Solar Batteries*

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Summary—**The introductory part of this paper will provide a brief summary of how recent advances in military electronics for ground and space applications have created an urgent need for new energy sources and power supplies. In this search for new sources of power, considerable attention is being devoted to the utilization of solar energy.**

A short summary will be provided of the applications of USASRDL-developed solar cells in the satellite field to date. This will include a discussion of the apparent reliability and efficiency of solar cells in operating situations and the environmental factors affecting solar cells. A brief discussion will be given of the various methods of mounting solar cells with succinct comments on the advantages and disadvantages of different methods. Reference will also be made to USASRDL quality control methods and the quality vs cost problem.

The primary portion of the paper will be devoted to a detailed discussion of those energy conversion devices which employ static methods for direct conversion of solar energy to electrical energy, *i.e.*, those types which utilize the thermoelectric, Edison (thermionic emission), photovoltaic and photoemission effects.

The relative merits of these systems based on present and anticipated conversion efficiencies are reviewed, in brief, for guidance as to future possibilities of these types of devices and their utilization in the satellite program.

RECENT advances in military electronics for ground and space applications have created an urgent need for new energy sources and power supplies. In this search for new sources of power, considerable attention is being devoted to the utilization of solar energy.

Under the title "Solar Batteries," those energy conversion devices which employ static methods for direct conversion of solar energy to electrical energy will be discussed, *i.e.*, those types which utilize the photovoltaic, photoemission, the thermoelectric, and the Edison (thermionic emission) effects.

The relative merits of these systems based on present and anticipated conversion efficiencies will be reviewed with emphasis on space applications. The theory of these systems has already been well covered in a number of presentations by various authors and this information is readily available in the literature [1]–[13].

Photovoltaic Effect

The photovoltaic effect has been successfully employed for the conversion of solar energy to electrical energy in Vanguard I, Sputnik III, and Explorers VI and VII, through the use of the silicon photovoltaic cell, quite often called a solar cell or solar battery, originally developed by the Bell Telephone Laboratories [14], [15]. A number of space vehicles to be launched in the near future will also depend on this type of solar power supply.

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Silicon solar cells having efficiencies in the order of 9 to 10 per cent are now obtainable in reasonable quantities. In outer space, for earth orbiting satellites, solar energy is available at the rate of 2 cal/cm^2/minute or 1400 watts/meter^2 or 440 BTU/square foot^2/hour, with the receiver at normal incidence. Assuming an efficiency of 10 per cent (sea level reference 1.5 cal/cm^2/minute cell temperature at 25 degrees C) 14 mw/cm^2 of active cell surface is realized. In an actual design of a solar power supply, consideration is given to the type of orbit, duty cycle, spinning or oriented vehicle, cell temperature, erosion of protective covers by micrometeorites (dust), spectral shift from sea level to outer space, and protection for the cells during preflight tests and handling in addition to conditions existing during the launching period. After corrections for the above conditions, 8 mw/cm^2 or 7.4 watts/square foot of active cell area is generally considered available. A power-to-weight ratio of 0.25 watt/pound, including storage system, for a nonoriented satellite was achieved in an actual solar power supply, shown in Fig. 1 mounted on the satellite. The power supply [16], including the sealed nickel cadmium storage batteries, weighed 22½ pounds. The nonoriented solar power supply was rated at 5 watts and weighed 17½ pounds. If orientation were possible, using similar design methods, a power to weight ratio of 1.5 watts/pound would have been possible instead of the 0.25 watt/pound which was realized.

Looking into the near future, it is expected that 1×2-cm cells with efficiencies in the range of 12 to 15 per cent can be obtained in reasonable quantities. Because of the expected future higher power requirements, oriented expansible arrays of cells must be employed. The use of oriented arrays affords new possibilities in limiting the equilibrium temperature of the cells to the order of 0°C or lower. This low cell temperature can be achieved through the use of spectrally selective optical coatings which would increase the emissivity of the cell surface in the far infrared and reject radiant energy in the portions of the spectrum not utilized by the cell; it can be achieved by providing a good thermal path from the back of the cell to the rear surface of the array and by coating the rear of the array to obtain high surface emissivity to take advantage of the cooling effect of space. Even lower cell temperatures are a definite possibility. Initial information from the "paddlewheel" (Explorer VI) satellite indicates that the temperature of the cells is about 8°C.

