NASA Technical Memorandum 88884

Advanced Solar Dynamic Space Power Systems Perspectives, Requirements, and Technology Needs

(NASA-TM-88884) ADVANCED SOLAR DYNAMIC
SPACE POWER SYSTEMS PERSPECTIVES,
REQUIREMENTS AND TECHNOLOGY NEEDS (NASA)
30 p CSCL 10B
N87-12606
Unclas
G3/20 44620

Miles O. Dustin, Joseph M. Savino, Dovie E. Lacy
Lewis Research Center
Cleveland, Ohio

Robert P. Migra
Sverdrup Technology, Inc.
Lewis Research Center
Cleveland, Ohio

Albert J. Juhasz and Carolyn E. Coles
Lewis Research Center
Cleveland, Ohio

Prepared for the
Solar Energy Conference
cosponsored by the ASME, JSME, and JSES
Honolulu, Hawaii, March 22–27, 1987

ADVANCED SOLAR DYNAMIC SPACE POWER SYSTEMS PERSPECTIVES, REQUIREMENTS, AND TECHNOLOGY NEEDS

Miles O. Dustin, Joseph M. Savino, and Dovie E. Lacy
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Robert P. Migra
Sverdrup Technology, Inc.
Lewis Research Center
Cleveland, Ohio 44135

Albert J. Juhasz and Carolyn E. Coles
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Projected NASA, Civil, Commercial, and Military missions will require space power systems of increased versatility and power levels. The Advanced Solar Dynamic (ASD) Power systems offer the potential for efficient, lightweight, survivable, relatively compact, long-lived space power systems applicable to a wide range of power levels (3 to 300 kWe), and a wide variety of orbits. The successful development of these systems could satisfy the power needs for a wide variety of these projected missions. Thus, the NASA Lewis Research Center has embarked upon an aggressive ASD research project under the direction of NASA's Office of Aeronautics and Space Technology (OAST). The project is being implemented through a combination of in-house and contracted efforts. Key elements of this project are missions analysis to determine the power systems requirements, systems analysis to identify the most attractive ASD power systems to meet these requirements, and to guide the technology development efforts, and technology development of key components.

INTRODUCTION

Photovoltaic systems have successfully met the needs of the nations space power systems for commercial and military satellites. These systems have been relatively low power, 10 kWe or less. Future NASA, military, and commercial space missions will require much higher power levels. In low earth orbit (LEO) more efficient power systems with their smaller drag areas will result in lower orbit maintenance propellant requirements. Advanced Solar Dynamic (ASD) systems can provide high power efficiently and reliably in a compact, lightweight manner. These systems can operate in any orbit because they will not be affected by high radiation levels. NASA's Lewis Research Center is engaged in an aggressive ASD research project under the direction of NASA' Office of Aeronautics and Space Technology (OAST) through a combination of in-house and contractual efforts. The project will use systems analysis to identify promising technology areas and desired characteristics of key components. Advanced concepts for the key components of ASD systems will be pursued and related technologies developed. These components are the concentrator, receiver, radiator, and thermal energy storage material. The goal of the program is to demonstrate the technology readiness of these power systems for flight applications beyond the 1990's. This paper will discuss the content, status, and results of the various component development projects to date.

MISSIONS ANALYSIS

A review of future NASA and DOD missions clearly shows a trend to higher power requirements. It is essential, in the case of LEO missions, to investigate space power systems with lower drag area than conventional photovoltaic power systems. In addition, Advanced Solar Dynamic (ASD) Power Systems offer the potential for lightweight, highly reliable, long-lived systems that can survive in a variety of altitudes and orbits. A recent NASA-funded System Definition Study conducted by Rocketdyne using their own data base, which is a compilation of NASA and DOD data bases plus other government and industry sources, identified nearly 100 missions in the 1992 to 2010 timeframe for power systems that require in excess of 3 kW and many that will use over 15 kWe. The distribution of these missions by power level is shown in Fig. 1. A partial listing of these missions, their required power levels, and scheduled launch dates are shown in Table I. Of particular interest are power levels required of material processing units, the polar orbiting Solar Terrestrial Observatory, and the Geosynchronous Earth Orbit (GEO) Communications Platforms.

The availability of space power systems with high power capability would enable missions with requirements for 75 kW or more. A study done by the Civil Missions Advisory Group resulted in the large number of future missions listed in Table II. These missions include the space station, orbiting satellites, and asteroid exploratory missions. All of these missions could be accomplished with a nuclear power source such as would be provided by SP-100; however, ASD systems do provide a nonnuclear alternative.

ASD systems could also provide power for military missions such as Space Defense Initiative (SDI) systems, surveillance satellites, and housekeeping power for weapons platforms. Some military missions are indicated in Table III but most are classified.

ADVANCED SOLAR DYNAMIC SYSTEMS

As the needs for higher power levels evolve, solar dynamic systems become of increased interest to mission planners. This is becoming more apparent as the Space Station developers are considering both photovoltaic and Solar Dynamics for the Initial Operating Condition (IOC) 75 kW power level. In view of this increased interest, ASD applications are being looked at not only for high power missions but also for a broad range of applications over a variety of power levels, orbits, and altitudes. Because of this wide range of mission requirements, two module sizes were chosen as representative of the large variety of future missions, 7 and 35 kWe. The System Definition study was done at these two power levels, assuming that missions of larger power requirements would use multiple modules.

Two thermodynamic cycles are being considered at this time for the ASD systems, Brayton and Stirling cycles. Initially a high temperature liquid metal Rankine cycle was also being considered, however, the System Definition Study showed that at realistic temperatures the specific mass of the Rankine cycle was far too heavy to be of further interest. The organic Rankine cycle, which uses Toluene at about 700 K as the working fluid, is not being considered in the ASD program, but is, along with the 1000 K Brayton, a candidate for the IOC Space Station, and is therefore considered present day technology.

Brayton Cycle

The schematic in Fig. 2 shows the Brayton cycle space power system. Solar energy is focused by a parabolic mirror (concentrator) into the cavity of the receiver. The working fluid, a mixture of helium and xenon heated to a high temperature, carries the energy to the turbine where the thermal energy is converted to shaft work by expansion through the turbine. The hot gases then pass through the recuperator where a portion of the waste heat is returned to the system. The balance of the waste heat is given up in the heat exchanger and radiator. An alternator connected to the turbine shaft furnishes the electrical power. The gas is compressed and returned to the recuperator to recover some of the waste heat before returning to the receiver.

Stirling Cycle

Figure 3 shows a schematic diagram of a Solar Stirling Free Piston Space Power System. This scheme shows heat pipes being used to deliver the thermal energy from the receiver to the Stirling engine heater. Liquid metal pumped loops can also be used. Similarly, either heat pipes or liquid metal pumped loops can be used to carry the waste heat to the radiator. Since the Stirling cycle uses an oscillating free piston to convert the energy to useful work, a linear alternator is the most straight forward means for generating the electrical power.

Thermal energy storage systems utilizing the latent heat of fusion of a phase change material are used to supply the heat for ecliptic operation of the power system for both systems.

System Comparisons

Space power system characteristics of interest to the user are the specific power of the system, the specific area in a plane perpendicular to the direction of motion, and the launch vehicle packaging shape and volume. In most of the studies done to date the systems have been compared on a specific power and specific area basis; however, as systems become better defined, the constraints offered by the launch vehicle in terms of stored package volume, stored mass, and location of launch vehicle center of gravity will be of greater concern. In this paper parameters of comparison will be system specific power and concentrator specific area. As a part of the System Definition Study, a comparison was made between the present day solar dynamic Brayton cycle technologies and photovoltaic technologies. This comparison is shown in Fig. 4. Both the solar dynamic and photovoltaic technologies are based on current space station designs. Complete results of the study, for both 35 and 7 kWe systems are presented in bargraph form in Figs. 5 and 6. Both mass (Fig. 5) and area (Fig. 6) comparisons are made. The bar graph in Fig. 7 shows the distribution of the mass between the individual components for the 35 kWe system. The photovoltaic systems used nickel hydrogen batteries for storage during the eclipse portion of the orbital cycle. Other system parameters used in the study are shown in Table IV.

HIGHER TEMPERATURE EFFECTS

Solar dynamic systems considered to date both for terrestrial and space applications have been limited in maximum turbine inlet temperature in the vicinity of 1000 K. This is about the limit that superalloys can be used for long periods of time. Higher temperatures require the use of refractory metals or ceramics. Because of oxidation problems terrestrial systems have used either stainless steel or superalloys. Studies done at NASA Lewis, resulting in the curves presented in Fig. 8, have shown that reductions in specific power and concentrator area result from operating at higher temperatures, up to the vicinity of 1400 K. The single specific mass value labeled, System Definition Study, represents present day technology using Brayton cycle, space station design as determined in the Rocketdyne study. The curves of specific power (Fig. 8(a)) and concentrator specific area (Fig. 8(b)) which, represent goals of the ASD program, were generated by assuming that at each temperature the thermal energy storage (TES) material has the same heat of fusion and density as LiF, which melts at 1100 K. In this way, only temperature effects are considered. Improvements in specific power that result from Stirling cycle technology, lighter concentrator construction methods, and by improving the concentrator surface accuracy, or ability to focus energy into the receiver aperture, are also included. At higher temperatures, increased reradiation losses from the aperture exceed the gains resulting from higher cycle efficiency. It can be seen from these curves that to make these gains in specific weight:

(1) A TES material that has properties (heat of fusion and density) as good as LiF but at the higher temperature must be found.

(2) A concentrator with a surface error of 1 mrad or less must be developed. (Present day technology is about 2 mrad.)

(3) The concentrator mass must be reduced from present day technologies of 4.9 kg/m^2 by a factor of 4.

COMPONENT DEVELOPMENT

It has been shown that gains in ASD system performance will be derived from operating at a higher TES material melting point, using a concentrator surface accuracy of at least 1 mrad, and developing concentrator fabrication and deployment techniques that reduce the concentrator mass. The NASA Lewis component development program therefore stresses these important areas.

Receiver

Space power receivers differ from terrestrial receivers in several important areas. Terrestrial receivers do not utilize energy storage to enable the system to continue to produce power during periods of no sun energy. A space system on the other hand must store enough energy during the sun period to allow the production of power during the eclipse portion of the orbit. This amounts to about 36 min in a low-earth-orbit (LEO). In a solar dynamic system, thermal storage in either a latent heat or possibly a sensible heat system will be used.

Parallel contracts have been awarded to two companies, AiResearch Manufacturing Company and Sanders Associates to develop concepts for advanced receiver designs. Under this program AiResearch has presented, as a baseline receiver, the receiver shown in Fig. 9. This receiver passes the working fluid through tubes in the walls of the receiver where it absorbs heat. The TES material surrounds the working fluid tubes. The TES system is fully charged during the sun period when the phase change material is fully melted. During the eclipse part of the cycle all of the energy has been extracted when the TES has completely solidified.

Latent heat TES. The latent heat TES concept being discussed here results from a solid to liquid phase change. The heat receiver incorporates the thermal energy subsystem where the phase change salt is contained within a metallic structure. When the system is not in the earth's shadow the solar insolation melts the solid phase change material thus storing thermal energy in the liquid, to be used during the eclipse portion of the orbital cycle. During the eclipse the liquid salt releases its energy and solidifies. With most salts the volume of the salt increases when melting. For example LiF has a volume change of approximately 30 percent. If this increase in volume is not properly designed for, so that melting first occurs adjacent to the void, serious damage to the containment vessel could result from overstressing experienced in each cycle (thermal ratcheting).

In addition to being able to withstand the effects of the volume change of the TES material, the containment vessel must also be compatible with the TES material and it must be able to withstand high temperatures for extended periods of time. In the case of the ASD it must remain as a minimum, corrosion resistant for 7 to 10 yr which is one of the operational requirements for the program. It must also have a very low creep rate and must be able to withstand the space environment, i.e., atomic oxygen and ultraviolet radiation.

