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POSITIVE VOLTAGE HAZARD TO EMU CREWMAN FROM CURRENTS THROUGH PLASMA

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ABSTRACT

The International Space Station (ISS) in its transit through the ionosphere experiences a variable electrical potential between its bonded structure and the overlying ionospheric plasma. The 160 volt solar arrays on ISS are grounded negative and drive structure to negative floating potential (FP) relative to plasma. This potential is a result of the asymmetric collection properties of currents from ions and electrons moderated by geomagnetic; so called v × B induction distributing an additional 20 volts both positive and negative across ISS's main structural truss element.

Since the space suit or extravehicular mobility unit (EMU) does not protect the crewperson from electrical shock, during extra vehicular activity (EVA) the person is exposed to a hazard from the potential when any of the several metallic suit penetrations come in direct contact with ISS structure. The moisture soaked garment worn by the crewperson and the large interior metal contact areas facilitate currents through the crewperson's body.

There are two hazards; Negative and Positive FP. The Negative hazard is the better known risk created by a shock hazard from arcing of anodized material on the EMU. Negative hazard has been controlled by plasma contactor units (PCU) containing a reserve of Xenon gas which is expelled from ISS. The PCU provide a ground path for the negative charge from the structure to flow to exterior plasma bringing ISS FP closer to zero.

The understanding has now emerged that the operation of PCUs to protect the crewmen from negative voltage exposes him to low to moderate positive voltage (≤15V).

Positive voltage is also a hazard as it focuses electrons onto exposed metal EMU penetrations completing a circuit from plasma through interior contact with the moist crewman's body and on to ISS ground through any of several secondary isolated metal penetrations. The resulting direct current from positive voltage exposure is now identified as an electrical shock hazard.

This paper describes the model of the EMU with a human body in the circuit that has been used by NASA to evaluate the low positive voltage hazard. The model utilizes the electron collection characterization from on orbit Langmuir probe data as representative of electron collection to a positive charged surface with a wide range of on orbit plasma temperature and density conditions. The data has been unified according to non-linear theoretical temperature and density variation of the electron saturated probe current collection theory and used as a model for the electron collection at EMU surfaces. Vulnerable paths through the EMU connecting through the crewman's body have been identified along with electrical impedance of the exposed body parts. The body impedance information is merged with the electron collection characteristics in circuit simulation software (SPICE).

The assessment shows that currents can be on the order of 20 mA for a 15 V exposure and of order 4 mA at 3V. These currents formally violate NASA protocol for electric current exposures however the human factors associated with subjective consequences of noxious stimuli from low voltage exposure during the stressful conditions of EVA are an area of active inquiry.

1. INTRODUCTION

The International Space Station (ISS) is a large spacecraft moving rapidly through electrically conducting ionospheric plasma. The architecture of ISS incorporates an approximately 100 m long main truss. In the typical flight attitude the truss presents a geometric extension perpendicular to the direction of motion. Voltage adjusts naturally on the vehicle and is induced by a solar power system operation and vehicle architecture. Electrical currents flow through the vehicle and through the environment between different parts of the vehicle.

1.1. Electric Current Collect from Ionosphere Plasma

The solar arrays operate at positive 160 Volts and are grounded at the negative terminal. All metal parts of the vehicle are carefully bonded. Although the solar arrays do not expose any electrically conducting metal, there are gaps between the glass covering the electrically conducting photoactive substrate. This permits electrons to collect on the positive charged substrate and drive current to the structural metal through the negative ground.

Also, the vehicle is moving rapidly through the ionospheric plasma. The Earth's magnetic field is embedded through this electrically conducting medium and presents an electrical dynamo electro-motive force. The flowing plasma induces an electrical voltage drop in the environmental plasma across the structure. The bonded structure always assumes a near constant potential. The induced electrical force has its origin in the Lorentz electric field which is proportional to the cross product of vehicle velocity and the Earth's magnetic field at the vehicle location:

$$E = v \times B \quad (1)$$

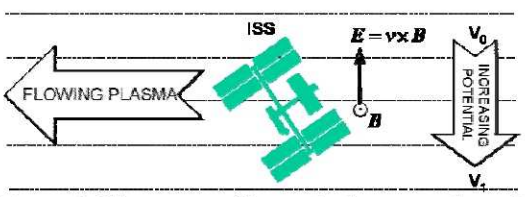

Figure 1. Illustration of how vehicle motion through geomagnetic field induces a voltage drop through the plasma surrounding the spacecraft.

