Estimates of Photochemically Deposited Contamination on the GPS Satellites

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After about three years on orbit (altitude ≈ 20,000 km), it became apparent that the solar array output from the first block of Navstar Global Positioning System (GPS) satellites was degrading faster than could be accounted for on the basis of radiation damage alone. There are at least two possible explanations. Either the Van Allen radiation environment was causing unexpected damage, or contamination, such as would result from outgassing by the spacecraft itself, was partially obscuring the solar panels. An extensive analysis is presented of the outgassing properties of the materials used on the GPS Block I vehicles, their masses, temperatures, locations, and possible outgassing paths. It is shown that if a small fraction of the matter impinging upon the solar panels is subject to a photochemical reaction initiated by the solar uv and sticks, a sufficient amount of matter will remain on the panels to account for the unexplained degradation. The calculation is repeated for the GPS Block II vehicles now being launched, and estimates for the expected lifetimes of these vehicles are presented.

Nomenclature

E_a	= activation energy
k	= Boltzmann's constant
m	= mass
M_t	= outgassed mass
P	= power output of contaminated array
P_o	= power output of uncontaminated array
P_v	= vapor pressure
r	= radius
$R(\lambda)$	= spectral response of solar cells
T	= temperature
t	= time
α_s	= solar absorptance
$\alpha(\lambda)$	= spectral absorption coefficient
ϕ	= angle of impact
$\Phi(\lambda)$	= solar intensity
λ	= wavelength
θ	= angle of emittance

Introduction

BEGINNING February 2, 1978, a series of 12 navigational satellites, the Navstar Global Position System (GPS) Block I vehicles built by Rockwell International, were launched into a 55 deg inclination orbit at ½ geosynchronous altitude, 20,000 km (see Fig. 1). The GPS, like most spacecraft, uses Si solar photovoltaic cells (K4 ¾ cells) as its primary source of electrical power in space. The electrical power output from these cells decreased with on-orbit time more rapidly than could be expected, on the basis of the known effects, due to penetrating ionizing radiation, principally Van Allen electrons (Fig. 2).[1] The reasons for this rapid decrease, which did not become apparent until after about three years on orbit, have been matters of conjecture for some time. The most likely explanations for this anomalous behavior were either unexpected radiation damage or contamination from the spacecraft itself.[1]

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The Van Allen belts are known to produce solar cell degradation due to their effects on charge carrier lifetime.[2] However, the GPS observations require that either the Van Allen environment is more severe than expected, or that the Van Allen belts produce unexpected effects on some component of the solar cell stack (including antireflective coating, cover slide, or adhesive). The main reason for suspecting the Van Allen belts is the fact that, when solar cell degradations for various spacecraft in different orbits (altitudes) are compared, the observed solar cell degradations are greatest for spacecraft exposed to the largest total dose, and the GPS spacecraft orbit in the most intense portions of the outer Van Allen belts.[3-6] (Figure 1 in the paper by Stewart et al.[1] illustrates the increase in spectral absorptance for several satellites.)

However, there is evidence to support the hypothesis that, actually, contamination is responsible for the anomalous degradation in GPS solar array output. An experiment flown on two GPS vehicles that was designed to measure the change in absorptance of four thermal control coatings indicated a rapid increase in α_s for all samples.[7] The experiment measured

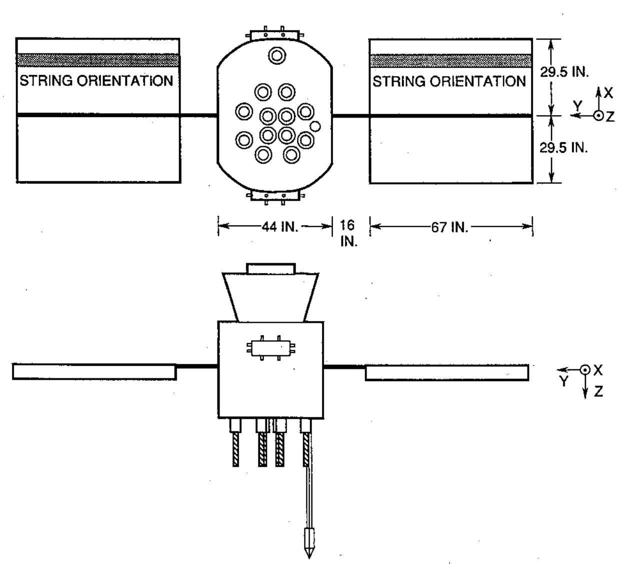

Fig. 1 The Navstar Global Positioning System (GPS) Block I vehicles.

