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SOLAR ENERGY IN THE EXPLORATION OF SPACE

BY HUGH L. DRYDEN* AND A. E. VON DOENHOFF†

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

All space vehicles require some source of power for operation of the instruments and the radio communication equipment which makes possible the remote recording of the data obtained.   Current satellites and space probes require relatively low power; for example, Pioneer V, whose data were recorded at distances up to $22\frac{1}{2}$ million miles from the earth, carried out its mission with a power of 30 watts.

Many satellites use chemical energy stored in nickel-cadmium or silver-zinc base batteries, which have a limited life dependent on the battery weight and power requirements.   Others, such as Vanguard I, use solar power, giving much longer life. Vanguard I is still transmitting after three years in orbit.

Many of the hurdles that have stood in the way of the use of solar energy for generating electric power on the earth's surface are absent in the case of space vehicle applications The difficulties of earth stations have been associated primarily with the prolonged periods of cloud cover, the relatively long periods of complete darkness at night, and the bulkiness and unwieldiness of the solar energy collectors.   To provide a continuous flow of power under these conditions requires a large energy storage device.   Since earth satellites may enter the earth's shadow, energy storage is also required in space applications of solar power, but the requirements can be met with less difficulty because of the shorter periods of darkness.

Solar Cells versus Chemical Batteries.—It is of some interest to make a brief comparison of solar energy devices with chemical sources.   At the position of the earth's orbit, the solar radiation density is about 0.140 watts per square centimeter or 130 watts per square foot.   The most frequently used conversion device is the photovoltaic silicon cell usually called simply a solar cell.   These cells have relatively low efficiency because of losses of energy by reflection and transmission.   It is reasonable to expect an output of about 10 watts per square foot from an oriented solar array.   One specific design for a future spacecraft indicates a total weight of the complete solar power system of about 2 pounds per square foot.   The net specific output is then approximately 5 watts per pound.   By comparison, a silver-zinc chemical battery stores energy with a specific weight of about 50 watt-hours per pound.   Since the weight of a battery is proportional to the total energy stored, whereas the weight of the solar cell source is more nearly proportional to the rated power, it is clear that a solar energy source would be far superior to a chemical battery when the power is to be used for a long time.   For example, in the case cited, the solar cell array would be lighter than the silver-zinc battery if the power is required for a time longer than 10 hours.

Power Requirements for Spacecraft.—An indication of the important part played by solar energy in the exploration of space may be found from a review of the estimated electric power requirements for some present and future space vehicles given in Figure 1.   Some typical spacecraft or missions and the associated power levels are given as a function of actual or probable initial launch date.   Pioneer V and Tiros I were each fitted with a large number of photovoltaic silicon cells that
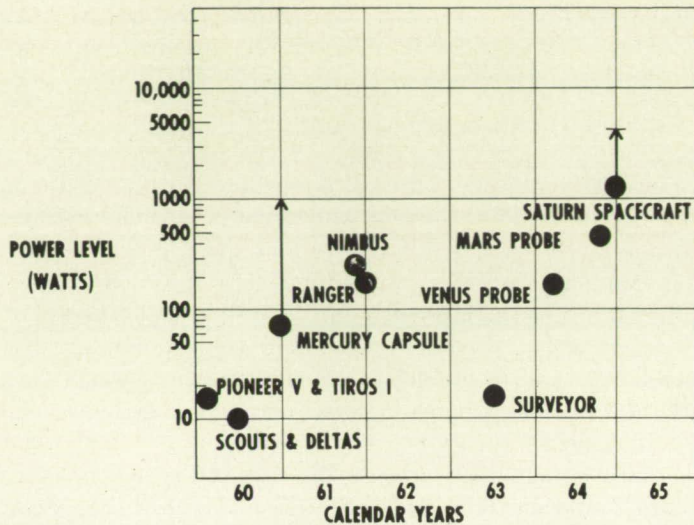
Fig. 1.—Estimated electric power requirements for various spacecraft and missions.