We refer to the induced voltage drop in the plasma as **v ×B** ("V cross B"). The magnitude of **v ×B** is about ¼ to ½ volt per meter and can amount to about 40 volts across the entire ISS structure at some geographic locations along its orbit.

There is another source of electrical charging. The ISS solar arrays are 160 volt direct current sources and are negative grounded to the station structure. There is

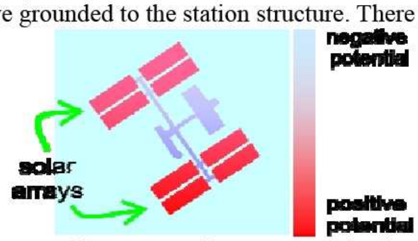

Figure 2. Illustration of how grounded solar arrays and v × B induction drive structure to a negative potential relative to the outside plasma.

ample exposed conducting area and several hundred square meters of chemically anodized aluminium that can store charge [0]. The amount of electrical charge on the structure is established by convergence of currents from electrons collected at positively charged surfaces and from positive ions impacting negative charged areas that remove electrons from the surface.

The Boeing Company has developed numerical modelling technology used to predict and assess ISS electrical charging theoretically and NASA has installed a floating potential measurement unit (FPMU) to observe the floating potential directly. Boeing's theoretical model is the Plasma Interaction Model (PIM) [2]. The model in PIM simulates electron collection at positive surfaces and the removal of electrons by ions from negative bare metal surfaces. The collection and removal processes are simulated in PIM. The processes are moderated by simulation of **v×B** distributed in three dimensions across the structure with the geographic distribution of magnetic field. The capacitance contributed by the anodized elements is also simulated. The skill exhibited by the Boeing PIM is illustrated in Figure 3.

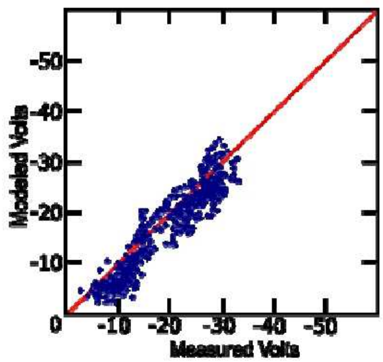

Figure 3. Demonstration of skill of the Boeing Plasma Interaction Model at eclipse exit.

The figure shows peak modelled potential at eclipse exit compared to the corresponding measured value from the FPMU.

2. ELECTRIC SHOCK IN EMU FROM FLOATING POTENIAL

The astronauts on ISS employ a space suit known to NASA as the Extravehicular Mobility Unit (EMU). The EMU illustrated in Figure 4 evolves from space shuttle applications. It consists of a hard shell upper torso which is articulated through stainless steel rings to the arm assemblies and the lower body assembly.

2.1. Susceptibility of Human Body in EMU

The EMU provides a life supporting environment. Inside the EMU the crewman wears a Liquid Cooling & Ventilation Garment (LCVG) which is a close fitting long underwear covering the torso, arms and legs. It incorporates a network of tubing circulating cooling water around the crewman's body. The EMU suit contractor and support personnel report that, despite the cooling provided by LCVG, the garment usually becomes soaked with moisture primarily from exhaled breath and other occasionally other sources of moisture such as urine, spilled drink and water leaks from the

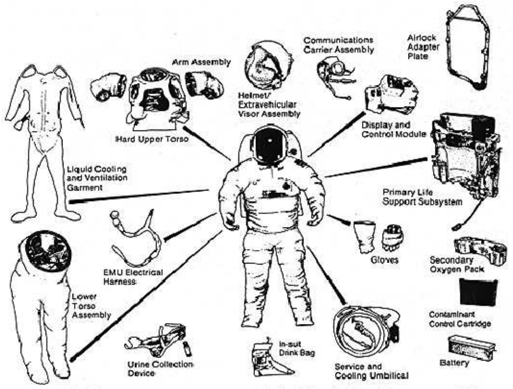

Figure 4. Demonstration of skill of the Boeing Plasma Interaction Model at eclipse exit.

