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Solar Array Electrical Performance Assessment for Space Station Freedom

Bryan K. Smith
*Lewis Research Center
Cleveland, Ohio*

and

Holly Brisco
*Lockheed Missiles & Space Company
Sunnyvale, California*

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FOR SPACE STATION FREEDOM (NASA)
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**SOLAR ARRAY ELECTRICAL PERFORMANCE ASSESSMENT
FOR SPACE STATION FREEDOM**

Bryan K. Smith*
NASA Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135-3191

Holly Brisco
Lockheed Missiles & Space Company
1111 Lockheed Way
Sunnyvale, CA 94089-3504

Abstract

Electrical power for Space Station Freedom will be generated by large photovoltaic arrays with a beginning of life power requirement of 30.8 kW per array. The solar arrays will operate in a Low Earth Orbit (LEO) over a design life of fifteen years. This paper provides an analysis of the predicted solar array electrical performance over the design life and presents a summary of supporting analysis and test data for the assigned model parameters and performance loss factors. Each model parameter and loss factor is assessed based upon program requirements, component analysis and test data to date. A description of the LMSC performance model, future test plans and predicted performance ranges are also given.

Introduction

The Electrical Power System (EPS) for Space Station Freedom (SSF) is being produced under contract number NAS3-25082 by the Rocketdyne Division of Rockwell International for NASA Lewis Research Center (LeRC). Lockheed Missiles and Space Company (LMSC) is responsible for providing the photovoltaic arrays that will be used to generate power for the SSF EPS. The solar arrays

are specified to produce a minimum beginning-of-life (BOL) power of 30.8 Kw and an end-of-life (EOL) power of 25.2 Kw per array. Voltage is specified at 161.1 Vdc (BOL) and 148.4 Vdc (EOL).

The arrays are designed to provide the specified power taking into account SSF program wide LEO environmental requirements and system losses within the array. LMSC has developed a computer model to determine the predicted electrical output that incorporates LEO environmental losses, system losses and other factors that affect array output. These individual losses or model parameters are determined through analysis and supporting test data. As part of the solar array development and qualification program, NASA-LeRC, Rocketdyne and LMSC have conducted a series of LEO environmental tests that will be used to verify the predicted electrical performance losses. The following provides a description of the solar array electrical design, performance model, model parameters, requirements and supporting analysis and test data.

Mission Description

Space Station Freedom will serve as an outpost in low-earth orbit that will be launched on several flights

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and assembled while on-orbit. SSF will operate between 180 and 240 nautical miles at an inclination of 28.5 degrees. The Initial Phase of Space Station Freedom includes two major milestones - Man Tended Capability (MTC) and Permanently Manned Capability (PMC). Power requirements will be supported with two solar arrays for the MTC configuration and six solar arrays for the PMC configuration.

Because the arrays will be launched at different times their electrical output will be different with respect to initial BOL power. This directly influences the design of other EPS hardware components that store, manage and continuously distribute SSF power. Therefore, it is important to predict what array power will be available over the design life in order to optimize the design of other EPS hardware components. This knowledge is also important for the assembly and operational phases of the program where power resources will support SSF housekeeping functions and user experiments. Additional arrays will be added as part of the Follow-on and Evolution Phases to accommodate future power demands.

Array Electrical Design

Each solar array is comprised of two blanket and containment box Orbital Replacement Units (ORUs) and a deployable mast structure. The containment boxes support the stowed electrical panels under compression during launch.

The mast structure deploys, supports and retracts the solar array blankets on-orbit. The extended solar array is 114 feet in length by 38.9 feet in width (Figure 1).

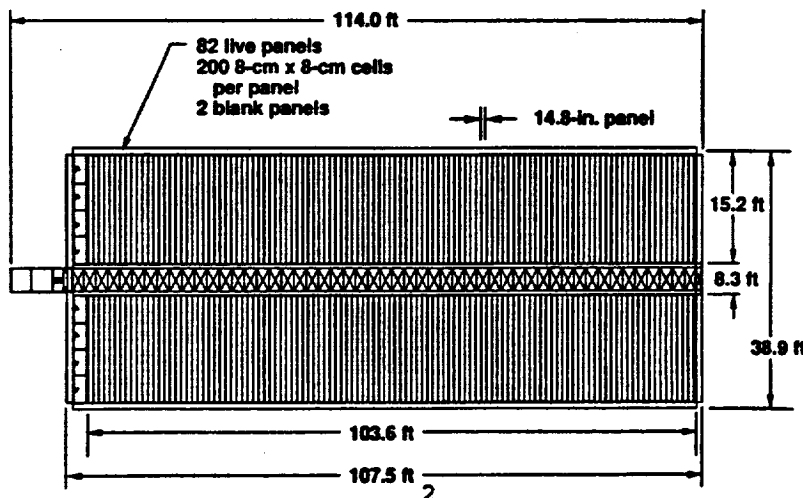
Each array blanket contains 82 active panels with 200 solar cells connected in series. Two panels are connected in series, 400 solar cells total, to obtain the required circuit voltage. Each of the circuits is routed down the array through a Flat Collector Circuit (FCC) and round cable assembly to the Sequential Shunt Unit (SSU). The SSU regulates array power and voltage through switching individual array circuits. The power levels addressed in this paper are at the input of the SSU.