Currently, high nickel superalloys such as Hastalloy and Niobium base refractory alloys possess the largest available data base in the area of high temperature applications. However, little data is available on the alloys ability to contain the molten salt mixtures for extended periods of time or of the effects that the mechanical properties of the salt, such as strength and creep, would have on the alloy (e.g., cycle fatigue). Also, the refractory alloys, which have a high affinity for oxygen, require special handling and fabrication techniques. For these reasons as well as others the long term in-house TES material compatibility program at NASA Lewis has an alloy development and TES mechanical properties testing program. The thermal conductivity is crucial because phase change salt systems tend to have very low thermal conductivities requiring some form of enhancement to get the heat energy stored in the salt to the working fluid of the dynamic power cycle.

Several innovative concepts have been proposed by AiResearch, Sanders, and others to improve the heat transfer properties of the TES material.

One method of enhancing the salts conductivity is to employ fins on the inner wall of the containment vessel to extend the heat transfer area and thus providing a conduction path for the heat out of the salt and into the cycle working fluid. Other methods include: (1) placing metallic wools or metallic felts inside the containment vessel with the TES material (2) employing what is known as a salt-metal or a slurry system where liquid metal is placed inside the containmemt vessel to co-exist with the salt, (3) encapsulating the phase change material in the void spaces of a porous ceramic matrix, (4) encapsulating the phase change material into small spheres for a pebble bed type concept or in a metallic capsule, and (5) using a pure metal instead of a salt as the phase change material.

TES material compatibility test program. The purpose of this long term in-house program is to screen, identify, and test high temperature, phase change, thermal energy storage subsystems for ASD systems. The program will identify combinations of phase change TES materials and containment vessel alloys suitable for use at temperatures between 1025 and 1400 K.

The program which began in October of 1985 consists of four phases as follows:

Phase I - Identify TES materials and conduct 100 hr corrosion studies with candidate commercially available alloys under vacuum conditions at 25 K over the TES melting temperature in sealed quartz tubes (Fig. 10).

Phase II - Conduct 1000 hr corrosion tests of selected TES/containment materials including tensile test specimens with and without welds, also in sealed quartz tubes.

Phase III - Bread pan capsules with approximately 50 tensile test specimens will be exposed to a vacuum for 2500 hr at a temperature 50 K over the melting point. One third of the specimens will be exposed to liquid salt, one third to salt vapor, and the last third serving as a control, will be exposed only to the vacuum (Fig. 11).

This program began late in 1985 and at the writing of this paper several Phase I tests have been performed in air furnaces at 25 K above the melting point to determine the feasibility of using evacuated quartz capsules with the salts selected for the initial corrosion study (Fig. 12).

Although the salts identified for the initial corrosion study have high heats of fusion per unit mass and their melting points are within the acceptable range for the ASD program, there are several other thermophysical properties associated with the salts which must be identified before the heat receivers TES subsystem can be completed. These include density, specific heat, thermal conductivity, surface tension, viscosity, vapor pressure, and volume change upon melting. These are critical in the design of the TES subsystem. As indicated by Table V, the thermophysical properties exist in the literature for most of the pure salts, but such is not the case for the eutectics. NASA is currently investigating the capabilities of Purdue's Thermal Physical Research Lab and RPI's Molten Salts Data Center as possible sources for determining the thermophysical properties of the eutectics.

TES Micro-Gravity Test Program

Since the behavior of the void, that results from shrinkage of the TES when it freezes, is fully dependent upon a continuous zero gravity field, tests on earth are not feasible. Low gravity testing by either drop tower or aircraft maneuvers are not of sufficient time duration for the tests. Therefore, a flight experiment aboard the shuttle coupled with the development of analytical prediction techniques is being proposed. Extensive ground testing is also required. The two essential elements of the program are as follows:

(1) An analytical capability (computer program) will be developed at the Oak Ridge National Laboratory to predict the performance of TES materials operating in a zero-g environment, including the formation and location of voids and their impact of heat transfer into and out of the TES. It is anticipated that the analytical techniques will be able to largely use existing theory and computer programs.

(2) Ground testing is required to assure the thermal performance of each experiment and demonstrate the safe survival of the shuttle launch environment. Thermal testing of each TES experiment will establish the transient thermal behavior and capability for 100 thermal cycles minimum. Thermal/vac testing of the complete experiment mounted in its carrier will assure proper thermal performance on the shuttle. Vibration testing of all components and the complete experiment in its carrier will assure adequate launch characteristics.

(3) Minimum requirements for the test program are as follows: (a) at least 10 melt/freeze cycles, typical of low-earth-orbit (60 min melt and 36 min freeze), are required, (b) sufficient instrumentation and data recording capability to define the thermal performance of the TES are required, and (c) the experiments shall represent typical TES materials and configurations for advanced technology solar dynamic power systems.

Current plans are to fly a minimum of two TES experiments and a maximum of four depending on the candidate materials, the advanced receiver designs, and how well the experiments correlate to the analytical predictions. The first experiment will be the thermal cycling (10 melt/freeze cycles) of LiF, a phase change salt which melts at 1121 K, has a heat of fusion of 1044J/kg and exhibits a volume change of 30 percent with the phase change.

Sensible Heat Receivers

In addition to latent heat TES systems, NASA is investigating the feasibility of using sensible heat as a means of thermal energy storage for the ASD program. The objective of this program is to compare a solid sensible heat system, using beryllium, or a liquid sensible heat system, using liquid lithium, to latent heat, phase change designs. The analytical program will be conducted on a systems level where system specific mass will be the primary evaluation criteria.

Concentrators

Solar concentrators have been successfully developed for terrestrial applications. Unfortunately, these concentrators have been designed to satisfy a set of requirements that are significantly different than those for use in space. For example, a terrestrial concentrator must withstand high winds, hailstones, dust, and many other conditions that are not present in space. These terrestrial conditions generally lead to concentrators that have heavy, stiff structures on which the reflector facets (which are also relatively heavy) are mounted. The facets are individually aligned during the assembly and checkout phase, something that cannot be done in space.

State of technology. Because of the huge differences between the terrestrial and space environments, very little of the technology developed for terrestrial concentrators is directly applicable to concentrators for space. Furthermore, since no solar dynamic power system has ever been built and operated in space, there is little state-of-the-art technology for such systems, especially for the concentrator itself. The consequences of this are that the first concentrators slated for space must of necessity be designed using a low risk approach to ensure successful operation.

A space concentrator is presently being developed for the space station. This concentrator design is an assembly of 19 hexagonal modules, each of which measures 3.46 m across the flats (Fig. 13). Each module consists of a structure on which are mounted 24 triangular shaped reflector sections. The structure is comprised of a main hexagonal shaped beam that forms the perimeter and a series of diagonal beams that join the corners of the main beam to the center to form the triangular shaped frames that supports the reflector elements, Fig. 14. All the hexagonal modules are joined by hinges and latches to form a rigid concentrator.

The hex-concentrator design was significantly influenced by the need to package it for launching into LEO in the shuttle bay, and deployment (or assembly) in space. This is one requirement that must be satisfied by any concentrator that is to be launched in the shuttle. Because the concentrator size is much larger than the shuttle bay dimensions, it had to be designed as an assembly of modules that could be launched in a compact stack, Fig. 15. One method for assembling the concentrator in space is depicted in Fig. 16. This method could be automated to eliminate the need for a large amount of astronaut time in EVA or it could be completely deployed by astronauts. The preferred method is still under study.

Future concentrator requirements. A second concept that has been developed (only as a conceptual design) is one that uses a deep, lightweight truss structure on to which are attached 86, 2-m square reflector facets (Fig. 17). The structure with the facets attached is collapsible into a compact bundle which fits into the shuttle bay for launch and then is unfolded in a systematic fashion once in orbit. The method for unfolding, i.e., manually by astronauts or automatic with astronaut assistance, has not been studied. The one big advantage of the deep truss structure is that it is estimated to be very rigid, which is a desirable property for a concentrator. The status of this concept is that the conceptual design is completed. No follow-on work is in progress. However, the deep truss concept appears to have potential for future space power applications. It is our intention to study this concept further starting perhaps in 1987 or 1988.

The weights of the hexagonal (18.4 m diam) and deep truss for a 25.7 m diameter size were estimated to be 450 and 1043 kg, respectively. These weights, when converted to specific weights are 4.5 kg/m^2. and 3.2 kg/m^2. A comparison of these specific weights shows that the deep truss has a weight advantage. The goal for future concentrators is about 1.2 kg/m^2

Future solar dynamic power systems can be made more efficient, and therefore, lighter in weight and smaller in size, only if the operating temperature of the heat engine is increased. Higher operating temperatures impose some stringent requirements on the concentrator. It must be capable of concentration ratios of over 2000. To achieve this, the reflecting surface must be accurately made (slope errors less than 1.0 mrad), smooth (less than 50 Å surface finish), and have high specular reflectivity (reflectivity greater than 0.95). In addition, the concentrator structure must be rigid (a natural frequency well above 1 Hz), packageable (foldable or segmented) for launch and assembleable in space. All these requirements, plus an expected service life of 7 to 10 years will be met if the appropriate technology is available. The objective of the concentrator development program, therefore, is to develop the technology with which lightweight, precisely made, and highly accurate space concentrators of various sizes can be designed, built and demonstrated.

The approach planned for meeting the objective will be to execute a series of long term projects both in-house and on contract. Innovative concepts and ideas with high potential for meeting the goals will be encouraged.

Micro-sheet glass. In mid 1986, an in-house effort was initiated to develop a concentrator which uses very thin microsheet glass (0.1 to 0.25 mm) as a second surface mirror. Glass is one of the most durable materials in a LEO environment and is therefore a prime candidate to consider. The extreme thinness was chosen to diminish the thermal gradients within the glass as the glass temperature undergoes its cyclical variation. Such thin glass requires a stiff substrate to support it and to maintain its contour. Work has started to find a suitable material for the substrate. In addition to providing support and adequate stiffness, the substrate is to (1) have a coefficient of expansion that is close to that of the glass, (2) be highly resistant to atomic oxygen, and (3) be lightweight. Also under study are methods for hot forming the microsheet glass into the shape of spherical elements (Fig. 18). When the substrate is developed and the thin glass is formed and coated with a reflective film, they will be bonded together to form a 20 cm reflector and then tested for the optical properties, stiffness, strength, resistance to LEO environment, and thermal cycling. If this approach results in a suitable concentrator, it will be used to fabricate a larger spherical segment reflector-about 1 m square.

Planned development effort. Contractual efforts are slated to start in mid 1987. Two or more (depending on the funds available and on the number of quality proposals) study contracts will be awarded. The objective of these procurements will be to develop the technology needed to design and build solar concentrators of various sizes for space applications beyond 1995. The intention here is to encourage the development of concentrator concepts that have the potential for meeting the goals set forth above. It is recognized that the development risks will be high for the more promising concentrator concepts. The studies will require developing concentrator designs for a variety of sizes (1 to 300 kWe), identifying the factors and barriers that will impede meeting the design goals and requirements, conducting research of these factors to eliminate the barriers, building and testing either full or reduced scale size or a representative segment thereof. It is planned that at the end of this 5-yr program, there will be available the technology with which to design and build advanced concentrator concepts for future use in solar dynamic power systems for a range of power levels and applications (NASA, government, commercial, and DOD). As a corollary to these accomplishments the technology needed to assemble, checkout, launch, and deploy these concentrators will also be available.

Domed Fresnel lens. A program that was started early in 1986 with a contract to Entech Inc. is investigating a concept that Entech has used in several terrestrial photovoltaic concentrator applications. The concept uses a domed Fresnel lens made of lightweight, flexible flouroplastic. The unique design uses a prismatic surface on the underside of the lens to provide refractive focusing of the solar energy into the receiver aperture. A section of the lens showing the individual prisms is shown in Fig. 19. This construction offers several advantages over a reflective type concentrator as follows:

(1) The refractive nature of the Fresnel lens provides slope error tolerance about 200 times as large as for a reflective concentrator.

