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Parabolic Dish Systems Development

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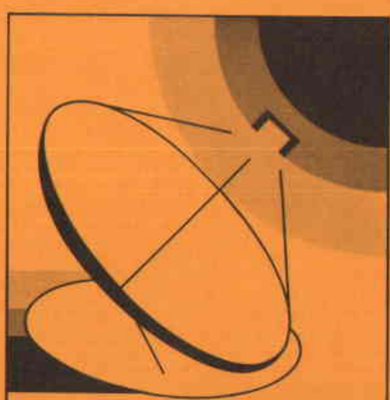

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COMPARISON OF ADVANCED THERMAL AND ELECTRICAL STORAGE FOR PARABOLIC DISH SOLAR THERMAL POWER SYSTEMS*

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ABSTRACT

Optional arrangements for generating electrical power from solar thermal parabolic dish systems are compared. An option which employs a cluster of two-axis tracking parabolic dish collectors to supply solar-derived heat to a ground-based thermal storage/power conversion unit is assessed. Each multi-dish cluster is a power module, and a large power system can be composed of a multiplicity of such modules. The use of advanced Stirling and Brayton engines is investigated.

An important finding is that promising multi-dish clusters employing advanced sensible and latent heat thermal storage attain energy costs comparable to those of dish-battery systems over a wide range of dish cluster sizes. This has major implementation advantages in allowing the selection of cluster sizes and associated engines that are tailored to application system requirements and, in particular, permitting the use of a wide range of engines that are being developed for other applications.

INTRODUCTION

This study analyzes multi-dish cluster concepts (Fig. 1) involving the use of high-temperature thermal storage (operating at temperatures of ~1500°F) and advanced Stirling and Brayton power conversion systems. This multi-dish/thermal storage concept is compared to dish/battery storage systems (Refs. 1-2) in terms of performance potential and requirements for technology development.

The scope of the effort encompasses both sensible and latent heat thermal storage concepts. Sensible storage concepts include containment of heat in (1) molten salts, (2) liquid metals, and (3) solid bricks (checker stove). Latent or phase-change concepts include three fundamentally different design approaches characterized as passive, active, and direct contact.

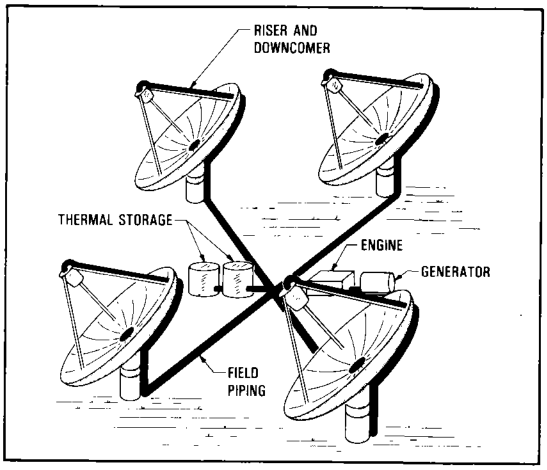

Figure 1. Multi-Dish Cluster/Thermal Storage Power Module

For comparison with thermal storage, four of the most attractive advanced battery storage concepts are analyzed. Based on the investigation of Ref. 3, the following batteries were chosen: (1) Redox, (2) Sodium-Sulfur, (3) Zinc-Chlorine, and (4) Zinc-Bromine.

CHARACTERIZATION OF SELECTED SYSTEMS

A set of candidate parabolic dish systems employing sensible heat, latent heat, and battery storage are shown in Fig. 2.

COLLECTOR	STORAGE	TRANSPORT	POWER CONVERSION
PARABOLIC DISH • BACK-SILVERED GLASS SURFACE • 11-METER DIAMETER	SENSIBLE HEAT • MOLTEN SALT (NaOH) • LIQUID SODIUM • CHECKER STOVE (CORDIERITE)	PIPE LINES • MOLTEN SALT (NaOH) • LIQUID SODIUM • AIR	STIRLING ENGINES • ADVANCED DESIGNS BASED ON TECHNOLOGY OF UNITED STIRLING OF SWEDEN P-40 AND P-75
	LATENT HEAT • MOLTEN SALT ($NaF \cdot MgF_2$)	PIPE LINES • MOLTEN SALT (NaOH) • MOLTEN LEAD	
	BATTERIES • REDOX (FeCr) • SODIUM SULFUR • ZINC CHLORINE • ZINC BROMINE	ELECTRICAL NETWORK	BRAYTON ENGINES • ADVANCED DESIGNS BASED ON TECHNOLOGY OF AUTOMOTIVE AGT

Figure 2. Matrix of Selected Systems

*The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U.S Department of Energy through an agreement with NASA.