LCVG. So the environment during EVA inside the EMU is usually very wet.

2.2. Moisture reduces human skin resistance.

The human skin illustrated in cross section in Figure 5 is composed of two layers. The outer layer known as epidermis is composed of keratin derived from dead cells. The Inner layer or dermis is comprised of a combination of living cells, blood vessels and bundles of collagen fibrils oriented in all directions. The distribution of skin thickness varies over different body areas. The epidermis thickness rages from 10 to 100 μm. The corneum; the outer most layer of dead cells

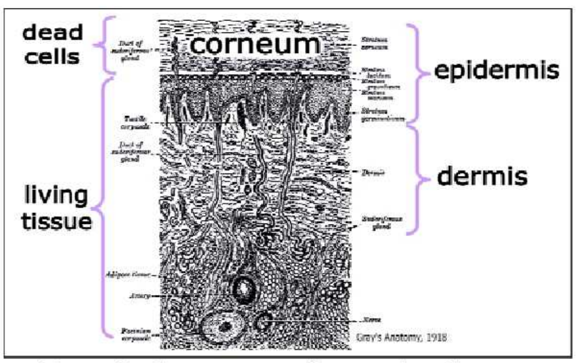

Figure 5. Cross section of human skin. Corneum stratum presents high electrical resistance which is diminished when skin becomes suffused with moisture in the EMU.

shown in Figure 5, is a poor conductor of electricity. It contributes relatively high resistance to electric shock.

When wet, sweaty or bypassed as with an injury, the conductivity rises dramatically. When the skin is soaked for extended periods the corneum layer becomes saturated resulting in a familiar clammy skin phenomenon. The liquid element in the clammy skin resembles sweat and is chiefly 0.1 to 0.4% Sodium Chloride with an electrical resistivity of about 140 Ω-cm. This effectively eliminates the resistance of the corneum layer compared to underlying tissue.

2.3. Human Body Electrical Impedance.

Electrical resistance in the skin contributes the largest fraction to the total impedance through current paths involving the human body. The internal resistance is difficult to study owing to ethical constraints on human body exposure to electric shock. It is known that impedance of living tissue is not linear in voltage owing to the biochemical response of the tissue to the electric shock. The impedance at low voltage (<40 volts), from hand to hand or from hand to foot, is an area of active research [3]. Resistance of paths between hands or from hand to foot when skin resistance is impaired is typically on the order of 100 to 1000 Ω.

2.4. EMU does not protect from electric shock.

The EMU does not provide protection from electrical shock. The suit incorporates multiple metal penetrations that simultaneously connect the crewman's body with the suit exterior. The most notorious example is represented by a strip of stainless steel surrounding the waist inside the suit and connecting to the outside through two D shaped rings used to connect a safety tether. There are also metal arm rings and wrist rings as well as metal contact points associated with a body seal enclosure around the hard upper torso assembly. None of these penetrations are intentionally bonded to a unified ground.

As a result of the un-bonded metal penetrations and his clammy skin, the astronaut's body presents low impedance electrical connection between unconnected metal contact points that are continuous with the exterior.

3. ELECTRIC VOLTAGE HAZARD

The ISS Vehicle floating potential distributes across the vehicle. During nominal operations the voltage floats to an overall negative potential and the **v×B** induction overlays across the truss as seen in Figure 6. The colour contours in Figure 6 denote the potential difference between the structure and the plasma. In Figure 6, the plasma is treated as a zero potential ground. However, the structure is actually at a nearly constant potential and the variation illustrated is a result of the induced v×B potential in the plasma outside the structure.

