CHARGING OF THE INTERNATIONAL SPACE STATION DUE TO ITS HIGH VOLTAGE SOLAR ARRAYS

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INTRODUCTION

The International Space Station (ISS) has the highest voltage solar arrays ever flown in Low Earth Orbit (LEO, see figure 1). The ISS power system (and structure) ground is at the negative end of the 160 V solar arrays. Due to plasma current collection balance that must be maintained in LEO, it is possible for a spacecraft to charge negative of the ambient plasma by up to its entire solar array voltage (-160 V for ISS, see reference 1).

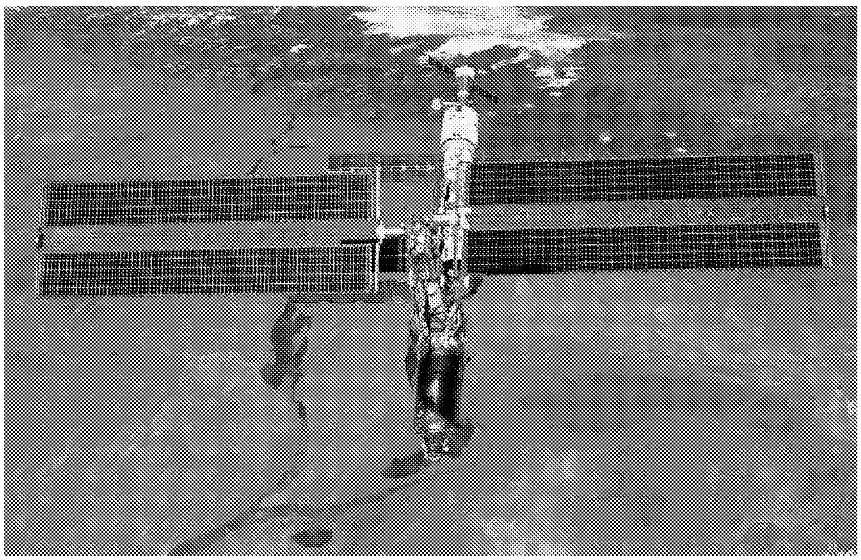
Figure 1. ISS after mission build 7A. The 160 V solar arrays are horizontal.

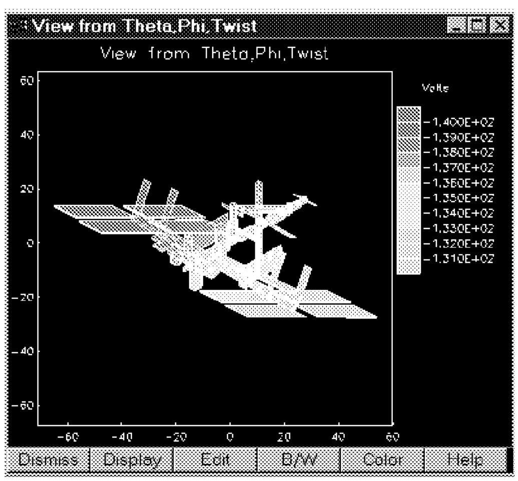

Figure 2. A model prediction of ISS “floating potentials.”

In 1990 and 1991, an Electrical Grounding Tiger Team was instituted to determine the effects on ISS of its 160 V negative ground system. The Tiger Team predicted that ISS would "float" at –140 V (see figure 2), and this would cause its anodized aluminum surfaces to undergo dielectric breakdown, ruining their thermal properties. The best estimate of the time to remove enough anodize to violate temperature constraints was determined to be two years (ref. 2). Because of this failure mechanism, in 1991, the Electrical Grounding Tiger Team recommended that the ISS potential be controlled by incorporating a Hollow Cathode Plasma Contactor to ground it to the ambient plasma (ref. 3). Plasma Contacting Units (PCUs) were baselined, constructed, and made ready to fly by ISS mission 3A, and would be activated by mission 4A, when the high voltage solar arrays would be launched and turned on (see figure 3).

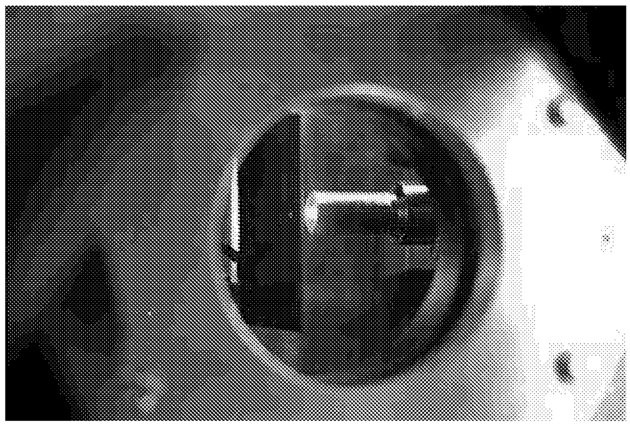

Figure 3. One of the hollow cathodes used on the ISS PCUs, undergoing ground testing in a GRC plasma chamber.