(2) It appears that the domed lens construction (Fig. 20) can be of very thin (0.5 to 1 mm) sheets or panels. Also because of the slope error tolerance, they do not have to be held as rigidly as does a reflective surface. Since the receiver and heat engine are located behind the lens, the receiver will not shadow the lens.

Initial investigations show that the flouroplastic lens material will be degraded by the atomic oxygen present in LEO. Methods of protecting the lens material being investigated by Entech include bonding thin (0.1 mm) glass to the lens outer surface. A conical shroud would be required between the concentrator and the receiver to protect the under side of the lens. A coating of magnesium flouride or Sol Gel is also being investigated. Glass is also being considered for use as the lens material in addition to the plastics.

CONCLUDING REMARKS

Although photovoltaic power systems have served NASA well for many years, mission analysis show that nearly 100 future NASA and DOD missions will have power requirements that exceed the practical limits of photovoltaics and will be operating at altitudes that are damaging to photovoltaics (Van Allen belt). Solar dynamic power systems can clearly provide these future needs. To fully meet this challenge, further performance gains in the areas of reliability, mass reduction, and drag area reduction have been made goals of the development program. In-house studies have shown that substantial reduction in system mass can be reached by

(1) The development of high temperature receivers and thermal energy storage systems,

(2) The development of high quality high surface accuracy concentrators,

(3) The use of the highly efficient free piston Stirling engine and
(4) The use of light weight construction techniques. These are the drivers of the NASA Lewis Research Center's Advance Solar Dynamic Development Program. Future considerations in system development must include launch package volume and deployment considerations.

TABLE I. - PARTIAL LISTING OF MISSIONS DEVELOPED UNDER SYSTEMS DEFINITION STUDY

Mission	Orbit	Mission date, yr	Power level, kWe
Materials processing			
Micro-G variable	LEO	1998	50
Automated material processing	↓	1996	10
Materials processing lab-Canadian	↓	1996	20
Commercial space processing	↓	1996	5.5
Life Science			
Production bio processing	LEO	?	7
Biological production units	↓	1996	16
General purpose research/European	↓	1992	10
Medical experiments technology	↓	1996	5
Earth observation systems			
LASAR-B	Sun sync.	2000	7.8
Doppler lidar	Sun sync.	1996	3
Synthetic aperture radar	Sun sync.	1996	4
Earth resources sensing	LEO	1999	10
Observation of upper atmo/Japanese	LEO	?	5
Ice-Earth monitoring radar/Canada	LEO-polar	?	4
Earth/sun interaction			
Solar terrestrial observatory	GEO-polar	1993	6 to 10
Communication			
Large platforms	GEO	1996	10 to 30

TABLE II. - MISSIONS IDENTIFIED BY CIVIL MISSIONS ADVISORY GROUP

Mission	Orbit	Mission date, yr	Power level, kWe
Manned orbital facility			
Initial space station	LEO	1990 to 2000	75 to 150
Growth space station	LEO	2000 to 2010	300 to 500
Advanced space station	LEO	2000 to 2010	500 to 1000
Earth science and applications			
GEO communications platform	GEO	1990 to 2000	100 to 200
Air/ocean traffic control	LEO	2000 to 2010	100 to 200
Transportation			
GEO payload delivery	LEO-GEO	1990 to 2000	100 to 200
Lunar payload delivery	LEO-lunar	2000 to 2010	100 to 200
Manned Mars mission	IP space	Beyond 2010	>1000
Asteroid base resources			
Material processing	IP space	Beyond 2010	200 to 500
Planetary exploration			
Multi-asteroid sample Return	IP space	2000 to 1010	100 to 200
Comet nucleus sample Return	IP space	1990 to 2000	100 to 200

TABLE III. - LISTING OF DOD MISSIONS

Mission	Orbit	Mission date, yr	Power level, kWe
DMSP	Polar	On-going	1.25
DSP		On-going	1.3
Space based radar	LEO	1990's	6 to 30

TABLE IV. - SYSTEM PARAMETERS USED IN SYSTEM DEFINITION STUDY

Unless otherwise indicated, the following values prevail:

Concentrator

Surface slope error = 2 mrad
Pointing error = 0.2°
Reflectivity = 0.9

Phase change materials considered

Name	Heat of fusion, J/g	Melting temperature, K (°F)	Maximum density and state	
LiF	1044	1121 (1558)	1820 kg/m^3	Liquid
NaF	802	1261 (1810)	2060 kg/m^3	Liquid

TABLE V. - PHASE CHANGE MATERIAL THERMOPHYSICAL PROPERTIES

Salt system, mol %	Melt temp, K	Heat of fusion, KJ/gm	Density kg/m^3		Sp. Heat cal/mol K		Conductivity J / cm-s, K		Volume change %	Vapor pressure Pa	Vis-cosity cp	Surface tension, dyn
			sol.	liq.	sol.	liq.	sol.	liq.				
NaF	1268	0.80	2060	(a)	14.106	16.866	0.0125	0.0435	24.0	60.84	1.96	185.5
LiF	1121	1.044	1820	↓	14.770	15.340	.0173	.0634	29.4	1.20	2.30	235.7
LiF-22CaF$_2$	1039	.74 to .76	2097	↓	(a)	(a)	(a)	(a)	21.7	3.11	(a)	(a)
LiF-32CaF$_2$	1083	.52 to .56	2327	↓	↓	↓	↓	↓	8.8	44.52	↓	↓
NaF-23MgF$_2$	1103	.64 to .67	(a)	2680	↓	↓	↓	↓	(a)	49.17	↓	↓
NaF-27CaF$_2$-36MgF$_2$	1178	.52	↓	(a)	↓	↓	↓	↓	↓	28.82	↓	↓
CaF$_2$-50MgF$_2$	1253	.61 to .65	↓	↓	↓	↓	↓	↓	↓	9.99	↓	↓
NaF-60MgF$_2$	1273	.7 to .73	↓	↓	↓	↓	↓	↓	↓	30.41	↓	↓
NaMgF$_3$	1303	.71	↓	↓	↓	↓	↓	↓	↓	(a)	↓	↓

[a] Indicates no data available.

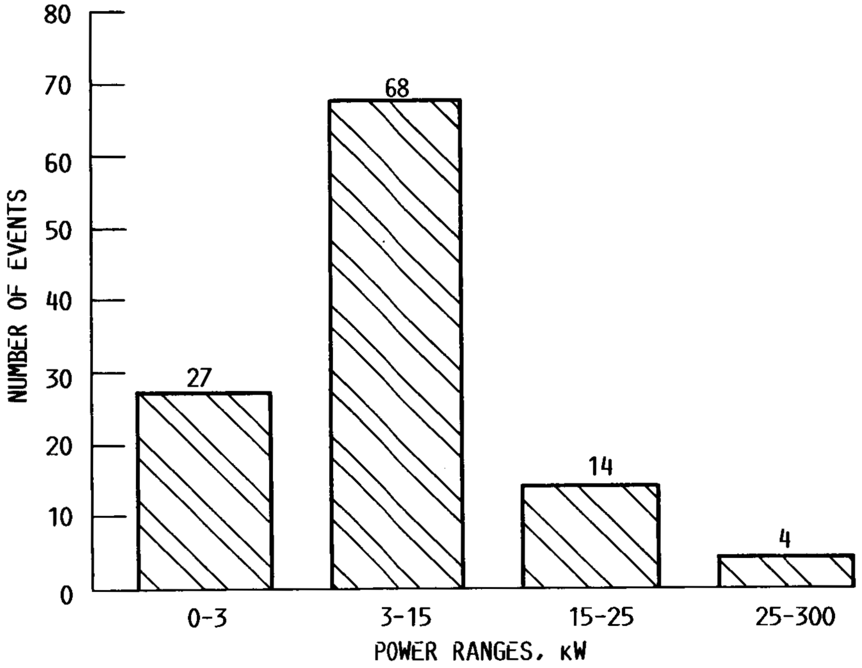


FIGURE 1.- DISTRIBUTION OF MISSIONS AS A FUNCTION OF POWER REQUIREMENTS FOR SYSTEM DEFINITION STUDY.

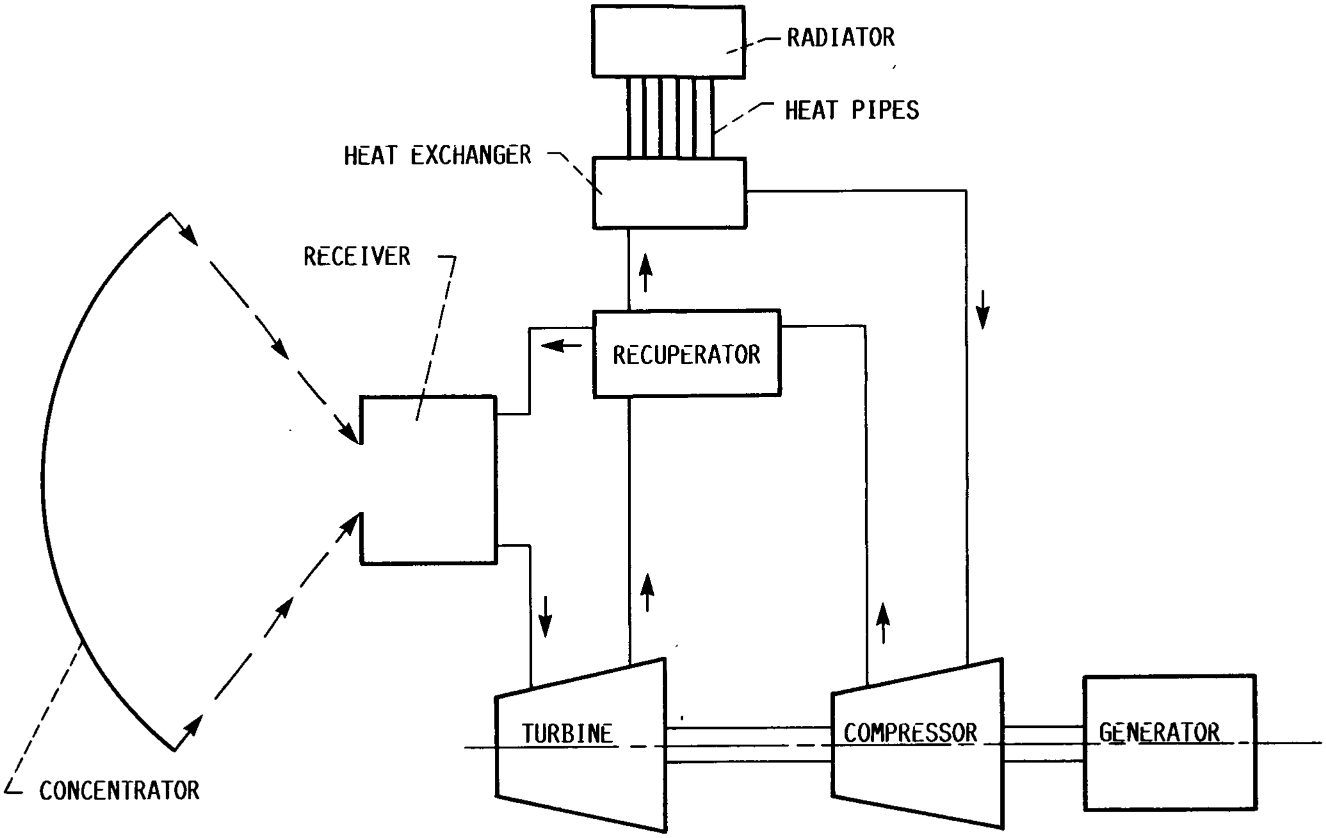


FIGURE 2.- BRAYTON CYCLE SPACE POWER SYSTEM.

