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Managing Space Station Solar-Array Electrical Hazards for Sequential Shunt Unit Replacement

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The U.S. solar-array strings on the International Space Station are connected to a sequential shunt unit. The sequential shunt unit's job is to shunt excess current from the solar array, such that just enough current is provided downstream to maintain the bus voltage while meeting the power load demand. Should a unit fail, its removal and replacement would normally be done with the solar arrays retracted to reduce the voltages and currents at the sequential shunt unit to safe levels. However, an alternate approach was desired to avoid the inherent risks associated with array retraction and redeployment. This approach allowed the replacement to be conducted via astronaut "space walk" or extra vehicular activity with the solar array still deployed. Removing a sequential shunt unit with the solar array in sunlight could result in substantial hardware damage and/or safety risk to the astronaut due to the voltages that may be present. Replacing the sequential shunt unit during eclipse would seem optimal, except that the maximum eclipse period is only 36 min, which is insufficient time. To guide the assessment and ameliorate hazards, the athours analyzed array string current and voltage capability during the various operating conditions using System Power Analysis for Capability Evaluation (SPACE), an electrical power system modeling code. This paper discusses six sequential shunt unit remove and replacement options and the associated analysis to develop a workable sequential shunt unit replacement procedure via extravehicular activity.

Nomenclature

*AM*0	=	air mass 0, in-space solar spectral irradiance that conforms to the solar constant of 1366.1 W/m^2
Isc	=	short-circuit current
Isc-albedo_back	=	backside albedo short-circuit current
Isc-albedo_front	=	front-side albedo short-circuit current
Isc-backside	=	backside short-circuit current
Isc-frontside	=	front-side short-circuit current
Iscref	=	normalizing parameter for *Isc*
Isc-total	=	short-circuit current total
Voc	=	open-circuit voltage
Vocref	=	normalizing parameter for *Voc*
Xpop	=	flight attitude placing the $+X$ axis perpendicular to the orbit plane
Xvv	=	flight attitude placing the $+X$ axis in the velocity vector
Yvv	=	flight attitude placing the $+Y$ axis in the velocity vector
β	=	angle between the sun vector and orbit plane

Introduction

THE U.S. P6 photovoltaic module currently on the International Space Station (ISS), activated in December 2000, consists of two solar-array wings (SAW) (see Fig. 1), each with two blankets composed of a total of 82 parallel strings. The strings are connected to a sequential shunt unit (SSU), which is responsible for maintaining the primary bus voltage at approximately 160 V. The SSU maintains this bus voltage set point by sequentially shunting individual solar-array strings such that the correct current level is produced to meet the channel load demand (to the dc-to-dc converter units and later to the service module American to Russian converter units) and to recharge the batteries (via a battery charge-discharge unit). This architecture is shown schematically in Fig. 2.

SSU Remove and Replacement Considerations

If the SSU fails, then its on-orbit removal and replacement would be conducted via astronaut extravehicular activity (EVA). With the spare SSU in hand, the astronauts would translate to the work site, in this case, to the base of the solar-array mast canister as called out in Fig. 1 and shown in greater detail in Fig. 3. The SSU must be mechanically demated from the ISS structure and electrically demated from solar-array power cable connectors. The desired SSU remove-and-replace procedure would be conducted during a single ~30-min eclipse pass when array strings are not energized by sunlight. Doing so would avoid potential electrical shock hazards to EVA crew members, that is, maintain exposed surfaces (i.e., connectors) below 32 V and with a current generation capacity below 0.001 A. This approach also eliminates the potential electrical arcing damage to hardware (which can occur if more than 3 A or 180 W per pin are generated).

Removal of the SSU during daylight is precluded as there are no upstream switches to shut off solar-array power. Thus the full capability of each solar-array string, greater than 200 V (when open circuited) and about 2.6 A (when short circuited), could be seen at the connector. With demated power connectors, solar-array string potential distribution will float independent of the ISS structure ground. To avoid triggering arcing from solar-cell edges to the space plasma, negatively biased solar cells must be maintained above a voltage threshold with respect to the plasma. Based on plasma vacuum tank testing, various values of this trigger voltage threshold have been reported for ISS solar-array circuits such as −360 V (see Ref. 1), −210 V (see Ref. 2), and −200 V (see Ref. 3).

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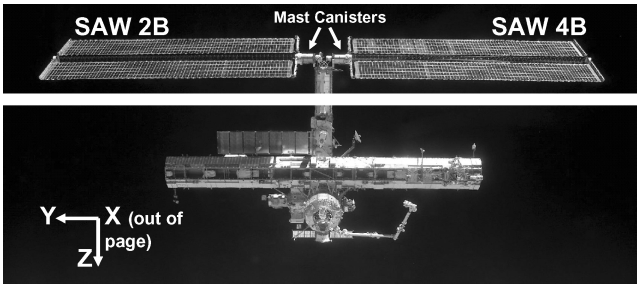

Fig. 1 International Space Station.

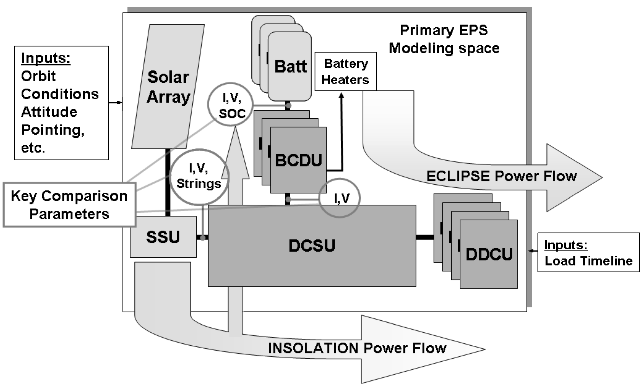

Fig. 2 ISS electrical power system schematic.