For the molten salt and liquid sodium systems, the simplest and most cost-effective arrangement involves use of a transport medium that is the same as the storage medium. The checker stove concept is based on use of gaseous transport media, and, for compatibility with open-cycle Brayton engines, air is chosen as the transport medium.

All of the latent heat concepts use the same molten salt phase-change material, a Sodium Flouride-Magnesium Flouride eutectic. This material was selected since it possesses the desired melting temperature of ~1500°F while also providing a relatively high heat of fusion. For transport, molten salt (sodium hydroxide) was selected as being more cost effective than liquid sodium and is therefore used in the passive and active concepts. Lead was chosen for the direct contact approach because it is immiscible with the selected molten salt and has a high density, which allows it to trickle down through the phase-change eutectic.

Sensible heat molten salt and liquid metal systems are characterized by use of dual tanks. The checker stove concept is distinguished by a single storage tank which is designed to function as a thermocline system. In this approach, a portion of the solid brick storage medium is at a high temperature while the remainder is at a lower temperature. A thermocline region of steep-temperature gradient exists between the hot and cooler portions. This thermocline region moves in the direction of heat transfer fluid flow during charging or discharging. Latent heat systems are characterized by a single tank containing phase-change material (molten salt). Battery systems employ focal-point-mounted power conversion units which supply electricity to ground-based battery storage.

Sensible Heat Thermal Storage

The selected sensible heat storage systems employ factory fabricated tanks with high-temperature internal insulation. The insulation between the storage medium (1500°F) and the tank wall is sized so that the tank wall is at a temperature of 600°F to permit the use of relatively low-cost carbon steel. Inexpensive low-temperature insulation is wrapped around the tank so that the temperature on the outer surface of this insulation is ~100°F. For molten salt (NaOH) and sodium, a thin Incoloy 800 liner is used to protect the internal insulation from the stored media. The internal insulation is a load-bearing material (e.g., Duraboard).

The most dominant consideration in selecting a storage medium is the product of specific heat and density (volumetric energy density). Since sodium hydroxide had a higher volumetric energy density than other candidates (Na, NaK, and Aluminum), it has been selected as the primary liquid storage candidate.

For molten salt and sodium, the temperatures of the stored medium in the hot tank is 1550°F, while the cold tank is at 1100°F when supplying heat to a Brayton engine. Heat is transferred to the engine working fluid via a counterflow heat exchanger which provides a temperature of 1500°F at the turbine inlet.

For the Stirling engine, the heater head of the engine operates at essentially constant temperature. If an engine temperature of 1450°F is to be maintained, large tanks and relatively large transport pipes with associated high costs will be required. If a lower engine temperature corresponding to a reduced engine efficiency is used, the temperature difference between the hot and cold tanks increases so that smaller storage tanks and transport lines can be used. Thus, a set of Stirling engine systems covering a range of engine temperatures is analyzed to delineate the most effective arrangement.

Latent Heat Thermal Storage

In a manner closely similar to that employed in sensible heat systems, latent heat systems use internally insulated tanks and externally insulated transport pipes. For all systems, the storage tank contains heat exchange tubes which melt the phase-change eutectic salt (NaF-MgF_2) during charging of the storage system.

Variations in working fluid and discharge heat exchanger design are governed by conditions emanating from the matching of storage and engine characteristics. These variations are summarized below:

Passive Systems--For Brayton engine configurations, the storage discharge heat exchanger uses engine air as the transport working fluid, whereas Stirling engine arrangements employ a single working fluid (NaOH).

Active Systems--In addition to use of air and NaOH discharge heat exchangers for Brayton and Stirling engine concepts, respectively, different approaches for actively removing solidified eutectic salt from heat transfer surfaces are investigated. These approaches range from mechanical scraping to speculative ideas involving the polishing or coating of surfaces to prevent the sticking of solidified material.