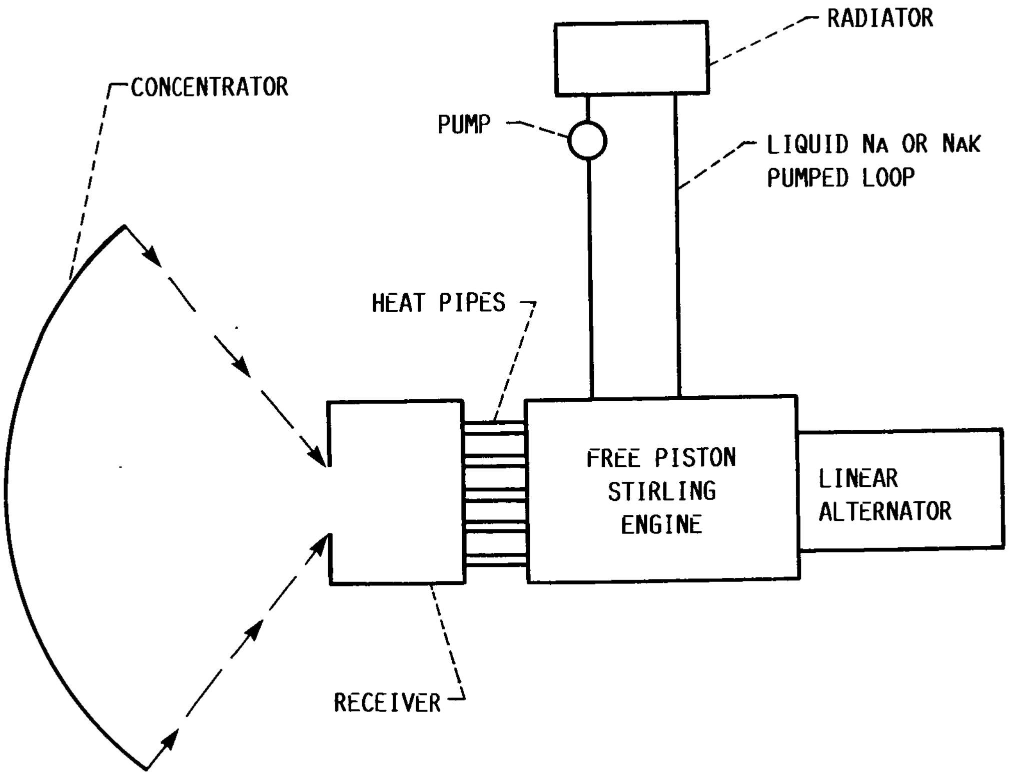


FIGURE 3.- STIRLING CYCLE SPACE POWER SYSTEM.

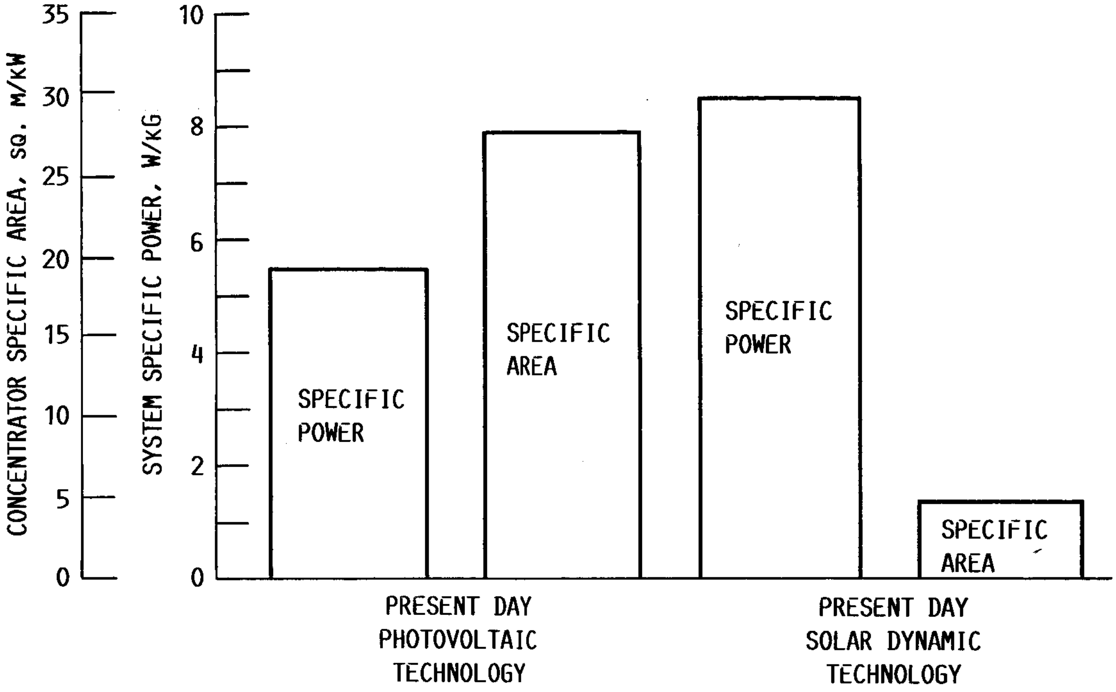
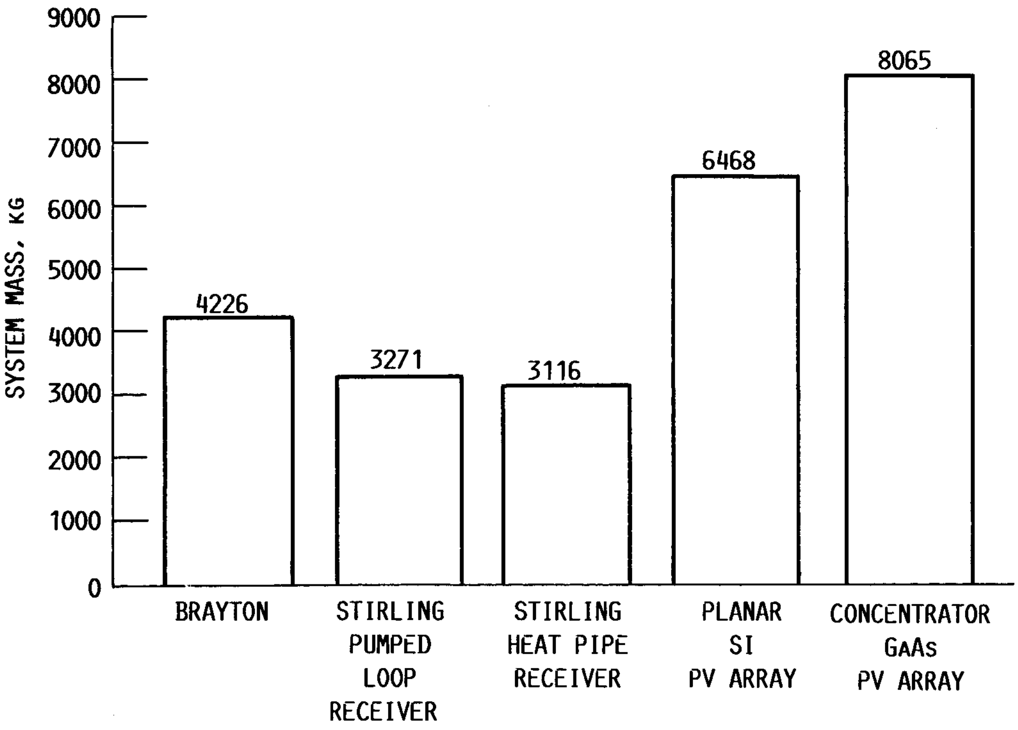
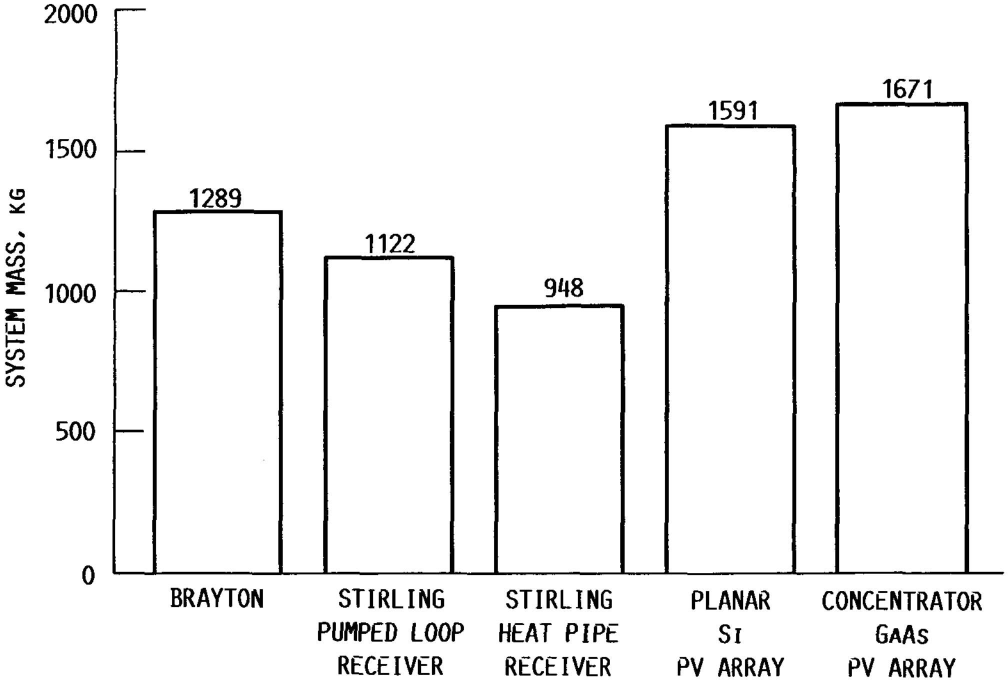


FIGURE 4.- COMPARISON OF PRESENT DAY PHOTOVOLTAIC AND SOLAR DYNAMIC TECHNOLOGIES FROM SYSTEM DEFINITION STUDY.



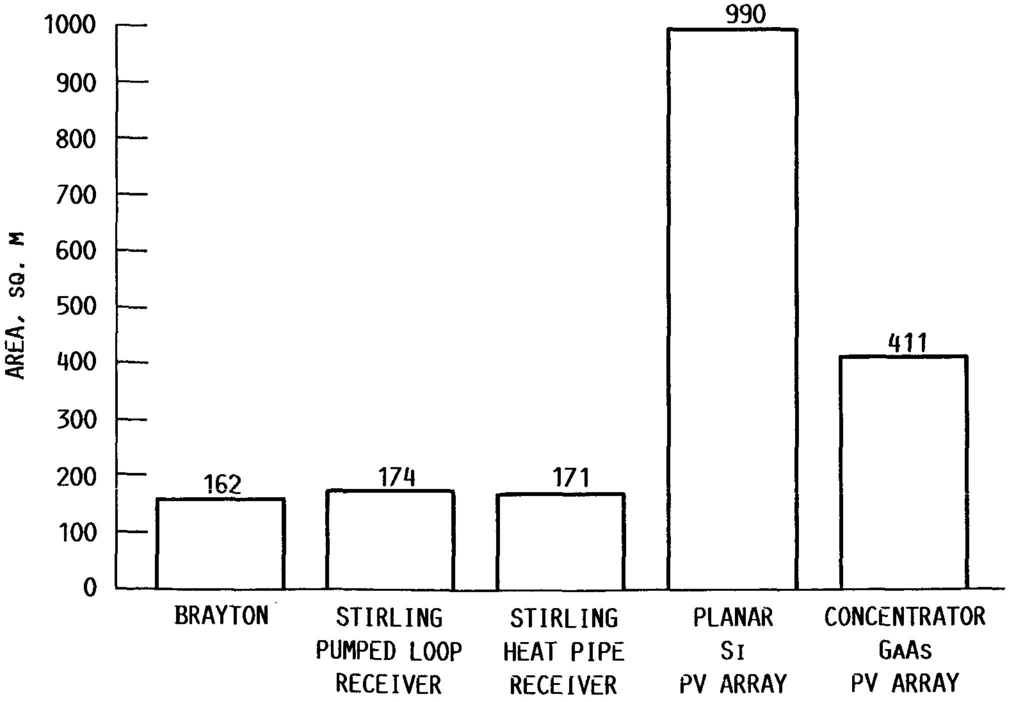
(A) 35 KWE SYSTEM.