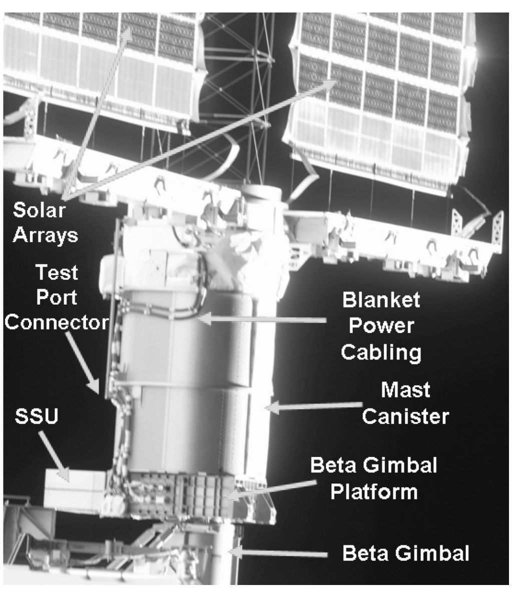

Fig. 3 SSU mounted on mast canister.

However, a single eclipse pass will not provide sufficient time for astronauts to complete the entire SSU remove-and-replace procedure, while still allowing time to resolve contingencies that might arise. Therefore, revised SSU remove-and-replacement procedures must be developed and assessed. The current baseline of first retracting the solar array and then removing the SSU has been developed. Although solar array retraction on the ISS has been certified as reliable via extensive ground testing, there are always concerns for proper deployment mechanism operation after years of exposure to the space environment. Thus, there was a request to find alternate approaches to SSU changeout. For example, it is possible to have the solar array mast damaged by meteoroids or orbital debris or approaching vehicles' accidental thruster plumes that could catch the array blankets and transmit high loads to the array mast. Should mast damage occur, then it is possible that the solar array cannot be retracted, or even worse, that it could get stuck in a partially deployed state, where it may not have sufficient strength capability to handle space shuttle docking loads. If this is the case, then the stuck array must be jettisoned. The baseline jettison procedure requires an ISS crew of at least three people: two EVA crew members and one crew member inside the ISS to operate the ISS Remote Manipulator System robotic arm. Until, at least the space shuttle program return-to-flight milestone is achieved, the ISS has only a two-person crew. Under this circumstance, the solar array jettison procedure is not feasible, which makes array retraction a higher risk approach than is presently desired by the program. Thus, it was decided that a secondary approach is advisable.

SSU Remove-and-Replacement Procedure Options

Several options for the SSU remove-and-replace procedure are being assessed along with a "leave-in-place" option. For the change-out options, it is assumed that the solar-array wing rotational beta gimbal will be "parked" at a prescribed, fixed angle. This is done for crew safety when located at the EVA work site at the base of the solar-array wing. These options, from the perspective of assessing and managing solar-array string electrical hazards, are briefly discussed here:

1) Leave the failed SSU in place with an attendant loss in power production for this electrical-power-system (EPS) channel.

2) Change out the SSU during one eclipse period. If the procedure were not completed, option 3 would have to be implemented.

3) Change out the SSU during several eclipse periods. The EVA crew allows the solar-array strings to be open circuited through the orbit sun period(s), provided the crew stands off a safe distance from the solar-array string power connectors and the solar cells. After entering the subsequent eclipse period, the EVA crew moves back to the work site to continue the SSU change-out procedure. If during an orbit sun period, the open-circuited solar-array string voltage drops below 200 V from plasma neutral, array solar-cell edges will arc to the plasma. For a solar-array string isolated from the ISS, the trigger arc voltage threshold will be exceeded for open-circuit voltages at or above approximately 228 V.

4) Retract the solar-array wing, to place solar-array string panels in a stowed configuration before changing out the SSU over multiple orbit sun and eclipse periods. When retracted, as shown in Fig. 4, the solar-array blanket panels are fan folded on top of each other and then mostly sealed in a containment box. In this configuration, minimal light reaches the solar-cell strings leading to nearly zero current and voltage production capacity, which is considered to be the safest option electrically. This is the current baseline.

5) Design, build, and install a temporary shunting plug on solar-array string power connectors and change out the SSU during several orbit sun and eclipse periods. The array string power connectors to the SSU input are shown in Fig. 5. The shunt plug will collapse the array string voltage through a low-resistance electrical shunt that is passively cooled.

6) Design, build, and install a temporary shunting plug on solar-array string test port connectors and change out the SSU during several orbit sun and eclipse periods. The array string test port connectors, shown in Fig. 6, are located on the solar-array mast canister

Fig. 4 Solar-array wing partially deployed on orbit.

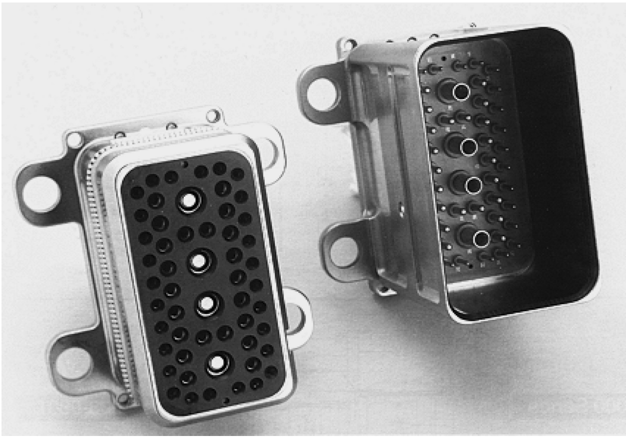

Fig. 5 Solar-array string power connectors (sockets on beta gimbal platform side: pins on the SSU side).

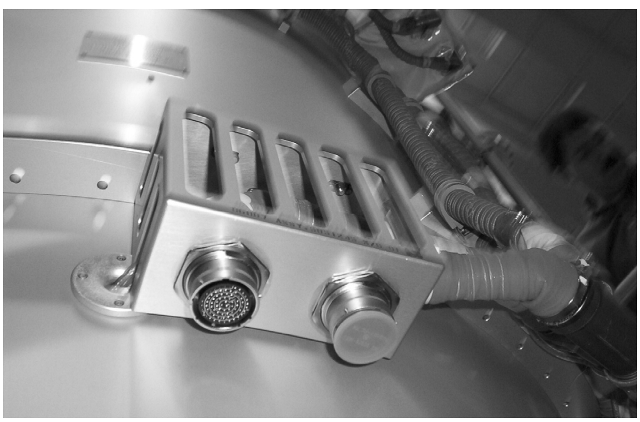

Fig. 6 Mast canister solar-array string test port connectors.

and connected to the array strings via spliced, 22-gauge conductor cable bundles. The shunt plug will collapse the array string voltage through a low-resistance electrical shunt. The derated bundle current per conductor is 2.5 A for 200°C rated wire. Because solar-array strings have common returns, the per-string current level must be kept below 2.5 A/2 = 1.25 A to meet the derated current requirement.