Direct Contact--Storage discharge is accomplished by trickling molten lead through the molten eutectic phase-change salt. Since NaOH has superior transport characteristics, Brayton engine systems use NaOH for charging and supplying heat to the engine during the sunlight hours. A separate heat exchanger is used for the lead transport circuit when discharging storage. For the Stirling engine, the heater head serves as the heat exchanger, and, hence, a single fluid (lead) must be used for both charging and discharging.

For latent heat systems, temperatures in the storage charging transport loop must be above the melting temperature of the phase-change material. Since the selected eutectic NaF-MgF_2 has a melting temperature of 1526°F, temperatures in the charging circuit of 1625°F entering storage and 1550°F leaving storage are employed. These temperature levels were selected on the basis of heat exchanger design/cost considerations. During discharge, the temperature leaving storage is $\sim$ 1500°F for all systems. Due to differences in fluid characteristics and associated heat exchangers, there are small variations in discharge circuit temperatures for different systems.

Battery Storage

In a manner analogous to thermal storage systems, the costs of the four selected battery storage units are divided into power-related and energy-related elements as shown in Table 1. The costs in these two major categories are further sub-divided into battery and balance-of-system costs, where the balance-of-system is composed of items such as inverters/ converters, and costs associated with installation and related engineering services.

Table 1. Characteristics of Advanced Battery Storage Systems

CHARACTERISTICS	ADVANCED BATTERIES			
	Fe-Cr REDOX	SODIUM-SULFUR	ZINC-CHLORINE	ZINC-BROMINE
ENERGY-RELATED COSTS ($/kWeh)				
BATTERY	22	47	27	32
BALANCE OF SYSTEM(1)	4	8	5	6
TOTAL	26	55	32	38
POWER-RELATED COSTS ($/kWe)				
BATTERY	132	0	59	0
BALANCE OF SYSTEM(1)	117	95	105	95
TOTAL	249	95	164	95
EFFICIENCIES				
BATTERY, %	75	75	72.5	77
STORAGE SYSTEM THROUGHPUT(2), %	69	69	66.5	61
LIFE				
CHARGE-DISCHARGE CYCLES(3)	10,000	3000	3000	3650
CORRESPONDING PERIOD, YEARS	27	8	8	10

(1) INCLUDES INVERTER/CONVERTER, BATTERY INSTALLATION, SHIPPING, DC BUS, ENGINEERING SERVICES, CONTINGENCIES, ETC.
(2) PRODUCT OF BATTERY AND INVERTER/CONVERTER EFFICIENCIES.
(3) BASED ON 80% DEPTH OF DISCHARGE.

The efficiencies of the battery, the balance of system and the entire storage system are given in Table 1. These efficiencies are the ratio of delivered to input energy and, in particular, the throughput efficiency accounts for all losses in the storage system. The estimated life of each of the various battery systems is also presented in Table 1. Achievement of a long operating life is a particularly important goal in developing advanced batteries. The short life of conventional lead-acid batteries is a major obstacle to near-term implementation.

Thermal Transport

The transport system comprises the insulated field piping and the associated equipment such as pumps, fans, and their control systems. The risers and downcomers are fabricated in the factory as an integral part of the dish assembly, and their costs are therefore generally treated as part of the dish cost. Techniques of automated factory fabrication and semi-automated field installation are assumed to be implemented (Ref. 4).

For temperatures of $\sim$1500°F, materials such as Inconel and Incoloy are used. The unit cost of the pipe, its supports, and installation are all clearly functions of pipe diameter. For small pipes of the order of one-half inch in diameter, which constitute the bulk of the piping for molten salt and liquid sodium transport, the labor-related, installation term dominates the cost.

To accomodate the tracking movement of the parabolic dish concentrator, the riser/ downcomers must incorporate swivel joints or flexible hoses. The use of flexible hoses is assumed because more substantial baseline data are available for hose systems. It is estimated that, on a unit length basis, the flexible hose will cost about 3.5 times as much as a rigid pipe of comparable diameter.

With regard to pipe insulation, the baseline system comprises Inconel pipes with external insulation. By locating supply and return lines in close proximity and containing them in a common external insulation package the quantity and cost of insulation for a specified rate of heat loss is reduced.

Baseline Parabolic Dish Subsystems

Excluding thermal storage and piping, the remaining baseline subsystems are (1) the dish collector consisting of a two-axis tracking parabolic dish concentrator having a cavity receiver at the focal point, (2) a power conversion unit consisting of an engine-generator assembly with associated controls, and (3) balance-of-plant items. Performance and cost characteristics for these baseline subsystems are given in Table 2, which is based on data in Ref. 2. The cost data from Ref. 2 have been approximately adjusted to 1980 dollars by employing the GNP deflator.

