reaction may be attractive from an economic standpoint, considerable basic research would be required before a thermal energy storage system of significant size could be built, tested, and evaluated.

Sulfur Trioxide³

The reaction



with a turning temperature of 1055 K (1440°F), had been suggested for both energy storage and energy transport⁶. The critical element to demonstrate feasibility of this reaction system is a catalyst capable of withstanding the required high-temperature endothermic reaction conditions.

The purpose of an ongoing catalyst program (described by Schmidt in Reference 3) is to evaluate the ability of currently available catalysts to function in the required environment, and if necessary, to develop more durable catalysts. To date, both vanadium- and platinum-based commercial catalysts have been tested. The primary degradation mechanisms with these materials have been determined to be 1) transport of active metal out of the catalyst area, and 2) loss of active surface area due to active material migration and support collapse.

With respect to new catalysts, twenty-two support materials have been considered, and six have been tested at 1155 K (1620°F) for stability of surface area with time. The best two support materials* have been used to make developmental catalysts with fourteen different active metals.

A considerable amount of the program effort has gone into improving the experimental techniques and equipment. A microanalytic balance has been developed for quick screening tests. The original test reactor has been replaced with a dual furnace system to double the speed of testing and to allow two long-term tests to be conducted simultaneously. An ultraviolet-visible spectrometer has been set up to continuously monitor the extent of reaction.

Later phases of this program would be concerned with the economics of catalyst preparation, raw material availability, and accelerated life testing.

Reaction Screening^{7,12}

In addition to the experimental investigations described, a reaction screening task has identified other potential reactions with turning temperatures in the range of one of three nominal temperatures: 590, 785, 1310 K (600, 950, 1900°F). Table I lists the reactions selected.

TABLE I
POTENTIAL REACTIONS FOR THERMAL ENERGY STORAGE SYSTEMS

SYSTEM A	SYSTEM B	SYSTEM C
Central Receiver Steam, Rankine 785 K	Central Receiver Open-Brayton Cycle 1310 K	Distributed Collection Steam, Rankine 590 K
$\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$	$\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3$	$\text{MgO} + \text{H}_2\text{O} \rightarrow \text{Mg(OH)}_2$
$\text{MgO} + \text{CO}_2 \rightarrow \text{MgCO}_3$	$\text{SO}_2 + 1/2\text{O}_2 \rightarrow \text{SO}_3$	$\text{MgO} + \text{CO}_2 \rightarrow \text{MgCO}_3$
$\text{MgCl}_2 + \text{NH}_3 \rightarrow \text{MgCl}_2 \cdot \text{NH}_3$	$\text{ZnO} + \text{SO}_3 \rightarrow \text{ZnSO}_4$	$\text{MgCl}_2 + \text{NH}_3 \rightarrow \text{MgCl}_2 \cdot 2\text{NH}_3$
$\text{CS}_2 \rightarrow \text{C} + 2\text{S}$	$\text{C}_2\text{H}_4 + \text{H}_2 \rightarrow \text{C}_2\text{H}_6$	$\text{FeCl}_2 \cdot \text{NH}_3 + \text{NH}_3 \rightarrow \text{FeCl}_2 \cdot 2\text{NH}_3$
$\text{NH}_3 + \text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{NH}_4\text{HSO}_4$		$\text{C}_6\text{H}_6 + 3\text{H}_2 \rightarrow \text{C}_6\text{H}_{12}$

Relative capital cost requirements of the reactions considered were the most important criteria in choosing the reactions listed in Table I. The capital cost requirements for a storage subsystem based on each reaction were estimated from the simplified storage subsystem schematics presented in Reference 6. Additional criteria used in conjunction with the capital cost

*One is a γ -alumina support made by Reynolds Metal Company, and the other is a silica-alumina support made by Davison Chemicals.

estimates in decisions for which these estimates would not have been sufficient by themselves include reversibility, data availability, corrosivity, and toxicity.

The physical, thermochemical, and kinetic properties of each of these reactions have been tabulated, and conceptual designs of storage subsystems for specified solar thermal electric power plants have been developed. The technical and economic data generated have been used in the systems analyses described in the next section.