To guide the assessment of these proposed options and ameliorate the EVA hazards, the authors used the bifacial solar-array model incorporated in the System Power Analysis for Capability Evaluation (SPACE) electrical power system modeling code[4,5] to analyze array string current and voltage capability during the various operating conditions. Using these computational results, we assess the efficacy of the various SSU remove and replacement EVA options in the context of hardware design, ISS operations, and risk to crew and hardware.

Photovoltaic-Array Performance Modeling

The SPACE code is a highly integrated electric power system analysis tool that is validated with flight data.[5] It models ISS configuration, flight mode, solar-array gimbaling, solar-array shadowing orbit mechanics, and orbital environments to provide the necessary inputs to calculate solar-array thermal and electrical performance. Within SPACE, the solar-array modeling starts with a single exponential current-voltage solar-cell electrical model and a three-node, lumped-capacitance transient solar-cell thermal model. Solar-cell thermo-optical and electrical performance parameter degradation from orbital environments, such as electron and proton irradiation, is included in the solar-cell model. Currently, this model has been tasked to reduce orbital performance data and determine the trend in operational solar-array performance loss.[6] Because the solar cells are mounted on a thin, transparent panel, generalized bifacial performance modeling is included to predict cell current-voltage output under arbitrary solar and Earth albedo illumination conditions on the panel front and back sides.[7] Individual solar-cell performance is then scaled to that of a 400 solar-cell, series-connected string factoring in conductor and diode voltage losses. Recently, specialized plots have been added to the code output to display two key performance parameters relevant to these SSU change-out option assessments, that is, solar-array string normalized *Isc* and normalized *Voc*. String *Isc* is a key parameter for the option (5) and (6) shunt plug designs from the standpoint of electrical and thermal dissipation performance. String *Voc* is a key parameter for option (3) where string floating potential distributions must be determined along with the resulting plasma arcing characteristics.

Table 1 Solar-array performance analysis parameter space

Parameter	Values
Solar-array time on orbit	Beginning of life (BOL) (0 years) End of life (EOL) (15 years) Present age of P6 arrays (4.5 years)
Orbit solar beta angle (angle between orbit plane and sun vector)	0 deg 60 deg
Earth albedo (51.6-deg inclination orbit; >3-h time period)	Low (0.20) Average (0.30) High (0.40)
ISS flight mode (see Fig. 1 for ISS coordinates) {$vv =$ ISS velocity vector, $pop =$ perpendicular to orbit plane}	Xvv (Earth inertial) Yvv (Earth inertial) *Xpop* (solar inertial)
Solar-array articulation	Sun tracking Sun tracking edge-on to sun Parked (backside to sun at orbit noon) Parked (edge-on to sun at orbit noon) Parked (front side to sun at orbit noon)
Solar-array string cell grade (current capacity at 0.495 V)	Grade 7 (2.46 A; wing average) Grade 10 (2.57 A; maximum)
Bifacial model	Full bifacial Array front side only

Parametric Solar-Array String Current/Voltage Analysis

In this study, we have analyzed solar-array performance with the parameters listed in Table 1.

This trade space was selected in order to generate a wide range of array string electrical performance results and to also address specific approaches designed to minimize array string current and/or voltage capacity, that is, operating the ISS in the *Xpop* solar inertial flight mode.

Parametric Solar-Array Performance Results

Baseline Performance

Figure 7 shows the baseline SAW string normalized *Isc* and *Voc* variations vs time through an orbit. For reference, the first 36 min of the orbit, shaded gray on the plot, is the orbit eclipse period. Baseline analysis conditions include sun tracking articulation, Xvv ISS flight mode, 0-deg orbit solar β angle, average Earth albedo, BOL-grade 7 solar-cell properties, and bifacial performance modeling. For this plot, and those that follow, *Iscref* and *Vocref* are based on the average grade 7 solar cell operating under standard conditions of 1-sun *AM*0 front-side-only illumination and 28°C temperature. The reference values for normalizing *Isc* and *Voc* are *Iscref* and *Vocref*, which are 2.651 A and 246.8 V, respectively. This implies a normalized *Voc* limit of 228 V/246.8 V = 0.92 above which trigger arcing will occur on the solar array for SSU remove and replace option (3). (228 V is the trigger arc threshold mentioned in the first section in the SSU Remove-and-Replacement Procedure Options subsection.) For SSU remove-and-replace option (6), the normalized *Isc* limit to meet the current derating requirement is 1.25 A/2.651 A = 0.47. (1.25 A

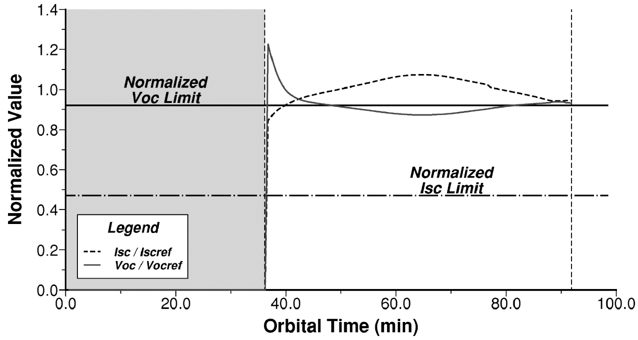

Fig. 7 Baseline normalized SAW string *Isc* and *Voc* through an orbit, solar $\beta = 0$ deg, *Xvv* attitude, average solar flux.

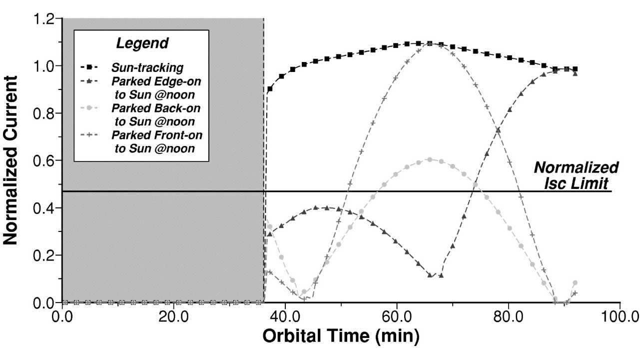

Fig. 8a Normalized *Isc* versus solar array articulation mode, solar $\beta = 0$ deg, in *Xvv* attitude.

