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Solar Dynamic Power for Earth Orbital and Lunar Applications

James E. Calogeras, Miles O. Dustin,
and Richard R. Secunde
Lewis Research Center
Cleveland, Ohio

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SOLAR DYNAMIC POWER FOR EARTH ORBITAL AND LUNAR APPLICATIONS

James E. Calogeras
Miles O. Dustin
Richard R. Secunde
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

ABSTRACT

Development of solar dynamic (SD) technologies for space over the past 25 years by NASA Lewis Research Center brought SD power to the point where it was selected in the design phase of Space Station Freedom Program as the power source for evolutionary growth. More recent studies have shown that large cost savings are possible in establishing manufacturing processes at a Lunar Base if SD is considered as a power source. Technology efforts over the past 5 years has made possible lighter, more durable, SD components for these applications. A review of these efforts and respective benefits is presented herein.

INTRODUCTION

Development of solar dynamic (SD) technologies for space use has been under way for more than 25 years by Lewis Research Center and others. This development has brought SD power to a point where it was selected in the system design phase of the Space Station Freedom (SSF) Program as the power source for the evolutionary phases of that program. Selection of SD power was based on studies and analyses which indicated significant savings in life cycle costs, launch mass and EVA requirements when compared with an all-photovoltaic (PV)/battery power system. These results were obtained with conservative SD designs based on the use of available technology, needing only the development required for flight hardware.

Development of more advanced SD technologies in the last 5 years has progressed to the point where an SD system might be considered for uses beyond Space Station Freedom, and could offer even greater advantages over PV systems than those already identified with present technology. These future uses include earth orbiting satellites and stationary lunar-based power systems.

This paper briefly describes the SD power system for SSF and presents a discussion of advanced SD technologies and potential applications to future space missions. It augments earlier reports [1] and [2] related to the cost advantages of SD power systems in earth orbital and lunar surface applications, respectively. Finally, it presents initial conceptual design aspects of a 5 kWe PV/SD hybrid power system integrated with an earth-orbiting satellite.

SD POWER FOR SSF

SSF Configuration

In the design which existed at the beginning of the flight hardware phase of the SSF program (phase C/D), in 1988, electric power for the manned base of SSF was to be supplied from two Solar Power Modules (SPM's) [1]. One SPM would be located on the port side of the transverse boom of the manned base and the other on the starboard side, each joined to the central part of the transverse boom by a single degree-of-freedom rotating joint (alpha gimbal). Initially, the SPM's on Freedom would supply users with a total of 75 kilowatts of electric power using photovoltaic (PV) power modules as shown in figure 1. As Freedom evolved to greater capabilities, increased power needs would be satisfied by the addition of SD power modules at the outboard ends of the initial SPM's as also shown in figure 1. Each SD module (fig. 2) would supply users with 25 kWe. For the first growth increment, which was expected to be 50 kWe, one SD power module was to be added on each side. The evolution of Freedom was expected to require power capability growth to about 300 kWe total. The total power developed by the PV and SD modules would, of course, be greater than that delivered to the users by the amount needed to account for losses in the distribution system.

The solar dynamic electric power system for SSF is shown in diagrammatic form in figure 3. Heat is supplied to the system by means of a reflecting concentrator which focusses incident solar energy into a cavity-type heat receiver. The receiver includes heat exchanging tubes for transfer of heat energy to the gaseous working fluid of the closed Brayton cycle (CBC) heat engine. Also in the receiver, is a eutectic mixture of $LiF-CaF_2$ salts, contained in capsules surrounding the tubes. The fluoride salt mixture is an effective thermal energy storage medium due to its high latent heat of fusion. The phase change (freeze-melt) temperature of the salt mixture is near 1040 K (1420 °F). During the sunlit portion of Freedom's orbit, sufficient thermal energy is stored so that the temperature of the gaseous working fluid exiting the receiver remains within a range of about 990 K (1330 °F) to 1030 K (1400 °F) throughout the orbit.