developed about 20 to 30 watts.   The Scout and Delta boosted vehicles require 10 watts or less.   The one-man Mercury capsule is intended to be a relatively short-lived vehicle.   Because of the limited total energy requirement, the average power of 70 watts can most conveniently be supplied by about 150 pounds of silver-zinc primary batteries.   The Nimbus meteorological satellite will require an average power of about 250 watts which will be derived from a solar cell array.   The Ranger spacecraft to be launched on lunar landing missions will be fitted with over 4,000 solar cells mounted on panels.   These cells will develop a little over 100 watts. They will be used for the approximately 3-day transit period from the earth to the moon.   When the spacecraft is near the moon, a small capsule will be detached and landed nondestructively.   Techniques have been developed that will permit reception of signals from the capsule which will transmit at a level of $1/4$ watt of radiated power.   The power required by the transmitter is small enough for it to be operated several days with a few pounds of batteries.   The Surveyor spacecraft is, like Ranger, to be launched on lunar landing missions. It is however, a more sophisticated second-generation vehicle.   The power level of 15 watts shown is the average power desired after a "soft" lunar landing.   The power requirements during transit are much as for Ranger and will be supplied by solar cells.   The Venus and Mars probes (Mariner spacecraft) will have a configuration much like Ranger.   The solar panels for the Mars probe must, however, be somewhat larger both because of the large communication distances involved and because of the decreased solar intensity at the distance of Mars from the sun.   As is shown in Figure 1, it is estimated that the Saturn spacecraft power requirements will be substantially larger than for the Ranger and Mariner series spacecraft.   This review, then, indicates that most of the spacecraft to be launched within the next few years will use power from the sun.

Energy Storage Requirements.—In designing a power system for a space vehicle, it is frequently desirable to have power available when the vehicle is in eclipse.   It is

also desirable that the size of the solar cell array or other solar collector be deter-
mined by the average power demand rather than the peak power demand. Both of
these requirements indicate the need for an energy storage device, which is usually
a group of chemical batteries, charged from the solar cells while in the sunlight.
For earth satellites, the size of the storage device is dictated by the maximum time
the satellite can be expected to be in the earth's shadow. Figure 2 is a plot of the
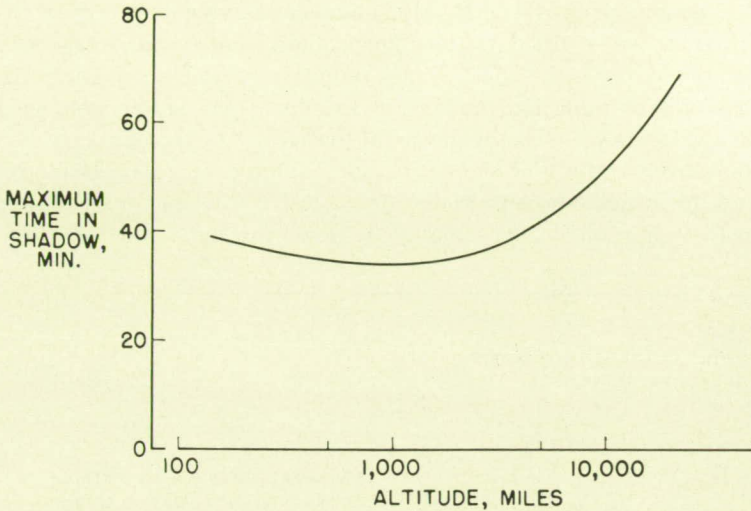

FIG. 2.—Energy storage for passage through the earth's shadow. Maximum
shadow time versus altitude for earth satellites.

maximum time in shadow against altitude for circular geocentric orbits. It is
seen that for altitudes up to 5,000 miles the maximum shadow time stays relatively
constant at about 35–40 minutes. For very high orbits, for example, the so-called
24-hour orbit, the maximum time in shadow increases to 69 minutes.