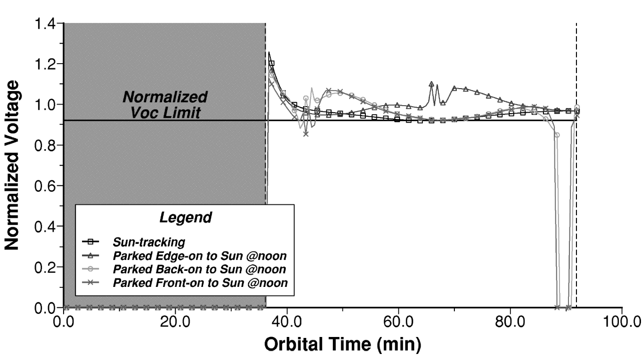

Fig. 8b Normalized string *Voc* vs solar-array articulation mode solar $\beta = 0$ deg, in *Xvv* attitude.

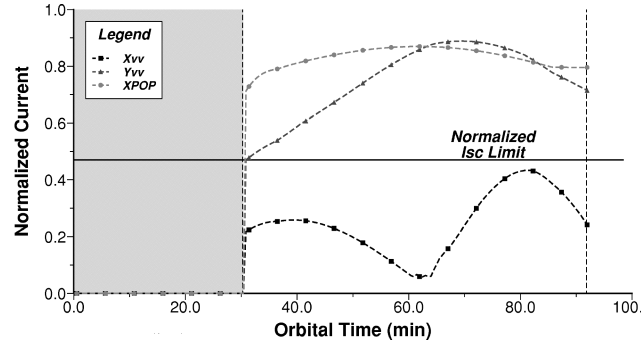

Fig. 8c Normalized *Isc* vs ISS flight attitude with parked arrays to accommodate EVA, solar $\beta = 50$ deg.

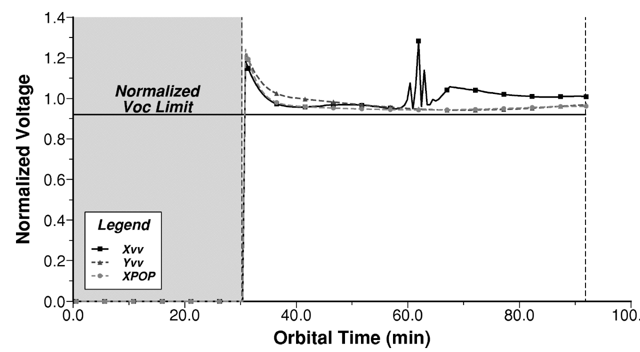

Fig. 8d Normalized string *Voc* vs ISS flight attitude with parked arrays to accommodate EVA, solar $\beta = 50$ deg.

is the derated current-carrying capability for 22 gauge wire, also mentioned in the first section, in the SSU Remove-and-Replacement Procedure Options subsection.)

Parametric Effects

Solar-Array Articulation and ISS Flight Mode

For the SSU removal-and-replacement EVA, the solar-array wing must be parked at a set angle for EVA crew safety. Figure 8a shows the solar-array string normalized *Isc* for a 0-deg solar β angle, Xvv flight mode case for three different solar-array park angles, and a sun-tracking solar array for comparison. The three park angles were chosen, such that at orbit noon the array wing blanket would be either edge-on to the sun, front side normal to the sun, or backside normal to the sun. Results show that the orbital *Isc* is lowest for the backside to sun case, but still exceeds the 0.47 threshold for approximately 15 min centered about orbit noon. A companion plot for normalized string *Voc* is shown in Fig. 8b. Through essentially the entire orbit, the normalized *Voc* threshold of 0.92 is exceeded. This result shows that there is no array sun pointing strategy (even edge on to the sun) that can reduce an open-circuited string voltage to low enough levels to avoid trigger arcing to the plasma.

The *Isc* and *Voc* are also a function of the space station flight attitude. The nominal ISS flight attitude is Xvv, which is the $+X$ ISS axis in the velocity vector. Other flight attitudes can be with the $+Y$ axis in the velocity vector or *Xpop*, which places the $+X$ axis perpendicular to the orbit plane. In the Xvv flight attitude, with the solar arrays parked at an angle to accommodate crew EVA access to the SSU at a solar β angle of 50 deg, the normalized *Isc* remains below the 0.47 threshold (Fig. 8c). The Yvv and *Xpop* flight attitudes produce much higher *Isc* values. The Yvv and *Xpop* attitude *Voc* are comparable; however, the *Voc* for Xvv spikes when the array transitions through the edge-on to the sun orientation (Fig. 8d). This is because of SPACE applying an array pointing error to the gimbal angle in the direction that will yield a conservative result. The normalized *Voc* values for all three orientations are above the 0.92 threshold for most of the orbit.

Orbit Beta Angle and Earth Albedo

Figure 9a shows normalized *Isc* vs orbit time with 0- and 60-deg orbit solar β angles and an Xvv ISS flight attitude. Because the solar-array beta gimbal only tracks the sun on one axis, the solar array is off pointed 60 deg from the sun for this 60-deg orbit solar β angle case, assuming a near-zero vehicle roll angle. At 60-deg off pointing, currents are reduced about in half and essentially remain below the 0.47 normalized *Isc* threshold value for the complete orbit for both the sun-tracking and parked array cases. However, normalized string *Voc* values, shown in Fig. 9b, exceed the 0.92 threshold for all cases throughout the orbit sun period.

The impact of Earth albedo value on normalized string *Isc* is shown in Fig. 10a for 3-h-averaged, albedo values of 0.20 (the minimum value for the ISS 51.6-deg inclination Earth orbit) and 0.40 (the corresponding maximum value). The chosen albedo value has only a small impact, about 20% or less, on predicted normalized *Isc* values near the 0.47 threshold value. Similarly, normalized string *Voc* values, shown in Fig. 10b, change by only 5% or less. However, for the maximum albedo case, the array string operating temperature increases. This increase is enough to lower the normalized *Voc* values below the trigger arcing threshold value, 0.92, for approximately 15 min centered about orbit noon.

