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ABSTRACT

To provide electrical power during an exploration mission to Mars, a deployable tent-shaped structure with a flexible photovoltaic (PV) blanket is proposed. The array is designed with a self-deploying mechanism utilizing pressurized gas expansion. The structural design for the array uses a combination of cables, beams, and columns to support and deploy the PV blanket. Under the force of gravity a cable carrying a uniform load will take the shape of a catenary curve. A catenary-tent collector is self shadowing which must be taken into account in the solar radiation calculation. The shape and the area of the shadow on the array has been calculated and used in the determination of the global radiation on the array. The PV blanket shape and structure dimension were optimized to achieve a configuration which maximizes the specific power (W/kg). The optimization was performed for four types of PV blankets (Si, GaAs/Ge, GaAs CLEFT, and amorphous Si) and four types of structure materials (Carbon composite, Aramid Fiber composite, Aluminum, and Magnesium). The results show that the catenary shape of the PV blanket, which produces the highest specific power, corresponds to zero end angle at the base with respect to the horizontal. The tent angle is determined by the combined effect of the array

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structure specific mass and the PV blanket output power. The combination of carbon composite structural material and GaAs CLEFT solar cells produce the highest specific power. The study was carried out for two sites on Mars corresponding to the Viking Lander locations. The designs were also compared for summer, winter, and yearly operation.

INTRODUCTION

The ability to establish an outpost on the Martian surface is initially dependent on the availability of an adequate power source. The ideal power supply would require very little implementation time and have a high reliability for operation. Also, to meet the constraints of launching and transportation it would need to be light weight and capable of being stowed in relatively small volume. A photovoltaic (PV) array whose configuration is optimized for maximum specific power (W/kg) can meet these requirements.

One structurally-efficient design for a nontracking solar array is the "tent" configuration which has been proposed for solar arrays for the moon.[1,2] An advantage of the "tent" configuration is that it provides significant power shortly after the sun rises above the horizon, where a horizontal array has very low power at dawn and dusk due to low sun-angles. The tent array has the advantage over tracking arrays of requiring no moving parts subject to failure due to cold, wind, or thermal cycling. Most of the structural and operational advantages which make the tent design desirable for the moon are also applicable to Mars, particularly the simple structure and absence of moving parts. On Mars it is also desirable to use an array which is lifted off the ground, and thus less subject to dust deposition.

This analysis was performed to optimize a tent shaped PV array for maximum specific power at the Viking Landers locations (VL1: latitude 22.3 °N, longitude 47.9 °W, and VL2: latitude 47.7 °N, longitude 225.7 °W) on the Martian surface. The array is designed with a self-deploying mechanism utilizing pressurized gas expansion as the deployment mechanism. The array structural design uses a combination of cables, beams, and columns to support and deploy the PV blanket. The array is stowed with the blanket either folded or rolled, depending on the particular blanket's flexibility. Details on this design are given in Ref. 3.

Each structural component of the design was analyzed to determine the size necessary to withstand the various forces it would be subjected to. Through this analysis each component's weight was determined based on the structural loads it would experience both during deployment and once fully deployed. Once this was accomplished, an analysis of the output power of the PV blanket was performed. This included analyzing the global radiation (direct, diffuse, and reflected) as well as any partial shadowing which would occur on the PV blanket due to its catenary shape. The combination of output power and structural weight were used to achieve a configuration which maximize the specific power of the array at the given location.

The optimization was performed with four types of structural materials (Carbon VHS composite, Aramid Fiber composite, Aluminum, and Magnesium) and with four types of PV blankets (Silicon, Gallium Arsenide on Germanium, Gallium Arsenide CLEFT, and Amorphous Silicon).[4]

STRUCTURE ANALYSES

A tent-shaped structure with a flexible PV blanket for solar power generation was proposed in Ref. 3. An artists conception of the array is shown in Fig. 1. The array structure was designed to be capable of supporting the PV blanket and have the ability for autonomous deployment and compact stowage. The PV blanket is held in place on the structure by a series of cables evenly spaced along the blanket length. Under the force of gravity these cables, which are supporting the weight of the PV blanket, will take the shape of a catenary curve which is shown in Fig. 2 and given by $z = f_c(y)$ where:

$$f_c(y) = K\left\{\cosh\left[\frac{D/2 - y}{K} - 1\right]\right\}$$

where K is the catenary constant determined by $f_c(0) = H$. The beams on which the cables are attached are supported by a series of telescoping columns which also act as the deployment mechanism for the array.[3]

