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Integration Assessment of Visiting Vehicle Induced Electrical Charging of the International Space Station Structure

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Abstract

The International Space Station (ISS) is a large low earth orbit (LEO) satellite. The ISS electrical charging properties in this environment affect its operation. The 160 V solar array (SA) system on ISS is grounded negative. Small exposed conductors on the SA collect electrical charge from the environmental plasma driving the metal structure through the electrical ground to a negative floating potential (FP) relative to plasma. This potential is variable in location and time—a result of asymmetric current collection properties moderated by local ionospheric conditions. So called v × B induction distributes up to 20 additional positive and negative volts across ISS depending on its attitude and geographic location.

Visiting Vehicles (VV) are now a regular part of ISS operations. In addition to time-tested Russian Soyuz and Progress spacecraft, the European Automated Transfer Vehicle (ATV) and the Japanese H-II Transfer Vehicle (HTV) have completed missions to ISS. Commercial space transport interests, both SpaceX and Orbital Sciences, are moving forward with VV development. Both have active plans to dock with ISS. The United States NASA VV concept is a configuration of the Orion capsule, under development by prime contractor Lockheed-Martin Corporation, from the Constellation program.

Most VV, just like the ISS, incorporate SA power systems. Any of these VV may experience charging by the same process as ISS. Upon physical contact with ISS, the current collection properties of a VV combine with ISS and any other docked VV. This is a vehicle integration concern as FP must be controlled because the vehicle may experience degradation of its anodized aluminum surface coatings if electrical hull arcing were to occur and an extra vehicular activity (EVA) crewman is also exposed to shock hazard. ISS FP is controlled by plasma contactor units (PCU) which operate only during EVA.

This report is an assessment of the Orion SA induced charging of ISS and motivates a generic limiting electric current delivery specification for any docked VV. The Orion SA incorporates a negative grounded, 130 V, UltraFlex (ATK Space Systems) SA being developed under subcontract by Alliant Techsystems Inc. (ATK) of Goleta, California.

The Orion SA presents small amounts of exposed metal cell interconnects and photoactive germanium substrate. To assess the current collection characteristic, Orion solar cell test coupons were constructed and subjected to plasma chamber current collection measurement. Current collected by the coupons from the plasma was measured as a bias potential was swept between 0 and 120 V. This current voltage sweep data determined at the chamber plasma state temperature and density (n and T) was scaled to arbitrary geophysical n and T according to Langmuir probe theory. The data and the theoretical scaling are combined in a numerical model which is integrated into the Boeing Plasma Interaction Model (PIM). It was found that the SA design for Orion will not affect ISS by more than about 2 V during worst case charging conditions. A trade study was conducted with PIM to determine that no single or combined fleet of docked VV should deliver more than 5 mA of current. PCUs can reject up to about 10 A and therefore can control additional VV if they meet the combined docked fleet total of 5 mA.

1.0 Introduction

Solar array power systems provide a direct current (DC) electrical potential for spacecraft. Designs for such systems yield significant efficiencies if power is distributed at high voltage. High voltage requires less current and therefore less conductor and lower weight. On the other hand, high voltage requires greater care in isolating energized elements and voltage step down converters are needed for any low voltage subsystems.

On most spacecraft it is customary to ground the negative side of the electrical system. Grounding the electrical supply polarizes the system providing a means to isolate energized conductors to subsystems when power is off. A subsystem with an exposed heating element for example is safe electrically if the on-off switch breaks the hot side conductor. A grounded system also provides a return path for noise transients. Nevertheless, it is possible to design systems that function with ungrounded power as are used in the standard 440 V system on United States Navy vessels (Ref. 1).