The maximum temperature in the CBC has been selected so that refractory materials are not needed anywhere in the system. The gaseous working fluid is a mixture of helium and xenon with an equivalent molecular weight of 40, which results in the best combination of heat transfer and thermodynamic performance. Although, components and system are designed for space operation the performance can be proven with confidence in test facilities on earth.

Benefits of SD

There are two primary reasons for the interest in the solar dynamic system as the source of SSF growth power. A PV/SD hybrid system offers the flexibility of a power system with two types of sources, thus assuring an uninterrupted supply of power in the unlikely event of a major or systematic problem in either type source. But even more compelling is the potential cost savings that can be realized with SD. The SD power generating and storage components have longer lifetimes than PV arrays or batteries. These SD lifetimes result in substantial cost savings in hardware replacement, launch, and on-orbit installation costs. Because of the significantly higher solar-to-electric power efficiency of a SD system, it has a solar collection area only about 25% of that for a PV system for a given power output. This translates to about one-half the aerodynamic drag and correspondingly lower reboost requirements. For constant drag operation, SD systems would allow Freedom to operate at lower altitudes. This would permit the Shuttle orbiter to rendezvous with Freedom at lower altitudes, significantly increasing the orbiter's payload capacity, and lower the launch cost per pound to orbit. Studies have indicated that the various operations and hardware cost savings resulting from the use of SD power rather than PV power for Freedom's growth would amount to a reduction in life cycle costs of several billion dollars over the 30-year life of Freedom. The results of one such study are shown in figure 4 (Lewis Space Station internal memo No. FE-289 entitled Solar Dynamic vs. Photovoltaic Life Cycle Cost Analysis by Sue Motil, 10/29/90). A comparison of projected astronaut time resources needed for assembly and maintenance of PV and SD power modules is shown in table I. These results were obtained with the conservative SD designs based on the use of existing technology, needing only the development required for flight hardware.

Advanced Technologies

With a given power conversion unit, space solar dynamic system performance will largely depend upon the quality of the concentrator and heat receiver and their ability to collect store and transfer energy from the sun into the thermodynamic power conversion system.

Concentrator Technology - The goals set for attaining the required concentrator performance, listed in detail in reference [3], include high concentration ratio, acceptable surface reflectance, low weight, long life, and low degradation of performance with time.

Concentration ratios required for high temperature receiver operation are only realized if, in addition to having the correct geometric form, the concentrator surface has the required high surface accuracy. Required concentrator performance is only possible if careful attention is paid to achieve a highly specular surface, free of dents, dimples and blemishes. This can be accomplished by careful selection of surface materials, surface thickness and epoxy bonding material. Highly specular surfaces require the use of special surface leveling techniques or the application to the surface of a thin layer of glass (microsheet) [4]. Both of these approached have been pursued.

A high quality all metal concentrator is being developed by Solar Kinetics, Inc. using aluminum face sheets bonded to both sides of a 0.625 cm. aluminum honeycomb. Leveling of the surface is accomplished by the application of a thin monomer coating over the front face sheet. Then a very thin aluminum reflective coating is applied. Finally a layer of Al_2O_3 protective coating is added.

Microsheet glass surfaces, being developed by both Hughes Danbury Optical Systems and by the NASA Lewis Research Center [5], are probably the best protection against atomic oxygen attack and provide an excellent substrate for applying highly reflective surfaces. Issues that have been addressed include, cleaning the substrate, applying of adhesive without trapping bubbles, slumping the glass to the correct contour and reducing substrate "print through." To date, techniques for fabrication and handling large sheets of microsheet glass have not been developed.