The efficiency of a photovoltaic cell increases with a decrease in temperature. For instance, a cell with an efficiency of 12 per cent at 25°C will have an efficiency of 13 per cent at 0°C. Assuming that cells with an efficiency

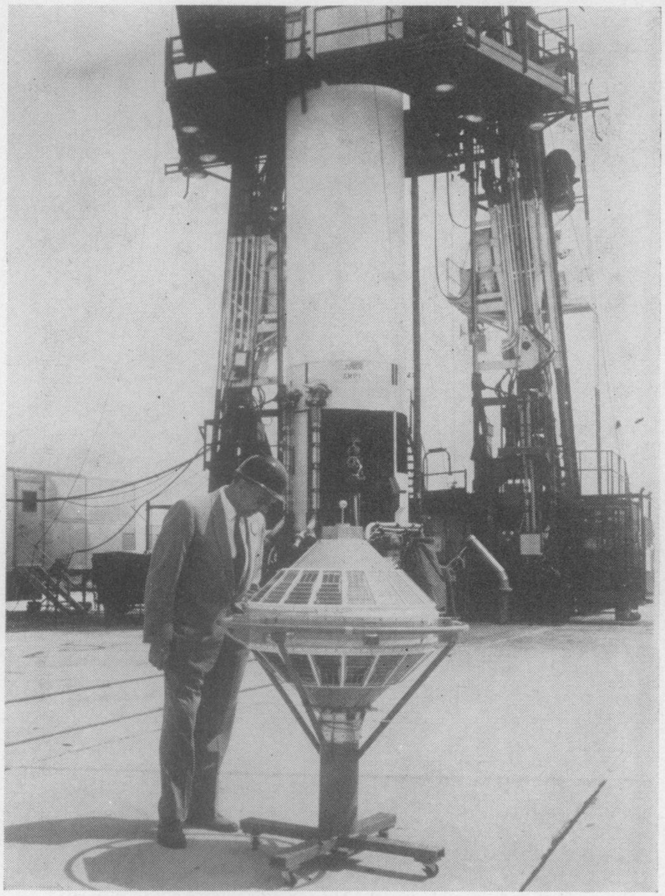

Fig. 1—Explorer VII showing solar power supply. Dr. Kurt Debus, director of the Army Ballistic Missile Agency's Missile Firing Laboratory, looks over the Explorer VII satellite at the launching site. The 91.5-pound satellite was placed in orbit by the Juno II rocket shown in the background (U. S. Army photograph).

of 12 per cent (25°C) are available and that a cell temperature of 0°C can be obtained, an output of 18 mw/cm² of active cell surface can be realized. Compensating for transmission losses through cell covers sand blasted by meteoritic dust and the so-called spectral shift, the output is reduced to 14 mw/cm² or 13 watts/square foot. Using this figure with present design methods for the mounting of cells, orientation of plaque, and required protective covers and housing, a figure of 3.5 watts/pound (including storage batteries) can be calculated for the power output.

Programs are now in effect for the investigation of new materials for solar cells, multilayer and variable energy gap cells for greater utilization of the spectrum, high efficiency silicon cells, large area cells, multiple junctions on a single thin film of silicon, and high temperature cells. As a result of these efforts, efficiencies of 15 per cent for single gap cells and efficiencies of 20 to 30 per cent for cells of new materials and devices utilizing a greater portion of the spectrum may be possible. Present costs for photovoltaic cells are high and a program has been initiated for the investigation of methods leading to high production yields of efficient cells at a reasonable cost.

Photoemission Effect

The photoemission effect [3], [4], [5], [6], [12] has been known for many years but little effort has been made in the past to use it for the conversion of radiant energy into electrical energy of sufficient magnitude for use as a source of power. A photoemission diode is analogous to the thermionic diode. When the photoemissive layer is illuminated, light photons release their energy to the electrons upon collision. If the amount of energy is greater than the work function of the material, the electron escapes with a kinetic energy equal to the excess of the quantum energy over the work function and it will reach the anode. In the thermionic diode, the anode is maintained at a lower temperature than the cathode, but in the photoemission diode, the anode is kept "dark," to prevent emission which would result in an opposing current. It is also subject to space charge limitations. Recently, several organizations have been investigating the possibility of increasing the efficiency of a device utilizing this effect, and 3 per cent appears obtainable. The chief advantages for this device are a high power-to-weight ratio and relatively low cost-per-unit power. Preliminary calculations indicate that approximately 3 kw of power at 28 volts can be obtained if the cells are mounted on a 30-foot diameter balloon. Fifty to 150 watts/pound appears feasible. The material costs are fairly low and large area devices may possibly be fabricated by vapor deposition of the photoemissive materials.