The energy storage problem is particularly severe for long-lived near-earth satel-
lites. A satellite in a 300-mile orbit has a period of about 90 minutes. This means
that it encircles the earth about 6,000 times in the course of a year. A secondary
battery with an extremely long cycle life must be chosen for such an application.
At the present time, rechargeable nickel-cadmium batteries seem best suited for
this purpose. A detailed analysis considering many of the significant factors that
determine battery life is given by Thomas.[1] Obviously, many factors in addition
to number of cycles are involved, such as the maximum permissible overcharging
current and the minimum overcharge required. At the present time battery char-
acteristics are not known well enough to predict the permissible depth of discharge
as a function of battery operating conditions with a high degree of precision. How-
ever, it is clear that conditions in a low orbit are particularly severe and that the
battery can only be used to a relatively small fraction of its total capacity if a
long battery life is to be attained. A nickel-cadmium battery can store approxi-
mately 14 watt hours per pound. If to obtain adequate battery life it is necessary
to limit the discharge to 10 per cent of capacity, then the effective specific battery
weight is 1.4 watt hours per pound.

Solar Cell Deterioration.—Solar cells have proved to be reliable devices. Some evidence has, however, been accumulated which indicates that the service life of these cells may be severely limited, if the cells are subjected to irradiation by high-energy particles. Some basic work on this subject has been presented by Loferski and Rappaport.[2] It was shown that the solar output was reduced to 75 per cent of its initial value by irradiation with (1) 5×10^{13} electrons per square centimeter having an energy of 1.7 mev; (2) 3.5×10^{10} protons per square centimeter with an energy of 17.6 mev; or (3) 4.4×10^9 alpha particles having an energy of 40 mev.

At the time this work was done, insufficient data were available on the Van Allen belts to be able to assess the effect of this radiation on the life of solar cells. More recently a study of radiation damage in satellite solar power systems has been carried out by Denney.[3] The evidence on the nature of the effects to be expected was obtained from a study of the data from Explorer VI. The Explorer VI data are particularly valuable because radiation intensity and solar cell charging current were measured simultaneously. Figure 3 shows the measured variation in solar
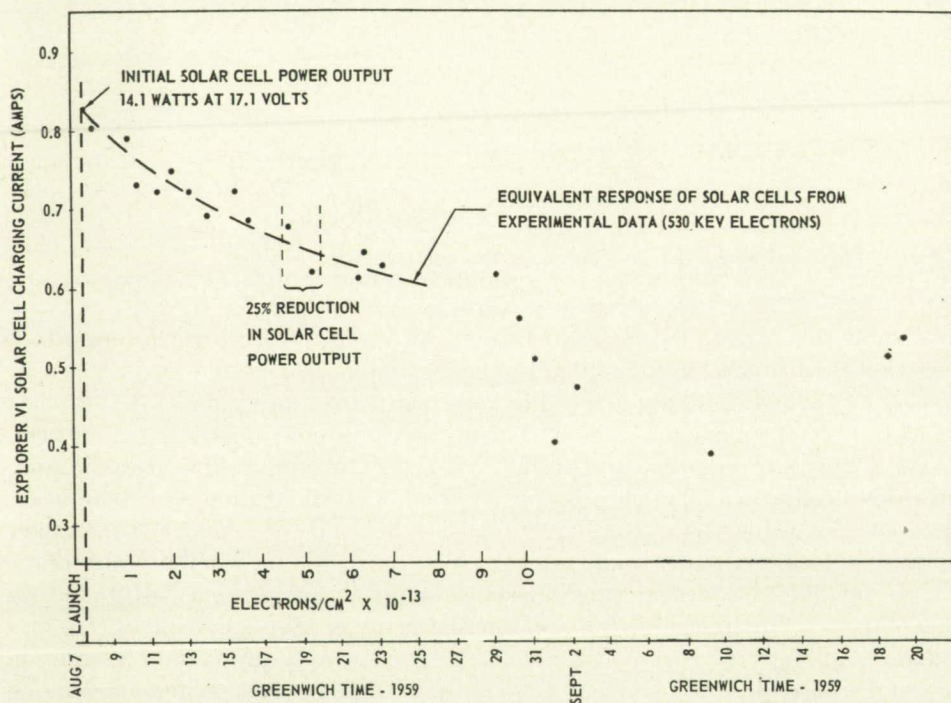

