to increase the engine specific impulse often cause the engine mass to increase at the same time. Are the improvements acceptable? The results derived from Figs. 2 and 3 can be used to assess the improvements of the SSME-derivative engines. If the improvements can increase the specific impulse by 10 m/s and the engine mass increases less than 88 kg at the same time or if the improvements can decrease the engine mass by 88 kg and the engine specific impulse decreases less than 10 m/s at the same time, the improvements are acceptable.

Conclusion

For the given flight mission, the single-stage-to-orbit vehicle powered by the DF/DX engines has the minimum dry mass, and the dry mass of the tripropellant-engine-powered vehicle is less than that of the bipropellant-engine-powered vehicle. For the SSME-derivative-engine-powered, single-stage-to-orbit vehicle, the optimal expansion ratio of the derivative engine is about 51. For the vehicle powered by the derivative engines with expansion ratio 50, the effect on the vehicle dry mass of reducing the engine mass by 88 kg is equivalent to the effect on the vehicle dry mass of increasing the engine specific impulse by 10 m/s, and this result can be used to assess the improvements of the SSME-derivative engines.

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Revised Estimates of Photochemically Deposited Contamination on the Global Positioning System Satellites

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Introduction

IN 1991, Rockwell International Corporation presented analysis that supported photochemical deposition of contamination on the Global Positioning System (GPS) solar arrays as being the most likely cause of an anomalous degradation in power on the Block I spacecraft.[1] The same study developed predictions for the behavior of the Block II (13–21) and Block II-A (22–40) spacecraft (Table 1). Note that spacecraft 18–21 are identical to spacecraft 13–17 save that they have more strings of cells present on the solar arrays, which result in a greater power production capability. Spacecraft 22–40 have the larger solar arrays and are more tightly sealed as the result of extensive electromagnetic interference reduction techniques, which physically close most outgassing vents. As a result, the original contamination study predicted identical contamination for spacecraft 13–21 and essentially no contamination for spacecraft 22–40. The lifetime requirement was 7.5 years for all spacecraft.

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After several years of on-orbit data, it became obvious that spacecraft 22–40 were experiencing an anomalous degradation, in contradiction to the original predictions. The power degradation observed was in rough agreement with the degradation predicted for spacecraft 18–21. As a result, a new study was initiated to reexamine the assumptions and conclusions of the original study in an attempt to develop a higher-fidelity model of the outgassing. It is seen that the higher-fidelity model is capable of predicting a noticeable degradation in power for the Block II-A spacecraft, in rough agreement with that seen on orbit.

Revised Contamination Estimates

The procedure used to predict contamination-induced power loss is composed of five independent, sequential steps as summarized in Table 2 (Ref. 2). Note that the main difference between the old study and the new is fidelity. In the new model, mass deposition was determined for every string in the solar array, not just a few selected points as in the earlier study. Similarly, the rotation of the solar array about the solar array drive train was factored into these calculations, whereas static averages were used in the original study. In addition, several other points, originally thought to be secondary or tertiary in nature, were reexamined in an attempt to devise a model that could predict degradation on the Block II-A spacecraft (Table 3).

The initial degradation predictions for the new model, without any modification, showed good agreement with the original model. This is a confirmation of the fact that the simplifications used in the original model were justified. The benefit of the new model is that it is easily modified. Because both the new and old models predict more contamination-related power loss than is seen on orbit, it is appropriate to reexamine the initial assumptions.

One assumption that could be questioned is the use of a source mass term equal to 1.0% of the mass of organic material interior to the vehicle. The 1.0% assumption was based on a typical 1.0% total mass loss (TML) value for spacecraft organics. Reducing the source mass by a factor of 10 was seen to give better agreement with the on-orbit data. This may be an indication of the fact that it is more appropriate to utilize the standard 0.1% collected volatile condensable material value for the source mass rather than the 1.0% TML.

Calculations of the mass exitance and view factors are based on the vehicle geometry and can be quite rigorously justified. Calculation of the sticking coefficient, being based on a very few data points from a single experiment, is subject to critique. However, having no other available data to compare this assumption with, the issue of sticking coefficient cannot be reexamined. The contaminant absorptance profile is quite possibly a large source of error, but using any contaminant profile other than the one chosen would further reduce the available power predictions, not increase them.

After further review of the model, it was determined that an additional plausible correction would be to reduce the efficiency of the outgassing vents seen to be the main source of contamination. Many of the possible spacecraft vents are covered by multilayer insulation (MLI). It was initially assumed that the MLI could slow the rate of outgassing but would otherwise have no effect on the amount of contamination that passed through it. This is obviously a very pessimistic assumption, from the viewpoint of contamination deposition, as a contaminant molecule that is bouncing around the various layers of MLI would have a fairly good chance of re-entering the vehicle and exiting through another vent or of slipping through the various MLI layers to another portion of the overall spacecraft blanket that has no line of sight to the arrays. It was seen that allowing the MLI to transmit only 10% of the mass that would otherwise outgas through it, together with the reduction in source mass already discussed, gave the best agreement with the data.