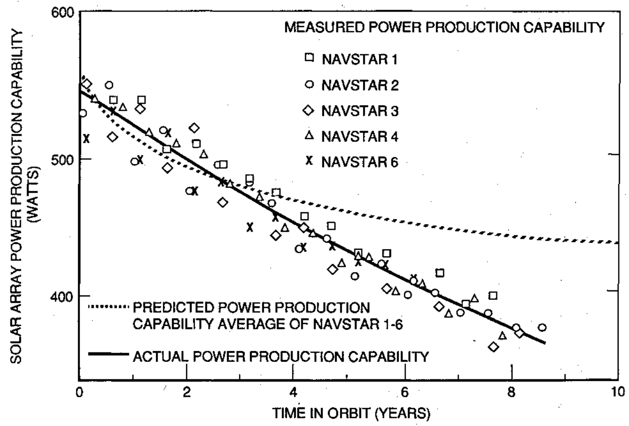

Fig. 2 GPS Block I solar array output vs time (from Ref. 1).

the changes in α_s, inferred from temperature measurements, for samples of 5-mil silvered Teflon®, fused silica mirror (OSR), 5-mil silvered Teflon coated with indium tin oxide, and S13G/LO white paint. Although the initial values of α_s for the four coatings were all different, the slopes of the $\Delta\alpha_s$ curves for the first three materials were similar, suggesting that the degradation mechanism was acting approximately equally on all three coupons—characteristic of contamination. The last coating, the white paint, indicated a much more rapid change in α_s. However, there is reason to suspect it is the radiation vulnerability of the silicone binder of the S13G/LO white paint that is responsible for the rapid increase of its α_s.[8] The silicone is a hydrocarbon organic, and their chemical bonds are known to have lower binding energies than those of the fluorocarbon bonds of Teflon. Thus, it is probably reasonable to ascribe the difference between the $\Delta\alpha_s$ of the S13G/LO white paint and that of the other coupons to radiation damage. The data on the other three coupons could be explained on the basis of contamination alone, if the contamination accumulated at the rate of about 2.5 Å/day. The argument in favor of contamination is strengthened by the observation (in the laboratory) that the presence of ultraviolet light greatly increases the sticking probability of molecules striking the surface in a vacuum.[1,9-11] In situ observations by the SCATHA spacecraft also indicate that the presence of uv light greatly increases the amount of contaminants that can accumulate on spacecraft surfaces.[12]

Initial estimates by Stewart et al.[1] indicated there might be enough material outgassed by the GPS vehicles sticking on the solar panels to account for the anomalous degradation. As the GPS is one of the few spacecraft at this particular altitude of 20,000 km, a more in-depth examination of this problem was warranted in order to determine if current solar cell radiation damage models were inadequate, or if contamination was responsible. The degradation from the first five GPS vehicles was virtually identical (see Fig. 2), the majority of the scatter in the data shown arising from the variations in temperature that the solar panels are subjected to as the Earth-sun distance changes during the course of the year. If radiation was responsible, this may have serious implications for future vehicles flown in this environment, most notably the next generation of 28 GPS vehicles, referred to as the Block II and Block II-A vehicles, which are currently arriving on orbit. (The first of the Block II vehicles was launched on February 14, 1989.) If contamination was found to be responsible for the degradation of the Block I vehicles, similar degradation may occur on the Block II vehicles (Fig. 3). Finally, as it is a photochemical reaction with the solar uv that is suspected of being responsible for the contamination sticking to the solar panels, this could be an important in situ confirmation of this phenomena.

This paper will present an in-depth analysis of the materials used on the GPS Block I vehicles—their masses, temperatures, locations, and outgassing paths—in order to determine the fraction of matter that outgasses onto the solar panels and the probability that this matter would be subject to a photochemical reaction that would cause it to remain on the panel as a contaminant layer. The result will be a prediction of the amount of degradation in power output that the GPS Block I vehicles may attribute to contamination.