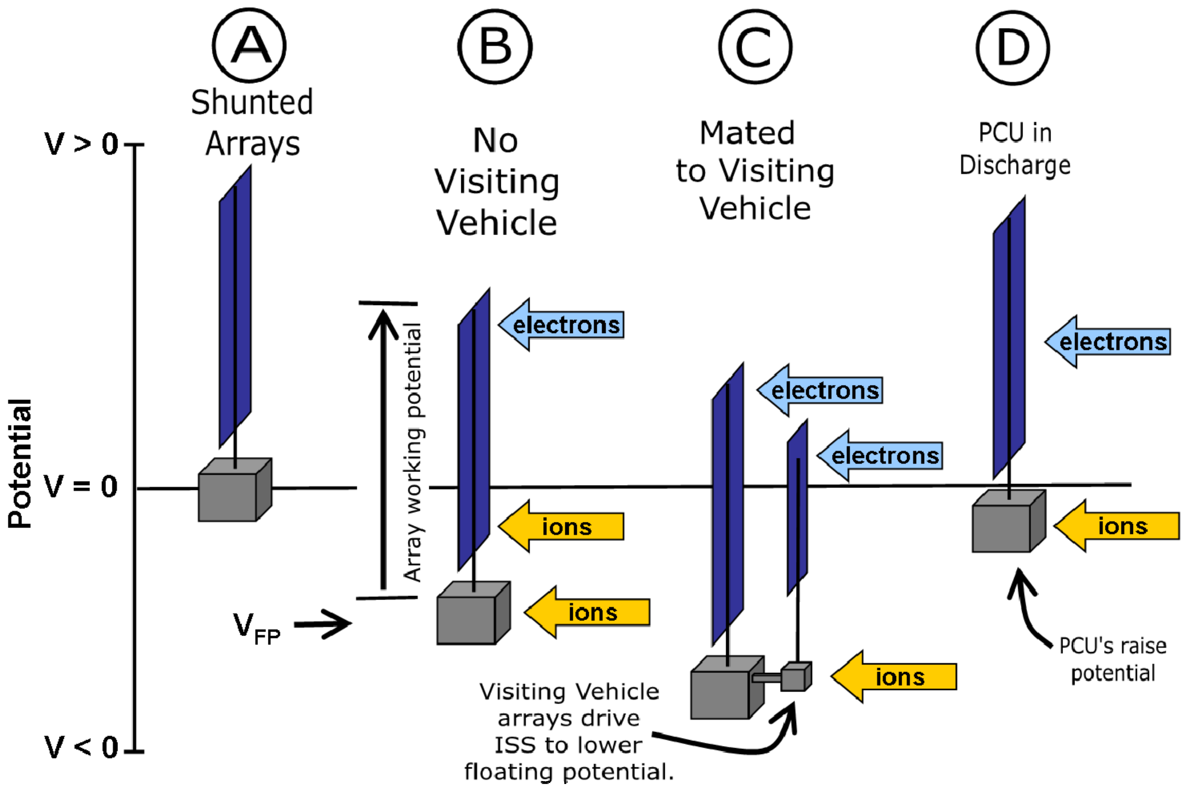

Figure 1.—Illustration of electron and ion collection on solar array and satellite structure driving voltage negative relative to external plasma. Shunted arrays (A). Active arrays with no PCU control (B). Active arrays plus Visiting Vehicle contribution to electron collection (C). Active arrays with PCU control (D).

In developing the power distribution system for ISS and VV a number of these technical, economic and sometimes legal and political requirements are balanced in trade studies where the competing requirements are reconciled. A 160 V, negatively grounded, DC system was the outcome of a trade study performed for ISS. The Orion program, through a similar process adopted a 130 V DC design, also grounded negative.

When a VV docks with ISS the respective electrical ground of the two vehicles become effectively bonded. At the same time the external environment of ISS is an electrically conducting plasma and most solar array designs provide exposure of electrical conductors to the plasma. Currents will generally flow through the plasma and any exposed metal on the structure. Negative grounded arrays cause negative charge collection on the combined VV-ISS structure contributing to accumulated negative electrical potential on the structure.

Therefore, because the ISS must accommodate mated operations with this variety of VV, a technical integration assessment of the electrical charging effects from these vehicles must be performed. This report describes the special challenge involved in developing assessment standards for the United States Orion Vehicle. A trade study is also performed here which provides general guidelines for the amount of current that the ISS can accept safely from any combined fleet of docked VV.

1.1 ISS Electrical Charging Properties

Solar array electron collection at exposed conductors on the positively charged arrays will drive the ISS (or any so configured satellite) to a negative potential. Four charging scenarios are illustrated in Figure 1. In this figure which has been adapted from an unpublished report (Ref. 2) the array configuration is abstractly pictured as a single SA oriented along the direction that electrical potential is distributed. The bonded structure ground is represented by a cube of metal.

In Figure 1 scenario A, the arrays are depicted in a shunted configuration where no potential is supplied. In this scenario the structure potential adjusts in response to currents from electrons and ions. The electrical potential of the structure floats slightly negative. This is the voltage providing equilibrium between electrons and ions collected from the plasma.

In the Figure 1 scenario B, the arrays are active. The positive voltage distributed across the arrays drives electrons through the negative ground until a new equilibrium potential is achieved wherein the active collection of electrons at the arrays is balanced against collection of ions on the bare metal of the structure.

Our concern regarding VV effect on charging is illustrated in Figure 1, scenario C. When mated to ISS the arrays of the VV contribute additional exposed conductor at positive potential driving the structure to a lower potential than is achieved in the unmated scene B.

In general the lower potential is an operational concern. Lower potential applies an electric field across thin (1 to 15 µm) anodized aluminium on the ISS and can cause it to arc. Such arcing is readily observed in the laboratory and the characteristic anodized material covers nearly all the non-Russian pressurized and the external truss elements (Refs. 3 and 4). The anodized coating is carefully designed to facilitate optimum thermal protection and such arcing, if not mitigated, would degrade and eventually remove the protection. The potentials are also a hazard to crew during extravehicular activity (Ref. 5).

1.2 Magnetic Induction (v × B)

Direct charging of the vehicle from the arrays as described in Figure 1 is not the only agent affecting the FP. The motion of ISS through the magnetized ionosphere induces an electric field drop in the plasma across the linear extent (L) of the vehicle structure. It is proportional to the cross product of velocity (v) and geomagnetic field vector (B). The induced (v × B)·L potential is illustrated in Figure 2. This v × B induction moderates electron and ion collection at conducting areas of the vehicle.

The masts supporting the SA are made, in part, of stainless steel struts or wires. The wires, although not bonded by design, provide metal to metal contact communicating among all the struts to the ISS structural metal. The Russian pressurized elements also provide an electrically conducting mesh on the exposed side of their multilayer insulation blankets (Ref. 6). The mesh is intentionally grounded to structure and completely shields the Russian elements.

In darkness electrons collect on the SA masts and on exposed conductors on the arrays themselves. The aggregate effect of v × B induction on ISS potential results in that slow, broad, half orbit structure seen in the FP signature of Figure 3. This electron collection tends toward an equilibrium with ions recombining primarily at the Russian modules, but also at masts and sometimes at the SA.

1.3 Measurement of ISS Floating Potential and Plasma State

The ISS is equipped with a set of tools developed to monitor the plasma state. The instrumentation is the Floating Potential Measurement Unit (FPMU) developed for NASA. The FPMU is described by Wright et al. and references contained therein (Ref. 7). The floating potential (FP) probe, among the complement of instruments incorporated in the FPMU, comprises a gold plated spherical shell isolated from the bonded structure by an approximately 10^{11} Ω impedance and deployed on a 150 cm boom.

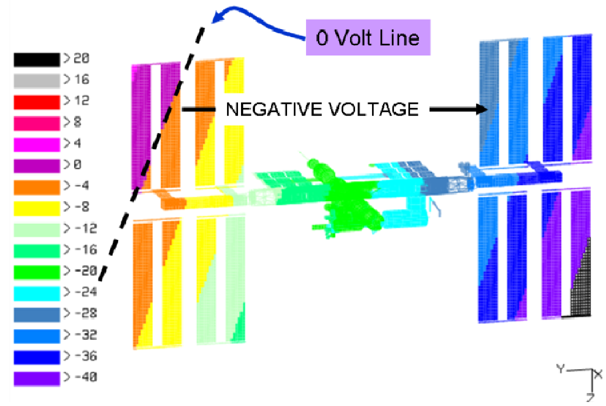

Figure 2.—Induced v × B potential in the plasma distributed across the structure with PCU not active.