FIGURE 5.- SYSTEM MASS COMPARISONS BETWEEN SOLAR DYNAMIC AND PHOTOVOLTAIC SYSTEMS FROM SYSTEM DEFINITION STUDY.



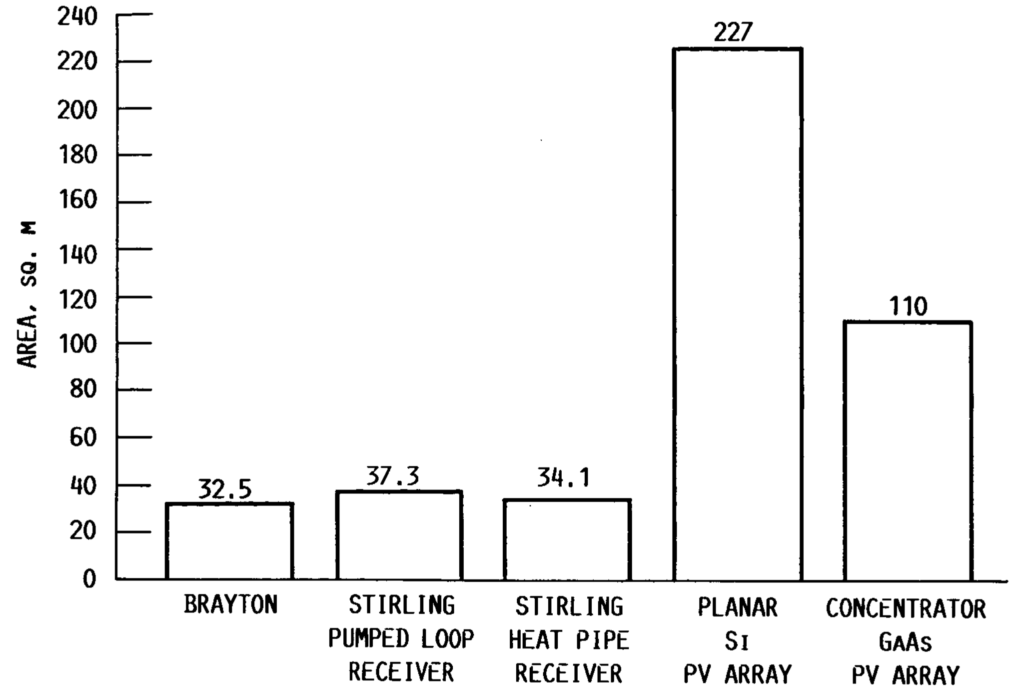
(B) 7 KWE SYSTEM.

FIGURE 5.- CONCLUDED.



(A) 35 KWE SYSTEM.

FIGURE 6.- SYSTEM AREA COMPARISONS BETWEEN SOLAR DYNAMIC CONCENTRATOR AND PHOTOVOLTAIC ARRAYS FROM SYSTEM DEFINITION SYSTEM.



(B) 7 kWe SYSTEM.

FIGURE 6.- CONCLUDED.

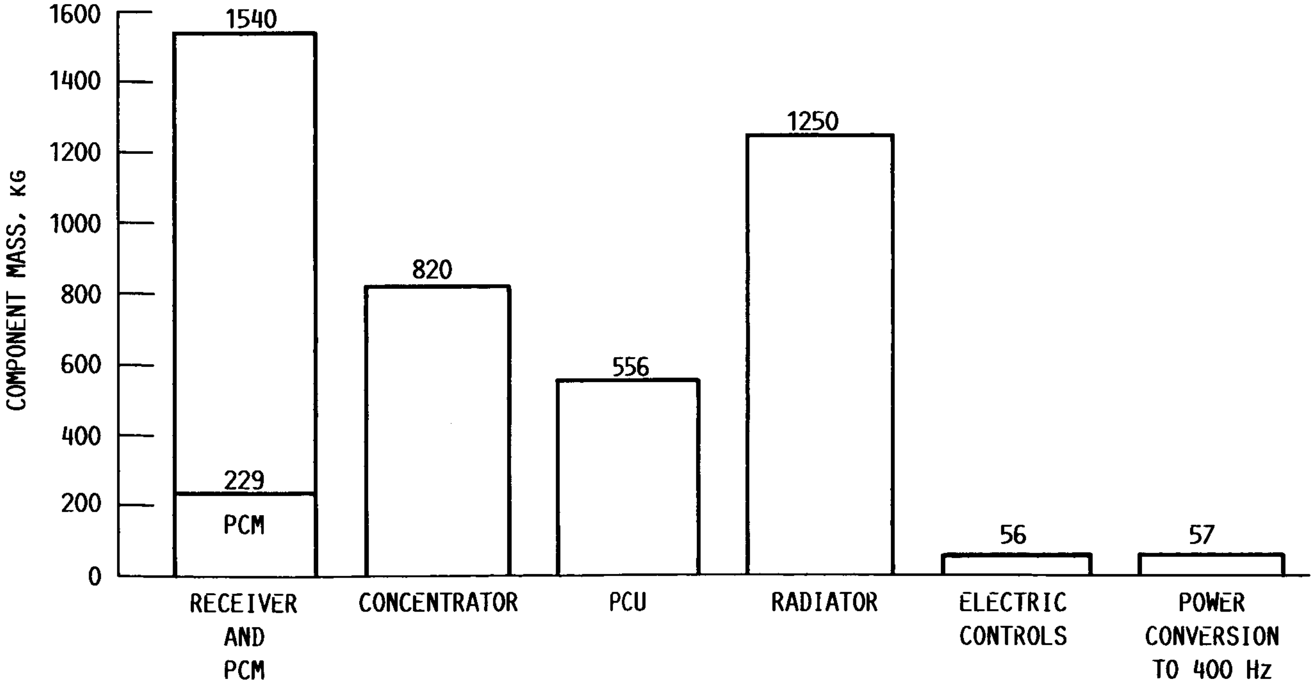
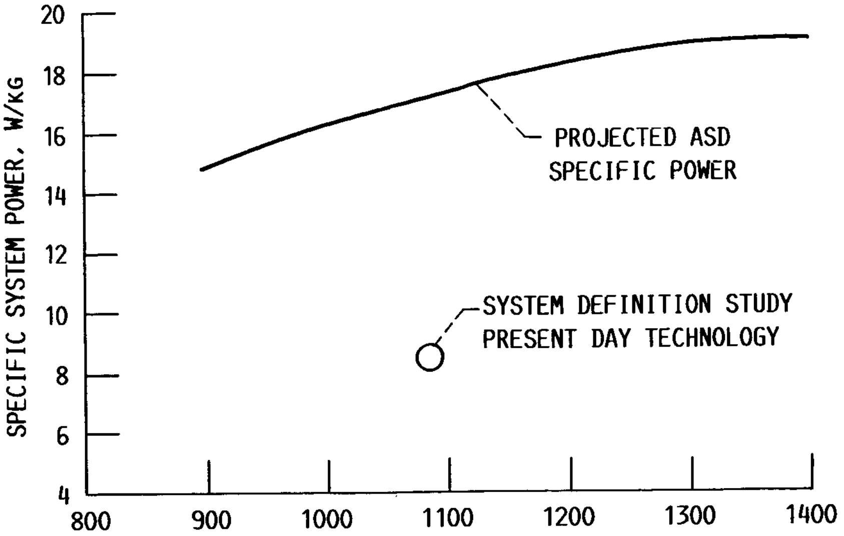
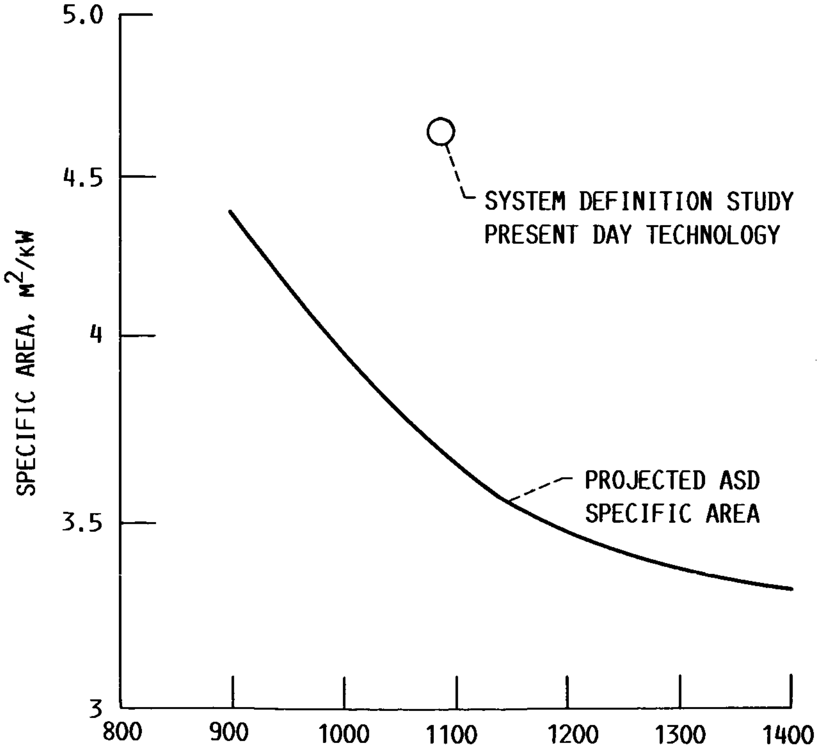


FIGURE 7.- MASS DISTRIBUTION OF COMPOENTS IN 35 kWe SOLAR DYNAMIC BRAYTON SYSTEM FROM SYSTEM DEFINITION STUDY.



(A) Specific system power.

Figure 8.- Advanced solar dynamic (ASD) program projected gains compared topresent day technology.



(B) Concentrator specific area.

Figure 8.- Concluded.

ORIGINAL PAGE IS
OF POOR QUALITY

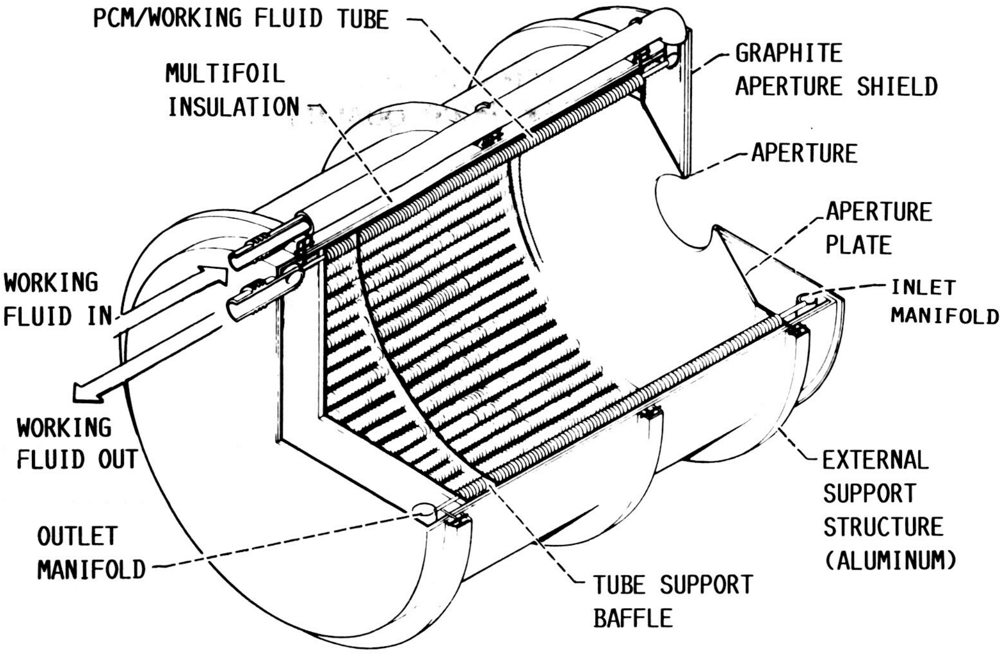


FIGURE 9.- BASELINE RECEIVER.