RECENT DEVELOPMENTS

In the meantime, the phenomenon of sustained arcing was discovered (by partial destruction on orbit of some SS/Loral solar arrays, see ref. 4). Sustained arcing occurs when an arc into the space plasma transitions into an arc between spacecraft surfaces that can be powered in a sustained manner by the spacecraft power system. Like the arc in a welding torch, one such sustained arc can lead to immense damage. The prospect of this new type of catastrophic arcing, combined with acceptance testing difficulties with the PCUs in early 2000, led to a re-examination of the criticality of PCU operation. After the author presented talks at the Johnson Space Center (JSC) at the invitation of the Independent Assessment Office (ref. 5), a PCU Tiger Team was set up to find answers before flight 4A in December, 2000.

Figure 4. A sustained arc on a solar array in a simulated LEO plasma.

The PCU Tiger Team results were surprising. Although sustained arcing was not verified in testing, it was found that the arc threshold voltage for materials on the Extravehicular Mobility Unit (EMU, or spacesuit) was less than -70 V (see ref. 6). A safety rule now requires that the EMU voltage be held less than -40 V from the plasma. A "sneak circuit" analysis, performed by Hamilton Standard, the EMU manufacturer, found that the astronaut would be in the path to ground of arc currents on his suit through his tether to ISS. The capacitance discharged in an arc would be >1000 μF, leading possibly to arc energies of > 10 Joules. Lethal arc currents of > 1 A were predicted in an astronaut's body.

Suddenly, arcing on ISS became a catastrophic hazard to the astronauts, requiring two fault tolerance (3 independent controls) during EVAs (extravehicular activities, or space walks). Testing showed that both PCUs could be operated simultaneously, giving two controls.
The third control would have to come from passive techniques – shunting the arrays or pointing them into their own wakes, so they couldn't collect charging currents.

Passive potential control techniques would have to be verified on orbit, requiring measurement of the ISS floating potential. A floating potential probe (FPP) would have to be implemented on ISS before flight 4A. Amazingly, the FPP (based on plasma probes flown on STS-62, see fig. 5) was designed, constructed, qualified, integrated, and flown in only 6 months (June-November, 2000). On 4A, it was installed atop the ISS truss structure by astronauts Tanner and Noriega (fig. 7). On December 8, 2000, FPP started measuring ISS potentials and parameters of the ambient plasma.

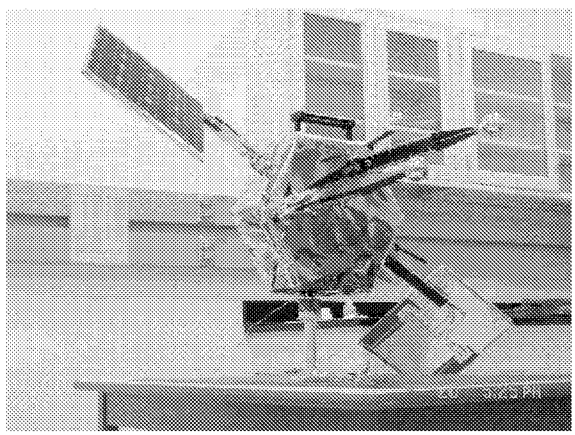

Figure 5. The FPP at Cape Canaveral, prior to launch.

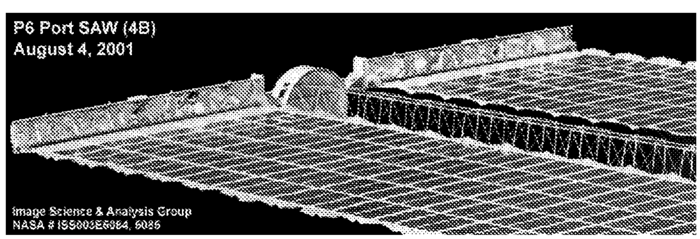

Figure 6. Wires on the Solar Array Mast collect ions.

FPP RESULTS

FPP showed that shunting and/or pointing the arrays even a little into their wakes were valid EVA shock hazard controls. FPP also showed that even with the arrays inactive, the ISS floating potential can vary by 15 volts or more during an orbit. This is due to electron collection by wires on the solar array masts (fig. 6). vxB.l is the amount of charging caused by the passive electron collection. This vxB charging must be added to real solar array charging for various places on the ISS structure to find the potential with respect to the surrounding ambient plasma.