III. Analytical Studies

In this section, some of the systems considerations of solar thermal electric conversion (STEC) plants with thermochemical energy storage subsystems are discussed. The purpose of the ongoing analyses is to develop an understanding of the applications for which thermochemical systems would have unique advantages. Specific topics to be considered here are: (1) the efficiencies of thermochemical energy storage systems, the reasons for these efficiencies, and the studies under way to more fully quantify them; (2) the methodology employed to determine the technical and economic implications of various storage subsystem characteristics on the complete STEC plant; and (3) general results and highlights of the systems integration analyses conducted to date.

Efficiencies

The primary advantage of chemical reaction systems for energy storage is that long-term, ambient-temperature storage of the chemicals is possible without the thermal losses inherent to systems based on high-temperature latent or sensible heat storage. A major disadvantage of chemical systems, however, is that both the conversion of heat to chemical energy and the subsequent reconversion back to heat involve other types of losses. These losses are reflected in the efficiencies of storage as shown in Table II. Here it can be seen that for the major TES systems of interest, not only are the efficiency estimates disappointingly low, but the trend is that they have decreased upon more detailed analyses. (Of course, this effect is not unique to TES.) Both the nature of the losses and the historical trends are detailed below.

Storage system losses can be considered either as heat losses (first law losses) or availability losses (second law losses). For a solar-electric interface, the latter viewpoint is more useful in that it takes into account the possibility that the heat delivered from storage may be at a lower temperature than the heat delivered to storage. In addition, availability losses can be related directly to irreversibilities in the individual steps of a system.

TABLE II
HISTORICAL TRENDS OF ROUND TRIP EFFICIENCIES* (%)

System	Early Estimate (Based on conceptual designs)	Recent Estimate (Based on detailed designs)
SO ₂ /SO ₃	53	42
SO ₂ /SO ₃ (RRC)	44	32
NH ₃	44	27
CH ₄	~80	29

*Round trip efficiency is defined as the ratio of the net thermal energy recovered from storage to that required to charge storage.

A detailed examination of storage system losses require that four levels of constraints to the efficiency of a process be considered: 1) the maximum theoretical efficiency of a reversible process; 2) unavoidable losses of energy (creation of entropy) due to the irreversible nature of any real process which must take place at a finite rate in equipment of less than infinite size (for example, to overcome resistance to heat transfer in heat exchangers, a minimum temperature difference of ~20 K is normally required); 3) further losses of energy which result because economics and not efficiency ultimately determines the design of a process; and 4) additional parasitic energy requirements of a process due to institutional considerations, such as environmental protection and safety⁸.

The first level of constraint applies to the overall process and is determined by the maximum and minimum temperatures of the process and the efficiency. For a process in which heat is converted to chemical energy, the maximum theoretical efficiency is the Carnot cycle efficiency times the ratio of the change in enthalpy to the change in free energy. The second and third levels of constraints apply to the individual steps in a process. For example, one of the most common process steps is heat transfer. The driving force for heat transfer is a temperature difference. The size and therefore the cost of a heat exchanger decreases as the temperature difference increases. The degree of irreversibility, however, increases with the temperature difference. The design of a heat exchanger is an optimization between cost of the exchanger and the efficiency at which the heat is transferred. Whereas a temperature difference of 20 K would result in a loss of availability of less than a percent, standard optimization techniques yield heat exchangers for which the temperature difference is 50 to 100 K and the loss of availability is 1 to 2% of the duty of the exchanger. In addition to unavoidable irreversibilities resulting from heat transfer, those resulting from chemical reaction, expansion of gases, and mixing of reactants must be included in the analyses.

The historical trend of reported efficiencies for chemical reaction systems points out the importance of developing an understanding for the practical efficiencies that can be expected. Early estimates of the efficiency of a process are normally based on conceptual designs which take into account only the first and, perhaps, the second levels of constraints as discussed above. As understanding of the process increases, cost tradeoffs (third level of constraints) can be performed. Finally, after technical and preliminary economic feasibility has been demonstrated, detailed design and costing of a "to-be-built" plant can be undertaken. This final design must account for all four levels of constraints to the efficiency.