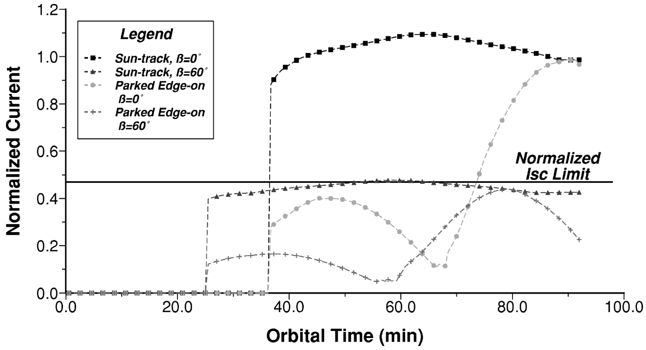

Fig. 9a Normalized *Isc* vs orbit solar β angle in *Xvv* attitude.

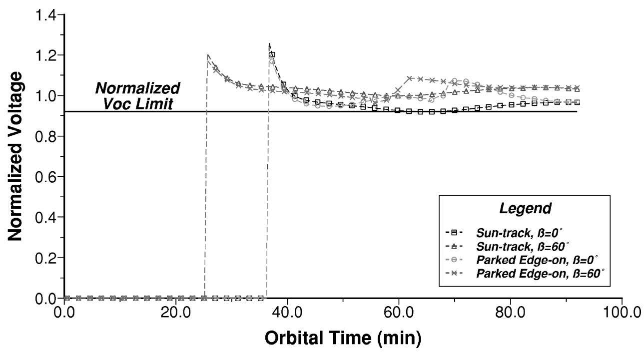

Fig. 9b Normalized string *Voc* vs orbit solar β angle in *Xvv* attitude.

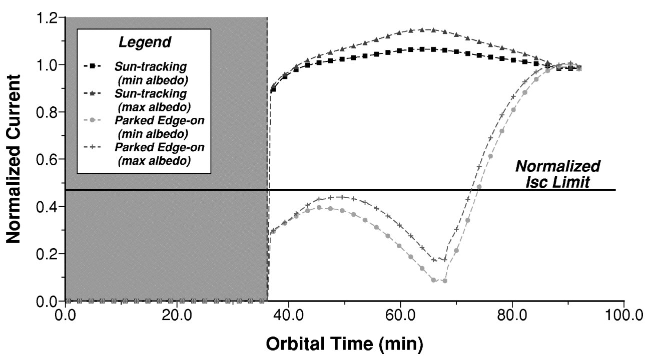

Fig. 10a Normalized *Isc* vs Earth albedo (min = 0.2, max = 0.4).

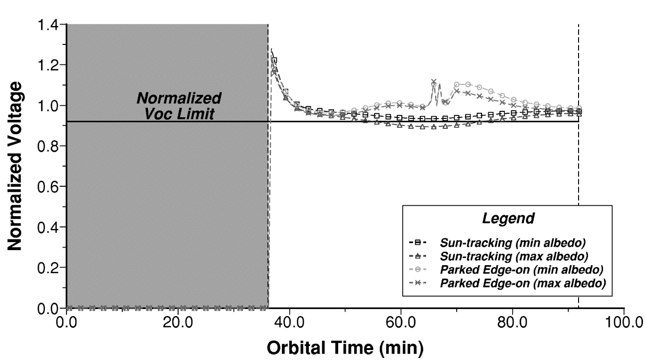

Fig. 10b Normalized string *Voc* vs Earth albedo (min = 0.2, max = 0.4).

Bifacial Modeling

Solar-array string bifacial modeling accounts for current and voltage performance from front-side (solar cell side) and backside (blanket panel side) illumination from the sun and Earth albedo. Traditionally, solar-array string performance is based solely on front-side solar illumination alone. Figure 11a shows the normalized string *Isc* predictions based on bifacial modeling and front-side solar-only modeling for the cases of sun-tracking arrays and arrays parked edge-on to sun at orbit noon (for 0-deg solar β angle). The bifacial model predicts current levels about 10% higher than the front-side model for sun-tracking arrays. For a parked array, the bifacial model predicts significant backilluminated current production (not predicted by the front-only model), whereas when front illuminated, the bifacial current predicted is about 20% higher than that of the front-only model near the threshold current value 0.47. In both cases, the threshold normalized *Isc* value is exceeded for some part of the orbit.

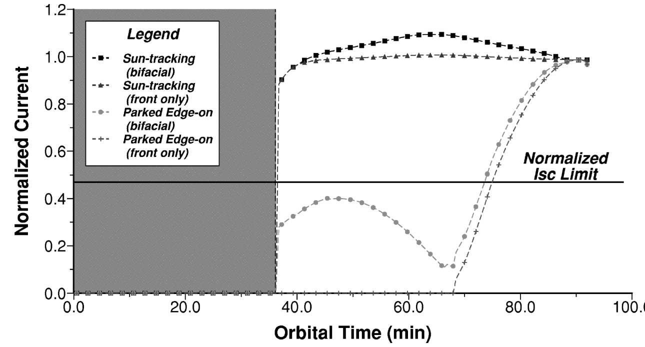

Fig. 11a Normalized *Isc* vs bifacial modeling, solar $\beta = 0$ deg, *Xvv* attitude.

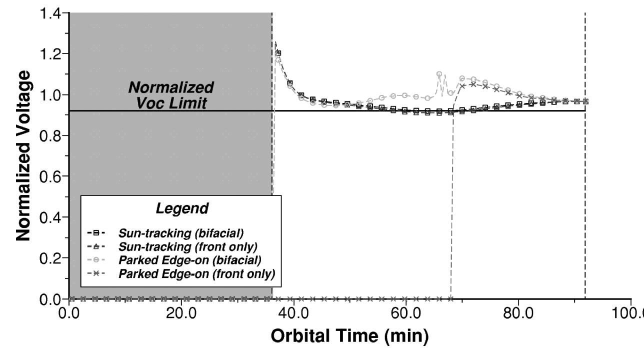

Fig. 11b Normalized string *Voc* vs bifacial modeling, solar $\beta = 0$ deg, *Xvv* attitude.