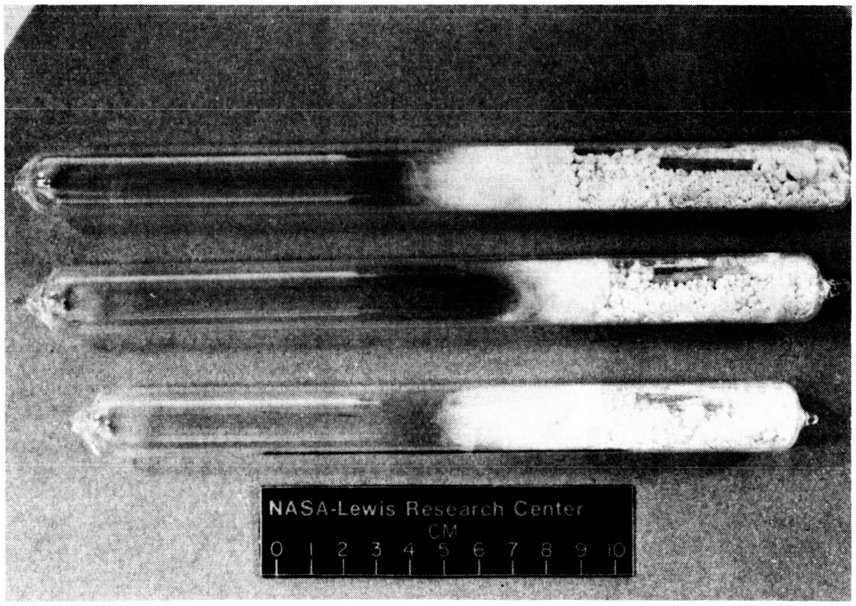


FIGURE 10. - QUARTZ TUBE CONTAINING THERMAL ENERGY STORAGE PHASE CHANGE MATERIAL AND CONTAINMENT MATERIAL ALLOY.

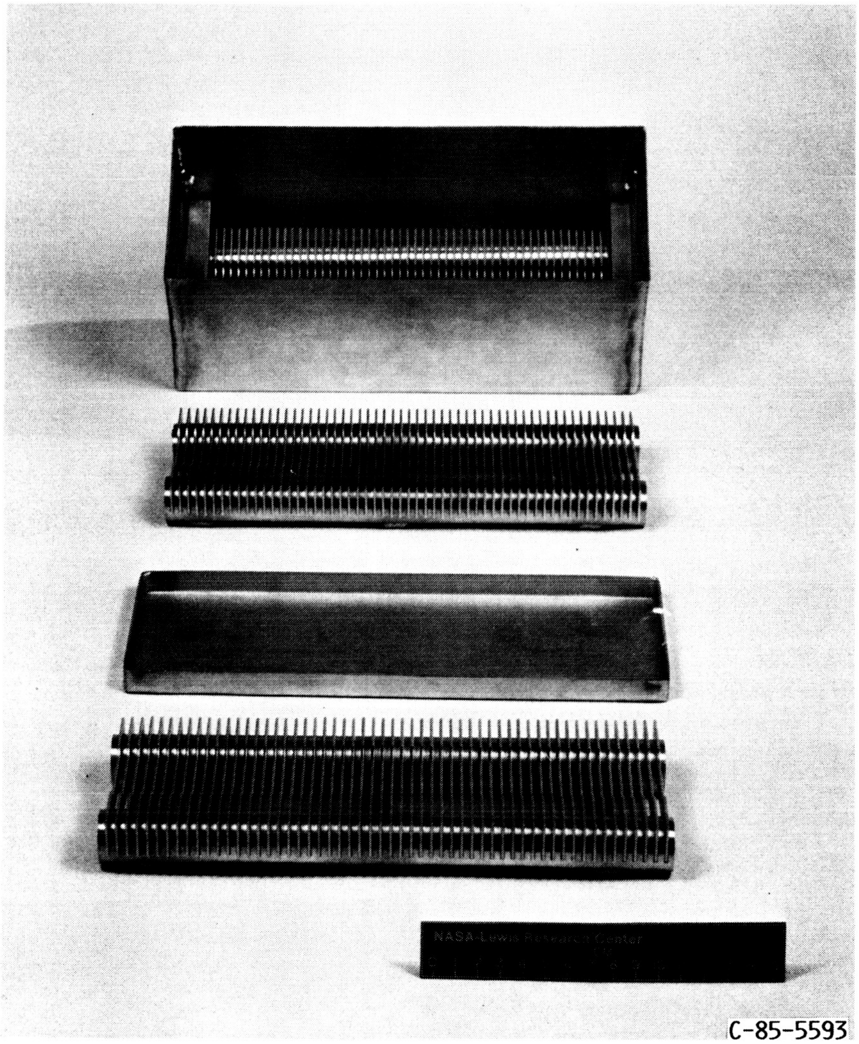


FIGURE 11. - BREAD PAN ASSEMBLY.

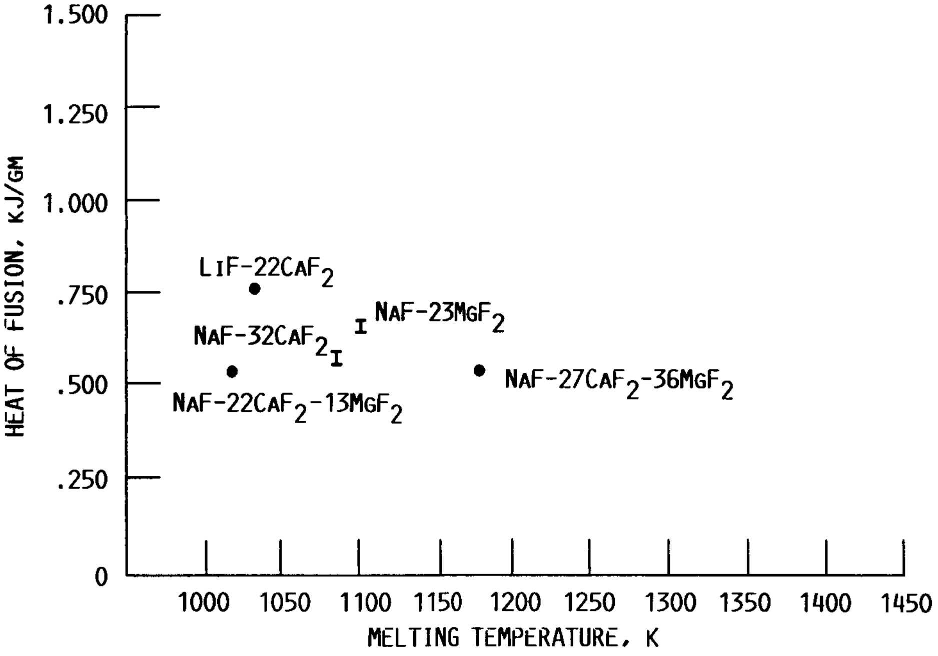
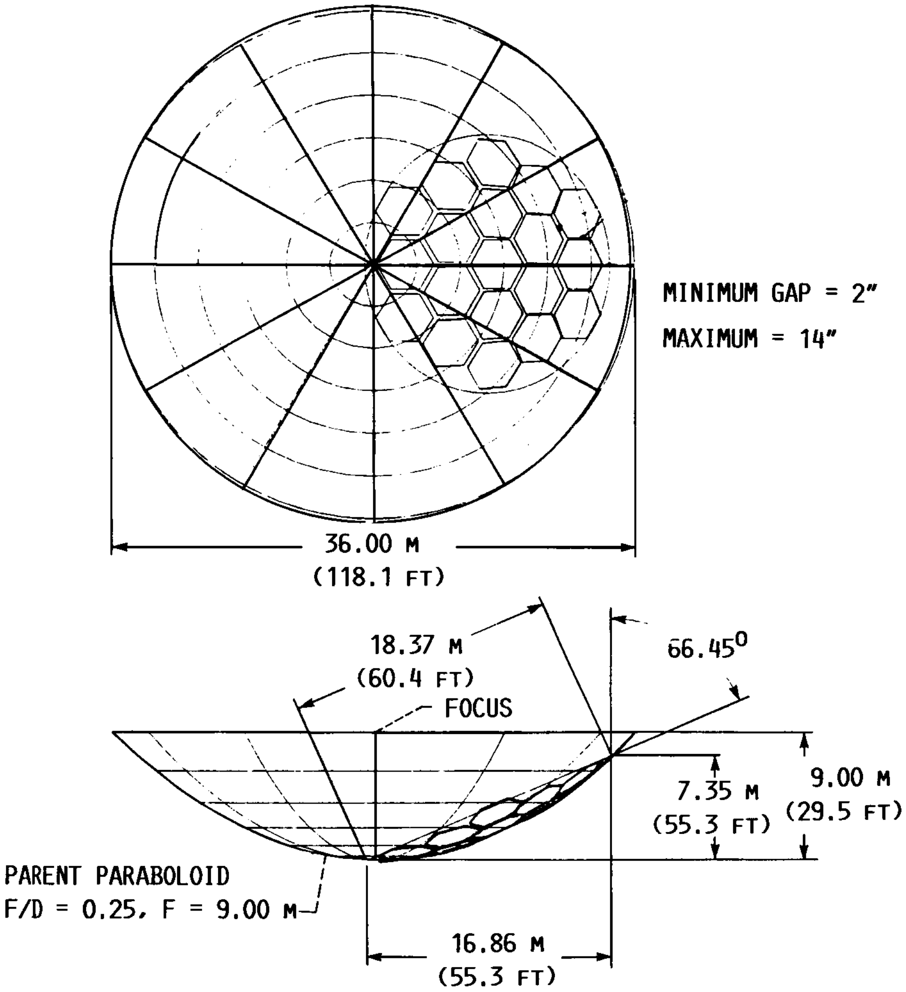
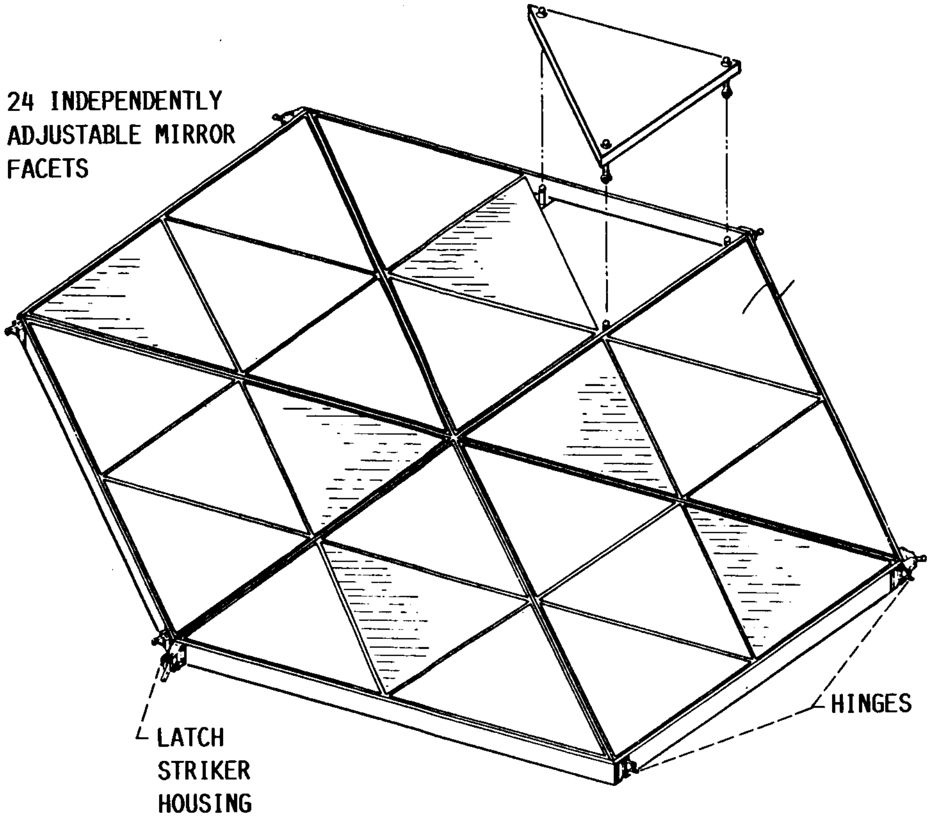


FIGURE 12.- SALTS SELECTED FOR INITIAL CORROSION/ COMPATIBILITY TESTS.