It has been demonstrated under the SSF program, using neutral buoyancy facilities, that erection of large concentrators (about 18.24 m.) in a reasonable time is possible using astronaut EVA. Automatically deployed concentrators will be required, however, for unmanned satellites. Smaller deployable concentrators are being considered for use on these missions. A two meter deployable concentrator (fig. 5), based on technology of the Sunflower solar concentrator developed at TRW in the 1960's [6], is being designed at Cleveland State University's Advanced Manufacturing Center.

Receiver Technology - Another issue addressed in the Advanced SD technology program is cyclic distortion of the thermal energy (TES) canister. A goal of the program is to eliminate this effect and at the same time reduce the mass of the receiver to one half that of the SSF design while retaining reliability and long life.

Distortion of the TES canister is caused when a wall of the canister is exposed to uneven heating, and as the TES material adjacent to the wall melts, it expands (up to 30% for LiF) forcing the canister wall material to be stressed beyond its yield point. If this happens each cycle (thermal ratcheting), the wall may be gradually stretched to the point of failure. The SSF design avoided this problem by encasing the TES material in small canisters, a conservative but weighty approach. This thermal ratcheting phenomenon is illustrated in figure 6.

An advanced Brayton heat receiver, designed by Sundstrand Corporation and shown in figure 7, avoids the problems of hot spots and thermal ratcheting through considerations in the design of a heat pipe cavity [7]. In daylight operation, the solar receptor is the heat pipe evaporator and the combination of the TES wedge -shape canisters and heat engine gas tubes serve as the heat pipe condenser. Since the heat pipe is inherently an isothermal device, the heat pipe cavity, in effect, receives uneven solar flux on the cylindrical solar receptor, and redistributes the flux evenly to the TES canisters and the heat engine gas tubes. This results in uniform melting of the TES material and no hot spots are generated.

To verify that an evenly heated canister concept does, in fact, avoid thermal ratcheting, an experiment was conducted to repeatedly heat a TES canister isothermally to beyond the melting point and then cool to freeze the TES media. The rate at which the heat was applied to the canister corresponded to a low-earth-orbit application. To heat the canister isothermally, the experiment was conducted in a fluidized bed furnace (fig. 8). The canister was carefully measured after each heating and cooling cycle, in a special fixture, for evidence of distortion. No indication of thermal ratcheting was found. This experiment and results of the tests are described in reference [8].

An additional experiment to investigate the performance of the heat pipe cavity is being planned. This experiment will simulate a section of the cavity including the cylindrical solar flux receptor, a TES canister, a heat engine gas tube (for removing heat), wicking, and the heat pipe working fluid. Operation and performance of the cavity will be observed with carefully located instrumentation over the equivalent of low-earth-orbit cyclic operation.

LUNAR BASE SD SYSTEMS

The production of oxygen on the moon from materials found on the surface of the moon may be an essential process as oxygen will be used for fuel and to maintain life at the lunar base. A solar dynamic system is being proposed to supply the power for this process from a Brayton heat engine and alternator. A portion of this electrical power will provide the needs of motors, lights, etc. required by the process. A smaller portion of the power will be converted to the heat needed to extract the oxygen in the process. The thermal energy storage system for this endeavor must accommodate large quantities of heat over a long time period if operation of the process is to continue during the lunar night (14 earth-days).

Analysis of a lunar TES scheme proposed by the University of South Florida [2] is currently underway. By using the lunar regolith as the storage media, large mass savings and thus, large transportation cost savings will be possible. In this scheme shown in figure 9, several carefully grouped probes would be buried in the loose lunar regolith. These probes would carry gas heated in a heat receiver. The gas would need to be hot enough to melt the regolith (1400-1500 K) during the lunar day (14 earth-days). Enough of the regolith would be melted to operate the Brayton cycle engine during the lunar night (also 14 earth-days).

A weight comparison of the University of South Florida's concept with a PV/battery system, a PV/pressurized storage regenerative fuel cell (RFC) system, a PV/cryogenic storage RFC and a lunar regolith sensible heat system is shown in figure 10.