Thermoelectric Effect

Solar powered thermoelectric generators are being considered as a source of power for space applications. Many groups are actively engaged in the investigation of thermoelectric materials and generator design. A survey of the literature and reports resulting from various programs sponsored by the Department of Defense indicates that a number of thermoelectric materials have been investigated and their efficiencies over a given operating temperature range have been determined. Fig. 2 and Fig. 3 show the efficiencies of N- and P-type materials in terms of a figure of merit, Q^2/pK, when $Q^2 = \text{volts} \times \text{deg}^{-1}$, $p = \text{ohm}^{-1} \times \text{cm}^{-1}$, $K = W \times \text{deg}^{-1} \times \text{cm}^{-1}$, which is based on the measured thermoelectric properties of the materials. It does not represent the over-all efficiency obtainable in a generator where losses caused by contact resistance between members of the thermocouples, lateral heat losses, and transfer of energy from the source to the hot junctions must be taken into consideration. For example, the over-all efficiency of a solar powered thermoelectric generator will be

$$\text{Efficiency} = \frac{\text{Electrical output}}{\text{Total intercepted energy}}.$$

It can be seen in Figs. 2 and 3 that the materials with the highest figures of merit are P-type $BiSbTe_3(Se)$ and

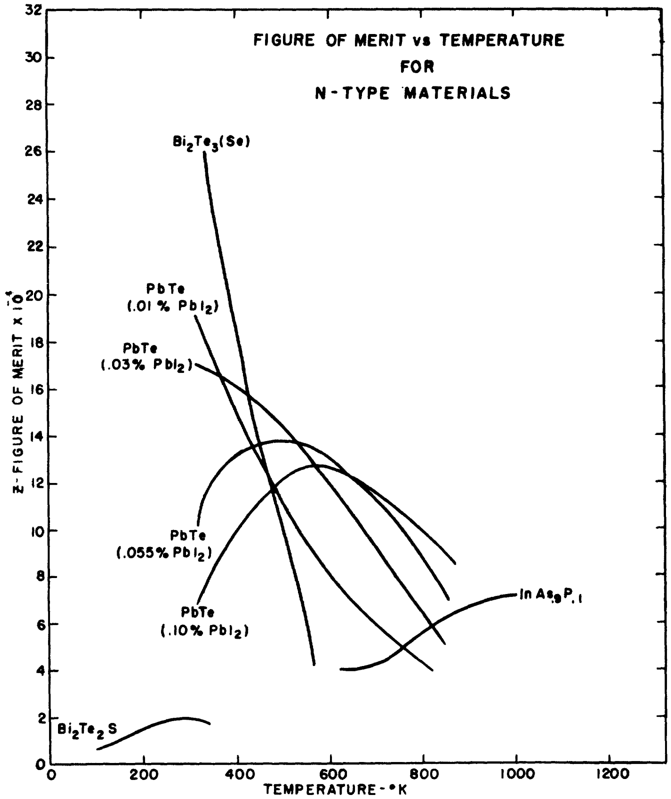

Fig. 2.