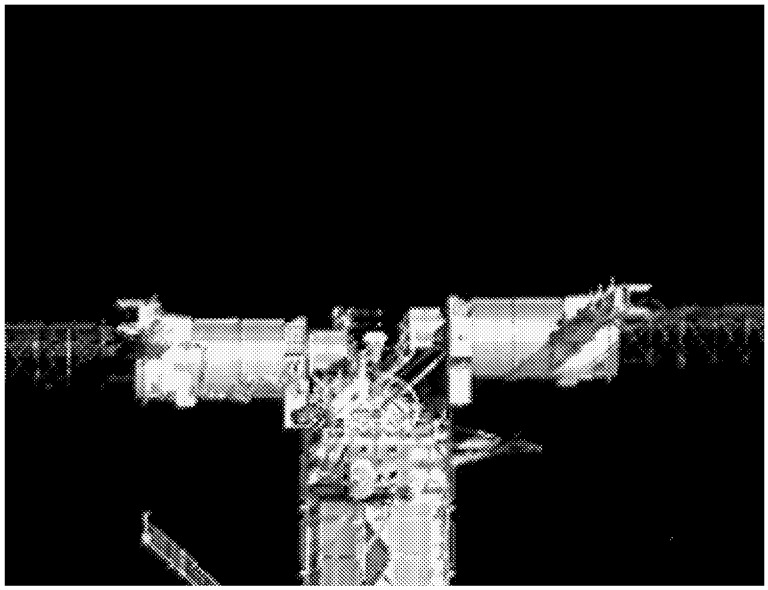

Figure 7. FPP on orbit. The two plasma diagnostic spheres are near the picture center.

FPP tests done outside EVA periods with the arrays fully unshunted and the PCUs purposely turned off showed that both solar arrays now on ISS together only charge it about -25 volts, not the –140 volts predicted (see fig. 8). Even counting a maximum of 15 volts of vxB charging, this amounts to only –40 V. Why were the predictions inadequate? The two reasons:

1. The solar arrays collect much less electron current from the plasma than expected from the previous ground and flight-test experiments.
2. The ISS structure has about 10 m^2 of extra, exposed grounded conductor in contact with the plasma, which collects ions and reduces ISS charging.

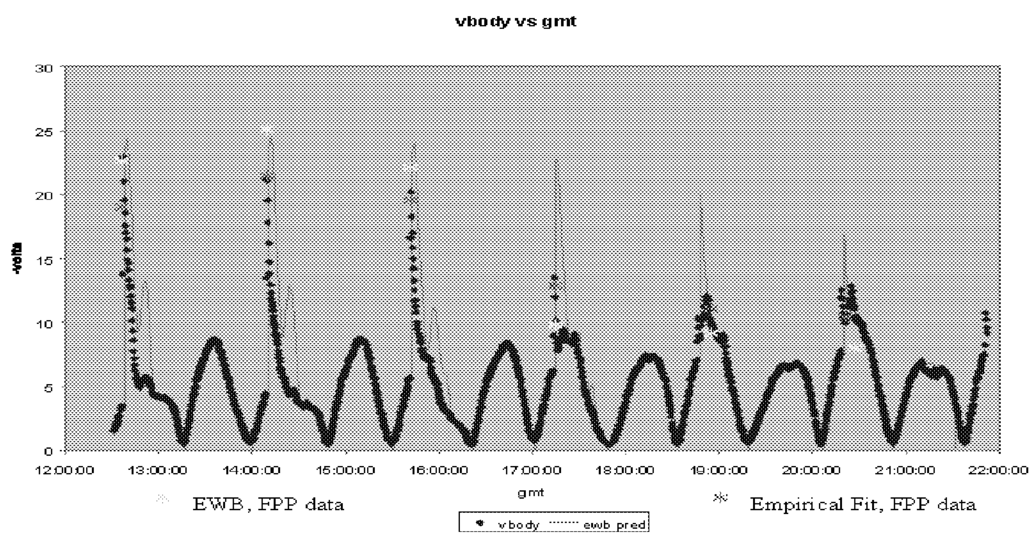

Figure 8. FPP measurements (blue) and model fits (other colors) for April 11, 2001.

ISS solar array electron collection was expected to be somewhere between the results found from the SAMPIE and PASP Plus flight experiments (1994, ref. 7). On ISS, the solar arrays collect even less current than the least amount found in those two flight tests. Although ISS is advertised to be completely covered with insulating material (thermal blankets or anodized aluminum) bare stainless steel grounded fasteners are located all over ISS structure, and these act to collect ions from the ambient plasma, minimizing negative charging.

NEW FINDINGS ABOUT PLASMA DEPENDENCES

ISS solar array electron collection and ISS charging have been found from FPP measurements to be strongly inversely related to the ambient electron temperature. An empirical ISS charging relationship (the Ferguson-Morton relation, ref. 8) has been found from FPP data to be:

$$-V = 2.69\, N_e^{\,0.1}\, e^{-8T_e},$$

where N_e is the electron density (m^{-3}), and T_e is the electron temperature (eV). This surprising relation says that ISS will charge more negative when the electron density is high (a weak dependence) but the electron temperature is low (a strong dependence). Electron temperatures are lowest at dawn.

POSSIBLE FUTURE ISS CHARGING PROBLEMS

On future ISS missions (> 12A, November 2002) more solar arrays will be added, but it is unlikely that the amount of added ion collecting truss structure will be able to keep up. The new main ISS truss will maximize vxB charging. From one end of the truss to the other, vxB.l itself amounts to almost 40 V (the maximum the safety rule allows). Also, FPP has stopped working, and it may not be replaced by 12A. When changing arrays, or when replacing PCUs, one PCU must be inactivated. As time goes on, the ionospheric plasma temperature will decrease, as we get closer to solar minimum again. All of these circumstances make catastrophic arcing more probable.

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