To properly evaluate this concept, several activities have been started:

1. Thermal analysis will continue at The University of South Florida and at NASA Lewis to aid in sizing the probes and to determine the performance of the concept.
2. A grant has been issued to the University of Arizona to measure the thermal-physical properties of the lunar regolith. This will be done using basalt mined in Minnesota that closely resembles the lunar basalt returned to the earth during Apollo missions.
3. Oak Ridge National Laboratory will design an experiment to determine the performance of a large scale storage system.
4. A smaller experiment is being set up at Lewis to melt a small canister (20 cm. dia. by 46 cm. long) of simulated regolith to determine the nature of the melting process.
5. A small contractual effort at Rocketdyne will investigate the use of in-situ lunar materials for thermal energy storage on the moon. This effort will explore the benefits of the system and identify some of the key issues.

Previous analyses have shown that operating most heat receivers at temperatures above 1300 K results in high receiver losses from reradiation out of the aperture. As a result, a direct fluid absorption receivers concept is being pursued by Indiana University under a NASA grant, for high temperature applications [9]. This receiver uses a working gas in which a small amount of halogen gas has been added. The halogen gas absorbs energy directly by focusing the solar energy from the concentrator through a quartz window. Proper design allows for the absorption to take place within a cavity leaving the metal surrounding the cavity some what cooler than the gas. A second advantage of the direct fluid absorption receiver is that, since the gas itself does not reradiate, the aperture can be larger than with other receivers, which results in reduced concentrator requirements.

At Indiana University a small (500 watt) prototype is being built for testing with a xenon lamp heat source. This experiment is shown in figure 11. The prototype receiver is totally enclosed in a quartz tube with the aperture window at the end of the tube. The gas is circulated by means of a small compressor. Heat from the lamp is absorbed in the cavity. The guard heater eliminates the need for insulation. Heat is removed by the water cooled heat sink. Testing with this apparatus is imminent.

SMALL EARTH ORBIT SATELLITES

The life of small satellites powered by PV/battery systems is typically limited by the life of the batteries. The possibility of extending the satellite life is being investigated in a small NASA/Naval Research Laboratory effort to design a 5 kWe PV/SD hybrid powered satellite. A critical design requirement of the system is that the SD system be gimballed so that the SD concentrator can be pointed at the sun while the satellite is pointed at the earth. One of the configurations being considered is shown in figure 12.

CONCLUDING REMARKS

Recent developments would enhance the life cycle cost payoff of using SD power systems in evolutionary SSF phases. Enabling SD technologies for certain process power operations on the lunar surface can provide large savings in transportation costs by using in-situ thermal energy storage schemes. Future efforts will investigate the possibility of extending the useful life of a small satellite power system by adding a SD module to compliment the PV system.

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Table I. Projected Astronaut times for assembly and maintenance of PV and SD power modules

	25 KW SD Module (Man Hours)	18.75 KW PV Module (Man Hours)
On Orbit Assembly		
IVA	60	40
EVA*	21	12
Total/Module	81	52
Man Hours/KW	3.24	2.77
Maintenance**	(Man Hours/Year)	(Man Hours/Year)
IVA (Robotic)	5.4	24.4
EVA	17.9	7.4
Total/Module	23.3	31.8
Maintenance Man Hours/Year/KW	0.93	1.70
Resupply Mass**	1708.0 lbs/yr	2825.5 lbs/yr

* 24 M.H. of EVA Available per Shuttle Flight for Planning Purposes
** Engineering Estimate, No Margins