The structural analysis takes into account the tension in the blanket and support cables, weight of the structural components and PV blanket, forces incurred during deployment, and wind loading. It should be noted that on Earth, wind loading constitutes the main loading force. On Mars, however, the wind loading is not nearly as great due to substantially lower atmospheric density of about 7 to 9 mbar. The structure design parameters, shown in Fig. 2, are: the tent base length D, the tent width W, the tent height H, the tent angle θ_t, and the blanket end angle θ_1. The details of the structural analysis used to determine the component weights and dimensions are given in Ref. 3. This study shows that the optimal blanket shape, which is characterized by the end angle θ_1, for minimum structure specific mass is obtained for $\theta_1 = 0$, i.e., a blanket having a natural catenary shape. This result is shown in Fig. 3 for Carbon VHS composite material, GaAs/Ge PV blanket, $\theta_t = 15°$, and 20 m/s wind speed. Similar trends were found for all other material/PV blanket combinations.

SOLAR POWER ANALYSIS

A catenary-tent-collector is self shadowing (e.g., side B is shadowed by side A in Fig. 2) this must be taken into account in determining the PV blanket output power. A detailed analysis of the shape and the area of the shadow on the array and hence the beam irradiance incident on the blanket is given in Ref. 5. The diffuse and albedo irradiance were also calculated to determine the global irradiance on the array. A solar radiation model for Mars was developed in Ref. 6 and the solar output power of the PV blanket was determined based on this model.

There will be some shadowing of the array during the day due to the catenary-tent shaped configuration. This nonuniform illumination can lead to efficiency losses and hot spot heating on the PV blanket due to partial illumination of series connected cells. This analysis has assumed that the efficiency is independent of the shadow pattern.

The effect of the azimuthal orientation of the catenary tent on the irradiance was investigated and the results are shown in Fig. 4 for yearly average irradiance at VL1 based on the solar radiation model. The figure shows the variation of the direct "beam" irradiance on both sides A and B of the PV blanket, and the corresponding average beam irradiance. The diffuse irradiance is assumed to be independent of the azimuth, therefore, the global irradiance on the tent-blanket follows the variation of the beam. The yearly average irradiance varies very little with tent orientation. However, the diurnal variation of the global irradiance, and hence the time profile of the output power, changes significantly.[2] The azimuth angle for side A is measured from true south (0°) positively in a clockwise direction.

OPTIMAL CATENARY-TENT-ARRAY

The shape of the PV blanket is determined by an optimization between the change in both array structure weight and output power over various array geometries. The blanket end angle, θ_1, has no effect on the irradiance. This has been shown in Ref. 5. Since the blanket end angle greatly affects the specific mass of the structure, Fig. 3, and has no influence over the irradiance and hence on the array output power, the optimal shape of the blanket takes the natural catenary curve, i.e., $\theta_1 = 0°$, which minimizes specific mass of the structure.

Structure specific mass (kg/m^2 of blanket) and array specific power (W/m^2) are strong functions of the array tent angle, θ_t. A typical effect of the tent angle on the specific mass is shown in Fig. 5 for carbon VHS composite, GaAs/Ge PV blanket, and wind speed of 20 m/s. The wind speed of 20 m/s was chosen as the design wind speed[3] since 99.9 percent of the winds experienced on Mars by the Viking Landers were below 20 m/s.[7] Figure 5 shows that the specific mass decreases with increasing of tent angle, and the tendency is toward a bifacial vertical array. This is due to the fact that as the tent angle θ_t approaches 90°, more of the loading is transmitted as compression in the vertical columns as opposed to bending which therefore requires less structural mass to support the array. The results for other material/PV blanket combinations were similar.

A stationary collector, either flat or curved (e.g., catenary) possesses an optimal tilt angle to maximize global irradiance depending on the variation of the solar radiation throughout the year at the location latitude. The variation of the yearly average global irradiance as function of the tent angle, θ_t, is shown in Fig. 6. The optimal array-tent angle, θ_{tm}, is determined based on both the specific mass and the array output power, and is expressed by the specific power of the PV array in W/kg. This is shown in Fig. 7 for carbon VHS composite and GaAs/Ge at VL1 and for wind speed of 20 m/s. Similar curves can be produced for all other structural material/PV blanket combinations.