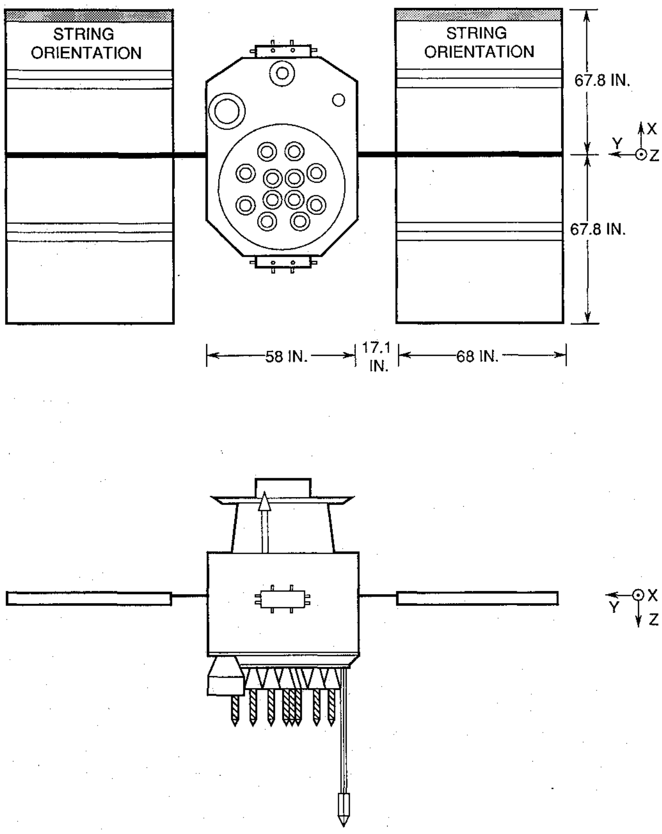

Fig. 3 The Navstar Global Positioning System (GPS) Block II vehicles.

Outgassing

The major outgassing mechanism that would be responsible for any long-term contamination of spacecraft surfaces is almost certainly bulk diffusion. Surface desorption will be complete within < 1 h, and molecular dissociations should not be a factor at the temperatures to which the organic materials inside the spacecraft are subjected. Finally, the long-term outgassing of organics has been observed to follow the $t^{-1/2}$ time dependence of the bulk diffusion process.[13] The temperature dependence of outgassing, especially bulk diffusion, will be $e^{-E_a/kT}$, where E_a is the activation energy, k is Boltzmann's constant, and T is the absolute temperature (K). (For most organics, E_a lies between 5 and 15 kcal/mole.[13,14]) The equation that describes the mass loss as a function of time is

$$\frac{\mathrm{d}m}{\mathrm{d}t} = Am\,\frac{\exp(-E_a/kT)}{\sqrt{t}} \tag{1}$$

with A being a constant.[13] This equation is solved as follows.

Materials in consideration for use on spacecraft are subjected to a standard outgassing test, ASTM E-595. This test holds the sample material at a temperature of 125°C for 24 h and measures the relative amount of mass outgassed in that time, called the total weight loss (TWL) value. In addition, a witness plate, held at 25°C, measures the amount of collectable volatile condensable material (CVCM) collected during the same time period. Typically, all materials qualified for space flight must have a TWL reading of less than 1% and a CVCM level of less than 0.1%. Using the values $dm/dt = 0.01$, $T = 125°C$, and choosing E_a to be 10 kcal/mole, the bulk diffusion outgassing rate is found to be

$$\frac{dm}{dt} = 3100m \frac{\exp(-5032/T)}{\sqrt{t}} \tag{2}$$

where m is measured in grams, T is measured in K, and t is measured in days. Thus, the amount of material outgassed between time t_1 and time t_2, at a temperature T, is