As we have pointed out the EMU provides un-bonded metallic penetrations coming in contact with the astronaut's body whose skin has become suffused with moisture. The reduction in skin resistance resulting from the moist environment provides several plausible electrical paths with current closing through the astronaut's body.

Figure 7. Arcing. Electrical breakdown of chemical coating on aluminium structural elements.

Two electrical hazards have emerged. One hazard is associated with the negative potential of the structure relative to the plasma and involves arcing of anodized elements on the suit with attendant electric current involving the astronaut's body. The other hazard involves direct collection of electrons to some limited bare metal areas on the EMU that can similarly close back to structure through the astronaut's body. In the following section we briefly examine the negative voltage hazard and the Plasma Contactor Units (PCU) that mitigate it. We then turn attention to a positive voltage hazard that emerges primarily as a result of operation of the PCUs.

3.1. Negative Voltage Hazard

The negative voltage on the structure, which under some condition may approach -80 volts at the tip of the truss, is a hazard to the crew. The hazard results from the fact that surface elements on the EMU can electrically breakdown or arc. The arcing which is sketched schematically in Figure 7, results from an electric field applying stress to the oxide coating. Arcing has been studied in the laboratory and is found to be controlled not only by the voltage but the amount of time exposed to the potential and the thickness of the oxide layer. Arcing for examples has been observed on EMU similar materials at negative voltage as low as 39 volts but such events require up to 24 hours of continuous exposure and once they commence proceed at progressively longer intervals.

The laboratory data in Figure 8 dramatically illustrates the result of a plasma chamber test of an anodized coupon biased to -80 volts under argon plasma. The plasma source was toggled on and off in 5 minute intervals. The test illustrates that there are no arcs occurring when the plasma source is off and then suddenly commence every few seconds when the source is on. Electrical systems on ISS are well protected from the resulting transient currents. If the currents associated with such arcs were to involve parts of the human body with associated impedance ranging over a few hundred ohms then 100s of mA are predicted to flow through the involved human tissue [4].

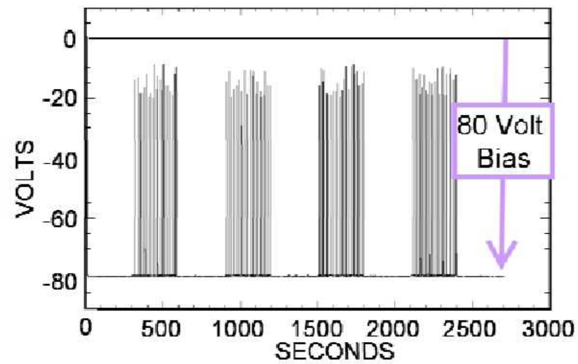

Figure 8. Plasma source is alternately turned on and off in plasma chamber. Electrical breakdown of chemical coating on aluminium structural elements occurs every few seconds while the source is on and is arrested when the source is off.

The arc could occur if a suit penetration were to come in contact with the structure. In that scenario, the penetration, say at the wrist, would contact structure at a location where it is charged to a negative potential, say -80 volts. The astronaut's EMU and his entire body assume that potential. The arc facilitates a current from the plasma, through the metal suit penetration and closing through the astronaut's body to a separate penetration touching the structure and back to ISS. The effect has been readily observed in the laboratory simulations where the astronaut's body is simulated with an appropriate electrical resistance.

4. PCU OPERATION

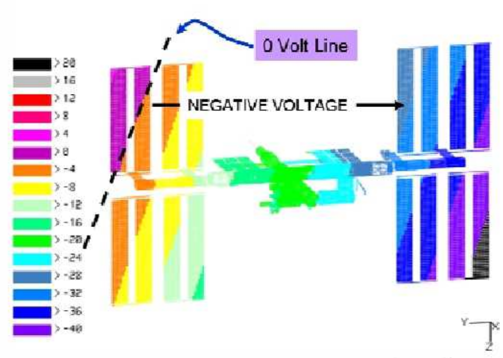

Figure 6. During non-EVA operation distribution of floating potential across vehicle on ISS floats to an overall negative potential. Induced v×B potential in the plasma distributes across the structure.