With the optimal tent angle for maximum specific power known, the remaining parameters, D, W, and H can be determined. Since output power per area of PV blanket is independent of these parameters, they are determined by minimizing array structure mass per area of PV blanket. The procedure for this is given in Ref. 3, and the results are shown in Figs. 8 to 10 for Carbon VHS composite, GaAs/Ge blanket, 20 m/s wind speed, and $\theta_t = 15°$.

In our study we analyzed four types of PV blankets made of Si, GaAs/Ge, GaAs CLEFT and amorphous silicon, and four types of structure materials made of carbon VHS composite, Aramid Fiber composite, Aluminum, and Magnesium. The locations on Mars are at VL1 and VL2, and variation in solar radiation corresponding to a full Martian year, a summer day, and a winter day. The specification of the structural materials and the PV blankets are given in Table 1(a)[8,9] and (b).[10,11] The solar cell efficiency values given in Table 1(b) are for 25 °C and air mass zero. The operating temperature of the cells may be much lower, thereby increasing their efficiency. The results of the optimization process for the PV tent array are summarized in Tables 2 and 3.

DISCUSSION

Through the analysis it was determined that of all the structural material/PV blanket combinations analyzed, the highest specific power is obtained using carbon VHS composite structural material and a GaAs CLEFT PV blanket, i.e., 37.3 W/kg. Optimal array geometry and other characteristics for all cases are listed in Table 2. The results for the amorphous silicon are marked with an asterisk and requires and explanation. The optimal solution for this combination is obtained for $\theta_t \approx 90°$ (i.e., a vertical surface with solar cells on both sides). The reason for it resides in the fact that amorphous silicon has a much lower blanket specific mass than the other types of PV blankets. As a result, the specific mass of the structural material decreases much more rapidly with increasing tent angle θ_t than it does with the other PV blankets. The optimal design with an amorphous silicon PV blanket is therefore obtained for very large tent angles tending to 90°. The values in Table 2 for amorphous silicon are calculated for $\theta_t = 80°$. Figure 11 shows the variation of the specific power with tent angle for the four types of structural materials with an amorphous silicon blanket.

In a situation where the array design must be altered or where one or more of the geometry variables are constrained, for example the catenary blanket being annexed to an existing structure, a new optimization would have to be performed based on the remaining unrestricted variables.

The effect of season (L_S) and latitude (ϕ) on the PV array structure was also investigated. The solar irradiance of a summer day $L_S = 135°$ with an atmospheric opacity of 0.5, and a winter day $L_S = 315°$ with an atmospheric opacity of 2.0 were compared with the yearly average irradiance for both Viking Lander locations VL1 ($\phi = 22.3°$) and VL2 ($\phi = 47.7°$) as shown in Table 3. The results show that the latitude has no effect on the design of the PV array. However, a higher specific power is obtained for the PV array at the lower latitude VL1 site due to higher irradiance. Higher specific power is obtained for a summer day ($L_S = 135°$) than for a winter day ($L_S = 315°$). The optimum tent angle is lower for summer than for winter; and the yearly installation results in values between the summer and winter range.

The wind speed and the PV blanket cell efficiency has no effect on the optimal angle of the array.[3] By increasing the wind velocity, the required structural mass increases and thereby increases the array specific mass. This increase occurs uniformly for all structural materials and PV blanket types. The best combination of structure material and PV blanket remains the same. The PV blanket cell efficiency affects the array specific power but not the optimal design point.

CONCLUSIONS

To provide electrical power during an exploration mission to Mars, a deployable tent-shaped structure having a flexible catenary photovoltaic blanket is proposed. The structural design for the array uses a combination of cables, beams, and columns to support and deploy the PV blanket. The PV blanket shape and the array dimensions were optimized to achieve a configuration which maximizes the specific output power (W/kg). The self shadowing which occurs when using a catenary-tent-array was taken into consideration in the direct beam solar radiation calculation. The diffuse and reflected (albedo) radiation were also taken into account. The natural catenary shape of the PV blanket, i.e., $\theta_1 = 0°$ is determined by the array specific mass. The tent angle θ_t is determined by the combined effect of the specific mass and the output power. Four structure materials (carbon VHS composite, Aramid Fiber composite, Aluminum, and Magnesium) and four types of PV blankets (Si, GaAs/Ge, GaAs CLDEFT, and a-Si) were considered in the array analysis for the Martian surface. The combination of carbon VHS composite structural material and GaAs CLEFT solar cells produces the highest specific power. A high specific power is also obtained with an amorphous silicon PV blanket as the tent approaches a vertical shape. The study refers to two locations on Mars, VL1 and VL2. The latitude location has no effect on the design point of the PV array, at least for the examined sites. Lower tent angles were obtained for summer operation than for winter. The tent azimuth has almost no effect on the optimal design point. The wind speed and PV blanket cell efficiency affects the numerical value of array specific power but not the optimal design point.