$$M_t = 6200m \exp(-5032/T)(\sqrt{t_2} - \sqrt{t_1}) \tag{3}$$

The amount of material outgassed is seen to be dependent upon the mass of the material and its temperature. Determining the masses and temperatures of all of the organics on the GPS Block I vehicles, and the corresponding value of the TWL, is straightforward, as there is a listing of the location and size of all organics on the GPS Block I vehicles. An examination of this list indicates that a very good approximation of the total can be made by assuming that ⅓ of the weight of the electronic subsystem boxes and the associated wiring account for all of the outgassing materials. A breakdown of the weight of systems on the GPS Block I vehicles is given in Table 1. The predicted temperatures of the three main bulkheads inside the GPS Block I spacecraft as a function of time for the five-year design life are shown in Table 2. Note that these bulkheads all lie in the x-y plane, with the FWD BHD being in the $+z$ direction, the AFT BHD being in the $-z$ direction, and the EQP BHD separating the two. Knowing the weights of the boxes and wiring, their location, and their temperatures, Eq. (3) predicts the amount of matter that outgasses as a function of time.

Table 1 GPS Block I—mass properties summary

Item	Weight, lbs
Launch weight	1920
Orbital insertion system propellant	745
Reaction control system propellant	64
Structure	180
Balance	30
Solar cells	114
Thermal	81
Wiring	125
Boxes	265
Other	316

Table 2 Calculated Block I interior temperatures vs time, average

Month	FWD BHD, °C	AFT BHD, °C	EQP BHD, °C
1	27	25	40
2	30	25	40
3	30	25	40
4	30	25	40
5	30	26	40
6	31	26	40
8	31	26	40
10	32	27	41
12	32	27	41
15	33	28	41
18	34	29	41
21	35	30	42
24	36	31	42
30	37	33	43
36	38	35	43
42	39	37	44
48	40	39	44
54	41	40	45
60	43	42	46

Note that scaling data from the ASTM E-595 test in this manner assumes that the outgassing characteristics of the spacecraft are adequately modeled by Eq. (3) over the lifetime of the vehicle. There are multiple outgassing materials within the vehicle, and the mass and activation energy for each of these materials will be different. Scialdone[13] reports activation energies for organics in the range 5–15 kcal/mole. This spread in E_a gives rise to almost a two-order-of-magnitude difference in the outgassing rates of materials at 25°C.[14] A low E_a material may deplete itself of volatiles early in the life of the spacecraft, whereas a high E_a material may continue to outgas at (relatively) high rates long into the mission. This "spread" is not accounted for in our model; however, $E_a = 10$ kcal/mole is a reasonable worst case assumption.

Geometrical View Factors

The outgassed molecules originating inside the spacecraft bounce around until they escape to the outside world through one of the orifices. The orifices in the GPS Block I vehicles are shown in Fig. 4. There are two "shear panels," oriented parallel to the x axis, which are used to connect the FWD and AFT bulkheads. (The location of the EQP bulkhead is illustrated by the dashed line.) There are also two "access panels," oriented parallel to the y axis, which complete the spacecraft enclosure. Note that of particular interest are the vents in the "shear panels" that have a line of sight view of the solar panels. The molecular exit probabilities are considered to be proportional to the fractional orifice areas. The total mass that is outgassed in a given month, i.e., the source strength, is given in Table 3. Note that the outgassing from the aft portion of the vehicle is different from the outgassing from the forward portion of the vehicle, due to the fact that orifices in the equipment bulkhead allow for venting between the two halves of the vehicle.

The molecules issuing from the spacecraft vents are assumed to travel in straight-line paths (free molecular flow), and to have a cosine distribution about the axis normal to the vent.[15] (Non-line of sight transport mechanisms would increase this flux by no more than a few percent.[16]) The fraction of these molecules that will strike any particular unit area on the solar panel is proportional to

$$\frac{\cos\theta \cos\phi}{\pi r^2} \tag{4}$$

(see Fig. 5). The fraction of mass striking the solar panel per unit area will be the product of the source strength, i.e., the mass flux/unit area leaving the vent, and the dimensionless view factor,

$$\int \frac{\cos\theta \cos\phi}{\pi r^2} \, dA \tag{5}$$

which is integrated over the area of the outgassing vent. If the position of the solar panel, relative to the spacecraft body, is known, it is straightforward to calculate the dimensionless view factor. The results of these calculations will be presented in the next section.