The solar cells are 8 cm by 8 cm silicon cells with a wrap-through contact design, boron back surface field, 10 ohm-cm base resistivity and a dual anti-reflective coating. The cell coverglass is a ceria doped CMX glass and is coated with an UV reflective surface to protect the cell to coverglass adhesive. The production cells are grouped into 10 categories, each having a 36 mA range, according to current output rated at 495 mV and 28°C, AMO conditions.

The array electrical design also utilizes one bypass diode for every 8 solar cells. The diode provides the solar cells protection from damaging reverse bias conditions that can result when the array or circuit is partially shadowed. The diodes also provide a shunt path that can bypass 8 cells if an "open" condition occurs in a cell.

Figure 1

Space Station Solar Array Deployed Configuration



Each cell is welded to a copper and Kapton Flexible Printed Circuit (FPC) at 10 contact points each through parallel gap resistive welding. Five manufacturing modules of 40 cells, 5 diodes and an FPC are electrically connected to form the panel assembly. This assembly is bonded to a second structural layer to form the completed panel assembly. The panels are hinged together and joined to the FCC to form a blanket. The FCC is connected to a round cable that is connected to the SSU. This comprises the complete array electrical circuit. Each of these elements is included in the system performance analysis.

DC Model Description

The LMSC power performance model is designed as a stand alone analysis tool. The program default values are based on the degradation and system loss factors presented in this paper; however, in anticipation of future test and analysis data, the model also allows for user input. The DC Model uses a pre-processor to calculate and store the wing operating conditions and a simulator to display the cell, circuit, and wing level outputs based on pre-processor input file data and user entered operating voltages.

Pre-Processor

The pre-processor consists of a series of screens and menus that allow the user to establish the array operating conditions. The main pre-processor screen offers access to cell and circuit level menus. The change in power output due to environmental losses is detailed at the cell level while the system losses are accounted for at the circuit level. To analyze a full wing both the environmental and the system losses need to be taken into consideration. For this reason the circuit level requires a cell level reference file. All system losses dependent on the degraded cell parameters are calculated using the reference cell data. In this way, data for the entire wing level system are accessed via the circuit level filename.

Cell Level The cell level

contains three screens. The first of these screens allows the user to view the cell parameter default values (Isc, Voc, Imp, Vmp,) for cell grades 1-10. These four cell parameters, obtained from qualification data, are then degraded to obtain the power output through EOL.

Screen two includes the launch date, cell operating temperature, and environmental loss factors for each of the four cell parameters. Degradation factor default value equations as a function of mission life were obtained for each cell parameter by curve fitting the BOL, 4, 10, and 15 year degradation parameters. Once the user inputs the launch date, year of mission, and day of mission the corresponding loss factor for each solar cell parameter is calculated and displayed.

The environmental factors for a given mission life are multiplied to obtain one parameter degradation factor which is used to degrade the screen one values. These degraded parameters are displayed on the third screen. Although cell operating temperature is included in the screen two display, it is not taken into consideration when determining the degraded cell value shown on this screen but is accounted for by the simulator program.

Circuit Level The circuit level includes all system level losses which affect the circuit and wing level outputs. It is comprised of three sections which are each broken into 82 subsections, one for each circuit of the wing. In this way, an individual circuit can be analyzed as well as the entire wing.

The first full 82 circuit section details each circuit's cell grade, FPC loss, harness loss (FCC and round cable assembly), current mismatch loss, circuit flatness and shadowing information. A circuit cell grade default value of 7 was selected, corresponding to the average blanket cell grade needed to meet the SSF power requirement, but the user may override this to create a blanket which contains a distribution of cell grades between 1 and 10.

The second level is an 82 X 10 matrix which contains operating temperature information. The entire matrix will default to the cell

operating temperature displayed in the circuit level header if a temperature filename is not supplied. If the user wishes to analyze temperature gradients across the wing, the program will read in a temperature file or the user can input the temperatures manually. The ten temperatures per circuit correspond to the ten 40 cell modules/circuit.

The third and final section details the bypass diode operating condition. There are 82 screens in this section, each containing a 10 X 5 matrix to account for the 50 diodes in each string. Each bypass diode can operate in one of three conditions; functioning, failed short, and failed open. The pre-processor default assumption corresponds to all diodes functioning but the user may modify any diode operating condition. If a diode fails short, the array accounts for the loss of eight solar cells in the circuit and the diode voltage drop. If a diode fails open, there is no impact unless the same sub module is also shadowed in which case the program assumes there is no output from the string.