SELECTED OPTIMUM DESIGNS

There is a tradeoff between the performance and cost of thermal storage systems (Fig. 3). A similar tradeoff exists for thermal transport (Fig. 4). These tradeoffs provide the basis for determining optimum designs for both storage and transport. The basic optimization criterion is the minimization of the levelized busbar energy cost (BBEC).

In a fundamental sense, BBEC is the ratio of the annualized cost of the power plant, including operation and maintenance, to the annual energy delivered. Costs of storage and transport are in the numerator while their efficiencies which affect energy delivery are in the denominator. These costs can be analytically expressed as a function of efficiency by curve fitting the tradeoff relations depicted in Figs. 3 and 4 for storage and transport, respectively. Approximate analytical relations which express energy delivery as a function of subsystem efficiencies have been derived previously (Ref. 5). By performing the indicated curve fitting and using the relations established in Ref. 5, an expression for BBEC as a function of storage and transport efficiencies is determined and analytically minimized.

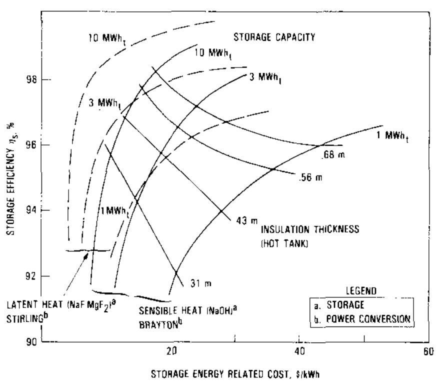

Figure 3. Storage System Performance and Cost Characteristics

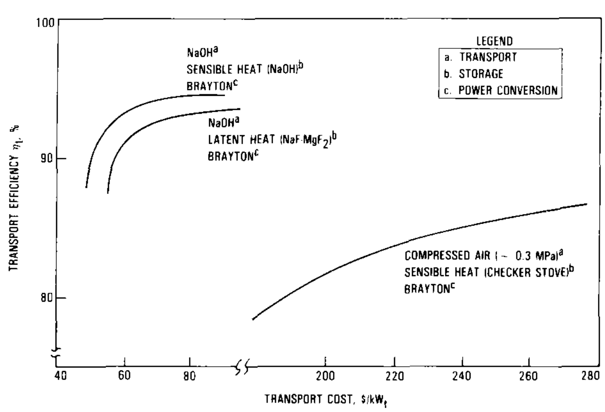

Figure 4. Transport System Performance and Cost Characteristics

The BBEC relation (Ref. 6) is a function of the costs and efficiencies of the baseline subsystems of Table 2. The optimum storage and transport characteristics are thus a function of these baseline subsystem characteristics. Further, the BBEC relation is a function of a set of financial parameters. The parameters established as part of the study reported in Ref. 2 are adopted herein since they are values reflective of long term trends which are expected to be relatively invariant. Key parameters are given below:

Cost of Capital to (and internal rate of return in) a Utility	0.0860
Capital Recovery Factor	0.0939
Annualized Fixed Charge Rate	0.1568

Since the above parameters are held constant, they will not affect relative comparisons among systems and design options.

Table 2. Baseline Subsystem/Component Characteristics

(COSTS BASED ON PRODUCTION RATE OF 25,000 MODULES PER YEAR)

SUBSYSTEMS	EFFICIENCY, %		COSTS, 1978$	
	DESIGN POINT	ANNUAL AVE	INSTALLED COST	OPERATION & MAINT.(1)
COLLECTOR				
CONCENTRATOR	89		$86/m^2	
	81	74		$2/m^2/yr
RECEIVER	92		$16/m^2	
POWER CONVERSION(2)				
BRAYTON	30	27	$156/kWe	$57/m^2/yr
STIRLING	38	34	$191/kWe	$390/m^2/yr
BALANCE OF PLANT				
POWER-RELATED(3)			$106/kWe	$6/kWe/yr
AREA-RELATED(4)			$43/m^2	$1/m^2/yr
INDIRECTS(5)			20%	