As shown in Table II, a recently reported¹⁰ second law efficiency for the SO_2/SO_3 system of 42% has been postulated instead of an earlier estimate of 53%. An even more detailed Rocket Research design¹¹ for an SO_2/SO_3 storage system has an efficiency of 32%. This latter value compares with an efficiency of 44% reported by RRC earlier⁶ based on a more conceptual design. The most recently reported efficiency for the chemical reaction system based on ammonia dissociation, which has received considerable study in Australia, is 27%.¹² As a final example, based on a conceptual design¹³ reported efficiencies were in the 80% range for a $\text{CH}_4/\text{CO}-\text{H}_2$ system.* For the same reaction system, a later report indicates an efficiency of 29% based on a process design for which equipment was sized and manufacturers' quotes were obtained.¹⁴ In general then, the trend in overall efficiency has been a lowering of estimates as more details of the system are included in the evaluation.

Discussion of Systems Analyses

While calculation of potential costs and efficiencies for TES systems is an important first step, the real issue is how such systems could impact the cost and performance of plants as a whole. Only then can 1) the true worth of developing such storage options be determined analytically; 2) appropriate applications for the technology be determined; and 3) reasonable criteria be developed to assay the value of such storage.

As an aid in evaluating the progress of the thermochemical energy storage technology projects, a concurrent economic systems analysis study was performed. This study was two-pronged: full multiparameter optimization simulation investigation at Sandia¹⁵⁻¹⁸ and a smaller effort as part of the Rocket Research reaction screening study detailed above.^{11,19,20} Although the methodologies of these studies were developed separately and are different in minor ways, their results are very similar, and only the first will be described in any detail. The application investigated for thermochemical energy storage is that of a stand-alone solar plant in various localities across the United States: Inyokern, CA; Albuquerque, NM; Miami, FL; Madison, WI; and New York, NY. Such a stand-alone plant will maximize the worth of long term storage and hence provide an upper bound for its use in any other

*Another factor contributing to this high efficiency is that the storage system is designed for a high level of integration with the accompanying power plant. (See last paragraph of Section III for further discussion of this point.)

application. While non-electric production (e.g. process heat) applications were not considered explicitly, the storage conclusions drawn from the studies to date should be useful there also. Sensible storage was also considered in these studies but only the chemical results are pertinent here.

Description of the Methodology.--The details of the simulation are described in References 15 and 19. In essence, a solar thermal electric conversion (STEC) facility is modeled as a collection of independent subsystems (e.g. heliostats, receiver, storage, EPGS) which process energy with various efficiencies and have various energy processing capacities. Of particular relevance is the storage subsystem, which is assumed to process thermal energy with a roundtrip efficiency (thermal to thermal) of 65%. (Based on Table II and the discussions above, this efficiency is an upper bound.) The storage charge rate and storage capacities were in all cases optimized iteratively to produce the lowest busbar energy costs.

A detailed hourly energy balance is performed between the insolation (thermal) and the load (electrical), taking all the relevant efficiencies into account. A sun-following dispatch strategy is employed to use the sun's energy as soon as it is possible (putting any excess energy into storage) and to discharge storage whenever sufficient direct solar energy is not available. Backup fuel (fossil) is used only when no other option exists for satisfying the load.

To determine the effect of diverse solar localities, simulations were carried out for four locations (Albuquerque, Miami, Madison, and New York) as characterized by the insolation data for a typical year (1960) from the SOLMET data base.²¹ Field efficiencies characteristic of a mirror field layout for a central tower system with an external absorber receiver were used. The receiver is assumed to match a closed helium Brayton cycle which has a net efficiency (electric to thermal) of 44% either direct from the tower or from storage.

Costs for storage have been divided into two groups: those that are energy related (i.e., related to how much energy can be stored at any one time), and those that are power related (i.e., relate to maximum charge and/or discharge rates of storage). Once these storage costs, the hourly insolation and load profiles, backup fuel costs, and other solar plant component costs have been specified, the methodology optimizes the various solar component sizes to obtain the lowest busbar energy cost. Thus the optimum hours of storage, field size, percent of the load satisfied by solar, busbar cost, and many other variables are determined objectively. Wide variations in solar component costs, back-up fuel costs, loads, and insolation data were investigated.¹⁶ A few general results and highlight from this analysis are discussed below.