Similar behavior is observed with the string normalized *Voc* shown in Fig. 11b. For the sun-tracking case, small differences in predictions exist for the bifacial and front-only modeling cases. For parked arrays, the front-only model predicts 0 voltage during backillumination (time = 36 to 68 min). Yet, the bifacial model predicts slightly enhanced *Voc* (compared to the sun-tracking case) as a result of the cooler operating temperatures of solar-array strings oriented edge-on to the sun. In both modeling cases, the 0.92 normalized string *Voc* threshold is exceeded for some portion of the orbit sun period.

Solar-Array Age and String Cell Grade

The impacts of solar-array orbital age, from 0 to 15 years, and solar-array string cell grade, from 7 to 10, on the calculated values for normalized current and voltage are small, less than 2%. Thus, these parameters will not have an appreciable impact on the assessment of SSU remove-and-replace options.

Case Strategy for Minimizing Solar-Array String Performance

Using the preceding parametric results, one strategy was analyzed to minimize solar-array string performance. Analysis results are discussed next.

An analysis was performed to evaluate using a three-orbit scenario to accomplish the SSU remove and replace. During the first eclipse pass, the SSU shunt plugs would be installed, the SSU swap would take place during the second eclipse pass, and finally the SSU shunt plugs would be removed during the third and last eclipse pass. The solar array with the SSU being replaced would be parked at an angle specified by the mission operators. For ease of analysis, both arrays were parked at the angles supplied by the mission operators. Figure 12 shows the solar arrays parked per this scenario.

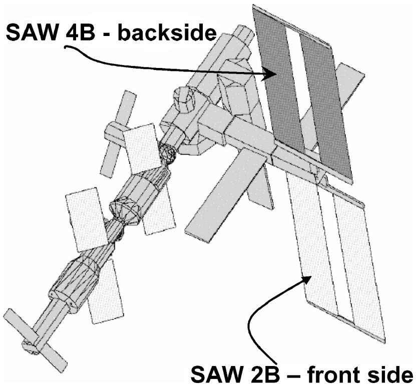

Fig. 12 Solar arrays parked for three-orbit remove and replace. Point of view from the sun, at a solar $\beta = 50$ deg, between orbit noon and orbit dusk.

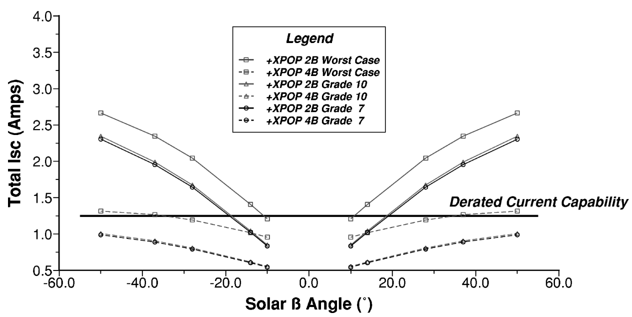

Fig. 13a Variation in *Isc-total* in the *Xpop* attitude as a function of solar β angle and cell grade. *Xpop* is not flown at low solar β angles, thus the analysis cutout between -10 deg $< \beta <$ 10 deg.

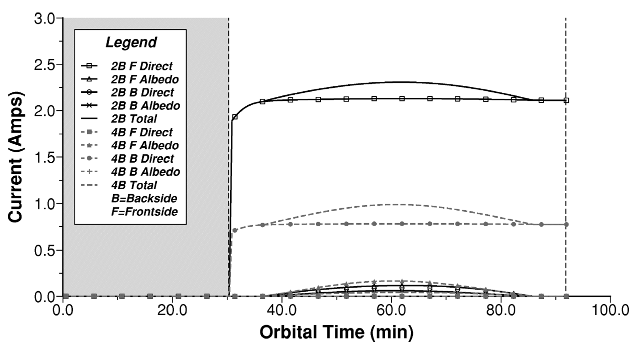

Fig. 13b *Isc-total* contributions for *Xpop* attitude for solar $\beta = 50$ deg, SAW 2B.

Only the solar-array wing, attached to the SSU to be replaced, will be parked for the actual on-orbit remove-and-replace activity. The other array(s) can continue to track. Because solar β angles above $|\beta| > 50$ deg result in eclipse times of less than 30 min per orbit, these orbits were not assessed for the SSU remove and replace because of insufficient time to react to any contingencies, such as SSU binding. The analyses were conducted using an energy balance over four orbits. For the first three orbits, the arrays were parked. The arrays were placed in to solar tracking mode for the fourth orbit. The *Isc* is taken from the first orbit. Figures 13a–13d reflect string *Isc*, which is used to approximate the current generated by a shunted string. The actual shunt current will be very close, but slightly less than *Isc* calculated by SPACE, but will be within $\sim$1%. The total *Isc* is calculated as

$$\begin{aligned} \textit{Isc-total} &= \textit{Isc-frontside} + \textit{Isc-backside} \\ &\quad + \textit{Isc-albedo\_front} + \textit{Isc-albedo\_back} \end{aligned} \tag{1}$$

An artificial "worst case" that consists of grade 10 cells only comprising the array blanket with a maximum Earth albedo of 0.6, maximum Earth infrared (IR) radiation, and maximum solar flux is analyzed. Note, however, that the maximum solar flux cannot occur above a solar β angle of 28.7 deg.

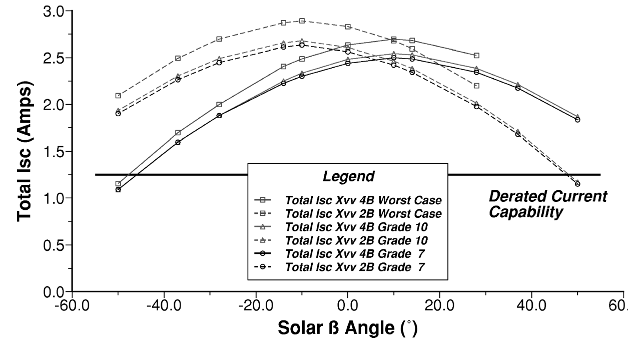

Fig. 13c Variation in *Isc-total* in the *Xvv* attitude as a function of solar β angle and cell grade.