Simulator

The Simulator first initializes the screen to display seven windows. Four windows serve for user inputs (main, cell, circuit, wing) and three output windows display I-V curves. The main window asks for a circuit filename (from the preprocessor file list) and uses this information to calculate the cell, circuit, and wing level outputs. The main window offers 8 options; cell model, circuit model, wing model, print cell I-V, print circuit I-V, print wing I-V, enter filename, and terminate process. The first three options will be described in more detail in the following sections.

The displayed output at all levels of the simulator is an I-V curve. The I-V curves are generated using the Hughes solar cell model equations which are derived from the basic solar cell equation (1).¹

$$I = I_L - I_0 \{ \exp[(e(V + IR_s)) / (kT)] - 1 \} - (V / R_{SH}) \quad (1)$$

Simulator Cell Level The key feature of the cell level is the ability to compare I-V curves for all ten cell grades. The user may input up to ten Vop values (one for each cell grade). The user can also choose to have the Vmp point displayed with the designated voltage operating point. The user can then view between 1 and 10 I-V curves simultaneously.

Simulator Circuit Level The circuit level allows the user to view one circuit output at a time. The user enters a circuit ID (1-82) and the cell grade is displayed for reference. The user is then given 5 options; skip, Vop, Vmp offset, grade 7 Vmp offset, and exit to main menu. The skip option displays the I-V curve with no Vop value. The Vop function allows selection of any operating point voltage. The corresponding current and power output will be displayed and the Pop point will be designated on the I-V curve. Options three and four allow the user to choose an operating point voltage based on the circuit Vmp point or a grade seven Vmp point. The Vmp values are displayed for reference. Again, the Pop point is displayed on the I-V curve and the corresponding current and power output values are given.

Simulator Wing Level The wing level offers 4 options; skip, Vop, Vmp offset, and exit to main menu. These functions are similar to the circuit level allowing the user to designate an operating point voltage based on an input value or an offset from Vmp. The Vmp value is based on a grade 7 solar cell assuming no diode failures and no shadowing and is again displayed for reference. Also, like the circuit level, the Pop point is displayed on the I-V curve and the corresponding current and power output values are given.

Parameter Assessment

The following is an assessment of the model parameters presently used in the DC model.

Solar Cell Assembly

Grading of the cells takes place during Acceptance testing at which time the test point current of every

solar cell is measured. The average of all kits delivered in a shipping lot must be a grade seven or higher where each kit contains cells for one panel. This assures that each solar array will be assembled with an average current grade of group seven.

During qualification and acceptance testing electrical measurements are made by the vendor, Spectrolab Inc. Electrical measurements are made with an X-25 Solar Simulator which is calibrated with a secondary solar cell standard. During the 3 March 1992 process qualification, 81 solar cells ranging in grade from 3 to 9 were tested and data for Isc, Voc, Imp, and Vmp was provided to LMSC. This data was then plotted and a linear regression was performed to obtain the average parameter values for each cell grade. The data was then extrapolated to obtain average parameter values for grades 1, 2 and 10. This data base forms the foundation of the DC Model.

Cell Mismatch

The cell mismatch factor accounts for the lowest current producing cell in a series string. Although the circuits will already be current matched by cell grade (1-10), the current distribution within the cell grade must be considered. This is accomplished by using the lowest current value for the selected current grade.

Additionally, fluctuations in the test equipment light source, set-up error and changes in the solar cell response to load are considered in this factor. A 1.5% loss in current output is used to account for both cell current mismatch and measurement errors.

Array Flatness/Orientation

The SSF power system is designed to have the solar arrays actively sun-tracking in the permanently mated configuration. This is accomplished through the alpha and beta gimbals that track the sun through the orbit and adjust for seasonal variations, respectively. Pointing errors will be introduced into the system through control resolution and positioning accuracy of the physical components.

Additionally, pointing error will occur on the array structure outboard

of the alpha and beta gimbals. A design requirement has been set at ± 2 degrees for local solar cell alignment, in both the x and y directions, and ± 3 degrees for overall blanket alignment relative to the main truss element of SSF. Performance loss from pointing errors results from a decrease in current output and can be predicted by the cosine function. Using the design requirements, a worst case combination for array alignment becomes: $[\cos(3 + 2)] * [\cos(2)] = 0.996$.

Thermal Cycling

At a rate of 6,000 orbits per year the array will experience approximately 90,000 160°C thermal cycles over the fifteen year design life. The temperature extremes will cause thermal stresses in the blanket materials and, over repeated cycles, result in structural fatigue of panel components and electrical connections. Of principal concern are the ten welded connections between each of the solar cells and the copper circuitry. With ten welds per cell each array will have 328,000 cell to circuit welds.