As a result of the identified negative potential hazard, plasma contactor units (PCU) are employed to control the voltage. The PCU is a Xenon plasma source. There are two deployed on ISS. The purpose of the PCU is to overcome the resistance of the plasma sheath surrounding the ISS structure which insulates the structure and supports the negative charge.

4.1. PCU Raises Potential of the Structure

It is appropriate to think of the plasma stream emitted from the PCU as "grounding strap" effectively increasing the flow of electrons from the structure and bringing its potential closer to zero volts. The effect is

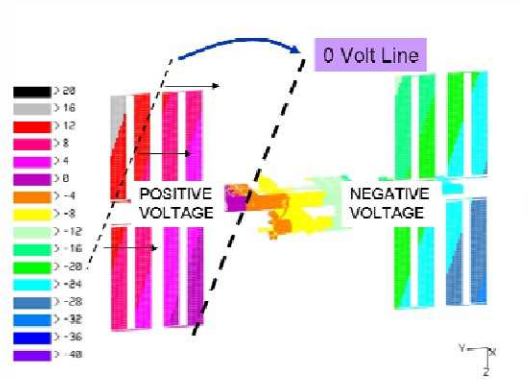

Figure 9. PCU operation brings negative potential on structure higher and shifts the null voltage point closer to the vehicle center. PCU cause significant positive voltage to appear on the vehicle.

illustrated in Figure 9 showing how the grounding effect from PCUs shifts the potential higher and brings the null contour closer to the center of the vehicle. The largest potential that astronauts will be exposed to is about 15 volts during EVA excursions to the truss tips.

4.2. PCU Enhance a Positive Voltage Hazard

The PCU therefore have the effect of protecting the astronaut from electric shock resulting from arcing. Experience with plasma diagnostic instrumentation on

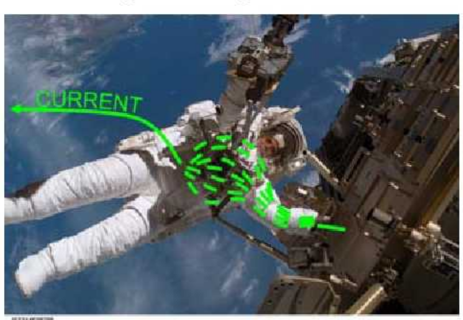

Figure 10. The positive voltage hazard. PCU cause positive voltage to appear on the vehicle which can attract electrons to bare metal parts on the EMU completing a circuit through the EVA crewman's body.

the ISS contributes to an understanding that positive voltage is also a hazard. Positive charged conductors attract electrons which are highly mobile.

A plausible scenario emerges as illustrated in Figure 10. The astronaut's wrist, in that example, comes in contact with the positively charged structure. At the same time, bare metal in electrical contact with an alternate suit penetration is exposed to electrons in the plasma. The electrons are strongly attracted to the positive surface and support a current which then closes through a portion of the astronaut's body to the wrist.

The same hazard does not exist at a negative voltage because the current through the circuit in that case would be constrained by the relatively heavy O^+ ions rather than the highly mobile electrons. The positive potential hazard exists, not because anodized material breaks down, but because electrons collect easily supporting direct current through the astronaut's body.

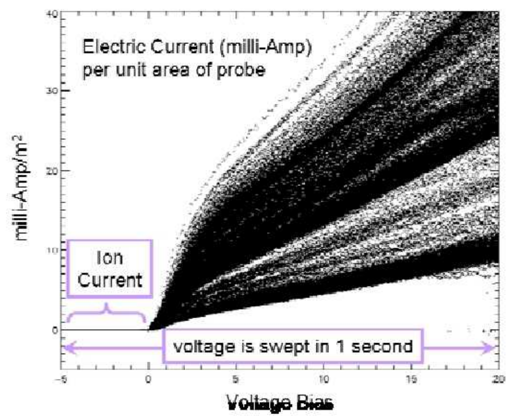

Figure 11. Langmuir probe current as a function of voltage bias. Electrons contribute to high current collected at a positively charged surface.