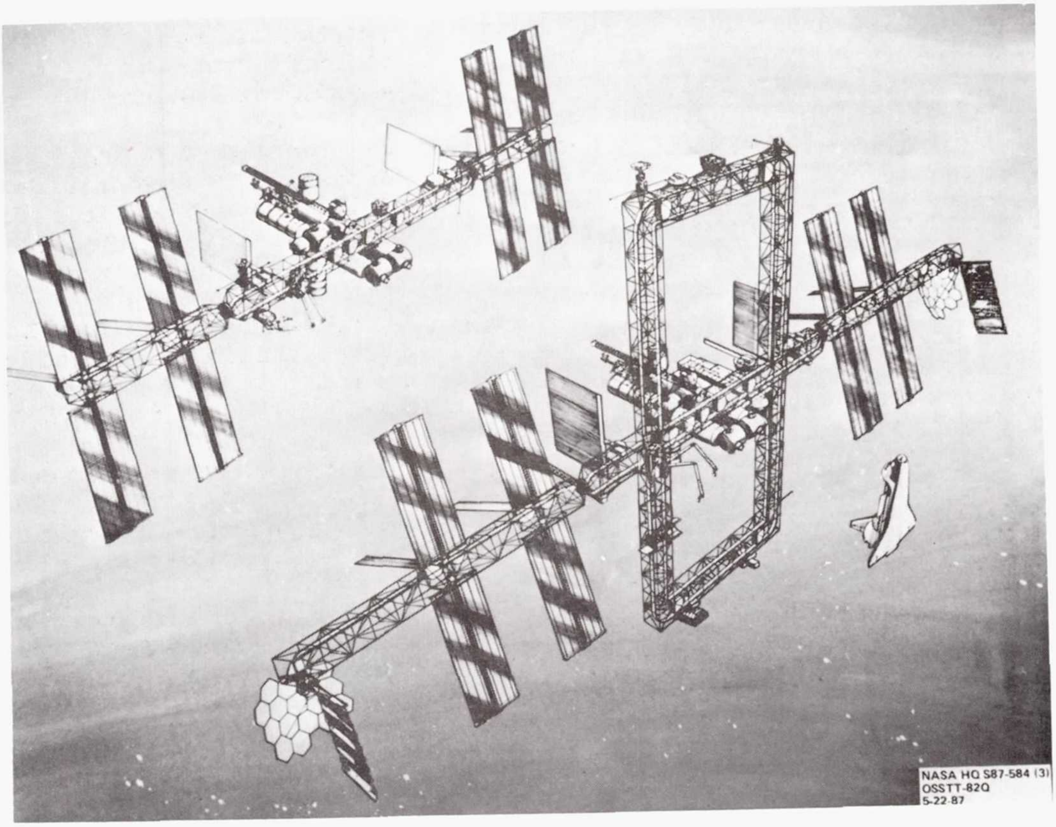


Figure 1. Space Station Freedom.

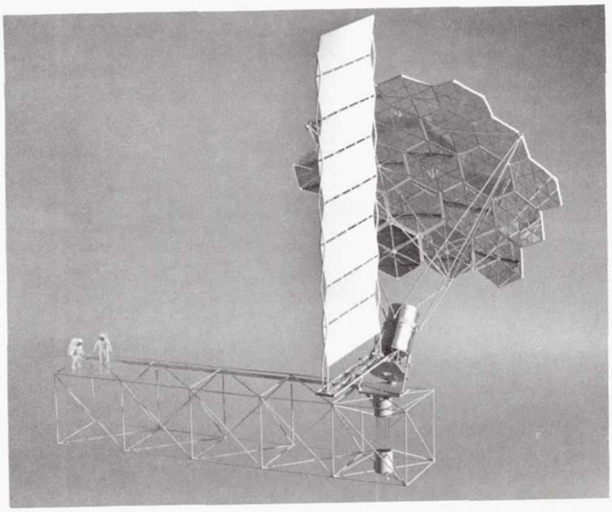


Figure 2. Solar Dynamic Module.