NASA-LeRC has completed a thermal cycling program that has evaluated five different flexible panel designs. The objective of the testing was to demonstrate the design lifetime of the welded interconnections and to determine a credible allowance for performance loss over the lifetime. A total of fifteen coupons with four cells each were cycled between $+70^{\circ}\text{C}$ and -100°C in a dry nitrogen environment at a rate of five minutes per full cycle. At predetermined intervals the coupons were removed for electrical performance measurements. The coupons that represent the final design configuration have completed 90,000 thermal cycles and have demonstrated that the predicted performance loss is under 1.0% for the 15 year design life. Although some early signs of fatigue were noted around the welds no physical separation of welds occurred.²

Additionally, LMSC conducted electrical measurements on single solar cells that simulated both N and P severed welds. The results indicated that a single P contact

separation would yield approximately 1.5% loss in voltage. The results of both types of testing have led to the selection of 0.0%, 0.3% and 0.5% loss for 4, 10 and 15 years, respectively.

Space Plasma Losses

The SSF space plasma environment is outlined in documents SSP 30420 "Space Station Electromagnetic, Ionizing Radiation, and Plasma Environment Definition and Design Requirements" and SSP 30425 "Space Station Program Natural Environment Definition for Design." Plasma interactions that are of concern to a high voltage array are ion sputtering, parasitic current collection and arcing. These effects are primarily a function of plasma density, array voltage, electrical system grounding, and array operation.

The SSF electrical power system specifies a negative ground. This means that the negative end of the solar array will be tied to the SSF reference ground. Because this grounding configuration causes portions of the array and the SSF structure to operate at a high negative voltage (>130 volts) relative to the plasma, a device called a plasma contactor has been added to the SSF program. The plasma contactor will emit electrons that will allow the SSF structure to operate at ± 40 volts relative to plasma potential. This also reduces the high potential difference between the array and plasma and mitigates any deleterious effects that may result from ion sputtering and the negatively grounded system.

Another potential source of ion sputtering to array surfaces is through array regulation or switching. The regulation occurs through the Sequential Shunt Unit (SSU) in two forms: the first is by switching complete circuits on or off as they are needed for power management. The second form is through operating each array circuit at a set point on the I-V curve by switching the circuit at 20 kHz. The high voltage transients caused by this form of regulation in a plasma environment can result in the degradation of the UV reflective coatings on the solar cell coverglass. Fortunately, the 20 kHz

switching concern is mitigated through the use of EMI filters on the SSU circuits. The filters reduce the high voltage transients caused by the switching and reduce the radiated EMI and severity of ion sputtering on the array surface. The coarse regulation of the circuits from a shunted to "on" position will however result in some level of ion sputtering. This is estimated to be below 1.0 % of array power over the design life if coarse power management of the array circuits is assumed to be less than 10 Hz.

NASA-LeRC has conducted full scale tests of SSF solar array panels in an simulated LEO plasma environment to address concerns regarding the effect of plasma interactions on high voltage arrays. Two full size panels were placed inside a vacuum chamber equipped with a cold wall, light source and plasma sources. The tests investigated parasitic current collection, arcing thresholds, out-of-eclipse simulation, dynamic response due to switching and effects due to the operation of a plasma contactor. Test results indicate that a parasitic power loss of less than 0.3% of total array power occurs.³ However, the tests also indicate that the incorporation of the plasma contactor will increase the collection current so a design to goal of 0.8% is being used until further definition of the contactor program is completed.

The arcing threshold was also measured as a function of plasma density. The tests determined that no arcing or power degradation due to arcing is expected to occur at the array operating voltage of 160 V.

Atomic Oxygen

The LEO atomic oxygen (AO) environment for SSF is specified at 9.1×10^{13} AO/cm²-sec for solar pointing surfaces and up to 3.6×10^{14} AO/cm²-sec for ram facing surfaces. Although this is one of the most stringent requirements for the design of organic materials and coatings it is considered relatively benign in terms of direct array power losses. With the exception of the solar cell edges, all of the power producing circuitry, including the solar cell interconnects, on the array are protected from the AO environment.

Tests at NASA-LeRC have indicated that AO interactions with array blanket materials and SSF induced contaminants may result in some subsequent level of redeposited contamination on the cell surfaces. These effects are taken into consideration as part of the contamination losses and changes in optical properties which are accounted for in the thermal model. Therefore, no power loss is predicted as a direct result of the atomic oxygen environment.

Contamination

SSF program external contamination requirements are governed by document number SSP 30426 Rev. B, "Space Station External Contamination Control Requirements", and are designed to establish requirements that control the release of neutral gases and particulates into the SSF external environment. Due to significant changes in the local contamination environment during shuttle docking and SSF reboost events, the requirement is defined for two conditions: quiescent and non-quiescent periods. For the quiescent period a molecular column density, particulate background and molecular deposition rate are specified for SSF surfaces. The deposition rate is a key parameter and is limited to 1×10^{14} g/cm²-sec (daily average) at 300 K. Non-quiescent periods include the contamination produced during SSF reboost and Space Shuttle docking events and limits the molecular deposition to 1×10^6 g/cm²-year at 300 K.⁴ From the program requirements, deposition rates of 32 angstroms/yr for quiescent periods and 100 angstroms/yr for non-quiescent periods can be derived for the solar array surface.