The electrically conducting nature of the plasma provides a well known shielding effect associated with the attraction and enhanced concentration of opposing polarity charge carriers in the plasma volume near any charge. This shielding property is characterized by a length scale known as the Debye length. It is effective in isolating the FP probe from disturbance associated with nearby charged surfaces. The FPMU deployment, in particular, locates the FP probe at least 2 Debye lengths away from any other structure over the range of plasma state conditions achieved on orbit. The FP probe sphere therefore floats near the plasma potential providing a reference for measurement of the ISS (Ref. 8).

Figure 3 is an example of FPMU telemetry along with our theoretical calculation of FP. The upper panel shows the FP probe data and our theoretical calculation for 4 orbits in mid-November of 2009. The abscissa scale is color-coded and yellow shows sunlit orbit intervals. We observe that the potential so illustrated reflects a negative potential of the vehicle structure relative to the FP probe shell. We will discuss the theoretical calculation in section 4.0.

The plasma state comprising electron temperature, T, and plasma density, n, are determined by Boeing's Langmuir probe (LP) reduction process. There are two LP; a spherical wide bias range and a narrow range cylindrical probe. These are known as the Wide LP (WLP) and the Narrow LP (NLP). The LP sweep voltage over a range and report the current collected from the plasma. The reduction processor determines density; n, from the negative bias ion collection region of the respective current-voltage (I-V) sweeps. The ion current model is then subtracted and temperature is determined from a optimal fitting of a appropriate electron current model across the near zero bias portion of the I-V sweep. The n and T from the WLP and NLP are illustrated in the bottom two panels of Figure 3.

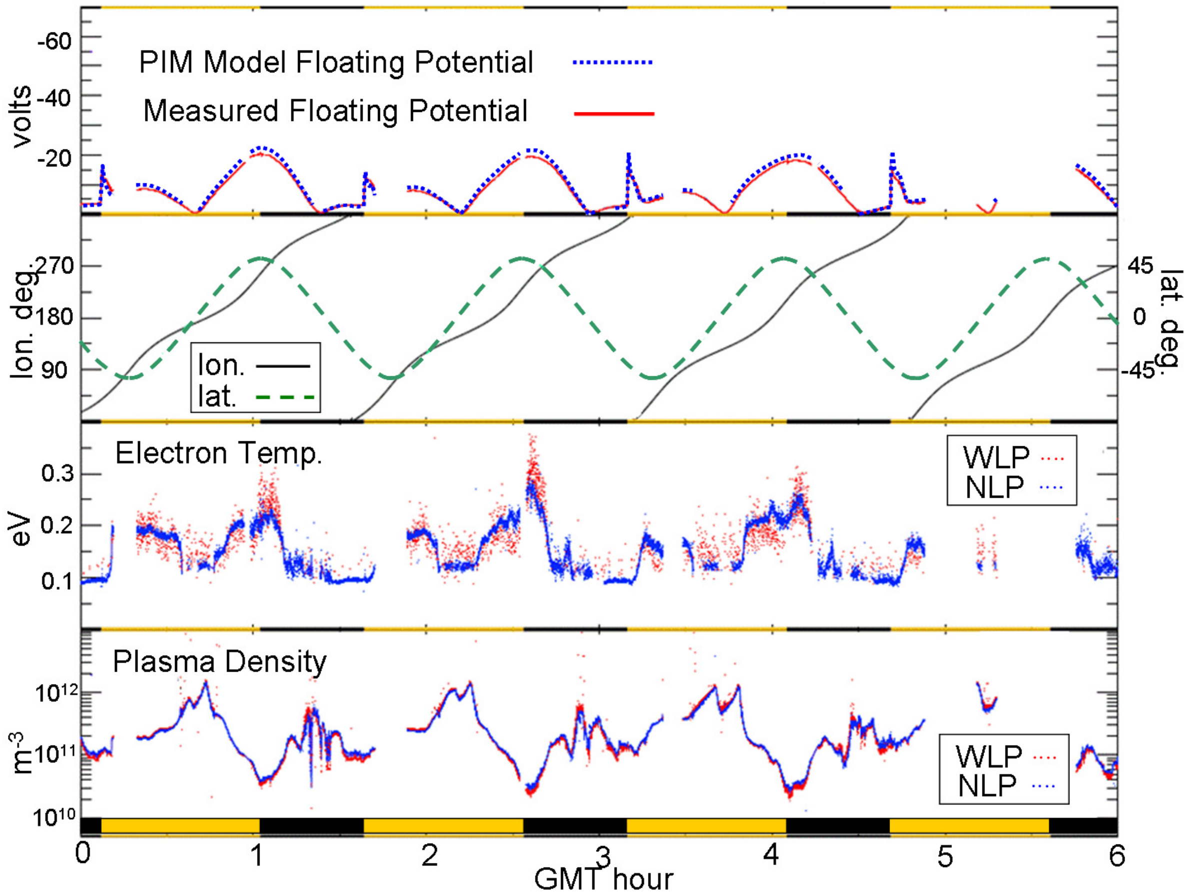

Figure 3—Example of FPMU telemetry collected November 18, 2009 with corresponding theoretical simulation for 4 orbits of ISS. Red line in the top panel is observed vehicle FP relative to deployed probe. The top panel blue line is theoretical FP referred to probe location and based on measured n and T seen in the bottom two panels.