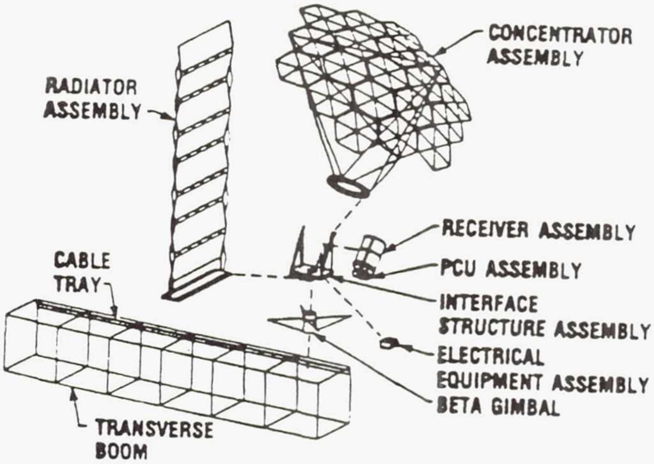
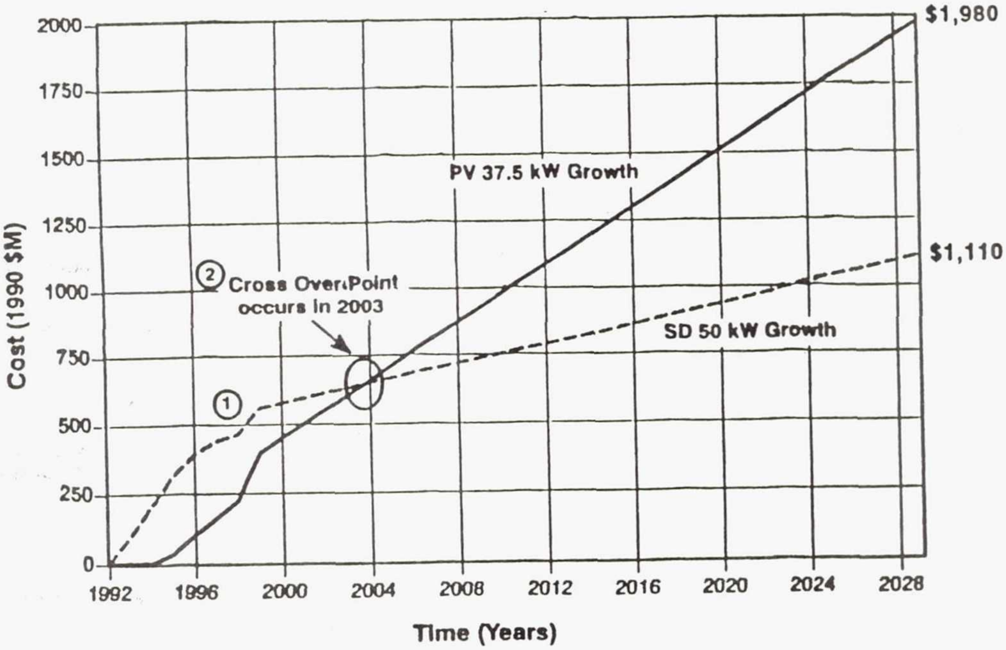


Figure 3. Schematic of Closed Brayton Cycle.



Notes:
1. Step change between 1998 and 1999 is due to initial launch cost.
2. Curves based on current 18.75 kW PV and 25 kW SD power modules, in a balanced station configuration. Cross over would occur prior to year 2000 for common growth power levels.

Figure 4. Photovoltaic vs. Solar Dynamic Cost Comparison.

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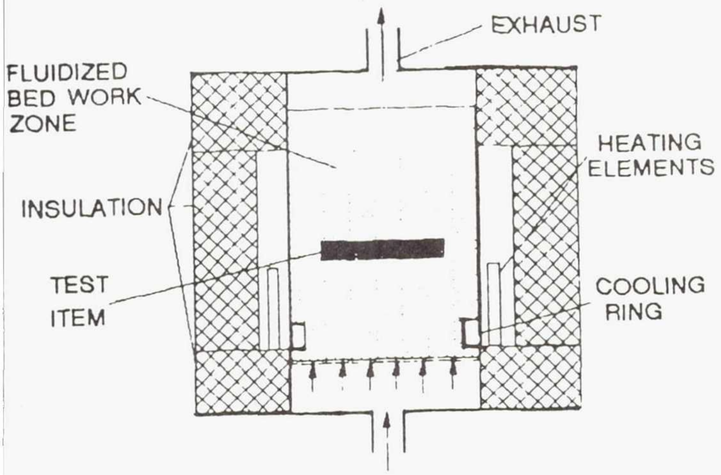


Figure 8. Fluidized Bed Furnace.