The physical principles governing current collection at conducting surfaces in plasma is well developed. The principle is exploited in instrumentation developed in the 1920s and attributed to Irving Langmuir to investigate the nature of plasma from its collection characteristics. The Langmuir probe is a bare conductor immersed in plasma and biased positive or negative while the current is recorded. Two Langmuir probes are deployed on ISS as part of the Floating Potential Measurement Unit (FPMU).

Figure 11 shows an ensemble of current voltage (I-V) sweeps from one of the ISS Langmuir probes. The characteristic signature from the I-V sweep is shown in the collection of many 1 second sweeps. The plasma environment in orbit with the ISS is predominantly singly charged atomic oxygen (O^+). At negative potential the current is very small corresponding to ion collection at the probe surface which recombines with an electron in the metal and leaves behind the ion's conjugate electron in the plasma. The net is that the O^+ provides a strongly limited current to the probe. At positive potential however, the O^+ is repelled and instead, electrons are readily attracted and contribute to current which is orders of magnitude larger than the corresponding current supplied by the ions at negative bias. This is the same physics contributing to the current collection asymmetry presented by a vacuum tube diode.

5. EMU MODEL

The data illustrated in Figure 11 forms the basis for a current collection model to evaluate the positive voltage hazard at the exposed elements on the EMU surface as described in commentary surrounding Figure 10. The wide variation in current we see in Figure 11 results from changing plasma state as ISS orbits Earth. The variation can be unified theoretically by normalizing to non-dimensional current and potential.

The plasma state, consisting of density (*n*) and temperature (*T*) are continuously monitored by our analytical evaluation of the Langmuir probe I-V sweeps while the FPMU is in operation.

5.1. Theoretical Treatment of Electron Collection

The normalized, non-dimensional current Ψ and voltage X are given by:

$$\Psi = \frac{I_{Probe}}{env_e A} \qquad (2)$$

$$X = \frac{eV}{k_B T} \qquad (3)$$

Where I_{Probe} is the current collected by the probe and V is the bias voltage as in Figure 11. Additional parameters are the electronic charge (e=+1.6×10^{-19} coulombs), the plasma density (n in m^{-3}). A is the probe collection area in m^2, k_B is Boltzman's constant (= 1.38×10^{-23} J/K. The term v_e is the electron thermal velocity; $v_e = \sqrt{k_B T / 2\pi m_e}$. A plot of Ψ versus X shows that the normalization unifies the variation seen in the original un-normalized data.

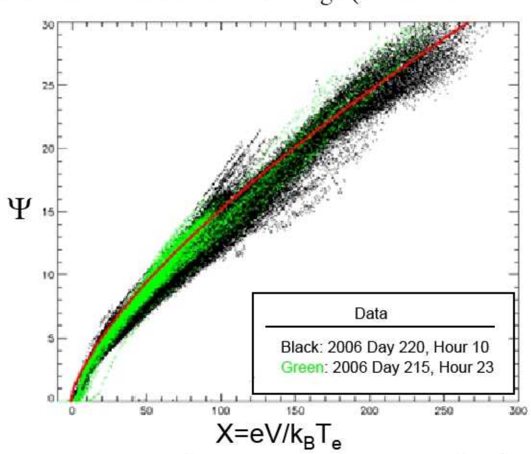

Figure 12. Same data as inFigure 11 normalized to electron temperature, density and collection area according to Equations (2) and (3).

Figure 12 then forms the basis of an electron collection model. The curve fit to the data is shown as a red line and is given by;

$$\Psi(X) = 0.6 \times (1 + X)^{0.7} \qquad (4)$$

With the definition of Ψ in Equation (2) we obtain:

$$I_T(n,T) = e \cdot n \cdot v_e A \times (1 + X)^{0.7} , \qquad (5)$$

and this provides a useful formula to model current to charged surfaces. We must point out that there is physical significance to the exponent (0.7) in Equation (5) but it is not of concern here. There is considerable uncertainty about the exact shape of current collection characteristics for the arbitrary shapes encountered on the EMU. We wish to emphasize clearly that Equation (5) only characterizes the data in Figure 11 which was collected over a wide range of plasma temperature and density encountered on ISS in its orbit around the Earth.