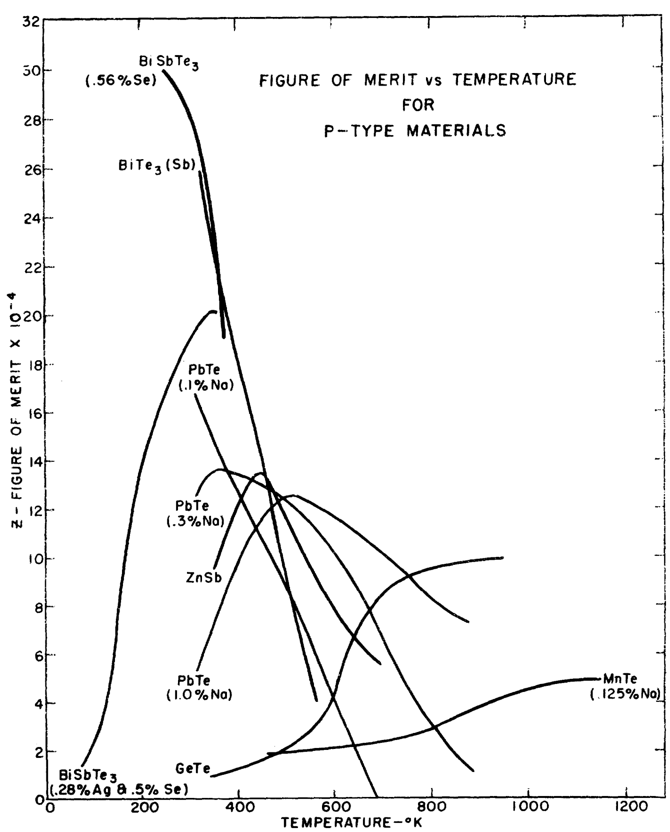

Fig. 3.

N-type $Bi_2Te_3(Se)$. Because of the low melting points of these materials, however, their use in a solar-powered thermoelectric generator does not appear feasible. Materials capable of operating at higher hot junction temperatures are required in order to obtain a reasonable Carnot efficiency. A recent paper [17], discusses the merits and design problems of a solar-powered thermoelectric generator and its possibilities for space use. Since the data presented was obtained from the performance of an actual device, it will be used later in this discussion for comparison to other systems.

Thermionic Emission

Considerable effort is being devoted to the utilization of the Edison effect as a means of converting thermal energy into electrical energy. A number of laboratories are actively engaged in this field and claims of efficiencies of 10 per cent for the close spaced vacuum diode have been made and predictions of efficiencies up to 40 per cent for the Cesium vapor type have appeared. As for its present and future possibilities in space applications, a recent paper [3] gave a comprehensive engineering analysis of a thermionic power supply using solar energy as a heat source. The data presented will be used as a basis for comparison with other systems later in this discussion.

Comparison of Conversion Systems

In comparing the relative merits of these various systems for the direct conversion of radiant energy from the sun to electrical energy, a number of factors must be taken into consideration. Some of these are listed below:

- Reliability,
- Power per unit weight, area or volume,
- Complexity of the system,
- Damage by meteorites; punctures and erosion,
- Radiation damage,
- Operating lifetime,
- Mechanical problems introduced by use of expansible arrays, concentrators, pumps,
- Accuracy of orientation,
- Effects of drag and radiation pressure on large collector surfaces,
- Effects of zero gravity,
- Conversion of electrical output to usable form.

The basic difference between these four systems is that the photoelectric and photoemission devices convert the direct incident radiation. The thermoelectric and thermionic devices are essentially heat engines and require the concentration of the incident radiation to the device or heat sink to achieve the required rate of heat flux per unit of cathode or heat sink area. The use of solar concentrators introduces a number of problems that require serious consideration. For temperatures in the order of 500 to 750°C, required for thermoelectric generators, small errors in collector geometry and orientation can be tolerated. For temperatures in the order of 1000°C and above for thermionic diodes, a high degree of accuracy in collector geometry and orientation is essential for reasonable collection efficiencies. Thermal energy conversion systems must include a means for transferring the heat from the receiver or sink to the conversion device possibly by means of a circulating heat transfer fluid and transferring the waste heat to a radiator for rejection to space. Circulating pumps will be required to accomplish this in a zero gravity environment.

Consideration has been given to various types of energy storage systems capable of furnishing power during the dark periods of the orbit. The storage of thermal energy has been suggested as an alternate means for the electrochemical storage battery. If the power requirements for a particular vehicle are such that the load is a continuous one, a thermal energy storage system may be satisfactory. If peak power demands are involved, a thermal energy storage system will not be adequate because of the thermal lag in such a system and, in addition, the conversion device will have to be designed for this maximum power. This will introduce a voltage regulation problem, particularly for the thermoelectric generator. The output voltage would change considerably from peak load to average load. It appears more practical to use an electrochemical storage system which will be capable of supplying the peak loads with adequate voltage regulation and design the conversion device to supply the average power on the light side of the orbit with additional capacity for the recharging of the storage batteries.