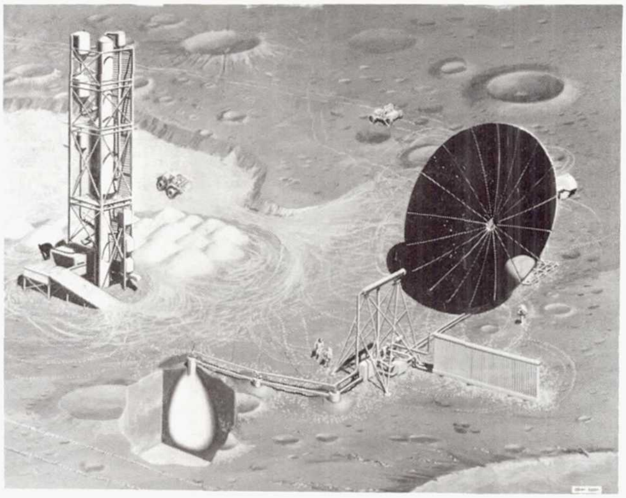
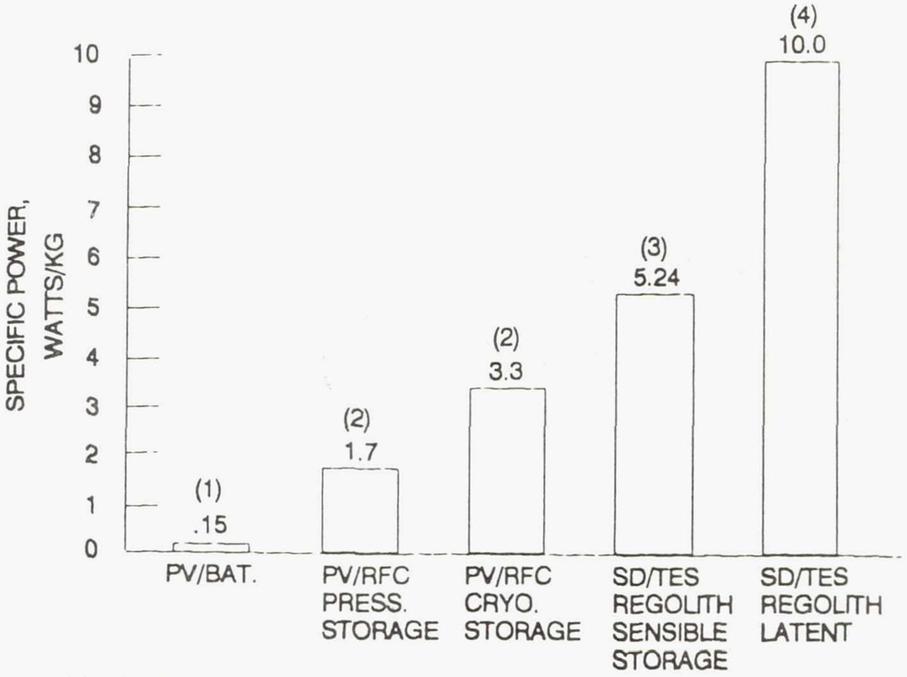


Figure 9. SD System at Lunar Base Oxygen Process Plant.