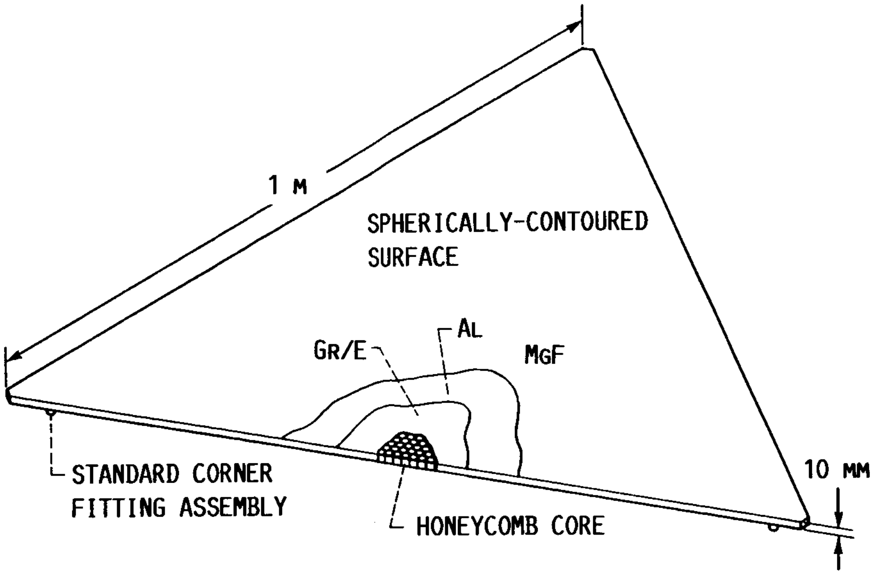
(A) General arrangement and dimensions of the concentrator.

Figure 13.- First generation solar concentrator for 25 kWe solar dynamic power system for operation in low earth orbit.



(B) SKETCH OF A TYPICAL HEXAGONAL REFLECTOR MODULE

FIGURE 13.- CONTINUED.



(C) A TYPICAL REFLECTOR FACET.

FIGURE 13.- CONCLUDED.

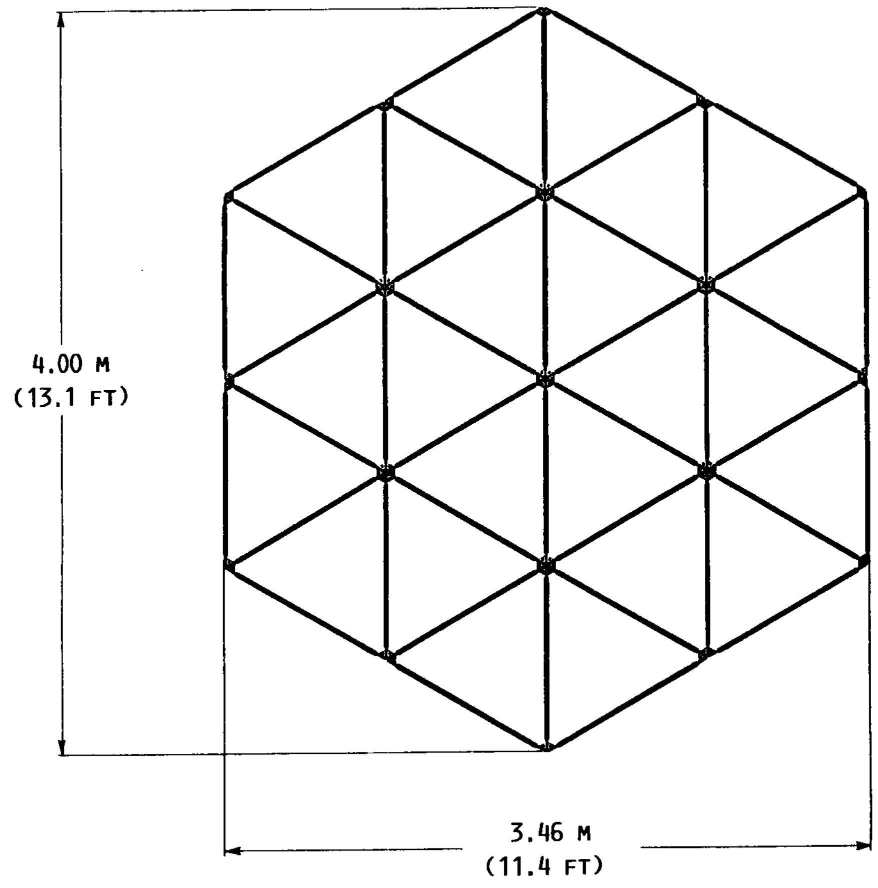


FIGURE 14.- STRUCTURAL FRAMEWORK OF A TYPICAL HEXAGONAL MODULE.

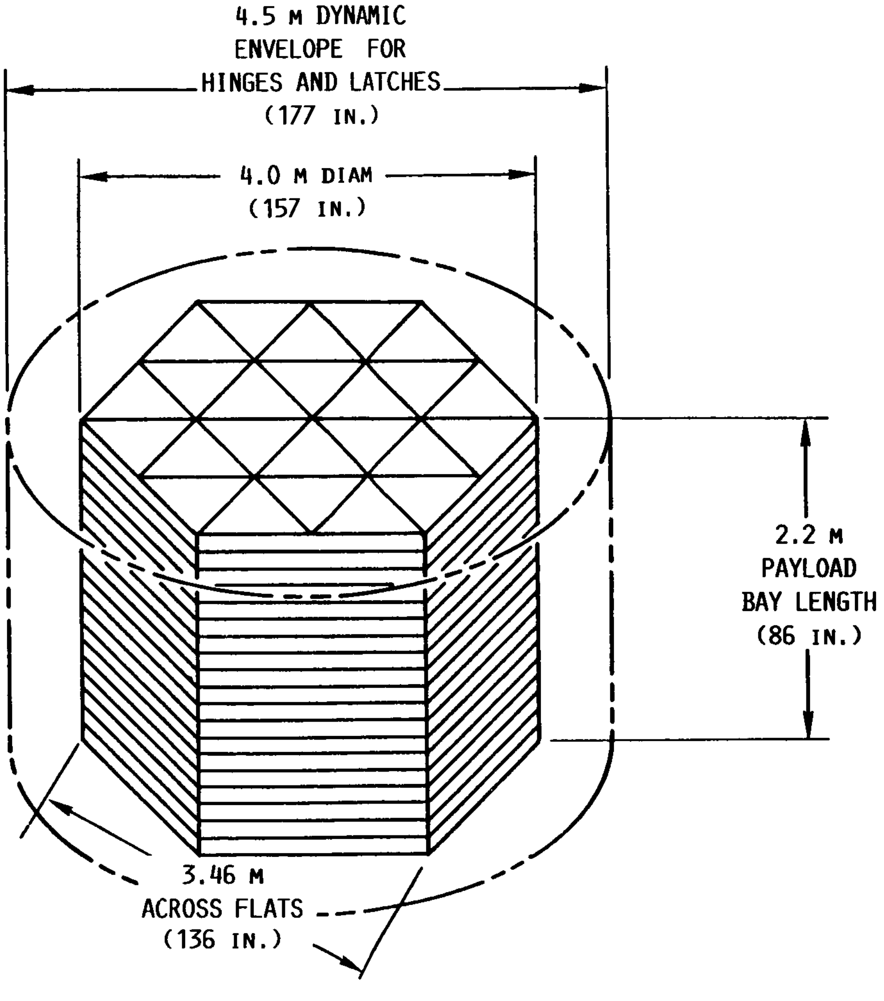


FIGURE 15.- A STOWED ARRANGEMENT OF THE HEXAGONAL MODULE FOR SHUTTLE LAUNCHING.

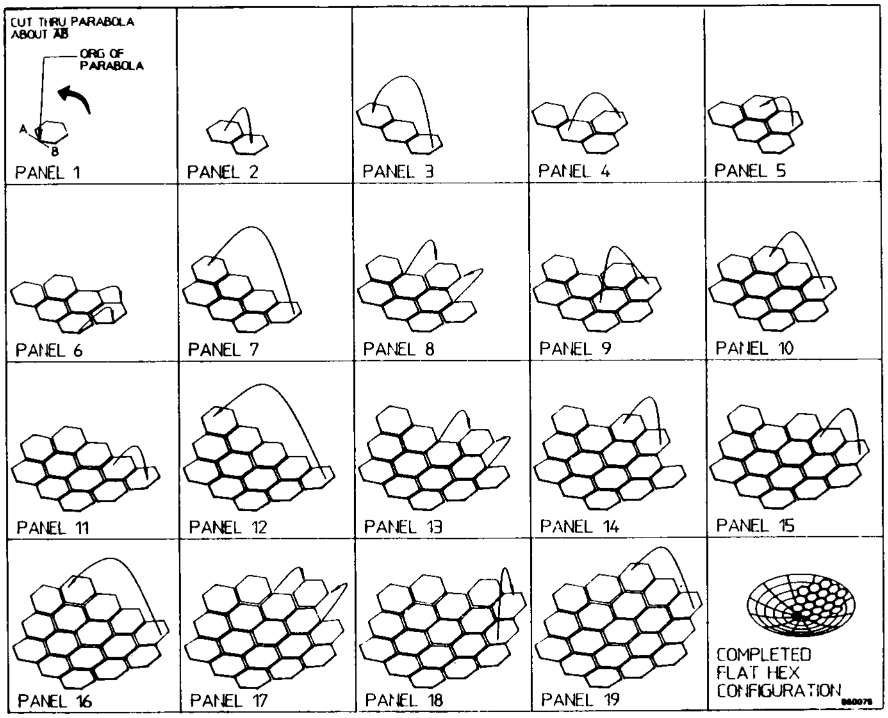
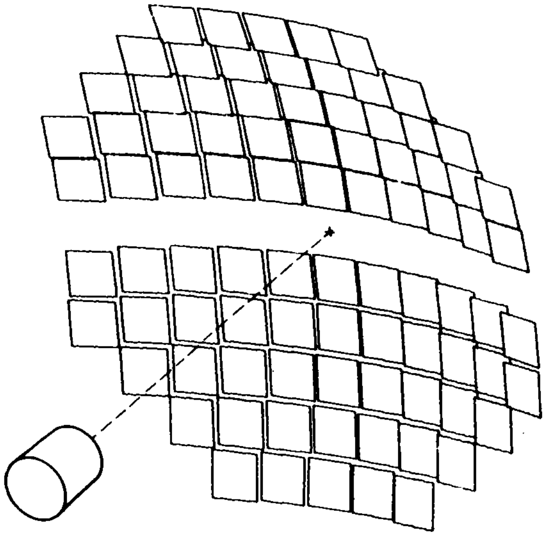
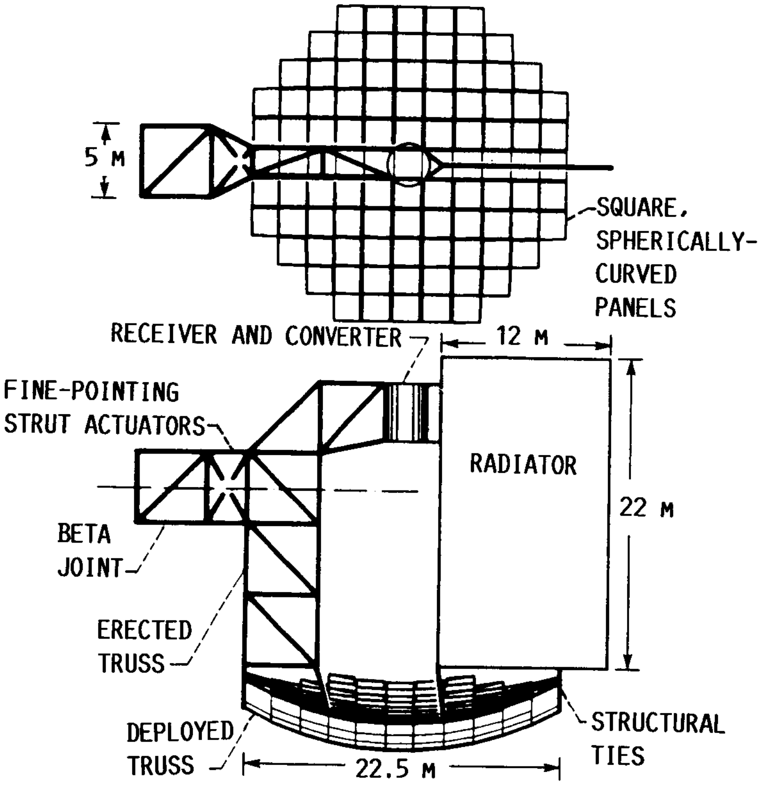