GPS Solar Panels

The solar cells on the GPS solar panels, which measure 67 × 68 in., are composed of 18 strings of cells, 9 strings on either side of the boom, each string being oriented normal to the spacecraft body (Fig. 1). It is important to note that the performance of a string of solar cells is governed by the performance of the worst cell in the string.[17] If one of two solar cells, connected in series, is shadowed, the output current decreases by a factor much in excess of 2. This is due to the fact that the shadowed cell not only ceases producing power, it becomes a consumer of power as well. For this reason, it is only necessary to calculate the thickness of the contaminant layer on the most adversely affected cell in each

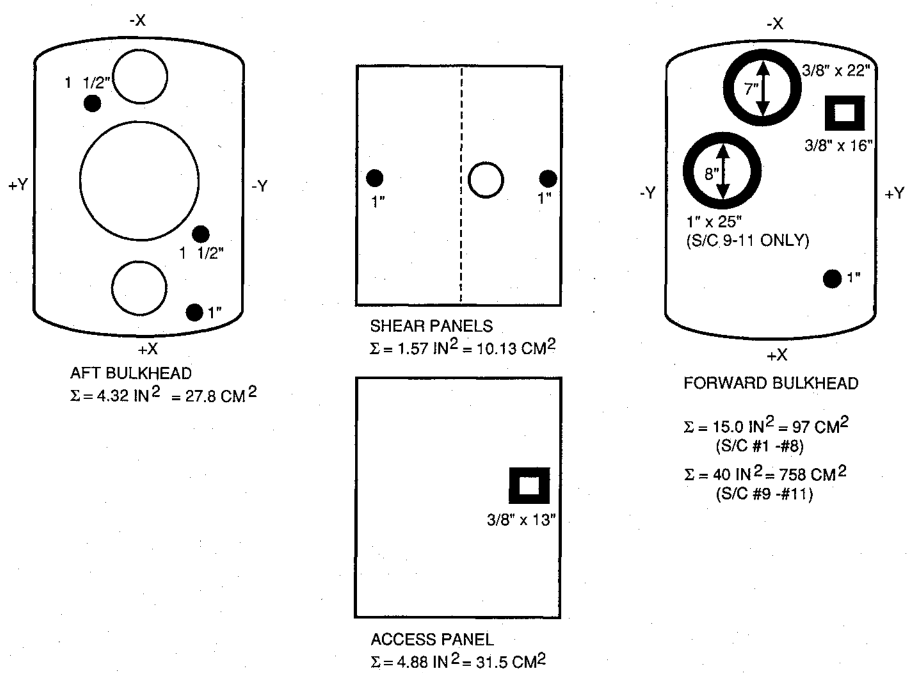

Fig. 4 GPS Block I aperture sizes and locations.

Table 3 Outgassed mass vs time

	Block I, g	
Month	FWD	AFT
1	123.1	82.6
2	51.1	34.2
3	39.2	26.2
4	32.9	22.0
5	29.3	19.6
6	26.4	17.7
8	22.6	15.1
10	10.2	13.5
12	18.9	12.6
15	17.2	11.5
18	16.5	10.4
21	15.1	10.1
24	14.0	9.4
30	13.2	8.8
36	12.1	8.2
42	12.0	8.0
48	11.2	7.5
54	10.9	7.4
60	11.1	7.4

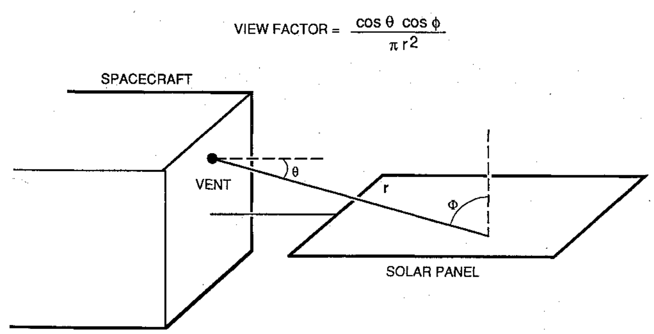

Fig. 5 Outgassing geometry.

string, which would obviously be the ones closest to the body of the spacecraft.