(1) AVERAGE ANNUAL VALUES WHICH ARE REFLECTIVE OF THE DETAILED MAINTENANCE SCHEDULES EMPLOYED IN REF. 4.
(2) INCLUDES BOTH ENGINE AND GENERATOR; LOSSES DUE TO POWER TRANSMISSION, CONDITIONING, AND PROCESSING ARE REFLECTED IN THE EFFICIENCY VALUES, AND COSTS ARE NORMALIZED TO RATED GENERATOR OUTPUT.
(3) INCLUDES SUBSTATION, CONTROL BUILDING, AND TEMPORARY FACILITIES WHOSE BASELINE COSTS WERE DETERMINED FOR A 5-MWe PLANT.
(4) INCLUDES CONTROLS, ELECTRICAL TRANSPORT NETWORK, LAND, AND SITE PREPARATION.
(5) ACCOUNTS FOR ARCHITECTS & ENGINEERS AND CONSTRUCTION MANAGEMENT AS PERCENT OF TOTAL DIRECT COSTS; ADDITIONAL COSTS INCLUDE 5% FOR SPARE PARTS AND 1.5% FOR SHIPPING OF COMPONENTS FOR WHICH THESE CHARGES ARE APPLICABLE.

SYSTEM COMPARISONS

Based on a screening analysis at a storage time of six hours, it was determined that the parabolic dish systems with advanced battery storage are within a range of levelized busbar energy costs, BBEC, from 120 mills/kW$_e$hr to 150 mills/kW$_e$hr. Multi-dish cluster systems with BBEC's in this range are considered to be promising.

Multi-dish thermal storage candidates are divided into the following ranges according to their BBEC values at six hours storage:

Promising: 120-150 mills/kW$_e$hr

Sensible Heat	Latent Heat
Salt-Brayton	Direct Contact Stirling
Salt-Stirling	Direct Contact Brayton
	Scraped Tube Stirling
	Passive Stirling
	Polished Tube Stirling

Worthy of Further Consideration: 150-170 mills/kW_ehr

Sensible Heat	Latent Heat
Sodium-Brayton	Scraped Tube Brayton
Sodium-Stirling	Passive Brayton
	Polished Tube Brayton

The checker stove sensible heat system has an energy cost > 170 mills/kW_ehr and is in the less promising category. However, successful developmental tests (Ref. 7) indicate that this system could be amendable to earlier implementation than other candidates.

For Stirling engines, a heater head temperature of 1300°F provides lower busbar energy costs and hence the systems in the above ranking are based on this lower engine temperature.

Effect of Cluster Size and Capacity Factor

For a storage time of six hours, selected multi-dish/thermal storage systems are compared with dish battery systems over a range of cluster sizes in Fig. 5. Since the dish-battery systems employ centralized storage for the entire plant, their energy costs are invariant with cluster size.

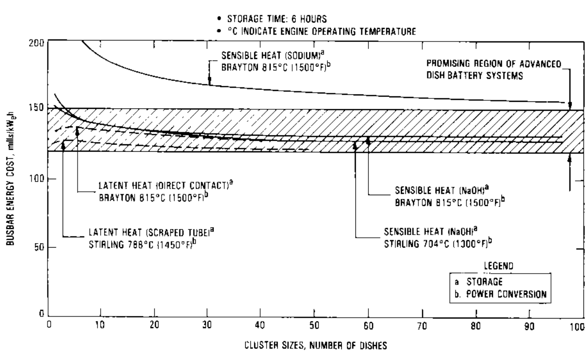

Figure 5. Effect of Capacity Factor on Energy Cost

For multi-dish systems, the curves show that BBEC tends to increase as the cluster size becomes small. This is primarily caused by scale effects associated with storage tanks. For large cluster sizes, the almost invariant value of BBEC over a wide range simplifies the matching of cluster size and engine by allowing the use of wide spectrum of engines.

The effect of capacity factor on BBEC is presented in Fig. 6 for selected systems which illustrate the main trends. The curves represent envelopes which give minimum BBEC's at every capacity factor for a power plant with a specified rating (Ref. 1).