Fig. 3.—Explorer VI charging current versus time (Fig. 6 of Denney paper).

cell charging current with time for Explorer VI. On the basis of a detailed analysis,[3] Denney indicated that the primary effective radiation in this particular case was the electron flux. On the basis of an ingenious qualitative argument, he indicates that the radiation damage suffered by the cells on Explorer VI would be equivalent to that of an equal flux of 530 kev electrons. It is seen that the degradation in the performance of the cell is equivalent to that calculated on the basis of the laboratory tests. It seems likely that the reason for the ultimate failure of the power system

on Explorer VI was radiation damage to the solar cells. It seems significant that a 25 per cent reduction in solar cell output occurred in a period of only 11 days.

This rapid degradation in the solar cell performance on Explorer VI appears to be contradicted by the experience with Vanguard I which is still transmitting after 3 years in orbit. Denney offers the following explanation: typical solar cell voltage characteristics are shown in Figure 4. Increasing the temperature of a

TYPICAL SOLAR CELL I-V CHARACTERISTICS.

— 1/6 OF MAX POWER LOAD LINE (20° C)

MAX POWER LOAD LINE (20° C) —

20° C
50° C

VOLTS

: 20° C (50% DEGRADATION)

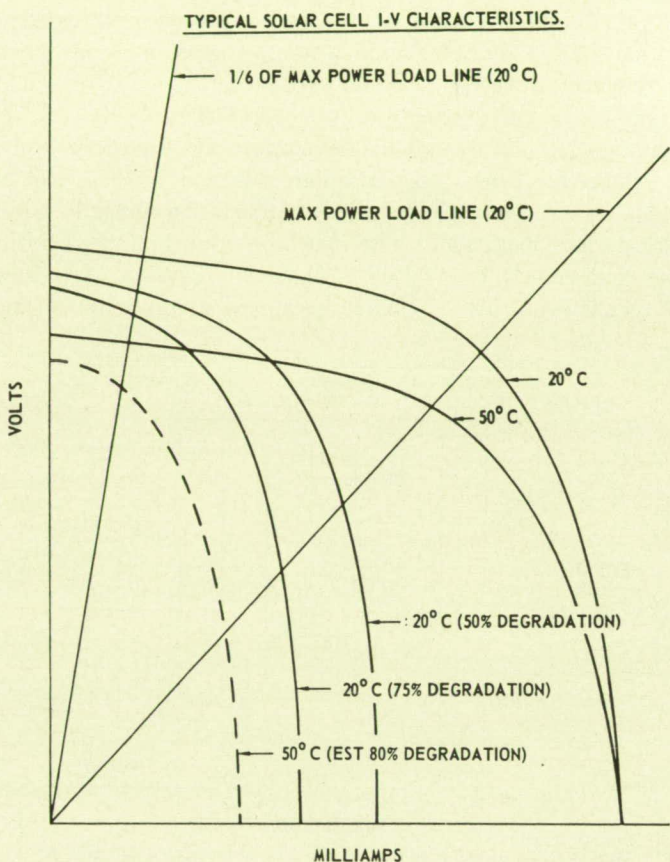20° C (75% DEGRADATION)

50° C (EST 80% DEGRADATION)

MILLIAMPS

FIG. 4.—Solar cell voltage characteristics (Fig. 9 of Denney paper).

solar cell decreases the open circuit voltage but changes the short circuit current very little. The effect of radiation damage, however, is to decrease the open circuit voltage only slightly and to cause a very large decrease in the short-circuit current. A load having an internal impedance corresponding to the maximum power point would suffer a very large decrease in power absorbed as the cells deteriorated. If, on the other hand, the load impedance were much higher than that corresponding to maximum power in the original cell condition, the relative decrease in power absorption with cell degradation is very much less. This, in fact, was the case for Vanguard I. The transmitter absorbed only about one-sixth of the power available from the cells at launch. It is estimated that in spite of the heavy cover glasses over the cells, they have suffered approximately 80-per cent degradation. It

nevertheless appears reasonable that the transmitter should continue to function for some time. This is one of the rewards of a very conservative design philosophy.