The constituent products of the contaminant are also important for determining the impact of a given deposition rate. For the quiescent period, the product is assumed to be siloxane compounds resulting from silicone compound outgassing. For the non-quiescent periods, the products are assumed to be 70% monomethylhydrazine nitrate (MMH-NO₃) and 30% residue of monopropellant thrust exhaust that can be a mixture of hydrazine hydrate, aniline and

propellant impurities.⁵ The net effect of each product is assessed through changes in array surface absorbance and transmittance. Increases in absorbance result in a higher operating temperature and consequently a lower voltage (approximately 0.8 V/°C). Decreases in transmittance, including attenuation, result in less solar isolation at usable wavelengths and consequently lower current or total power output. For modeling purposes, changes in absorbance are included in the thermal model while changes in transmittance or current output are accounted for in the contamination factor.

The Long Duration Exposure Facility (LDEF) data on solar cells indicated that both UV darkening and atomic oxygen "scrubbing" effects occur on the contaminants depending on their orientation relative to the atomic oxygen ram vector. Because the arrays are sun tracking and continuously rotate through the ram vector, the net effect of UV darkening and atomic oxygen "scrubbing" is assumed to be zero. NASA-LeRC has initiated a program to quantify the net effects of specific constituents on solar cell performance taking into account UV darkening and atomic oxygen exposure. Presently, the losses in transmittance are calculated to be 0.008, 0.014 and 0.017 for 4, 10 and 15 years respectively.

Meteoroid and Orbital Debris

The meteoroid and debris environment for SSF is defined in document SSP 30425 "Space Station Program Natural Environment Definition for Design". This document provides an approach to modeling the expected number of impacts and guidelines for determining size, density, velocity, and directional distribution of the particles. In addition to the basic environment, key assumptions used in determining the array power loss are the following: Active cell area is 62.2 cm², penetrations > 1/4 of the thickness of the cell will cause loss of the active silicon, fill factor loss to impacting particle diameter ratio is 12:1, and P_{mp} losses are evenly split between voltage and current.⁶ Electrical elements of the

array assessed for damage include the solar cells, FCC, printed circuit and round cables. The results of the analysis indicate that the power loss (Pmp) for the solar cell active area is 0.999, 0.999, and 0.998 for 4, 10, and 15 years. The analysis also indicates that one FCC trace will be severed in fifteen years resulting in one open circuit (0.988 Pmp). Impacts to the array circuit and cabling were determined to be negligible.

NASA-LeRC has conducted a series of impact tests on solar array coupons using the NASA-JSC Hypervelocity Impact Research Laboratory. Each cell evaluated received impacts from 0.4 mm aluminum projectiles traveling in the 7 km/sec range at normal and oblique angles. Results indicated that the damage was on the order of ten times the particle diameter. NASA-LeRC is continuing to conduct tests in order to quantify the actual damage and resulting performance loss.

Ionizing Radiation

The solar cell ionizing radiation degradation factors were calculated based on the fluence levels for the trapped electron and proton spectrums called out in document SSP30512 "Space Station Ionizing Radiation Emission and Susceptibility Requirements for Ionizing Radiation Environment Compatibility." This data was converted to a one MeV equivalent electron energy as a function of solar cell shielding thickness using the "EQFLUX" program. An equivalent shielding thickness which corresponding to the SSF stack configuration was calculated and the appropriate total per day fluence levels were determined.

During cell qualification testing, sixteen 1/4 size SSF solar cells (groups 6-8) were irradiated to fluence levels of 1.5E13, 1.0E14, and 6.0E14 1MeV equivalent electrons per square centimeter. Electrical measurements were recorded prior to irradiation and following completion of each fluence level. The solar cell ionizing radiation coefficients were determined using "Rafit", a least squares fitting program, and the solar cell qualification test results.

The DC Computer Model uses the

following formula to determine the ionizing radiation degradation factor:

$$\eta = 1 - C * \ln\{1 + [(\phi * y)/\phi_0]\} \quad (2)$$

where η is the degradation factor, C and ϕ_0 are the cell constants for each solar cell parameter, ϕ is the 1MeV fluence/year, and y is the user defined year of mission.

Table 1

Parameter	C	ϕ_0	ϕ
I _{sc}	6.825E-2	7.896E13	7.58E11
V _{oc}	3.515E-2	5.114E12	9.12E11
I _{mp}	7.672E-2	1.086E14	7.58E11
V _{mp}	3.476E-2	3.710E12	9.12E11

Temperature Coefficients

The temperature coefficients used to correct the cell output for increased or decreased array operating temperature are based on solar cell qualification data. Electrical measurements for sixteen 1/4 size, grade 7 solar cells were made at 28°C, 50°C, and 75°C. This data was then plotted and a linear regression was performed to obtain the temperature coefficient for each of the four cell parameters. Although the temperature coefficients are not linear over a large temperature range, it is assumed that a linear approximation is sufficient over the array operating temperature range of 28°C - 75°C.