1.4 Control of ISS Floating Potential

Early (1990) analysis predicted that the space station would float to 130 to 150 V below the plasma potential (Ref. 9). To address that projected severe hazard from hull arcing (as well as a list of other hazards), plasma contactor units (PCU) were developed and deployed on the ISS. These devices expel plasma generated from a xenon gas reserve. The effect of the PCU is to overcome the voltage gradient supported by a plasma sheath and provides a low impedance path from structure metal to ionospheric plasma. The PCU redistribute negative charge to the environment bringing structure potential closer to plasma potential as illustrated in scenario D of Figure 1.

The severe hazard prediction proved erroneous. Uncontrolled potentials assumed by the ISS have been much less than that needed to initiate arcing contrary to the predictions. The state of knowledge at the time of those predictions overstated the influence of secondary electron emission on solar array collection and seems to have had no way to account for all the mitigating effect of ion collection on conductors; particularly the Russian mesh mentioned in section 1.2. Arcing on the surface of the astronaut's spacesuit or Extravehicular Mobility Unit (EMU), although highly unlikely, has been determined to be, and remains, a catastrophic hazard. PCUs are therefore operated only during EVA to protect the astronaut (Refs. 4 and 5).

1.5 Visiting Vehicles

Presently four international interests have or are developing spacecraft to dock with ISS. The Russian Soyuz crew vehicle and Progress cargo carrier have accumulated decades of service including several dozen flights to ISS. The vehicles of other nations, notably the European ATV and Japanese HTV have docked with ISS and more are planned. Private commercial interests are well along in development of unmanned vehicles designed to deliver cargo to ISS.

The private company SpaceX has developed a vehicle designated Dragon. The Orbital Sciences vehicle is called Cygnus. The Orion vehicle under development by the United States is the planned crew transport vehicle following the end of Space Shuttle missions in 2011.

1.6 Integration of Docked VV to ISS

All of the space vehicles we discuss here have variable design approaches to power generation. Both Russian Soyuz/Progress and European ATV vehicles incorporate 28 V solar array/battery DC power systems. The Japanese HTV power system employs solar arrays that operate at voltages near 100 V. Dragon and Cygnus specifications are proprietary (although they are disclosed to the ISS program vehicle integration authority).

A formal integration assessment of visiting vehicles by the ISS program authority has therefore emerged as a requirement for safety and mission success. This report is an attempt to advance that agenda.

2.0 Orion Solar Arrays

The Orion capsule is outfitted with two disk shaped solar array wings seen in Figure 4. The final design study has converged on 90 strings of 67 solar cells per wing. The strings are laid out on 20 triangular "gore" segments distributed among the two wings. One of those gore segments is illustrated in Figure 5.

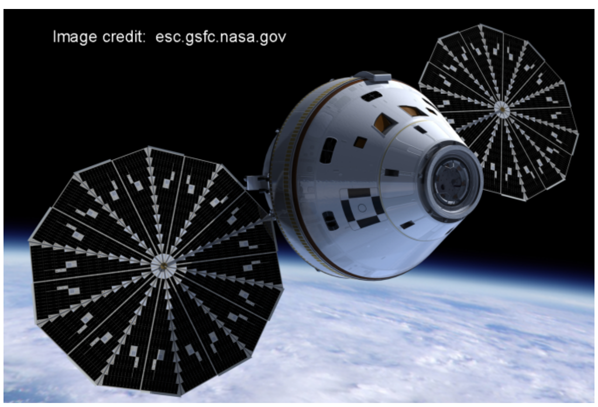

Figure 4.—The Orion solar array system has 20 "gore" segments distributed between two disk shaped wings.

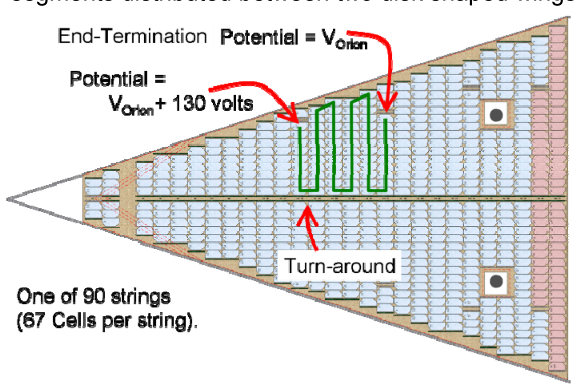

Figure 5.—Orion solar array "gore" segment highlighting one of 90 strings. Working potential of 130 V is distributed between the end-terminations and across the 67 cells in each string. The grounded end is at vehicle potential (V_{Orion}).

2.1 Characteristics of Orion SA

Each SA string constitutes a voltaic pile of solar cells. The active voltage of approximately 130 V is distributed across the pile between the negative grounded point which assumes vehicle FP. Although the active side of the cells are covered with 3-mil thick cover glass, gaps between cells are available to collect current from the plasma as are inter-cell interconnects seen in the photograph of a test coupon in Figure 6. Additionally, the backside of the cell and its electrically conducting substrate are covered with insulating material. There are also large metallic "end-termination" and "turn-around" connectors shown in Figure 5 which are not exposed to plasma.

2.2 Plasma Chamber Test of Orion SA Cells

Electric current collection tests on a SA cell coupon were conducted as a part of this study. The test coupon, shown in Figure 6, was designed and assembled by ATK. It comprises 16 solar cells arranged in a grid. Testing was conducted in a plasma chamber at NASA Glenn Research Center (GRC) (Ref. 10). The chamber with the cell coupon installed is seen in Figure 7.

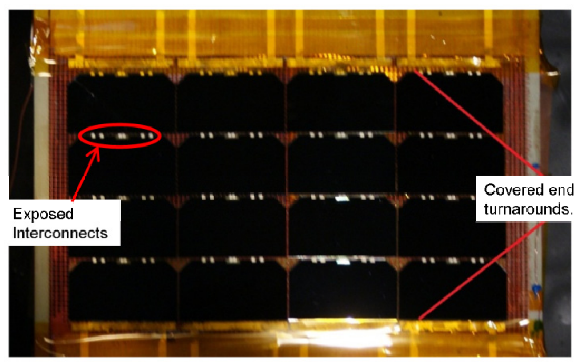

Figure 6.—Solar array chamber test coupon highlighting exposed interconnect and covered end-terminal and turn-arounds.