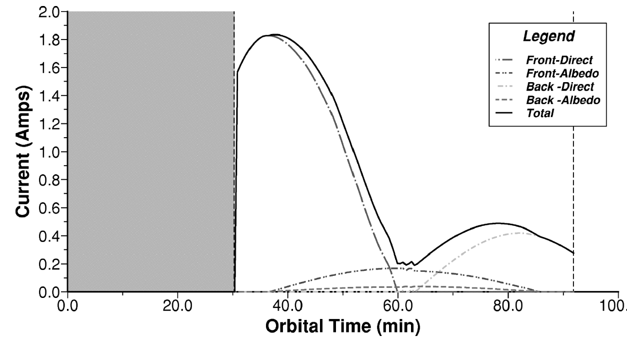

Fig. 13d *Isc-total* contributions for *Xvv* attitude for solar $\beta = 50$ deg, channel 4B.

The analysis assumed the following:

1) *Isc* values for an "average" grade 7 or grade 10 ISS solar cell are assumed. Individual circuits can have slightly higher or lower *Isc* values.

2) A bulk temperature calculation is used, though different strings can operate at different temperatures, and thus produce different currents.

3) The albedo used is the worst (highest) expected short-term value (time < 0.3 h), and the Earth IR is the worst expected long-term value (time > 3 h).

4) It cannot be guaranteed that a slightly worse environment might be seen.

5) The attitude can be maintained as specified throughout the remove-and-replace activity.

6) The test port 22-gauge wire harness resistance is not included in the array current calculation, but its effect is expected to be very small. Unfortunately, there are no on-orbit data to verify array performance under these "hot case" conditions.

The difference between the *Isc* from grade 7 cells and grade 10 cells is slight compared to the difference of assuming a worst-case day with very high Earth albedo, maximum Earth IR, and maximum solar flux. The results for *Xpop* and Xvv are shown in Figs. 13a–13d. Both arrays were parked for the following analyses such that data for both solar array wings could be evaluated. The *Xpop Isc* is acceptable for SAW 4B up to a solar β angle of $\sim$|36 deg| (Fig. 13a). SAW 2B exceeds the 1.25 A for $|\beta| > \sim 12$ deg under worst-case conditions. The components of the *Isc-total* for an orbit at $\beta = 50$ deg in *Xpop* are shown in Fig. 13b, where by far the main component of *Isc-total* is the solar front illumination. All the Xvv *Isc* results are above the 1.25 A limit for the 22 gauge wires (Fig. 13c), except for $|\beta| > \sim 46$ deg. For SAW 4B, shown in Fig. 13d, again the direct front illumination is the major component of *Isc-total*, but only for the first half of the insolation pass. During the second half of the insolation pass, direct back solar illumination is the main contributing current. The parameters are chosen to try to obtain the maximum possible *Isc* because *Isc* is a function of both incident flux and temperature, hence the choice of maximum Earth IR.

The basic premise is to reduce the current and voltage from the array for the SSU change out to minimize the voltage hazard to

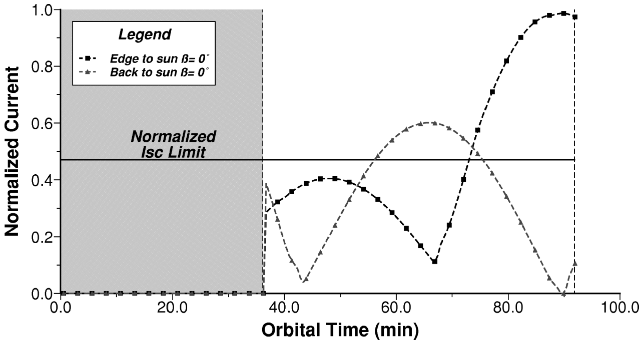

Fig. 14 Comparison of normalized *Isc* for the solar array parked edge on to the sun at orbit noon and parked with the backside facing the sun at orbit noon for *Xvv* attitude at solar $\beta = 0$ deg.

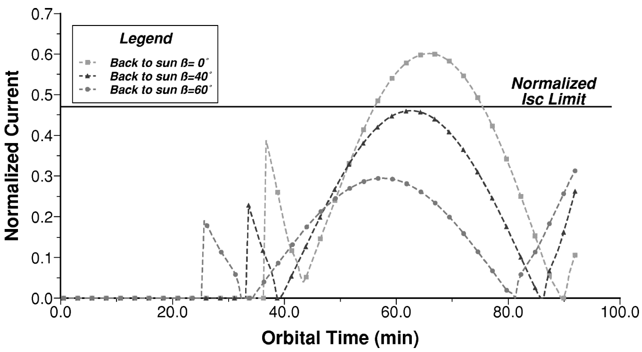

Fig. 15 Normalized current for *Xvv* attitude as a function of solar β angle with the solar arrays parked with the backside facing the sun at orbit noon.

the EVA crew members. Parking the array such that it is pointing edge-on to the sun at orbit noon yields a normalized current with local maxima of 0.39 at ∼9 min into the insolation. Once the solar illumination changes from the backside to the front side, at ∼30 min past orbit sun rise, the normalized current rises rapidly (Fig. 14). With the backside of the array parked such that it has minimal off pointing to the sun at orbit noon, the normalized current reaches a maximum of 0.601 at orbit noon.

The current off the solar array is also a function of the solar β angle. As the off pointing of the solar array increases with increasing solar β angle, the normalized *Isc* drops. For a solar $|\beta|$ angle less than or equal to 40 deg, the normalized *Isc* is under the threshold (Fig. 15).

Preliminary Feasibility Assessment of SSU Change-out Options

From the standpoint of the solar-array electrical performance, the preliminary feasibility of the various SSU remove-and-replace EVA options was assessed and is discussed in the following text.

Option 1: Leave the Failed SSU in Place

Leaving a failed SSU in place would disable the affected EPS channel associated with the solar array. For the current ISS configuration (Fig. 1), there are only two EPS channels supplying power to the ISS U.S. segment SAW 2B and SAW 4B. Thus, about half the U.S. power capability would be lost. This situation would be unacceptable.