A Solar Turbo-Electric System.—In addition to the photovoltaic cells there are, of course, a number of other methods of utilizing solar energy to obtain electric power. Most of these transform the solar energy into heat and then convert to electric power. Direct conversion devices such as the thermoelectric converter and the thermionic diode are of particular interest because they involve no moving parts. Development of these devices, however, has not progressed to the point where they are considered ready for application to specific missions in a solar device. The NASA is, however, developing a solar turbo-electric power source known as the Sunflower project.

One of the interesting features of this development is the method of energy storage. Energy is stored as heat. In particular, it is stored as the heat of fusion of a substance. This has the advantage of providing an essentially isothermal heat source for dark-period operation. The heat of fusion and the melting point for thermal storage materials to be used with solar heated systems are shown in Figure 5. It may be recalled that primary batteries stored energy with the specific weight
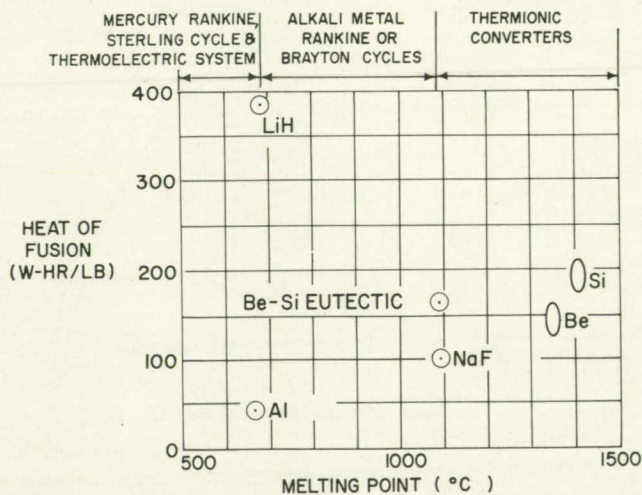

FIG. 5.—Heat of fusion versus melting point for various substances suitable for thermal storage.

of about 50 watts hours per pound. A nickel-cadmium battery had a specific storage capacity with a deep discharge of about 14 watt hours per pound and an effective multiple-cycle specific capacity of 1 to 3 watt hours per pound. The heat of fusion of lithium-hydride is shown to be 390 watt hours per pound. However, the heat of fusion must be multiplied by the thermal efficiency of the conversion cycle to obtain a proper comparison. A reasonable value for the thermal efficiency of the turbo-generator is about 10 per cent. Consequently, the comparative number for lithium-hydride would be 39 watt hours per pound. Even after allowance is made for the weight of the container, the effective specific energy storage weight of the lithium-hydride system is substantially lower than that of storage batteries.

The use of thermal storage is also advantageous for a mechanical conversion system because it permits the machinery to run continuously at constant power out-

put even during the shadow portion of an orbit.   This mode of operation eliminates some severe difficulties associated with repeated starting and stopping of the system.   It is indeed fortunate that not only does lithium-hydride have a high heat of fusion but also that the melting point is almost ideally suited to the use of mercury as a working fluid in a turbo-generator.