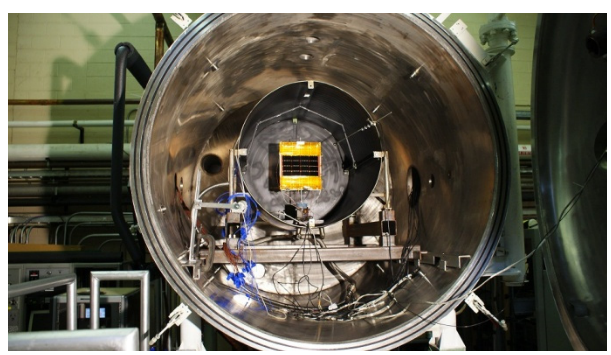

Figure 7.—Solar array coupon in plasma test chamber.

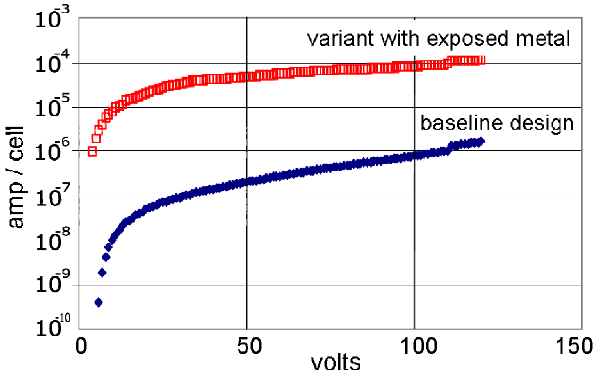

Figure 8.—Current collection from Orion solar array coupons undertaken by GRC. Dark blue diamond (♦) is the baseline design. Red square (□) is from special test coupons with exposed metallic end terminations.

The positive and negative terminals were on the test cell coupon shorted together and biased externally. The plasma state in the chamber was adjusted to a density, n = $1.0\times10^{12}m^{-3}$ and electron temperature, T = 0.2eV to reflect a typical ionospheric environment.

The measurements are shown in Figure 8. The current as a function of bias potential, or I-V sweep, from the primary baseline design is illustrated as the dark blue diamond (♦) symbol.

An alternate test was conducted with the coupon design altered to expose metal end turnarounds seen in Figure 6 and also exposing the backside of the array. For the alternate test, plasma state was adjusted to constitute a higher density; n = $3.5\times10^{12}m^{-3}$ with T = 0.25 eV. The I-V sweep for this variant coupon test is shown with the red open square (□) symbol in Figure 8.

The variant exposed metal design is in the nature of a control for the purpose of illustrating the effectiveness of the end turn-around coverings. We will refer to these as the variant exposed metal coupons.

The current from the variant control is seen to be about two orders of magnitude larger than the baseline design. Although the density is higher for the test of the variant, most of the increased current results from exposed metal on the variant. It will be shown to contribute significant charging to ISS.

3.0 Orion Solar Array Electrical Current Model

The physics governing electron collection of an Orion SA and the Langmuir probes are closely related. The Langmuir probe is a device used to ascertain plasma state conditions by observing the current collected from plasma as the electrical potential of the device is varied in time. The ISS Langmuir probe measurements provide flight like plasma state (T, n) and electric collection characteristics similar to metal surfaces on the Orion arrays. In contrast, Orion SA coupon data collected in the GRC chamber are measured at a single plasma state (T_0, n_0).

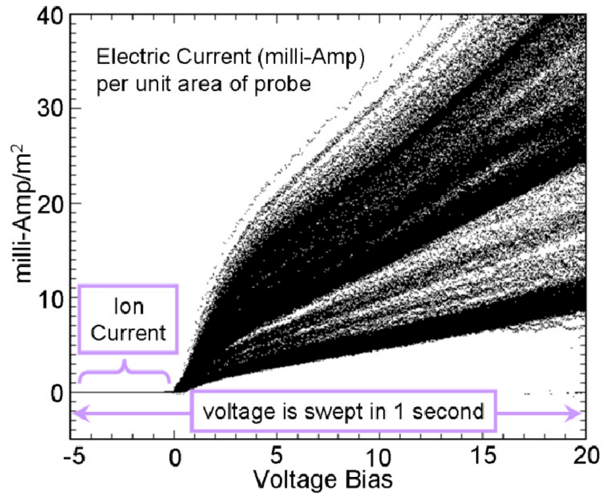

Figure 9.—Current collected to Langmuir probe deployed on ISS over a wide range of temperatures and densities.

Existing plasma Langmuir probe theory is accurate around the near zero bias potential (Ref. 11). The theory permits T and n to be observed but is not directly applicable to high positive voltage. The WLP described in section 1.3 provides high voltage I-V sweep characteristic curves. On-orbit assessment of electric current to the bare metal WLP probe biased from –20 to 80 V are available for a wide range of on orbit conditions. The data and the theoretical scaling provide us with a mathematical scaling:

$$I(V;T_0,n_0) \Leftrightarrow I(V;T,n) \tag{1}$$

relating the I-V sweep relationship in the chamber; $I(V;T_0,n_0)$ to the sweep at arbitrary T and n. The development of this scaling is discussed as follows.

3.1 Langmuir Probe Current Collection Theory

Figure 9 illustrates the current voltage characteristic for the Langmuir probe on ISS. The wide variation in current over voltage bias results from the changing T and n as ISS orbits earth. The variation can be modeled theoretically in a normalization to the electron thermal velocity and the probe collection area.