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TABLE 1.—PV BLANKET AND STRUCTURAL MATERIALS SPECIFICATION

(a) Structural materials properties

	Carbon VHS composite	Aramid fiber composite	Aluminum	Magnesium
Modulus, GPa	124	76	72	45
Yields strength, GPa	1.90	1.38	0.41	0.28
Density, kg/m^3	1530	1380	2800	1800

(b) PV blanket specifications

	Silicon	GaAs/Ge	GaAs CLEFT	Amorphous silicon
Efficiency, percent	14.5	19.5	20.0	10.0
Blanket specific Mass, kg/m^2	0.427	0.640	0.361	0.040
Cell thickness, μm	250	~250	20	2

TABLE 2—PERFORMANCE RESULTS FOR VARIOUS PV ARRAY/STRUCTURAL MATERIAL COMBINATIONS AT THE VL1 LOCATION BASED ON YEARLY OPERATION

	Array height, H, m	Array base, D, m	Array base, W, m	Tent angle, θ_t, deg	Blanket area, m^2	Total weight, kg	Specific mass, kg/m^2	Irradiance, W/m^2	Specific power, W/kg
Carbon VHS GaAs/Ge	1.16	8.69	3.75	15	34.16	40.97	1.1995	170.2	27.7
Carbon VHS silicon	1.39	8.56	3.75	18	34.30	33.29	0.9704	168.1	25.1
Carbon VHS GaAs CLEFT	1.47	8.51	3.75	19	34.35	30.89	0.8991	167.5	37.3
Carbon VHS amorphous Si	6.89	2.43	3.75	80	53.54	17.79	0.3323	113.1	34.0*
Aramid fiber GaAs/Ge	1.16	8.69	3.50	15	31.88	39.30	1.2330	170.2	26.9
Aramid fiber silicon	1.09	8.73	3.50	14	31.84	32.24	1.0123	170.6	24.4
Aramid fiber GaAs CLEFT	1.61	8.40	3.75	21	34.46	31.91	0.9270	166.5	35.9
Aramid fiber amorphous Si	6.89	2.43	3.75	80	53.54	18.40	0.3438	113.1	32.9*
Aluminum GaAs/Ge	1.97	4.53	3.25	41	20.54	30.72	1.4953	152.9	19.9
Aluminum silicon	2.12	4.24	3.25	45	20.66	25.46	1.2325	148.6	17.5
Aluminum GaAs CLEFT	2.72	4.41	3.25	51	24.12	26.90	1.1123	141.3	25.4
Aluminum amorphous Si	5.91	2.08	3.25	80	37.57	19.30	0.5138	113.1	22.0*
Magnesium GaAs/Ge	2.11	5.59	3.25	37	23.85	33.35	1.3985	155.5	21.7
Magnesium silicon	2.30	5.28	3.50	41	25.79	29.54	1.1454	152.9	19.3
Magnesium GaAs CLEFT	2.64	4.59	3.50	49	26.01	26.48	1.0181	143.3	28.1
Magnesium amorphous Si	4.92	1.74	3.50	80	35.08	15.57	0.4438	113.1	25.5*

*Not optimal solution.