Block II Spacecraft 13–17

The original contamination model, on-orbit data, and revised contamination model for spacecraft 13–17 are shown in Fig. 1. The average power requirement for the GPS Block II spacecraft, with battery charging, is 525 W. A linear fit to the data would predict a lifetime of 13.5 years before reaching this minimum. Between years 5 and 10, the new contamination model predicts that spacecraft 13–18 will lose power at the near linear rate of about 15.43 W per year

Table 1 Original power loss predictions

Power	Spacecraft 13–17	Spacecraft 18–21	Spacecraft 22–40
Beginning of life	928 W (100%)	1070 W (100%)	1070 W (100%)
7.5-yr prediction, natural radiation only	717 W (77%)	827 W (77%)	827 W (77%)
7.5-yr prediction, radiation and contamination	603 W (65%)	696 W (65%)	827 W (77%)
7.5-yr requirement	521 W (56%)	521 W (49%)	553 W[a] (52%)
Margin	82 W (9%)	175 W (16%)	274 W (25%)

[a]Minimum power requirement for Block II-A has recently been revised to 600 W.

Table 2 Molecular contamination deposition process

Step	Explanation
Estimate mass loss	Predictions of outgassed mass vs time are obtained by assuming bulk diffusion as the critical outgassing mechanism.
Estimate mass exitance	Knowledge of the vehicle's interior geometry provides estimates of the mass exitance through each spacecraft vent.
Calculate view factors	Knowledge of the orientation of the solar arrays, relative to each vent location, enables calculation of the view factor between each vent and each string of cells on the array.
Estimate sticking coefficient	Once the impact rate on a given solar cell is known, the sticking coefficient, which is experimentally seen to be a function of impact rate, can be determined. This, in turn, enables an estimate of mass buildup on a surface.
Estimate power loss	Once the contamination thickness is known, knowledge of the contaminant absorptance profile and the solar cell spectral characteristics allow power loss to be determined.

Table 3 Significant additions to the GPS contamination model

New model additions	Possible effect
Considers the effect of outgassing from possible sources that were initially omitted: plume shield, antennas, and solar boom cable bundles	Increases mass loss from the vehicle
Reexamines outgassing from the vehicle interior to the solar arrays by recalculating view factors from the navigation ring (a raised platform that is the structural support for the navigational antennas) and the solar arrays and by factoring in the higher percentage of mass loss that would occur through this ring	Increases mass exitance from the vehicle
Reexamines the degradation in power as a function of contamination thickness based on revised contamination degradation profiles	Increases power loss as a function of contamination thickness

Table 4 Revised power predictions

Power	Spacecraft 13–17	Spacecraft 18–21	Spacecraft 22–40
Beginning of life	928 W (100%)	1070 W (100%)	1070 W (100%)
7.5-yr prediction, natural radiation only	717 W (77%)	827 W (77%)	827 W (77%)
7.5-yr prediction, radiation and contamination	640 W (69%)	734 W (69%)	773 W (72%)
7.5-yr requirement	521 W (56%)	521 W (49%)	600 W (56%)
Margin at 7.5 yr	119 W (13%)	203 W (19%)	173 W (16%)
Power loss predicted (W/yr)			
New model	15.45	17.33	15.54
Linear fit	19	86[a]	53
Time to minimum power, yr			
New model	15.5	20.5	18.0
Linear fit	13.5	8.5[a]	8.0

[a]This value is based on only two data points and should be used with caution.

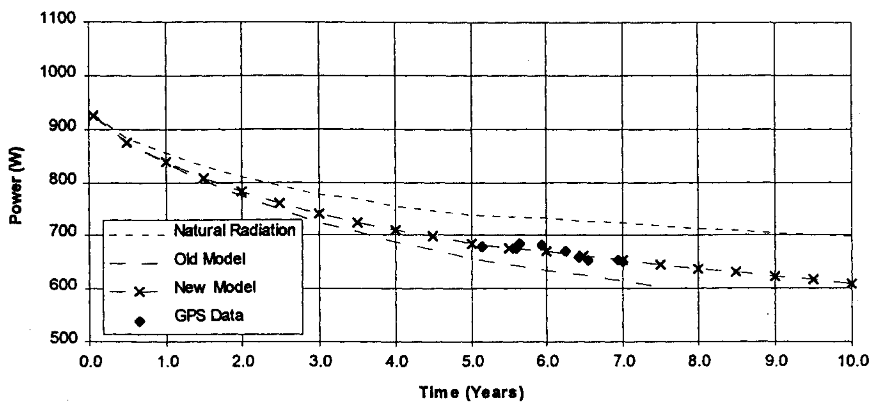

Fig. 1 Modified predictions of power degradation for Block II spacecraft 13–17.