During qualification testing, electrical measurements were made at 28°C, 50°C, and 75°C after the cells had been irradiated to fluence levels of 1.5E13, 1.0E14, 6.0E14 1MeV electrons per square centimeter. A change in the temperature coefficients at the highest fluence level was noted but, since the SSF EOL ionizing radiation fluence level is below 1.5E13 1MeV equivalent electrons/cm² and the change in the coefficients at this level was well within the error of the test equipment, coefficients derived from unirradiated cell data are used through EOL.

Flexible Printed Circuit

The flexible printed circuit resistance was calculated from the FPC configuration and the resistivity of copper at 20°C. The circuit is

comprised of 6 sections, solar cell interconnect with a turnaround, solar cell interconnect without a turnaround, intermodule jumper, left module to FCC jumper, right module to FCC jumper, and FCC turnaround, for a total circuit resistance of 2.3338Ω. This resistance is then corrected to reflect the resistance at the circuit operating temperature. The loss associated with the FPC voltage drop is determined based on the corrected resistance and the circuit maximum power point current and voltage values after all other losses due to temperature and the environment are taken into account.

Harness

The blanket configuration of 82 panels, 41 circuits, uses two harness assemblies, one on each side of the blanket. The assemblies consist of a Flat Collector Circuit (FCC) which runs from the panel edge to the base of the blanket, the transition element (flat cable to round cable assembly connector), and the round cable assembly which runs through the electrical connector bracket to the SSU interface. The panels are grouped into 20 sets of four with one additional, unmatched circuit. This configuration allows for a single negative conductor to be used for each set of two circuits for a total of 62 FCC panel conductors. The inboard harness uses an FCC which contains 30 panel conductors and the ground conductor while the outboard harness contains a 32 conductor FCC. As a result, the individual path length and resistance associated with each circuit is dependent on its position within the blanket, which corresponds to a given trace length and width, and an inboard or outboard round wire length. The resistance of each path length was calculated based on circuit configuration and the resistivity of copper at 20°C. The resistance is then corrected to reflect the FCC/round cable assembly operating temperatures.

Ultraviolet Radiation

The solar cell assembly consists of the solar cell and coverslide where the coverslide is bonded to the cell with DC93-500 adhesive which darkens under UV exposure. Also, the coverslide

absorbs UV which results in an increased cell operating temperature. To offset these effects, a UV reflective coating is applied to the outer surface of the coverslide. Testing of the UV reflective coating effectiveness was conducted at LMSC's Palo Alto Research laboratory. Six solar cell assemblies were selected from the first shipment of Engineering Evaluation Assemblies. Pre-exposure electrical and optical property measurements were made. Electrical and optical properties measurements were also made at 10, 25, 50, and 100% of full UV exposure (300 sun days). The results indicate no darkening due to UV and the electrical measurements support the optical property data. A 0.5% loss to account for test measurement tolerances is assumed.

Darkening of the Kapton on the back surface of the blanket due to UV will not directly cause a loss in power output but will cause the array operating temperature to increase. This effect is accounted for in the array operating temperature analysis.

Intensity Variation

The intensity variation factor accounts for the increase or decrease in solar insolation incident on the array due to changes in the earth-sun distance during the year with respect to the solar insolation at 1AU. The solar intensity is specified as 1326W/m² at aphelion, 1418W/m² at perihelion, and 1371W/m² at 1AU. Assuming a sinusoidal function, and knowing the period and amplitude, a function for the solar intensity was derived as equation (3). Once the solar intensity is determined, the intensity variation factor is then calculated using equation (4).

$$Q = 46.1 \cos(2\pi d/365) + 1372.8 \quad (3)$$

$$\eta = Q / 1371 \quad (4)$$

where:

Q = Solar Intensity in W/m²
d = day of the year - user inputs for the launch date and the day of mission are used to determine d.
η = intensity variation factor

An intensity variation factor of 0.9672 at aphelion and 1.0343 at

perihelion results.

Array Operating Temperature

The array operating temperature is a value entered by the user. The DC model does not include thermal modeling of the array but a three layer, 101 node thermal math model was constructed to analyze the SSF array on-orbit operating temperature through 15 years. BOL absorptivity and emissivity values were obtained from blanket assembly (cell assembly, FPC, and laminate) optical properties measurements performed at the LMSC Palo Alto Facilities. The BOL optical properties were then corrected through EOL based on contamination analysis results. Solar cell power equations are used in conjunction with thermal and electrical coupling equations and are iterated to solve for the cell operating temperature where the cell power equations account for changes in cell efficiency through EOL. The thermal math model includes the effects of FPC heat loads but does not account for thermal interaction between the solar cell and other SSF components. Also, nominal values for albedo at 30 % and earth thermal at 237 watts/m² are assumed. Table 2 lists the aphelion and perihelion array operating temperatures ($\pm 5^{\circ}\text{C}$) at BOL, 4, 10, and 15 years.