(1) REFERENCE [10]
(2) REFERENCE [11]
(3) PRIVATE COMMUNICATION, B. TILLOTSON, BOEING AEROSPACE AND ELECTRONICS
(4) REFERENCE [2]

Figure 10. Comparison of Alternative SD Power Systems for Lunar Base.

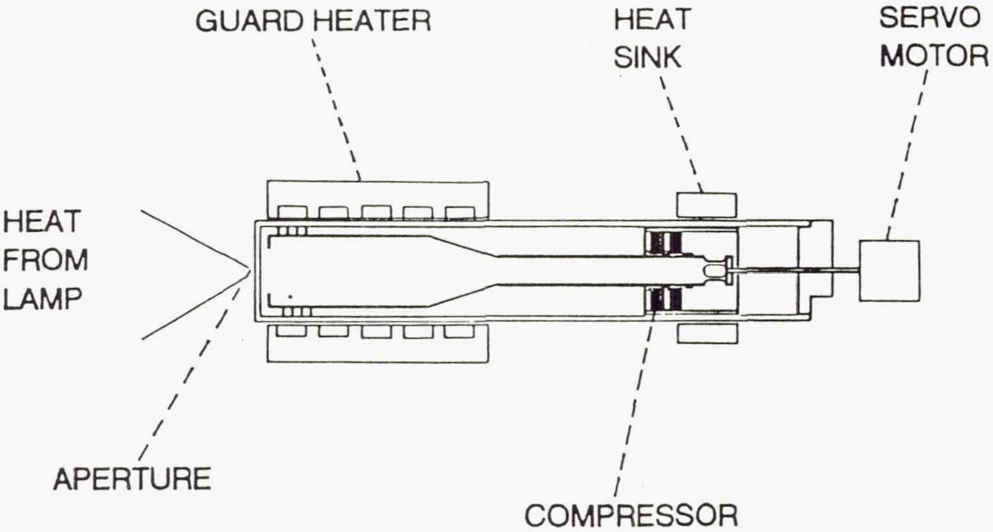


Figure 11. Direct Fluid Absorption Receiver Prototype Experiment.

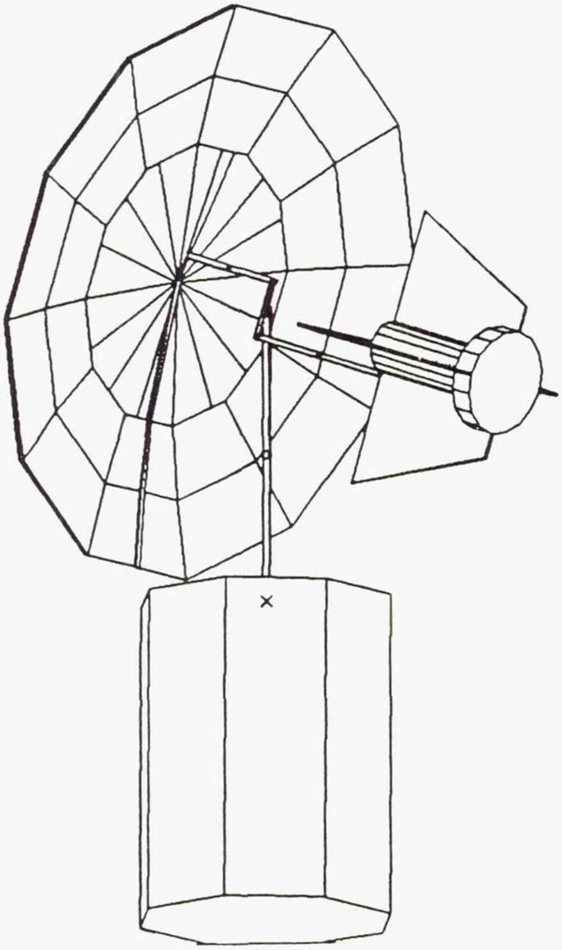


Figure 12. Proposed Configuration for SD Power System for Small Satellite.

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