TABLE 3—EFFECT OF SEASON AND LATITUDE ON THE ARRAY PERFORMANCE

[Carbon VHS, GaAs/Ge, 20 m/s wind speed]

	L_S, deg	Array height, H, m	Array base, D, m	Array width, W, m	Tent angle, θ_t, deg	Blanket area, m^2	Total weight, kg	Specific mass, kg/m^2	Irradiance, W/m^2	Specific power, W/kg
VL1 $\phi = 22.3°$	135	1.01	8.77	3.50	13	31.80	38.34	1.2058	289.8	46.9
	315	1.39	8.56	3.75	18	34.30	40.87	1.1916	147.9	24.2
	Year	1.16	8.69	3.75	15	34.16	40.97	1.1955	170.2	27.7
VL2 $\phi = 47.7°$	135	1.01	8.77	3.50	13	31.80	38.34	1.2058	235.0	38.0
	315	1.39	8.56	3.75	18	34.30	40.87	1.1916	45.1	7.4
	Year	1.16	8.69	3.75	15	34.16	40.97	1.1955	152.9	24.9

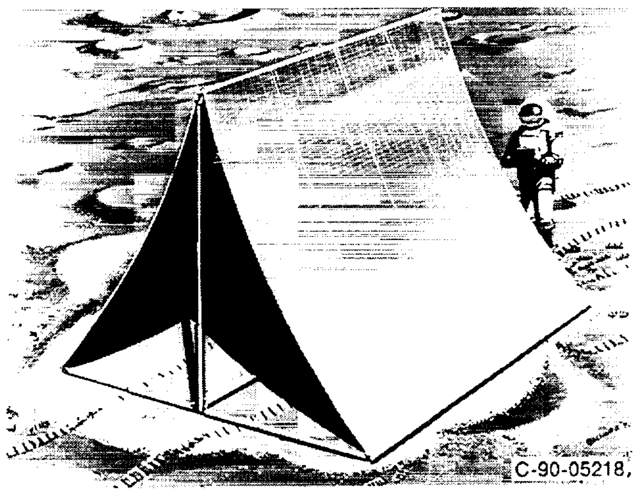

Figure 1.—Artists conception of a self-deploying PV tent array.

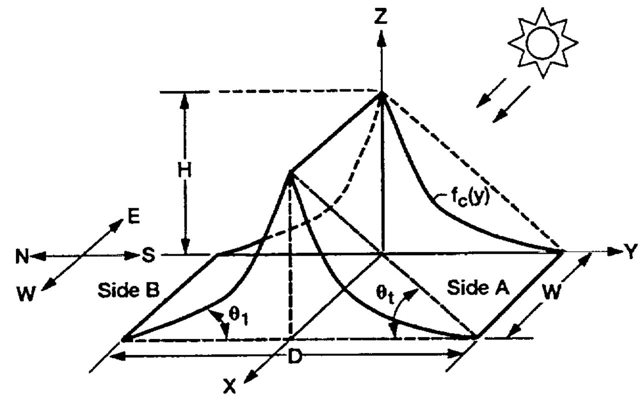

Figure 2.—Tent structure and PV blanket geometry.

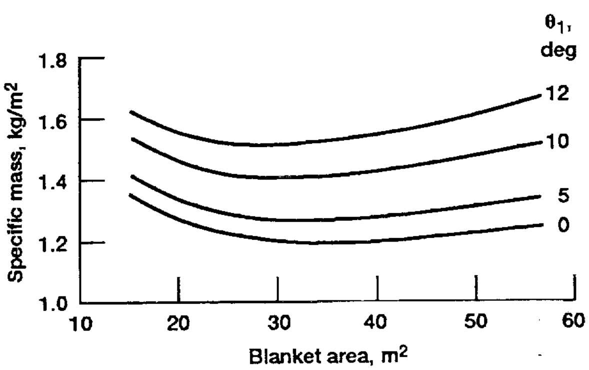

Figure 3.—Array specific mass variation with PV blanket end angle and area.

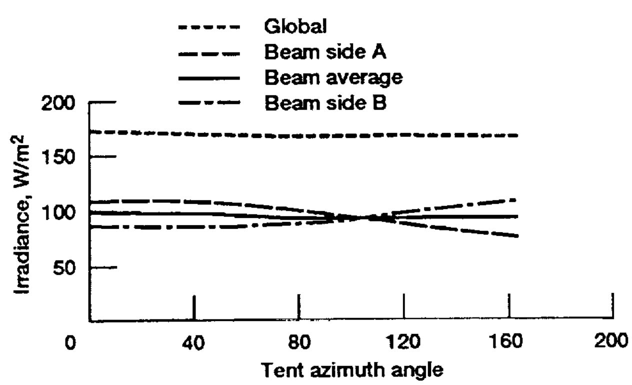

Figure 4.—Variation of the yearly average irradiance as a function of tent azimuth angle.