FIGURE 16.- A METHOD FOR ASSEMBLING THE HEXAGONAL MODULES INTO THE FINAL ORBITAL CONCENTRATOR CONFIGURATION.



(A) IDENTICAL PANEL CONCEPT PERSPECTIVE.



(B) DEEP TRUSS SUPPORTED, IDENTICAL PANEL CONCEPT.

FIGURE 17.- A CONCENTRATOR CONCEPT THAT UTILIZES A DEEP TRUSS AND SQUARE REFLECTOR FACET. SHOWN IS ONE ARRANGEMENT OF A SOLAR DYNAMIC POWER SYSTEM FOR USE IN SPACE.

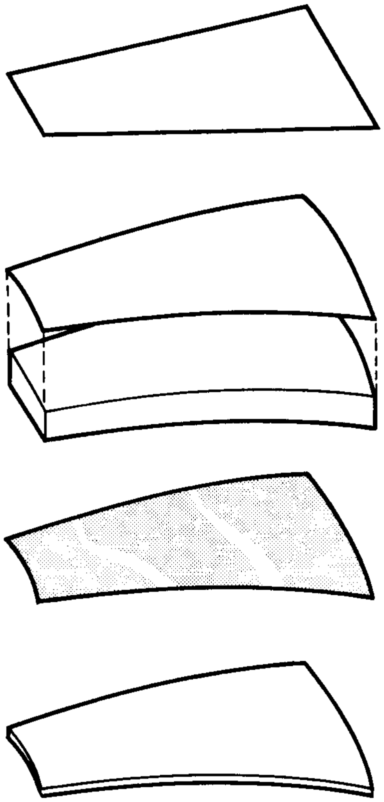


FIGURE 18.- FABRICATION OF MICRO SHEET GLASS REFLECTIVE SURFACE.

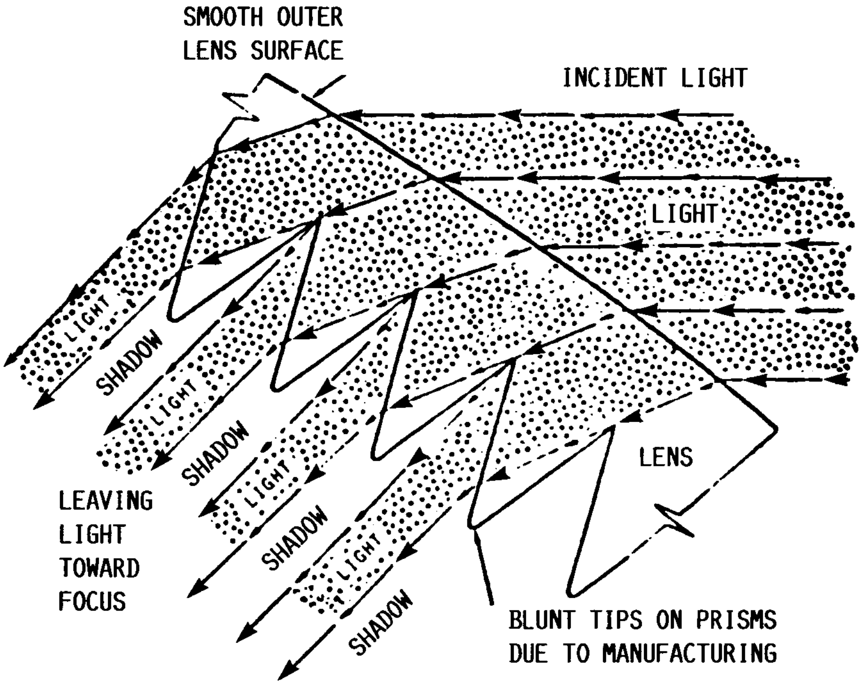


FIGURE 19.- TYPICAL PRISMS IN ENTECH'S DOME LENS CONCENTRATOR.

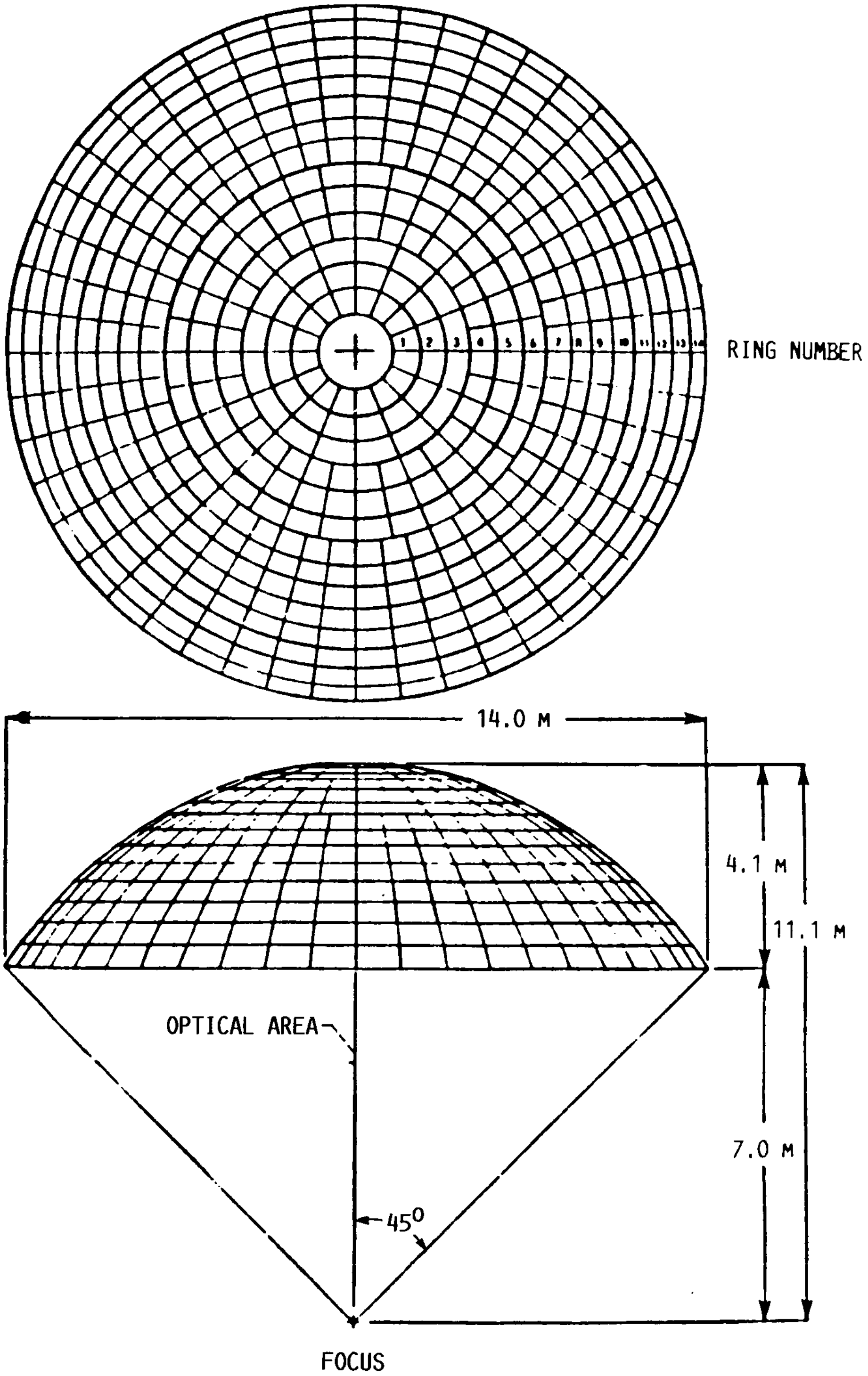


FIGURE 20.- ENTECH'S DOME LENS CONCENTRATOR CONSTRUCTION.

1. Report No.
NASA TM-88884

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Advanced Solar Dynamic Space Power Systems
Perspectives, Requirements, and Technology Needs

5. Report Date

6. Performing Organization Code
506-41-31

7. Author(s)

Miles O. Dustin, Joseph M. Savino, Dovie E. Lacy,
Robert P. Migra, Albert J. Juhasz, and
Carolyn E. Coles

8. Performing Organization Report No.
E-3292

10. Work Unit No.

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Solar Energy Conference cosponsored by the ASME, JSME, and JSES, Honolulu, Hawaii, March 22-27, 1987. Miles O. Dustin, Joseph M. Savino, Dovie E. Lacy, Albert J. Juhasz, and Carolyn E. Coles, NASA Lewis Research Center; Robert P. Migra, Sverdrup Technology, Inc., Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Projected NASA, Civil, Commercial, and Military missions will require space power systems of increased versatility and power levels. The Advanced Solar Dynamic (ASD) Power systems offer the potential for efficient, lightweight, survivable, relatively compact, long-lived space power systems applicable to a wide range of power levels (3 to 300 kWe), and a wide variety of orbits. The successful development of these systems could satisfy the power needs for a wide variety of these projected missions. Thus, the NASA Lewis Research Center has embarked upon an aggressive ASD research project under the direction of NASA's Office of Aeronautics and Space Technology (OAST). The project is being implemented through a combination of in-house and contracted efforts. Key elements of this project are missions analysis to determine the power systems requirements, systems analysis to identify the most attractive ASD power systems to meet these requirements, and to guide the technology development efforts, and technology development of key components.

17. Key Words (Suggested by Author(s))

Space power
Solar dynamics

18. Distribution Statement

Unclassified - unlimited
STAR Category 20

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161