The normalized current, Ψ and voltage, X are:

$$\psi = \frac{I_{Probe}}{env_e A} \tag{2a}$$

$$X = \frac{eV}{k_B T} \tag{2b}$$

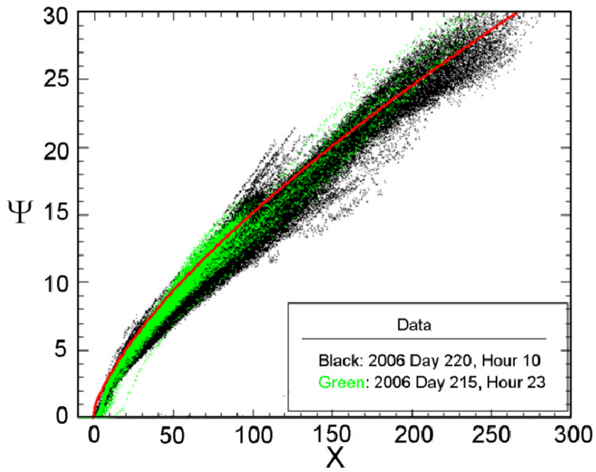

Figure 10.—Normalization of the data in Figure 9.

Where I_{probe} is the current collected by the probe and V is the bias as in Figure 9. Additional parameters are e; the electronic charge ($e = 1.6\times10^{-19}$coulombs), n; the plasma density (m^{-3}). A is the probe collection area in m^2, k_B is Boltzman's constant ($k_B = 1.38\times10^{-23}$ J/K. The term v_e is the electron thermal velocity $v_e = \sqrt{k_B T/2\pi/\ _e}$. A plot of Ψ versus X seen in Figure 10 shows that the normalization in Equation (2a) and (2b) unifies the variation in the original un-normalized data.

3.2 On-Orbit ISS Langmuir Probe Data

The red line in Figure 10 is a model of the current given by:

$$\psi(X) = 0.6 \times (1 + X)^{0.7} \tag{3}$$

With the definition of Ψ we obtain:

$$I_T(n,T) = e \cdot n \cdot v_e A \times (1 + X)^{0.7} \tag{4}$$

which then provides a basis for rationalizing the transform expressed in Equation (1). We use Equation (4) as a proxy for the actual on-orbit response to temperature and density.

3.3 Model of Orion Current Collection

The basis for the scaling in Equation (1) is contained in the proportional variation resulting from arbitrary density, n and electron temperature, T, as in:

$$I(V,n,T) = I_M(V) \times \frac{I_T(n,T,X=0) \times \Psi(V,n,T)}{I_T(n_0,T_0,X=0) \times \Psi(V,n_0,T_0)} \tag{5}$$

Here, I_M is the measured current taken from the data in Figure 8. It is implemented as a lookup table functionally dependent on bias potential ($I_M = I_M(V)$). The term in the numerator represents the model current variation at any arbitrary V, n and T whereas the denominator provides the model at the chamber state. A rearrangement provides the Orion electron collection model:

$$I(V,n,T) = I_M(V) \times \frac{n}{n_0} \sqrt{\frac{T}{T_0}} \times \left(\frac{1 + \frac{V}{T}}{1 + \frac{V}{T_0}} \right)^{0.7} \tag{6}$$

where the temperature T is expressed in eV. We see in Equation (6) that density scales current in direct proportion to n. Temperature variation is more complicated; related to empirical power law fit obtained in Equation (3). Equation (6) is the Orion current model.

4.0 ISS Plasma Interaction Model

In this section we present a brief description of the Plasma Interaction Model (PIM) developed by Boeing.

We introduce PIM here as a tool to evaluate the floating potential of the ISS (Ref. 12). The algorithm expresses accumulation of total electric charge from models of the electron and ion currents on conducting surfaces and from results of a space charge calculation at the active solar arrays performed by the Science Applications International Corporation (SAIC). The important contribution from SAIC is a finite element solver solution for a potential barrier generated by high voltage (0 to 160 V) at the solar arrays (Ref. 13).

PIM is a non-steady state solver based on a principle of electric charge conservation. The model incorporates subsystem model currents from three components; the ISS SA, the exposed conductors on the Russian element and from the SA masts.

Although the Russian elements appear to be covered by multilayer insulation blankets which ordinarily exhibit dielectric properties, the outer, exposed layer of these blankets is embedded with a silver coated copper mesh which is bonded to the structure ground (Ref. 6).

The subsystem models, including the Russian blanket model are parametrically controlled by the vehicle potential and plasma state (n and T) as well as attitude and orientation of the vehicle. The algorithm uses plasma state properties of density, n, and temperature, T, determined from on orbit FPMU Langmuir probe instrumentation. The lower two panels in Figure 3 show the plasma n and T from the Boeing Langmuir probe reduction processor. The upper panel illustrates measured and theoretical FP. The theoretical FP is referred, through the (v × B)·L calculation described in section 1.2, to the FP probe location. The comparison between the FP probe measurement and the PIM model output validates the PIM algorithm for the purpose of this study.

The Orion model of Equation (6) is configured in the PIM software along with the existing models of the solar array, Russian blankets and array masts. The FP for a characteristic variation in plasma state during a 1 hr time period is simulated in PIM. The period includes eclipse exit and is shown in Figure 11. Four different scenarios are assessed and we will discuss each in turn.

4.1 Baseline (No Docked VV) Floating Potential

In the No Orion, scenario A, represented by a green solid line in Figure 11, the PIM floating potential is evaluated as a baseline for comparison with the active model Orion currents. For this baseline and the three model scenarios to be discussed, the plasma state (n, T) seen in the lower two panels of Figure 11 are taken from a well known International Reference Ionosphere. The No Orion case is a typical variation of on-orbit conditions as seen in the measurements of Figure 3.

The charging of the Orion spacecraft is of greatest concern at eclipse exit where the spacecraft emerges from darkness and the arrays are in full ram; oriented toward the sun. As the orbit evolves, the sun orientation separates from the ram direction and electron collection is mitigated. The ISS SA also undergoes array regulation as batteries charge and system power demands vary.