The solar panels lie within ± 30 deg of the spacecraft y-z plane, facing the direction of the $+x$ axis, approximately 80% of the time. The geometrical view factors were calculated numerically for the cells closest to the vehicle for the case when the panels were at an angle of 30 deg to the y-z plane (when the view factor from the shear panel vents would be greatest). These results, which incorporate all of the spacecraft vents having a line of sight to the solar panels, are illustrated in Fig. 6. (Note that outgassing from the multilayer insulation covering the spacecraft was treated separately and found to be negligible in comparison.) The product of the outgassing rate and the view factor yields the rate at which contaminants impact the near edge of the solar panel.

Solar UV

The outgassed volatiles that emanate from the GPS body and strike the solar panels, $T \approx 60°C$, would be thought to have a very short residence time, approximated by

$$t \approx \frac{2 \times 10^{-9}}{P_v} \tag{6}$$

where t is in seconds and P_v is in atmospheres.[18] However, there is growing evidence to support the conclusion that if uv light strikes a contaminant molecule during the short time it is resident on the solar panel it can cause the contaminant to remain permanently.[1,9–12] Laboratory data collected during experiments at Hughes Aircraft Company (HAC), and reported by Hall, Stewart, and Hayes,[10] allow us to correlate the impact rate with the deposition probability. The product of the impact rate with the deposition probability is the rate at which contamination accumulates.

The effect of the contaminant layer on the output of the solar cells was obtained by multiplying the optical attenuation of the contamination as a function of wavelength[19] by the spectral response of each cell and the solar flux.[20] The power output that corresponds to a contamination layer of thickness X was obtained by evaluating the ratio

$$\frac{P}{P_o} = \frac{\int e^{-\alpha(\lambda)X}\Phi(\lambda)R(\lambda)\,\mathrm{d}\lambda}{\int \Phi(\lambda)R(\lambda)\,\mathrm{d}\lambda} \tag{7}$$

for all wavelengths.[17] The result is illustrated in Fig. 7. It should be noted that the solar cell power decreases primarily because the cell's short circuit current is affected, the effect upon the open circuit voltage being much less. Also notewor-

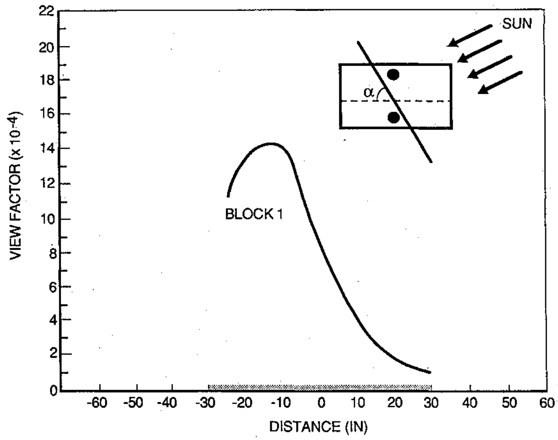

Fig. 6 GPS Block I view factors.

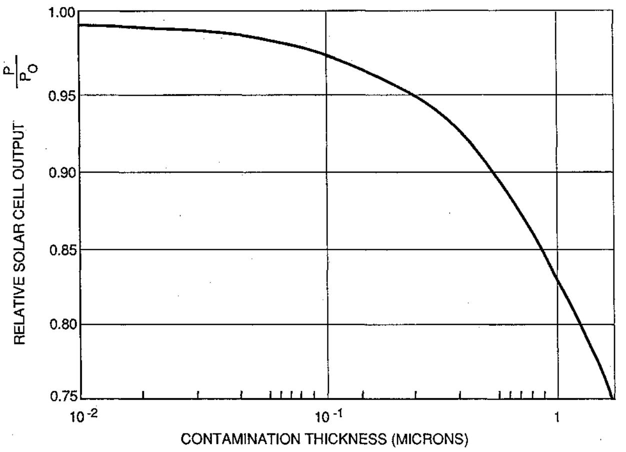

Fig. 7 Contamination film effect on solar panel output.