Another problem involving the orientation of solar concentrators or solar cell arrays is the degree of accuracy required. For a solar cell array, a deviation of 20° from normal incidence only results in a loss in power of approximately 6 per cent. For solar collectors with fairly high concentration ratios, accuracy of orientation of 1° or less is necessary. This imposes a severe requirement on the orientation system and indicates a need for accurate resetting on the dark side of the orbit in order to minimize the time required for orienting the solar collector upon entering the light side of the orbit. If this time is appreciable, it may represent a significant portion of the light side period of the orbit.

The effects of erosion or punctures by micrometeorites present problems for all four systems. The erosion of the active surfaces of photovoltaic cells can be prevented by providing them with protective, transparent, and radiation resistant covers. Allowances must be made for the transmission losses in this cover, including the losses that will eventually occur when it becomes frosted because of sandblasting. The effects of punctures resulting in a loss of a cell or cells by larger particles can be compensated for. The cells are usually arranged in series-parallel groups and allowances can be made in the design for loss of a certain number of modules. The possibility of erosion by dust and sputtering caused by the impact of high energy atoms or molecules of the highly reflective surfaces of a solar concentrator must be taken into consideration. The possibility of providing a protective cover for solar concentrators does not appear feasible. Punctures would remove only a very small fraction of the total collector surface area. In applications where heat transfer loops are used from the source to the conversion device and from the device to a heat exchanger for rejection of waste heat, punctures of these components by meteorites would tend to be catastrophic, particularly in those using a liquid heat transfer medium.

Radiation damage to the various components employed in these systems does not appear to be a serious factor. The solar cells on Vanguard I have been operating continuously since March 17, 1958. The Russians [2] claim that the solar cells on Sputnik III have not been affected by radiation. The use of organic materials in construction of these systems introduces a radiation damage problem. This problem is difficult to solve because there is insufficient knowledge of the deleterious effects that may occur in a large portion of the ultraviolet spectrum. A high vacuum environment may also cause a degradation of organic materials. The use of spectrally selective coatings for the heat sink to make it an efficient absorber or as a means to obtain a low ratio of absorbtivity vs emissivity for solar cells and the structural materials of the array is being investigated. The stability of these coatings under radiation and a high vacuum environment and under conditions of high humidity prior to launching will have to be determined.

The four solar energy conversion systems being considered here do not carry their prime energy source with them as is done in chemical or nuclear energy conversion systems. Rather, the solar energy is converted to electrical energy at the point at which it is available. The essential factors to consider then would be the power per unit of weight and per unit of area, system complexity and reliability, operating lifetime of the conversion device, effects of space environment and cost. The one system that has been proven in actual use in space applications is that employing the photovoltaic cell and electrochemical storage batteries [16]. Information for use in comparing the merits of the other systems to that of the photovoltaic cell is in the form of engineering estimates based on present results obtained on experimental models and predicted future capabilities of the conversion device. With this in mind, some approximate figures, as shown in Table I, can be arrived at to indicate the possibilities of these four systems.

At the present time, the photovoltaic system appears to offer the highest watts/square foot and highest system efficiency and the lowest watts/pound. The thermionic and thermoelectric systems require solar concentrators and the efficiency of these devices depends on the

TABLE I

System	Watts/Pound		Watts/Square Foot of Collector Intercept Area		Possible System[4] Efficiencies	Life of Conversion Device
	Present	Future	Present	Future		
Photovoltaic	1.5	5	7.4	13.5	10–12 per cent	2 years or more
Thermionic [1]	7.2[1]	17	2.2	3.5	2– 4 per cent	Not determined
Thermoelectric [17]	20[1,2,3]	30[2,3]	0.3	1	2– 3 per cent	Not determined
Photoemission	—	50–150[3]	—	3	2– 3 per cent	Not determined

[1] Experimental.
[2] The watts/pound are only for the thermoelectric materials.
[3] Does not include storage system.
[4] System efficiency is defined as $\text{Efficiency} = \dfrac{\text{Electrical output}}{\text{Total intercepted energy}}$.