Table 2

Season	BOL	4yrs	10yrs	15yrs
Aphelion	49°C	50°C	51°C	51°C
Perihelion	54°C	55°C	56°C	56°C

Bypass Diode

The diodes are 100% acceptance tested; therefore, it is assumed that all diodes are functioning at BOL. During normal operating conditions, fully sunlit and non-shadowed, a diode which fails open does not result in a loss in power but a diode which fails short causes loss of power from eight solar cells. A bypass diode reliability analysis was conducted assuming a bypass diode failure rate of 1×10^{-7} hours and that 65% of the random diode failures will be in the short circuit mode. Also, an additional 3% of diode failures are included to account for environmentally induced failures. The analysis concluded that 36 diodes per wing will fail short during the

15 year life of the space station. For the purpose of predicting power output it was assumed that only one diode per circuit will fail short.

Parameter Summary

Table 3

Parameter	Value
Cell Assembly @ 28°C, AM0	
I _{sc}	2.635 A
V _{oc}	0.615 V
I _{mp}	2.445 A
V _{mp}	0.499 V
P _{mp}	1.222 W
Radiation Degradation	
4 years:	
I _{mp}	0.998
V _{mp}	0.976
10 years:	
I _{mp}	0.995
V _{mp}	0.957
15 years:	
I _{mp}	0.992
V _{mp}	0.946
System Loss Factors	
I _{mp} cell mismatch	0.985
V _{mp} intercell resistance R/circuit(ohms) @ 20°C	2.334
Harness voltage drop	unique
Diode leakage current	0.999
Diode failure probability	
4 years	10
10 years	24
15 years	36
Environmental Loss Factors	
Thermal cycling (V _{mp})	
4 years	1.000
10 years	0.997
15 years	0.995
Meteoroid/Debris (P _{mp})	
4 years	0.999
10 years	0.999
15 years	0.986
Plasma (I _{mp})	
BOL	0.995
4 years	0.992
10 years	0.992
15 years	0.992
UV radiation (I _{mp})	0.995
Intensity Variation	0.967/1.034
Contamination (I _{mp})	
4 years	0.995
10 years	0.987
15 years	0.981

Manufacturing Verification

Model verification to the manufacturing measured parameters is critical in assuring the overall array and SSF electrical power system output. Presently, the only model parameter that has completed qualification testing is the solar cell. During the array qualification program larger pieces of the array will be electrically tested and correlated to the model. Electrical performance tests will be conducted at the manufacturing module level (40 cells), panel level (200 cells) and the circuit level (400 cells). The higher level tests will also capture other assembly loss factors such as the flexible printed circuit, FCC and base cable. At this time a full I-V curve will be generated for the panel and circuit. The blanket and wing I-V curves will then be obtained from the model and are based on measured data from the 82 circuits which are recorded during manufacturing verification.

Conclusions

Using the solar array performance model and assigned parameters in Table 3, the predicted electrical output of the SSF solar arrays is shown in Figures 2 and 3. The results indicate that the present SSF solar array design meets the electrical performance specifications for power and voltage over the design life of fifteen years. Further verification of the model and model parameters will occur during the solar array qualification program.

Figure 2

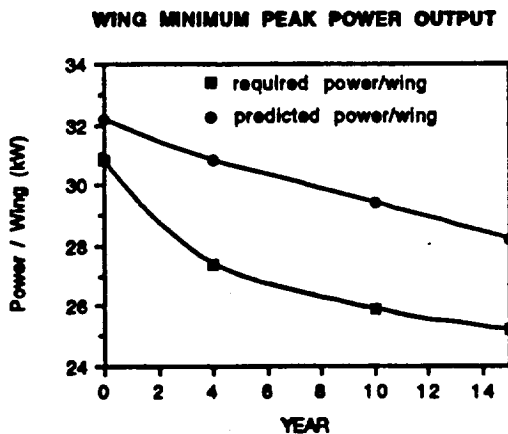
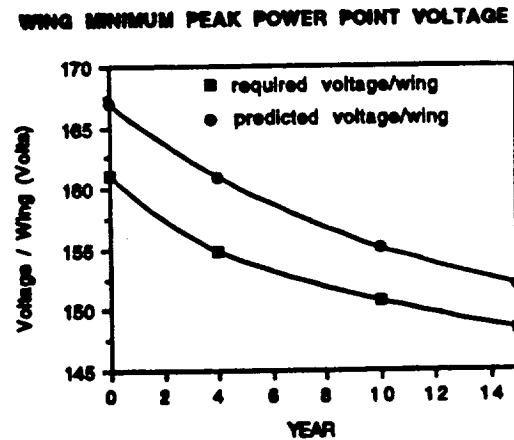