General Results and Highlights--The main benefit of chemical energy storage is as a long-term storage medium. The major difference between chemical and sensible (and latent) energy storage is that once a reactor (the most expensive component of storage) is built, the reactants can be stored separately from it. This feature has the potentiality of making the cost of adding an extra ten or one hundred hours of storage very small. However, this advantage is not realized for several reasons. First, the reactor

itself is very expensive¹¹, which makes the initial investment for several hours of storage prohibitive. Further, this reactor must be increased in size as storage is added. Thus, in many cases, even though the energy related costs of storing chemicals are small, the cost of putting them into storage (rate related) are much larger than for sensible. These large initial investments for the first few hours of storage can be overcome by increasing the hours of storage to make the "per hour cost" attractive; hence the region in which thermochemical energy storage appear attractive is at least two hundred hours and more likely, beyond. The operation of solar plants with such large storage sizes, however, is not economically sound. The main benefit of storage to a plant is provided by the first 8 to 16 hours of storage to handle nightly loads. The more frequently a portion of storage is used, the more cost effective it becomes. As an example, for a 100-hour storage system in Albuquerque, the first 10 hours of storage are 30 times more valuable than the last 90 hours on a per-hour-of-storage basis.¹⁶ Thus, while chemical energy storage looks better as the number of hours of storage increases, the benefit of having that storage decreases quickly.

Almost completely independent of load shape, the preferred option is a hybrid plant. Even with as little as 10% of its annual energy from fossil, the storage requirement of a solar plant can be reduced from about 850 hours down to 20 hours.^{15,16} With such extraordinary leverage, it is not surprising that the hybrid is preferred to the pure solar plant with seasonal storage^{15,16,19} even with exceedingly expensive fossil fuel costs. Similar results have been obtained with up to twelve years of insolation data for five locations with five load profiles ranging from 50% to 100% capacity factor. Even when the fossil backup option (hybridization) is removed, the optimum plant design is to greatly oversize the collector area rather than do true seasonal averaging storage. In other words, it is more economical to discard a large amount of energy on good solar days in order to make the most of marginal to poor days than to store energy for long periods.^{15,16,19} Thus, many hundreds of hours of storage are not necessary or attractive. See Figure 1.

At the above mentioned efficiency levels, thermochemical energy storage has another handicap. While low efficiencies can be tolerated for many hours of storage, they are not allowable for lesser hours where thermochemical energy storage must compete with sensible storage.^{17,18} The main reason is that the storage inefficiencies must be levered back through the expensive components of the STEC plant (e.g. heliostats and receiver), which makes the entire plant less attractive. Even if 40% efficient TES storage were free, it could not compete with 16 hours of sensible storage at 20 \$/KWh, and sensible storage costs well below this cost have recently been claimed.²²

Limitations of the Methodology--As indicated above, storage is modeled as a separate subsystem with no allowance for integration with the other subsystems. If integration were allowed better heat utilization could be accomplished, thereby increasing the efficiency of chemical storage subsystems over those low estimates discussed above. The roundtrip efficiency of 65% used in the systems analyses, however,²⁴ will probably remain an optimistic upper bound. Moreover, a recent study²⁴ indicates that, even with a highly integrated system, thermochemical energy storage is not competitive with sensible energy storage for storage durations of less than ~20 hours.

IV. Conclusions and Recommendations

Two conclusions may be drawn from the research conducted to date:

- (1) The preliminary technical feasibility of several storage reactions appears to be within reach, although additional research would be required before progressing to the demonstration phase.
- (2) Even if these storage concepts were developed to the demonstration stage, it is doubtful that they would prove economically justifiable for solar thermal electric plants. (This conclusion probably extends to non-solar and non-electric applications also.)

These two facts lead to the following recommendations:

- (1) Current research projects aimed at the near-term development of thermochemical energy storage systems should be terminated in an orderly fashion.
- (2) Future emphasis should be placed on more fundamental research and on systems analyses of other solar/chemical applications such as: energy transport, chemical production (including potential fuels), and chemical heat pumps.