5.2. EMU Electron Collection Surfaces.

In one sense, the Langmuir probes are optimally configured to collect electrons. On the other hand, conductors on the EMU are situated in unpredictable attitudes and orientation and mounted adjacent to dielectrics that guide currents in an unknown manner. We know that electrons collected at the gaps in solar cells do not collect according to a simple Langmuir probe theory – the surrounding glass has been shown to modify electron collection under some circumstances.

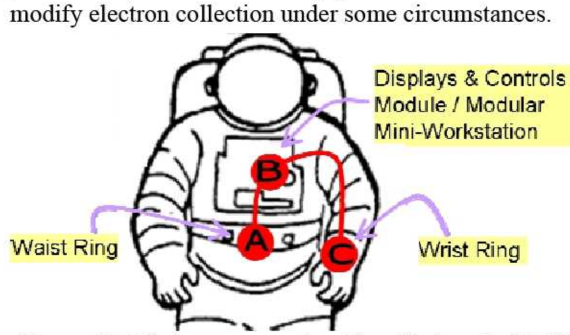

Figure 13. Likely contact points identified on the EMU. The area of the stainless steel tether combined with bare metal at point B provides up to 0.82 m2 of electron collection area at positive voltage.

The amount of bare metal area on the EMU was assessed by the EMU contractor for this study. It was found that there are three points where contact is possible. The role of the stainless steel safety tether is also involved with the amount of area available to collect electrons. It has been observed that the safety tether makes frequent contact with metal on the wrist, the waist and the Displays and Control Module or the Modular Mini-Workstation (DCM/MMWS). The three identified contact points are illustrated in Figure 13. With the tether contact, the largest area identified by the contractor was 0.82 m^2.

Our assumption is that EMU materials exhibit collection characteristics similar to Figure 11. It is fair to say that in Figure 11 we have a piece of metal maintained at 30 or 40 volts collecting 20 or 50 mA per square meter. We expect a similar characteristic for surface conductors on the EMU.

5.3. Model Implementation

The approach to modeling the human body in contact with the positive charged ISS described schematically in Figure 10 is illustrated in a circuit diagram in Figure 14. The switch designates metal contact with the station. In this model, the human body impedance labeled A, is simulated as a conventional linear resistance. The total current adjusts and voltage (15V) is divided at V_2. Electron collection surface interaction at exposed metal surfaces is designated by the impedance labeled B. The

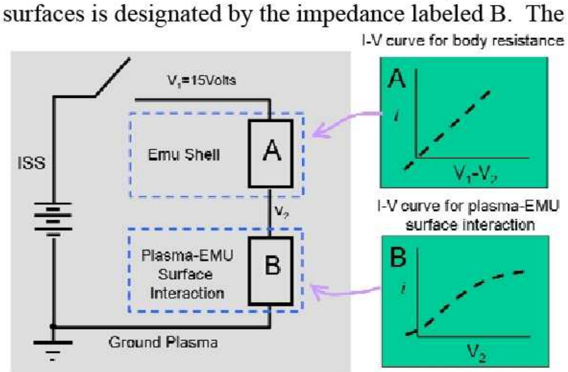

Figure 14. Circuit diagram for simulation of electrical path through human body in EMU suit.

surface interaction is treated as a non-linear device with the current voltage characterized by Equation (5). The Impedance component at B is analogous to a vacuum tube diode in series with some portion of the crewman's body.

The non-linear voltage divider is solved for current using the well know SPICE circuit analysis tool. The body impedance is simulated as a simple linear resistor. The plasma-EMU surface interaction is simulated using a non-linear voltage controlled current element in SPICE.

6. HAZARD ASSESSMENT

Positive voltage is an emergent hazard for EVA on the ISS spacecraft. It was discovered in planning for a recent solar array worksite EVA. The approach to electric shock hazard assessment demands a conservative stance owing to its life critical bearing during EVA. The EVA experience for the astronaut is physically demanding and often painful involving bruising. The EVA crew are engaged in intense physical work using tools and ISS hardware. Medical operations and the EVA office have pointed out that any noxious stimulus can cause involuntary movement in the EMU which is unacceptable. A suit puncture from an uncontrolled spasm would be fatal. Even vomiting in the suit is considered a life threatening event.