Figure 3



References

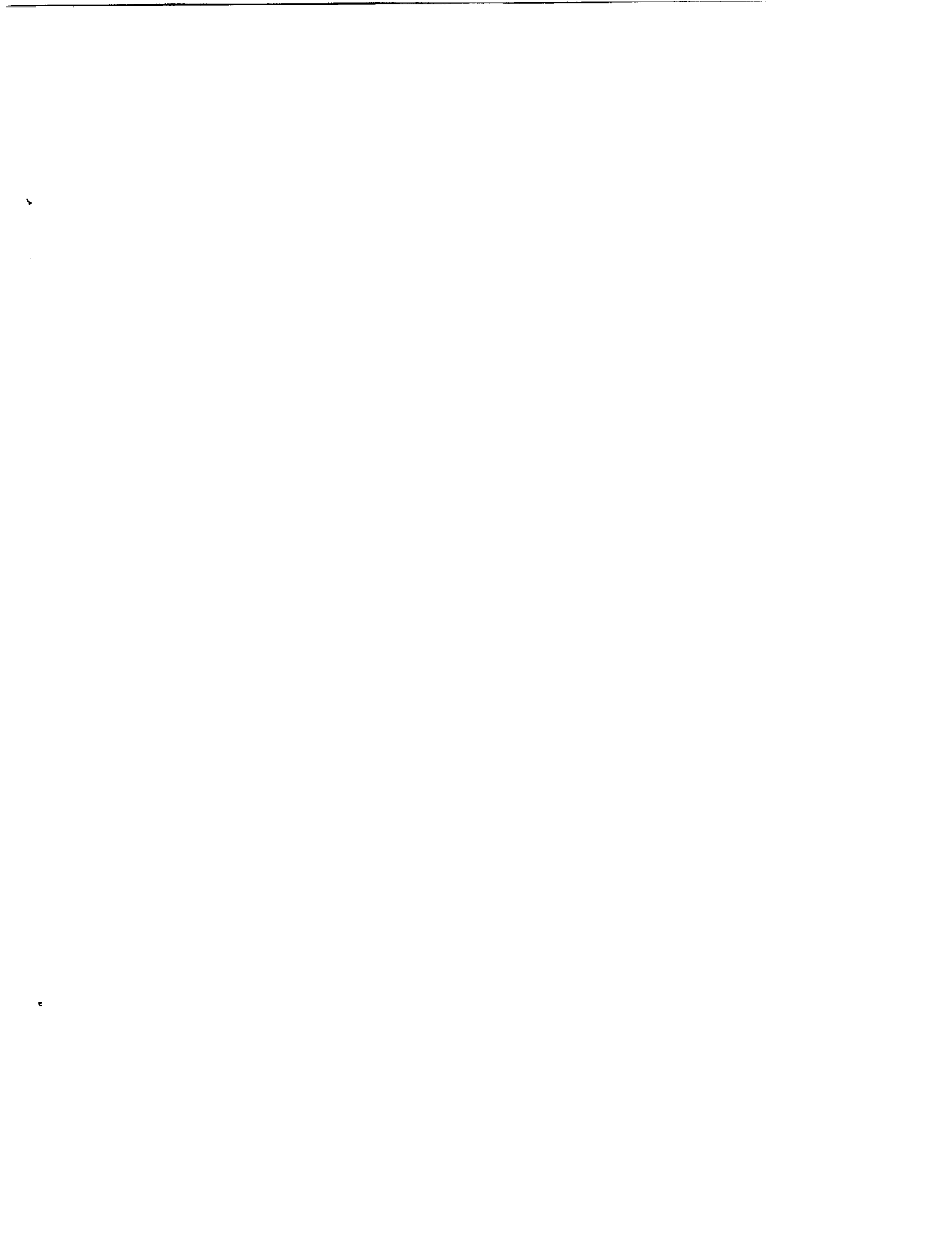
- 1) Jet Propulsion Laboratory: Solar Array Design Handbook, Vol 1. NASA October 1976 pp. 9.2-3,4.
- 2) Scheiman, D. A., Smith, B. K., "Rapid Thermal Cycling of Solar Array Blanket Coupons for Space Station Freedom", Solar Engineering, Vol. 2, ASME 1992, pp. 817-823.
- 3) Nahra, H. K., Felder, M. C., Sater, B. L., Staskus, J. V., "The Space Station Photovoltaic Panels Plasma Interaction Test Program: Test Plan and Results," NASA Technical Memorandum 102474, AIAA-90-0722, January 1990.
- 4) "Space Station External Contamination Control Requirements", NASA Space Station Freedom Program Office, SSP 30426 Rev. B, July 1991.
- 5) "WP-04 Technical Requirements Document", NASA-LeRC, LeRC-SS-0001, Rev. I, November 1992.
- 6) Dunson, Clark, "SSF Solar Array Critical Design Review Package", Lockheed Missiles and Space Company, Section 10.7, December 1992.
- 7) Nahra, H. K., Lu, Cheng-Yi, "Environmental Interactions of the Space Station Freedom Electrical Power System," NASA Technical Memorandum 104373, September 1991.

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