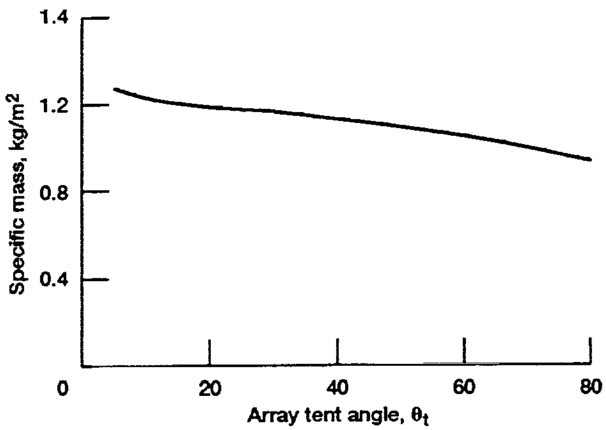

Figure 5.—The effect of the tent angle on the specific mass of the array (carbon VHS composite, GaAs/Ge solar cells, 20 m/s wind speed).

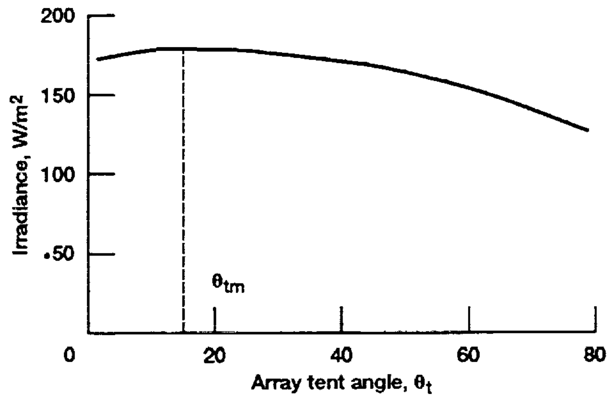

Figure 6.—Variation of the yearly average global irradiance as a function of tent angle.

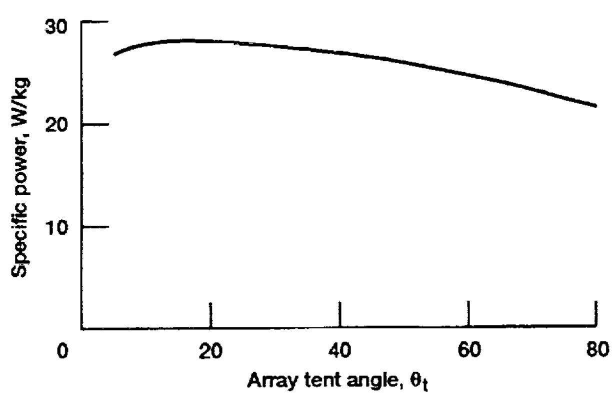

Figure 7.—Variation in specific power as a function of tent angle (carbon VHS composite, GaAs/Ge solar cells, 20 m/s wind speed at VL1).

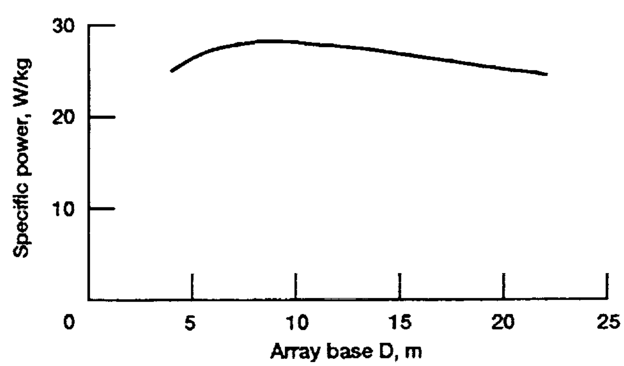

Figure 8.—Array specific power as a function of array base-D for W = 3.75m (carbon VHS composite, GaAs/Ge solar cells, 20 m/s wind speed, 15° tent angle).