An artist's conception of the Sunflower solar turboelectric power unit is shown in Figure 6.   This device is designed to generate 3 kilowatts of electric power con-
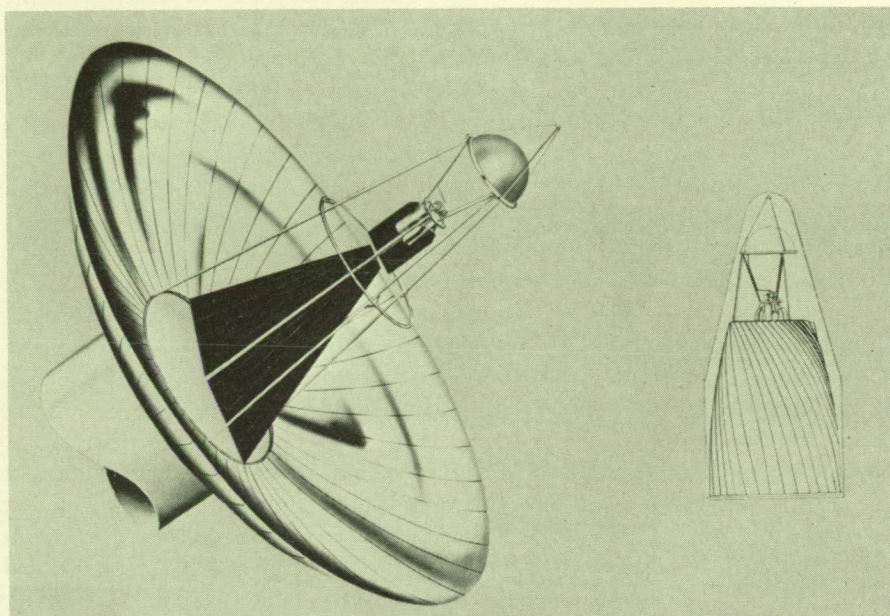

FIG. 6.—Solar turbo-electric power unit, Sunflower I.

tinuously for any circular orbit between 300 miles and 22,000 miles altitude.   It is planned to be able to demonstrate a 90-day service life by 1963.

The system consists of an erectile parabolic mirror having a diameter of 32 feet in the unfolded condition.   This mirror focuses the sun's rays onto the combination boiler and heat storage unit.   As indicated previously the heat storage material is lithium-hydride.   When the lithium-hydride solidifies it boils mercury in a tubular heat transfer unit.   The hot mercury vapor then passes through the turbine and is condensed in the radiator panels.   The liquid mercury is then pumped back to the boiler by a small centrifugal pump mounted on the same shaft as the turbine.   In fact, the turbine, generator, and pump all operate on a common shaft supported by two mercury lubricated bearings.

The design of the large parabolic mirror poses some difficult problems.   These are mainly concerned with conflicting requirements of lightweight construction and optical accuracy.   In order to achieve reasonable collection efficiency, it is necessary that the collector concentrate the light in a relatively small area.   If the temperature of the target is fixed as in the present case, the amount of heat reradiated out to space is directly proportional to the hot exposed target area and to the fourth power of the target temperature.   The present target temperature is

approximately that of melting lithium-hydride or about 690°C. At this temperature calculations indicate that a reasonable collection efficiency can be obtained if the area of the "hot spot" of the mirror is less than one-half per cent of the total mirror area. Fortunately, this requirement puts only a modest demand on the optical quality of the mirror. For higher temperatures, such as might be required in systems using some of the alkali metal vapors as working fluids, the degree of concentration required to achieve the same collection efficiency is considerably more.

Another characteristic that deserves attention is the need for orientation of the device toward the sun. In the case of solar cells, concentration of the solar radiation is generally not required. Consequently, the output of the solar panels is not sensitive to orientation provided the normal to the panel is within about 15° of the direction of the sun. When a high degree of concentration is used as in the case of the solar turbo-electric unit the orientation of the system must be fairly precise. The sun subtends an angle of about 32 minutes when viewed from the earth. Design calculations have indicated the desirability of maintaining a sun-directed orientation to within about 15 minutes.