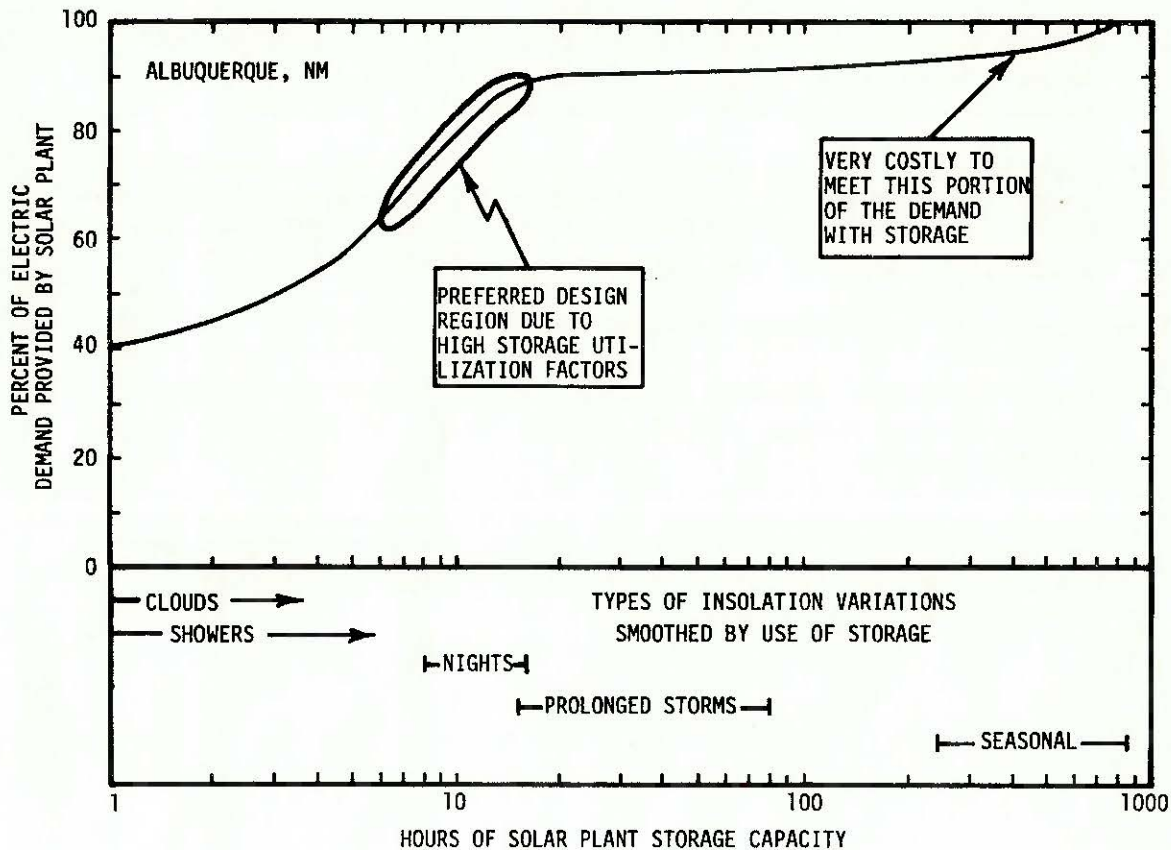


Figure 1. Effect Of Storage Duration On Percent Of Demand Provided By Solar

The question of how much storage is appropriate for a solar thermal electric plant hinges on two factors: the cost of storage (relative to the rest of the plant) and the type of insolation variations which need to be smoothed. Figure 1 shows the percent of electrical demand provided by the solar portion of a hybrid power plant as a function of the hours of storage available. As storage is added to a solar plant, the output electricity increases. While 100 percent of demand could be met by adding many hundreds of hours of storage, such plants run more economically with 16 or less hours. It is best to use a small amount of fossil fuel to cover for rare prolonged storms and for seasonal variations. Sixteen hours is sufficient to smooth the most frequent interruptions: cloud passage, showers, and nights.

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