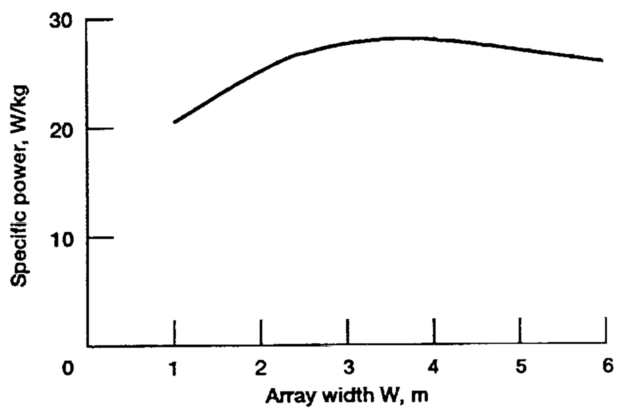

Figure 9.—Array specific power as a function of array width-W for D = 8.69m (carbon VHS composite, GaAs/Ge solar cells, 20 m/s wind speed, 15° tent angle).

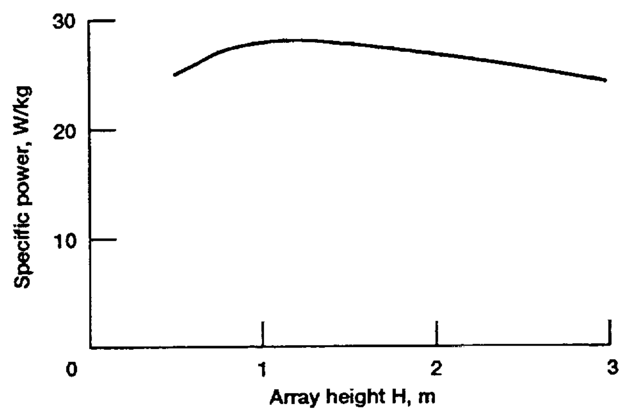

Figure 10.—Array specific power as a function of array height-H for W = 3.75m (carbon VHS composite, GaAs/Ge solar cells, 20 m/s wind speed, 15° tent angle).

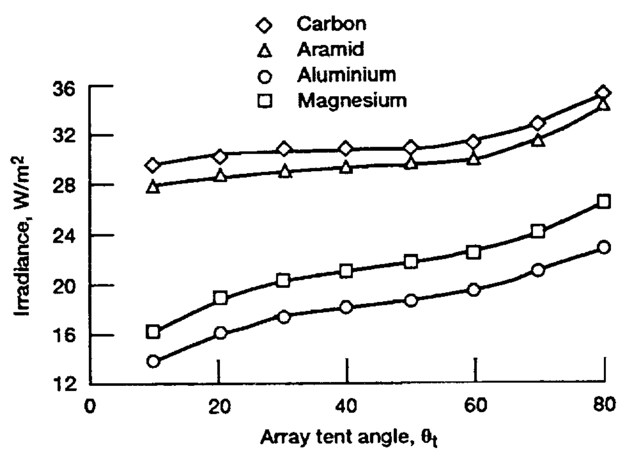

Figure 11.—Array specific power as a function of array tent angle θ_t for amorphous silicon blanket and different constructural materials for W = 3.75m, D = 8.69m, 20 m/s wind speed.

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13. ABSTRACT ***(Maximum 200 words)***

To provide electrical power during an exploration mission to Mars, a deployable tent-shaped structure with a flexible photovoltaic (PV) blanket is proposed. The array is designed with a self-deploying mechanism utilizing pressurized gas expansion. The structural design for the array uses a combination of cables, beams, and columns to support and deploy the PV blanket. Under the force of gravity a cable carrying a uniform load will take the shape of a catenary curve. A catenary-tent collector is self shadowing which must be taken into account in the solar radiation calculation. The shape and the area of the shadow on the array has been calculated and used in the determination of the global radiation on the array. The PV blanket shape and structure dimension were optimized to achieve a configuration which maximizes the specific power (W/kg). The optimization was performed for four types of PV blankets (Si, GaAs/Ge, GaAs CLEFT, and amorphous Si) and four types of structure materials (Carbon composite, Aramid Fiber composite, Aluminum, and Magnesium). The results show that the catenary shape of the PV blanket, which produces the highest specific power, corresponds to zero end angle at the base with respect to the horizontal. The tent angle is determined by the combined effect of the array structure specific mass and the PV blanket output power. The combination of carbon composite structural material and GaAs CLEFT solar cells produce the highest specific power. The study was carried out for two sites on Mars corresponding to the Viking Lander locations. The designs were also compared for summer, winter, and yearly operation.

14. SUBJECT TERMS
Photovoltaic array; Catenary collectors; Mars; Deployable-tent-blanket; Insolation on Mars

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