One of the heaviest items in the power conversion system is the radiator. In space, heat can only be rejected by radiation. The heat dissipated, of course, varies directly as the area, and as the fourth power of the temperature of the radiator. It is interesting to note that there is an optimum temperature which minimizes the necessary radiator area. If the simplifying assumptions are made that the machine, having a constant power output, operates with a thermal efficiency which is a constant fraction of the Carnot efficiency corresponding to the heat input and output temperatures, and that the heat input temperature is held constant, the radiator area will be a minimum for an absolute radiator temperature equal to three-fourths the absolute heat input temperature. If the radiator temperature is too low, then its area must be increased in order to counteract the lower radiant heat transfer coefficient. If the radiator temperature is too high, then the thermal efficiency of the device decreases to such an extent that it more than makes up for the higher radiant heat transfer coefficient at the higher temperature.

Another factor of importance in the design of the radiator is that of meteoroid damage. An indication of the importance of the problem can be obtained from Figure 7. This plot of the magnitude of the meteoroid against the number of hits to be expected per year of a given magnitude or larger is derived from the estimates presented by Whipple.[4] A tenth-magnitude meteoroid may be expected to penetrate about 10 millimeters of aluminum. A fifteenth-magnitude meteoroid can be expected to penetrate about 2 mm of aluminum. With an exposed radiator area of 100 square feet corresponding to one hit per year of an eleventh order or larger meteoroid, it is evident that the meteoroid damage problem will have a dominating influence on the weight of the radiator. The problem will become increasingly severe for larger power systems. The importance of obtaining more accurate and complete data on the number and size of meteoroids present at various locations in space is very clear.

Design calculations indicate that a 3-kilowatt solar turbo-electric unit can be built with a weight of less than 1,000 pounds and that it can be folded into a space compatible with a spacecraft designed for the Centaur launch vehicle.

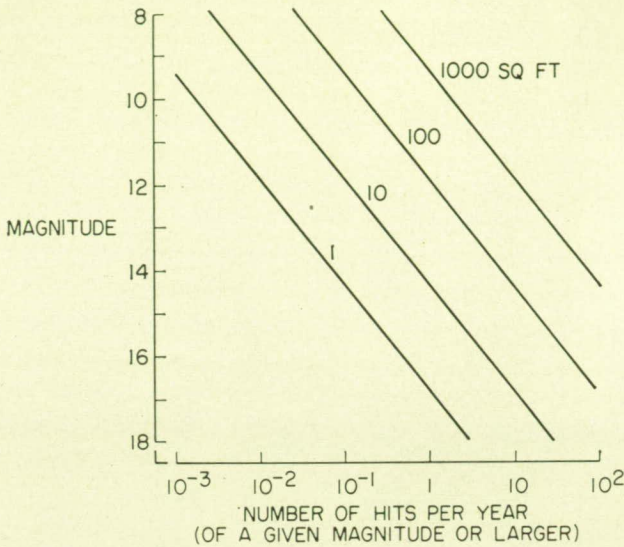*Summary.*—For amounts of power from a few watts to a few hundred watts,

FIG. 7.—Influx of meteorites.

silicon solar cells seem to be a reliable, convenient source of power in space. Such power levels appear adequate for minimum communication needs for missions as far as Mars. The generation of larger amounts of power from a solar turbo-electric system, such as Sunflower I, appears feasible but remains to be demonstrated. For power levels of many kilowatts or megawatts as may be required for electrical propulsion, nuclear energy sources and appropriate conversion systems will probably be required.

* Deputy Administrator.

† Lunar and Planetary Program (Spacecraft Technology).

[1] Thomas, U. B., "Battery considerations for a communications satellite," presented at the ARS Space Power Systems Conference, Santa Monica, California, September 30, 1960. (ARS 1308-60.)

[2] Loferski, J. J., and P. Rappaport, "The effect of radiation on silicon solar-energy converters," *RCA Review*, **19**, no. 4 (1958).

[3] Denney, J. M., "Radiation damage in satellite solar cell power systems," presented at the ARS Space Power Systems Conference, Santa Monica, California, September 30, 1960. (ARS 1295-60.)

[4] Whipple, F. L., "The meteoritic risk to space vehicles," in *Proceedings of the VIIIth International Congress, Barcelona*, October 6–12, 1957 (Vienna: Springer-Verlag, 1958) pp. 418–428.