In a postassembly complete ISS configuration, the U.S. segment will be powered by eight EPS channels. Loss of a single channel implies loss of about 12% of the power capability. Additionally, loads on the affected channel with a failed SSU could be switched to other, functioning EPS channels if they had sufficient capacity to handle increased loads. Therefore, the option to leave a failed SSU in place, although not desirable, is feasible for ISS post assembly complete configurations.

Option 2: Change-out the SSU During One Eclipse Period

This option is risky because one eclipse period of approximately 30 min might not provide sufficient time for the removal and replacement of an SSU especially allowing for contingencies. Therefore, this option is deemed unacceptable.

Options 3: Change-out the SSU During Several Eclipse Periods

In this option, the EVA crew, at a safe standoff distance from solar-array string power connectors and solar cells, allows the solar-array strings to be open circuited through the orbit sun period(s). The preceding parametric results show that the normalized string voltage is above the trigger arc threshold value of 0.92 for most of the orbit sun time. This suggests the solar-array cells will experience trigger arcing to the plasma. Although laboratory tests[1−3] indicate that trigger arcs will not hurt the performance of ISS solar-cell strings, such arcing is not desirable and should be avoided if possible. Material ablation at trigger arc sites increases the local neutral density and can lead to sustained Paschen discharge arcs between closely spaced, differentially biased solar-cells. Sustained arcs are damaging to solar-cell string hardware and must be avoided. Laboratory testing with nominal simulated space plasma indicates that sustained arcing will not likely occur for ISS solar-cell strings because of the multiple centimeter spacing between differentially biased solar cells. However, the possibility of sustained arcing cannot be definitively ruled out in the actual space plasma and in the presence of off-nominal events such as ISS venting, rapid material outgassing, and meteoroid/space debris impacts. Thus, option 3 is not feasible for the removal and replacement of a failed SSU because of the risk of solar-array sustained arcing that cannot be totally ruled out with ground-based testing or analyses.

Option 4: Retract Solar-Array Wing First, SSU Change-out over Multiple Orbit Sun and Eclipse Periods

When retracted, the solar-array blankets have nearly zero current and voltage production capacity and are considered electrically safe. This is the baseline SSU remove-and-replace approach that utilizes the array's inherent design feature of retractability.

Option 5: Install Shunt Plug on Solar-Array String Power Connectors at SSU Interface

The shunt plug will collapse the array string voltage through a low-resistance electrical wire loop. This approach will afford the EVA crew multiple orbits to accomplish the SSU remove-and-replace procedure. Also, this approach does not place any restrictions on allowable array string performance because the shunt plug would be designed to handle the maximum possible string *Isc*. An undesirable feature of this approach is the risk of connector socket damage when shunt plugs are inserted into the beta gimbal platform side of SSU power connectors. Also, the power connector shunt plugs cannot be installed until the failed SSU is removed, and the replacement SSU cannot be installed until the shunt plugs are removed, meaning that the solar-array strings will be open circuited, at times, during eclipse. This also adds time and complexity to the SSU remove-and-replace EVA timeline. Option 5 mitigates much of the risk associated with options 2 and 3, in that it is highly likely that it will be possible to install the shunting plugs. Option 5, however, still leaves open the possibility of the solar array being left open circuited in daylight should the SSU bind in place during removal or installation. Although option 5 has some added risk and complexity, this is a fairly low-risk approach.

Option 6: Install Shunt Plug on Solar-Array String Test Port Connectors

The test port connector shunt plug is installed on the array input side of the SSU and will collapse the array string voltage and dissipate string short-circuit current through a low-resistance electrical wire loop. This avoids the need to retract the solar array, while still eliminating the risks involved with leaving the solar array open-circuited. This approach will afford the EVA crew multiple orbits to accomplish the SSU remove-and-replace procedure and will allow an overlap time with both the SSU installed and the shunting plugs installed. At no time would the solar array be open circuited. Also, this approach does not introduce the added risk of damaging SSU power connectors because shunt plugs are inserted in the otherwise unused test port connectors. The test port connectors are located away from the SSU and thus do not impede the SSU remove-and-replace operations. The only undesirable features of option 6 are the inability to ground test the effectiveness of this approach, the risks associated with EVA installation on equipment that was not designed to provide an EVA interface, the inability to verify that it has been installed and remains installed correctly through the operation, and that there are restrictions on the allowable array string *Isc*. The normalized string *Isc* must be 0.47 or lower to maintain an acceptably low temperature in the test port connector 22-gauge wire bundles, as this test port was not intended to carry the full short circuit current of the solar array. As just described, operational strategies that maintained the normalized *Isc* value at acceptably low values for the ISS flight *Xpop* solar inertial flight mode, a wide range of solar beta angles, and the preferred solar-array park angle for EVA operations were devised. Thus, option 6 is a feasible approach.

Conclusions

Based on this preliminary feasibility assessment of the various SSU remove-and-replace EVA options from the standpoint of the solar-array electrical performance, the authors reach the following conclusions. The baseline option 4 (array retraction), even though fully certified, is vulnerable to externally induced damage that could jeopardize the operation. This makes a secondary approach desirable. Option 2 (SSU change out in one eclipse pass) is not feasible because it is impossible to ensure that the SSU will not bind in place, which would then leave the solar-array open circuited in the next sun pass. Option 1 (do not replace SSU) is not feasible for the current ISS configuration but might be feasible, although not desirable, for a postassembly complete ISS. Option 3 (replace SSU over multiple eclipse passes without solar-array shunting) is not feasible because array-to-plasma arc discharges will occur and could lead to damaging, sustained arcing of solar-array strings. Option 5 (SSU power connector shunt plug) appears feasible but still has open circuit and connector damage risk, along with some added operational risk and complexity. The last option, option 6 (test port connector shunt plug), is the preferred SSU remove-and-replace EVA procedural option. This option is feasible and imposes the least overall risk to hardware and EVA operations, even given the undesirable features noted earlier. The operational requirements to meet the short circuit current restriction of $Isc < 1.25$ A, such as wing park angle and ISS flight mode, can be defined a priori using validated array performance models and latest available orbital string performance data.[6]

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