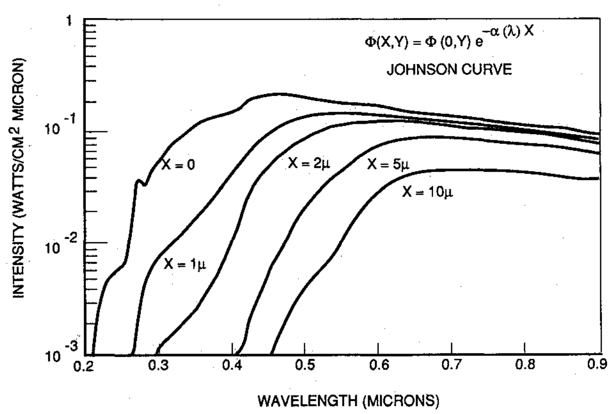

Fig. 8 Contamination film effect on transmitted sunlight.

thy is the fact that it is the response of the solar cell at blue (shorter) wavelengths that molecular contamination reduces (Fig. 8). This is of consequence because the other major solar cell degradation environment (Van Allen radiation) primarily affects the red (larger) wavelengths. The effects of contamination as a function of time were calculated for the worst cell in each string (e.g., see Table 4). The output from the individual strings were then averaged to obtain the output from each panel, which are summed to obtain the total power supply. When the model for the radiation damage is combined with the degradation due to contamination, the result is in excellent agreement with that observed (Fig. 9). Also worthy of note is that a similar analysis was performed to predict the change in α_s due to contamination for the thermal control coatings mentioned earlier. These estimates were in agreement with the 2.5 Å/day inferred from the data.

The fact that our predictions agree so well with observations may be somewhat misleading. For example, the view factors were evaluated for the solar panel orientation expected to result in the greatest amount of deposition, which would overestimate the final contamination level. Also, the values for the absorption coefficients determined from the HAC data were, in essence, treated as invariants, which is most certainly not the case. HAC's laboratory observations dealt with a single outgassing material, RTV-511, condensing on a 30°C surface, not a 60°C surface, as is the case here. It was noted that when the collecting surface was at temperatures lower than 30°C, the accumulation rate followed the relation

$$\text{Rate} = C_o \exp(E_a/kT) \tag{8}$$

If we assume that this relationship applies to higher temperatures as well, we would be forced to reduce our estimates for the accumulation rate by a factor of about 4. This would result in a predicted power output of 436 W at the end of 5 years, not the 406 W indicated in Fig. 9. However, as was previously discussed, there are multiple outgassing materials within the GPS vehicle. Each of these materials will outgas volatiles, whose masses and chemical properties would be expected to differ from those of RTV-511. It is reasonable to assume that, at least some of, the volatiles outgassed by the GPS will be heavier and/or more photochemically reactive that the volatiles from RTV-511, canceling the effect of the warmer collecting surface. How the absorption coefficients for the GPS volatiles compare to those for the RTV-511 is not known. In view of these uncertainties, the fact that our prediction agrees with the observations to within much less than an order of magnitude should be sufficient grounds for concluding that contamination is (at least partially) responsible for the anomalous degradation. However, more specific inferences, such as an absolute value for the thickness of molecular contaminants, should be avoided.

Table 4 GPS Block I solar power output, forward String 2

Month	Impact rate, Å/h	Deposition probability	Accumulation, Å Per month	Accumulation, Å Total	Power
1	162	0.002	233	233	0.992
2	67	0.002	97	329	0.992
3	51	0.003	110	439	0.990
4	43	0.004	124	563	0.988
5	38	0.004	110	673	0.986
6	35	0.004	101	774	0.985
8	30	0.005	108	984	0.981
10	26	0.005	94	1186	0.977
12	25	0.005	90	1370	0.972
15	23	0.005	83	1628	0.970
18	20	0.006	86	1883	0.966
21	20	0.006	86	2141	0.960
24	18	0.006	78	2387	0.956
30	17	0.007	86	2879	0.946
36	16	0.007	81	3383	0.940
42	16	0.007	81	3869	0.930
48	15	0.008	86	4373	0.922
54	14	0.008	81	4877	0.912
60	15	0.008	86	5381	0.904

GPS Block II and Block II-A Vehicles

Due to the apparent success of this approach in accounting for the degradation in power observed on the Block I vehicles (numbers 1–12), this calculation was repeated for the Block II vehicles, (numbers 13–21) and the Block II-A vehicles, (numbers 22–40), in order to determine if they would be susceptible to a similar unexpected loss of power. (The Block II and II-A vehicles are essentially identical, save for a minor structural modification on the II-A vehicles.) As is illustrated in Fig. 3, the Block II and II-A vehicles are larger than the Block I