The current from the three components in PIM are illustrated in Figure 12. It is seen that in darkness the solar array and the conducting elements on the Russian segments contribute a net positive current balanced approximately by electron collection on the stainless steel wires of the SA masts. At eclipse exit, the SA become active and immediately dominate electron collection pushing the masts together with the Russian segments to the positive current side of the collection model. Our primary concern therefore is the charging at eclipse exit where all ISS SA are contributing to electron collection.

4.2 Integration of Orion Model into PIM

To evaluate charging properties of Orion the model characterized by Equation (6) was incorporated as one more subsystem in PIM using the GRC I-V sweep data from Figure 7 to characterize $I_M(V)$ in Equation (6).

For the duration and location in the ISS orbit we adjust the ISS FP to account for Orion current, adding up the current contribution through each cell while simultaneously adjusting for its individual contribution to the working potential and its local $v \times B$ induction. We accumulate this sum all the way up to the positive terminal of the string.

Active Orion SA scenarios illustrated in Figure 11 include a single Orion designated case B and a Dual Dock case C. We will discuss first however the exposed metal case D characterising the electron collection properties of the Orion SA using plasma chamber data collected and seen in Figure 7 from test coupons prepared with exposed metal end terminations.

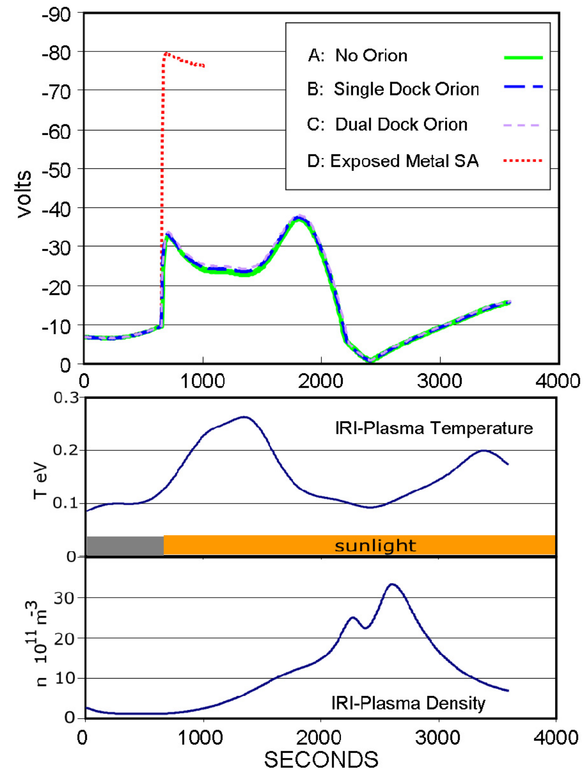

Figure 11.—PIM modelled floating potential for 4 docking configurations. Plasma state from the IRI model is illustrated in the bottom two panels.

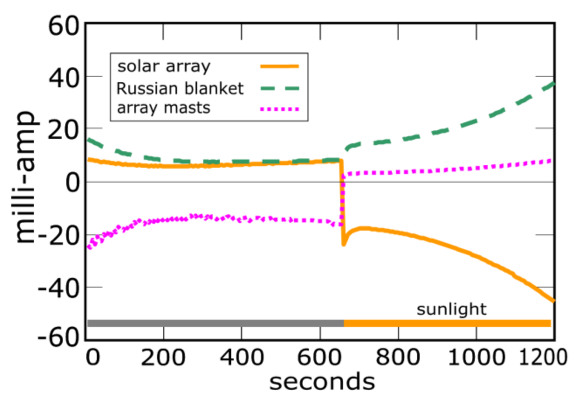

Figure 12.—PIM modelled currents contributing to ISS charging with No Orion; the case (A) in Figure 11.

The severe charging approaching –80 V seen in Figure 11 for the exposed metal variant SA case indicates that the end termination covering for the baseline design is effective in protecting ISS from charging. Currents modelled from the exposed metal coupon are illustrated in Figure 13. There is an immediate transient at eclipse exit. During the transient current balance is not maintained; corresponding to a rapid accumulation of several hundred milli-coulombs if negative charge on the ISS.

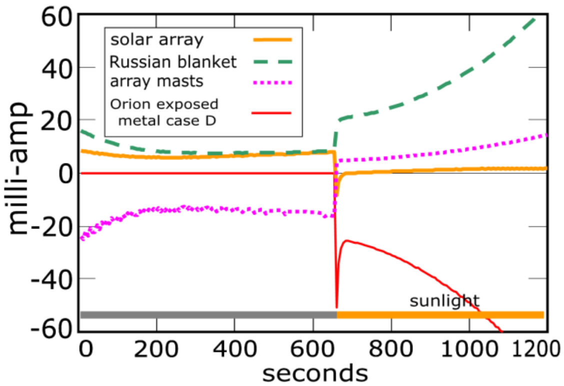

Figure 13.—PIM modelled currents using the exposed metal control data set.

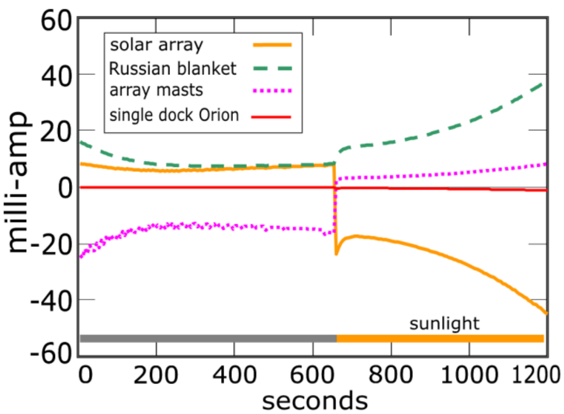

Figure 14.—PIM modelled currents with a baseline single docked Orion.

The currents, amounting to on the order of 50 mA, supplied by the exposed metal in this simulation overwhelm all other sources of negative current. This explains the rapid jump in floating potential seen in the simulation illustrated in Figure 11 for the exposed metal SA case. We emphasize that at eclipse exit current balance is not maintained and the metal on the vehicle accumulates a net negative electric charge of about 500 milli-coulombs until equilibrium in current balance is re-established after a few seconds.