accuracy of the reflector surfaces and orientation. Efficiencies of 60 per cent have been indicated for concentrators assuming geometrical perfection and proper alignment. Efficiencies in the order of 30 to 40 per cent appear more likely for large expansible concentrators. This low concentrator efficiency imposes a penalty on the thermionic and thermoelectric systems. This is indicated in Table I where the power output in terms of watts/square foot of collector intercept area is shown for the four systems. This is further illustrated by comparing the required collector intercept area for a thermionic system [1] where 4680 square feet are required for a 10-kw power supply employing diodes with a 5 per cent efficiency. If photovoltaic cells covered an equivalent area and produced 7.4 watts/square foot, the power output would be in the order of 34 kw. To produce 10 kw, only 1350 square feet would be required. To be competitive with the other systems, more efficient, high temperature materials will be required for the thermoelectric system. The photoemission system is in its early stages of development. Present indications are that it could offer the highest watts/pound and possibly eliminate the need for orientation if mounted on a balloon, but would require large surface areas.

Conclusion and Recommendations

It is not possible, at this time, to reach any decision as to which of the direct energy conversion systems will eventually be superior. A number of factors have to be considered. System efficiency is only important where it eventually determines total system weight. If weight is no longer of major importance and the problems of storing and protecting large collectors during launch, their erection and orientation in space, and the effects of radiation pressure and drag in low altitude orbits, are major ones, then system efficiency becomes an important factor. Reliability and lifetime of the conversion device are of major importance. The photovoltaic and photoemission systems appear to have advantage over the other more complex systems. The effects of radiation and damage by micrometeorites are common problems for all systems. A zero gravity and high vacuum environment will be a greater problem for systems employing heat transfer loops and radiators for rejection of waste heat. It does not seem reasonable to assume that any one system will be used for all space applications.

Although all of the solar energy conversion systems are in relatively early stages of their development, the photovoltaic system has frequently been referred to as the "Work Horse" of these systems, and it may have to carry the major load of direct solar energy conversion for a number of years. Because of the state of development, an accurate and realistic estimate of the future practical possibilities of these systems is impossible at this time. Research and development in these areas should be vigorously pursued in order that the most effective system can be determined and the best solar energy conversion devices can be developed for space applications.

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Radiative Cooling of Satellite-Borne Electronic Components*

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***Summary*—The basic principles of radiative cooling of electronic components and subassemblies in a satellite are discussed, and estimates are made of the lowest temperatures attainable in a satellite by completely passive means. It appears feasible to maintain some compartments within a satellite at temperatures of 250°K or lower, so an opportunity is presented for refrigerating components whose characteristics are enhanced at lower temperatures.**

Introduction

Noise in many electronic components is reduced at lower temperatures. In view of the current attention being directed toward electronic equipment for satellite installation, it is of interest to estimate the lowest temperatures which can be obtained by completely passive means in a satellite.

Satellite Heat Balance

In a satellite at stable-orbit altitudes the only sources of heat are internally-dissipated power, solar radiation, earth radiation and perhaps lunar radiation. (Stellar radiation is insignificant.) A previous study[1] has shown that if a satellite has an outer skin coated with a material (such as white porcelain enamel) having a high reflectivity in the spectral region of most intense solar radiation and high emissivity at longer infrared wavelengths, its skin temperature will become no higher than 55°C at the central "hot spot" on the side toward the sun. A spherical satellite with such a skin coating, which distributes absorbed heat uniformly around the skin by conduction or by rotation to give uniform exposure to solar radiation, will be at a temperature of about −40°C. Hass, Drummeter, and Schach[2] have found that the skin temperature might drop as much as 40°C while passing through the earth's shadow. Therefore, −60°C (213°K) might be taken as the average skin temperature, and the lowest temperature at which a non-heat-dissipating electronic component insulated from the skin can be maintained. However, these estimates of the temperature neglect the effect of internally-dissipated power. If the combined effect of all additional heat sources is equal to that of solar radiation, the minimum temperature at which a non-heat-dissipating component can be maintained is of the order of $2^{1/4}(213°K) = 253°K$ or −20°C. The actual average temperature probably is lower than this, but higher than −60°C.

The above temperatures apply to small satellites which receive fairly uniform exposure to solar and earth radiation. The attainment of temperatures below those estimated here will require a larger satellite whose orbit and attitude minimize the exposure of a certain part of the skin to both solar and earth radiation.

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