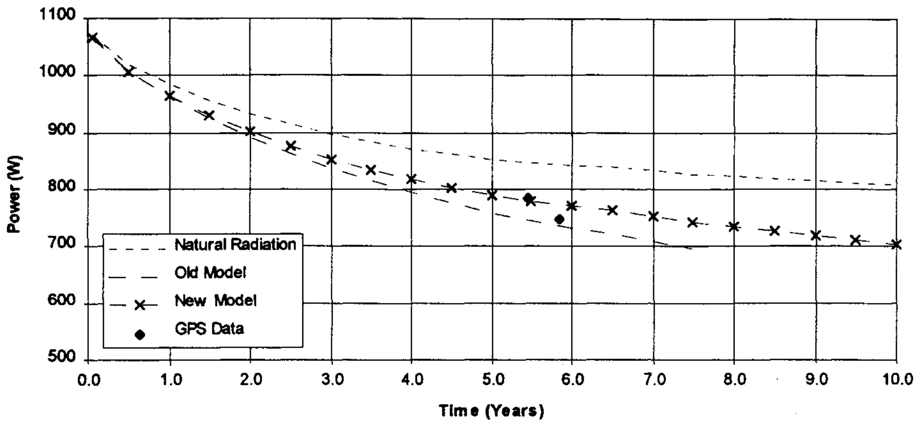

Fig. 2 Modified predictions of power degradation for Block II spacecraft 18–21.

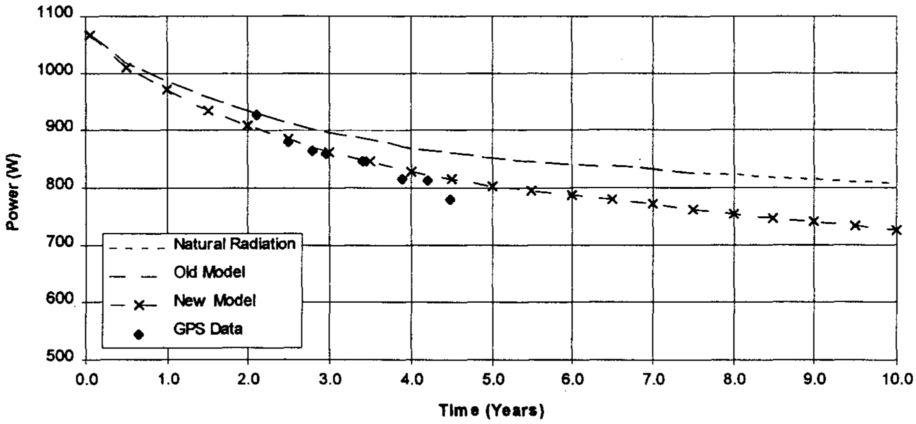

Fig. 3 Modified predictions of power degradation on Block II-A spacecraft 22–40.

(vs 19 W per year for the data fit). Extrapolating this power loss rate forward in time would predict a lifetime of 15.5 years.

Block II Spacecraft 18–21

The only difference between GPS spacecraft 18–21 and 13–17 is that spacecraft 18–21 have more solar cells on the solar array. Consequently, they produce 1070 W of power, rather than 928 W. The revised predictions for Block II spacecraft 18–21 are shown in Fig. 2. The new model predicts slightly less degradation than the old model, in agreement with observations.

Block II-A Spacecraft 22–40

The predicted degradation of the Block II-A spacecraft is shown in Fig. 3. Note that there is no difference between the natural radiation curve and the old model curve because the old model did not predict any degradation in power due to contamination. The new model does predict noticeable degradation and shows fairly good agreement with the data.

Summary

The revised estimates of GPS Block II/II-A lifetime prediction are shown in Table 4. As shown, it is now believed that the Block II-A spacecraft 22–40 can be expected to experience noticeable degradation in power due to photochemical deposition of contaminants on the arrays. The new model predicts less degradation for spacecraft 13–21 than did the original study. Based on the goodness of fit with the data, we have high confidence in the final result. As shown in Table 4, all GPS Block II/II-A spacecraft are expected to meet their 7.5-year lifetime requirement with power to spare. Even the most pessimistic approach, the linear fit to the data, agrees that all spacecraft should exceed their lifetime requirement.

This study has verified that photochemically deposited contamination traced to outgassing from the vehicle interior is the likely source of anomalous power loss on the GPS spacecraft. The lessons learned from this study appear to be virtually identical to those quoted in the original work, with one exception. It now seems plausible that contamination could reach the arrays by outgassing through the MLI. This being the case, spacecraft designers must pay attention to the location of even those vents that are covered by MLI.

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