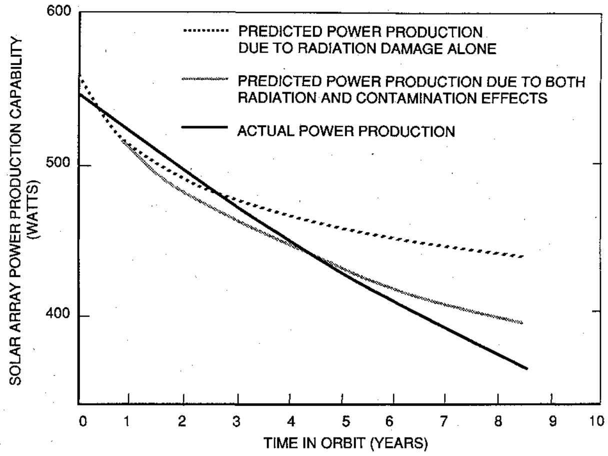

Fig. 9 GPS Block I solar array output estimates.

vehicles, have correspondingly larger solar panels, and a longer design life of 7.5 years. Unfortunately, the orientation of the strings remains unchanged, so that a thin contamination layer on the edge of the panels nearest the vehicle body would still be able to affect the power output. Bearing in mind the limitations discussed in the last section, it was found that Block II vehicles 13–17 should experience a noticeable degradation in output above that predicted by radiation damage alone, similar to the Block I vehicles, but would be expected to have a lifetime of at least 10.0 years, well in excess of the design life. Block II vehicles 18–21, which have more powerful solar panels, will also see a degradation due to contamination, but should reach 12.5 years of normal operation. Block II-A vehicles 22–40 should experience no loss of life due to contamination, and may very well reach 16 years of normal operation. This is due, indirectly, to the structural modifications mentioned earlier. Basically, the Block II-A vehicles have been more tightly sealed than were the Block II vehicles. The tighter seals act as physical barriers to the outgassing material so that the resulting contaminant molecules are, for the most part, contained within the vehicle or directed away from the solar panels. Comparing the performance of the Block II and Block II-A vehicles will be an important verification of the contamination degradation model used here. All the Block II and Block II-A vehicles have the same radiation environment. Vehicles 13–17 and 18–21 have the same contamination environment, but utilize different solar panels. An identical deposition of contaminants on these two sets of vehicles should produce different degradations. Similarly, the solar panels for vehicles 18–21 and 22–40 are identical, but their contamination environments are different. Any differences in the output from these two sets of vehicles will be due to contamination alone. Note that although the power output from the Block I vehicles was degraded, it was still sufficient to allow the vehicles to reach their design life of 5 years. Two Block I vehicles are still in operation after 10 years on orbit. Similar performance can therefore be expected from the Block II and II-A vehicles.

Discussion

We have seen that the unexpected degradation of power supplied by the solar arrays on the GPS Block I vehicles can be accounted for by contamination (outgassing) from the spacecraft itself, in agreement with the initial analysis by Stewart et al.,[1] and does not indicate a deficiency in solar cell radiation damage models. This contamination strikes the solar panels and undergoes a photochemical reaction with the solar uv, causing the contaminants to remain permanently. This type of photochemical reaction is not well understood and warrants further investigation, as it may have impacts on future space missions and laboratory simulations.

Our conclusion—that contamination is responsible for the anomalous degradation—is surprising in that solar arrays, nominally at a temperature of about 60°C, are normally thought to be relatively impervious to molecular contamination. This may have implications for future spacecraft because designers must take into consideration the fact that a few percent of the contamination incident on any solar illuminated surfaces may remain permanently, resulting in decreased power in the case of solar arrays, or increased values of α_s in the case of thermal control coatings.

We note that the effect of this contamination on the GPS vehicle would have been lessened had the solar arrays been farther from the vehicle, decreasing the amount of contaminants reaching the arrays, or had the strings of solar cells been oriented normal to the boom, rather than normal to the spacecraft, thereby decreasing the number of strings affected by the contamination. However, it is equally important to note that decreasing the impact rate does not produce a one-to-one decrease in the accumulation rate.[9,10] The safest course of action is to prevent contaminants from reaching sensitive surfaces in the first place.

Acknowledgments

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