There are clearly detailed differences in the curves shown in Fig. 6. However, a

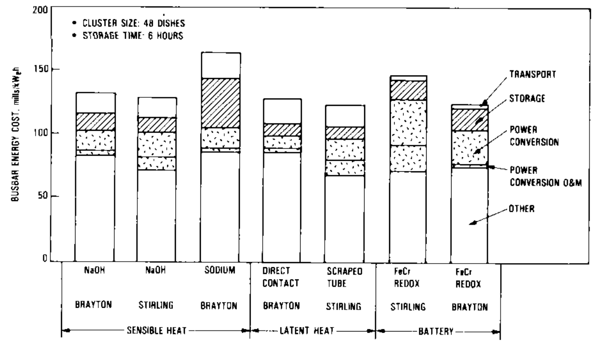

Figure 6. Comparison of Multi-Dish/Thermal Storage with Dish-Battery Systems

major finding is that rankings of systems for a six hour storage time (corresponding to a capacity factor of 0.5 to 0.6) is indicative of the performance of that system in the flat portion of the curve which is the zone of primary interest. Thus, results of this study are presented in terms of comparisons of systems with six hours of storage.

Breakdown of Energy Costs

The energy cost contribution of a subsystem is defined as the annualized capital and operation and maintenance (O&M) cost of that subsystem over the annual energy delivered from the plant. A key difference between promising multi-dish cluster systems and dish-batteries is shown by the breakdown in Fig 7. For example, comparison of the

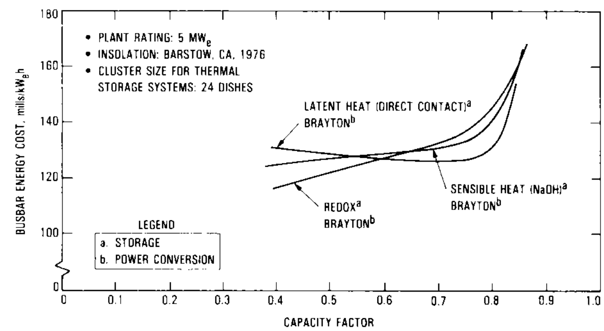

Figure 7. Promising Candidate Systems

sensible heat, molten salt-Brayton (far left bar) with the dish battery, Fe-Cr Redox-Brayton (far right bar) shows that the primary differences are (1) a larger transport cost for the multi-dish and (2) a larger engine cost for the dish-battery. These two factors essentially offset each other so that system energy costs are comparable. The larger transport cost for the multi-dish system accounts for the high-temperature, insulated piping network needed to transport heat to the groundbased storage/power conversion assembly. The larger engine cost for the dish-battery systems is a consequence of having to size engines to meet peak thermal loads.

Requirements for Technology Development

Key problems facing multi-dish cluster/ thermal storage include (1) materials compatibility between molten salts and contacting containment materials such as pipes and tank liners, (2) characteristics of molten salts when subjected to high-temperature thermal cycling and associated phase-change cycling for latent heat systems, (3) durability of load-bearing insulation materials under thermal cycling conditions encountered in the operation of thermal storage tanks, (4) development of pumps and valves for handling the selected molten salt materials and (5) durability of high temperature flexible hoses and/or swivel joints for dish riser and downcomer.

Key problems for dish-battery systems include (1) qualification of inexpensive tank materials and manufacturability of the ion-selective separator membrane for the Fe-Cr Redox, (2) extension of cell reliability and life, and qualification of lower cost materials for Sodium-Sulfur, (3) qualification of inexpensive materials for electrodes and containment along with cell performance optimization for Zinc-Chlorine and (4) establishment of long-term stability of cell construction materials, membrane, and dendrite inhibitor for Zinc Bromine.

CONCLUSIONS

Based on achieving energy costs in the same range of 120-150 mills/kWehr as that of dish-battery systems, the following multi-dish cluster/ thermal storage systems are identified as being promising: (a) Sensible heat systems employing molten-salt (sodium hydroxide) transport and storage with either advanced Brayton or Stirling engines, and (2) latent heat systems including Stirling engine powered concepts of direct contact, scraped tube, passive, and polished tube, and a Brayton engine concept employing the direct contact option.

Because it permits use of thermal storage and existing ground-based engines, the multi-dish cluster concept expands the base of technological options that can be used by dish systems and offers system implementation possibilities that complement those of the baseline dish-battery system. The dish-battery has the greatest inherent flexibility because it uses a single dish-engine unit as the basic power module and relatively simple electrical interconnections of modules to achieve a desired power level. Although both systems employ the same concentrating dish, the dish-battery system is predicated on different advanced technological developments consisting of (1) small heat engine-generator assemblies that are mounted at the focal point of the dish and (2) battery storage systems.

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