Figure 14 on the other hand illustrates Orion currents for the single docked baseline design adopted for the integrated vehicle. We observe that the modelled currents from the Orion are near zero which explains the close conformance of FP model result seen in Figure 11 between the baseline and single dock Orion result.

4.3 Simulation Result—Negligible Orion SA Impact

The Orion model results seen in Figure 11 illustrate that the Orion array design produces negligible impact on ISS charging for this typical scenario. An audit of the result indicates that the Dual Dock Orion (trace C in Figure 11) produces less than 2 V extra charging.

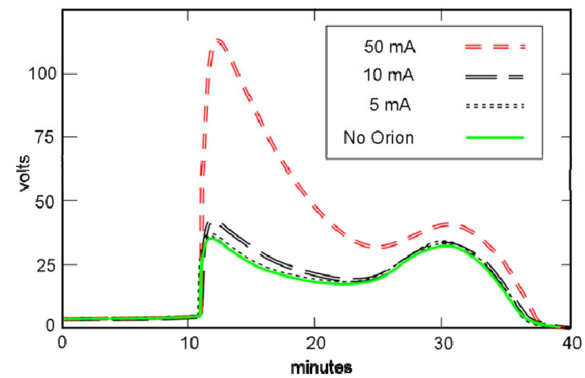

Figure 15.—Summary of trade study showing that 5 mA limit contributes negligible impact to mated ISS - VV configuration.

5.0 Trade Study

The simulation result described in section 4.0 contains uncertainty because the Equation (6) model is derived from Langmuir probe characteristics having near optimal current collection characteristics. In contrast, the arbitrary orientation and exposure of metal and semi-conductor on the Orion SA coupons presents an uncertain and complex electron collection characteristic. While the simulation, based on plasma chamber measured current suggests that the Orion design is acceptable, it is necessary for us to provide an objective standard to assess VV generically. To this end we have undertaken a trade study.

In the trade study we set aside the complex VV modeling strategy of Equation (6) that uses the data from Figure 7 and invoke instead an analysis to establish the VV induced current limit that yields negligible impact to ISS-VV integrated vehicle.

For the trade study the Orion model was modified to deliver a simple constant current when illuminated in sunlight and zero current when in eclipse. The parameter was varied among 5, 10, and 50 mA. This variation is consistent with the order of magnitudes seen in the simulation results for the exposed metal case of Figure 13 and the single docked baseline Orion case of Figure 14. The trade study result is shown in Figure 15. It is seen that when current delivered by a VV is 5 mA or less negligible additional charging is experienced by ISS.

6.0 Summary and Conclusions

The electrical power system design for the ISS and the various VV address requirements imposed by obligations associated with the particular vehicle architecture. As we have pointed out, when VV dock with ISS the electrical grounds are joined and the current collection characteristics contribute to the aggregate electrical floating potential of the combined ISS and VV.

We have studied theoretically the electrical charging contribution from the baseline Orion solar array and also from a special variant with exposed metal end turnarounds. The result of the calculation indicates that the baseline Orion arrays are a well integrated design and will contribute no more than about 2 V under worst case conditions to ISS electrical charge. The simulation from the exposed metal variant produced unacceptable charging of ISS approaching –80 V.

A trade study was undertaken to provide an objective criterion for VV integration into ISS. It was found that a 5 mA limit on current provided by VV made less than 2 V contribution to ISS floating potential under worst case conditions and it is proposed to be an acceptable electric current for design purposes.

6.1 Orion Design Characteristics Contributing to Electrical Charging Relief

The covering of the metal turnarounds seen in Figure 6 and covering of the photoactive substrate on the back of the cells is found to provide relief of ISS charging concerns. There remain metallic intercell interconnects and some exposed substrate in gaps between cells but these are not contributing significant current under the most adverse conditions encountered.

6.2 Multiple Docked VV Concerns

The ISS provides docking ports for multiple VV and we are proposing that 5 mA is a design criterion to limit adverse charging effects. This raises the challenge of apportioning 5 mA to any combined fleet of docked VV. The resolution of this matter is a subject of continuing study.

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14. ABSTRACT The International Space Station (ISS) undergoes electrical charging in low Earth orbit (LEO) due to positively biased, exposed conductors on solar arrays that collect electrical charges from the space plasma. Exposed solar array conductors predominately collect negatively charged electrons and thus drive the metal ISS structure electrical ground to a negative floating potential (FP) relative to plasma. This FP is variable in location and time as a result of local ionospheric conditions. ISS motion through Earth's magnetic field creates an addition inductive voltage up to 20 positive and negative volts across ISS structure depending on its attitude and location in orbit. ISS Visiting Vehicles (VVs), such as the planned Orion crew exploration vehicle, contribute to the ISS plasma charging processes. Upon physical contact with ISS, the current collection properties of VVs combine with ISS. This is an ISS integration concern as FP must be controlled to minimize arcing of ISS surfaces and ensure proper management of extra vehicular activity crewman shock hazards. This report is an assessment of ISS induced charging from docked Orion vehicles employing negatively grounded, 130 volt class, UltraFlex (ATK Space Systems) solar arrays. To assess plasma electron current collection characteristics, Orion solar cell test coupons were constructed and subjected to plasma chamber current collection measurements. During these tests, coupon solar cells were biased between 0 and 120 V while immersed in a simulated LEO plasma. Tests were performed using several different simulated LEO plasma densities and temperatures. These data and associated theoretical scaling of plasma properties, were combined in a numerical model which was integrated into the Boeing Plasma Interaction Model. It was found that the solar array design for Orion will not affect the ISS FP by more than about 2 V during worst case charging conditions. This assessment also motivated a trade study to determine acceptable plasma electron current levels that can be collected by a single or combined fleet of ISS-docked VVs.					
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