6.1. Plasma Voltage Prediction is Accurate.

The EVA worksite voltage exposure as seen in Figure 6 and Figure 9 using Boeing developed capability incorporated into the PIM is accurate. The voltage effect has been validated using measurements and its distribution across the structure is a well known geometric property involving the velocity and vehicle architecture [5]. A worst case positive exposure potential of 15 volts was identified from the Boeing analysis using the PIM tool.

The primary uncertainty to the assessment involves the measurement of density and to a certain extent electron temperature derived from the Langmuir probes on the FPMU. We believe most of the scatter seen in the validation in Figure 3 results from error in measured plasma state. Some of the uncertainty may also be attributed to the effect of photoemission from negatively charged surfaces. The geomagnetic field dependency however, is modeled according to a standard high fidelity analytic model.

6.2. Electric Current Exposure and Physiologic Effect are Uncertain.

There is, on the other hand significant uncertainty with respect to the electric current magnitudes and safe electric current exposure limits. The completion of the circuit through the various contact points in Figure 13 is stochastic. There are also uncertainties resulting from the unknown effect of orientation, surface condition and geometry of bare metal on the EMU. Additionally, the proximity of dielectric surfaces near to electron collection surfaces will guide currents in unpredictable ways.

The result of the calculation of current through modelled body impedance of the astronaut's body is shown in Figure 15. The illustrated results are calculated for the worst case exposure voltage of 15 volts and at 3 volts. Exposure at 3 volts in provides perspective on the range of current anticipated.

Plasma conditions for the simulation were varied to illustrate the effect of solar conditions on the current exposure. The sun provides ultraviolet radiation which populates the ionosphere with plasma. There exists a strong solar cycle dependence on the plasma density. We simulate solar maximum conditions in Figure 15. At solar maximum, the characteristic plasma density at the ISS orbit altitude is on the order of 1×10^{12} m^{-3}. At solar minimum the corresponding density is 2×10^{11} m^{-3}. Plasma electron temperature has a weak effect on electron collection. For the simulation in Figure 15 it was maintained at 0.1 eV.

Confidence in the assessment also suffers from uncertainty in the physiologic effect of low voltage current distributed over large areas of the moisture suffused skin in the EMU. The gray highlighted body resistance zone indicated in Figure 15 represents Medical Operation's suggested range of baseline body impedance

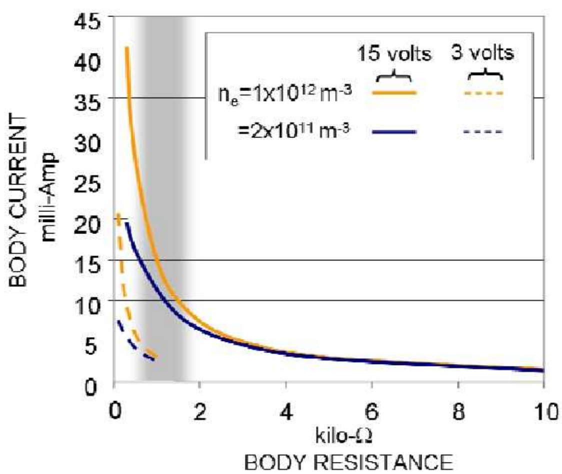

Figure 15. EMU Model Currents for 3 and 15 volt positive exposure as a function of body impedance. Bare metal collection area is 0.82 m^2. Dashed lines are 3 volt and solid lines are 15 volt exposure limits. Orange line denotes solar maximum conditions, blue line…solar minimum. Gray highlighted Body Resistance zone indicates Medical Operation's suggested range of baseline body impedance. The plasma temperature for the modeling was taken to be 0.1eV.

7. CONCLUSION AND SUMMARY

We calculate electric current exposure determined by the fundamental impedance of the human body and the characteristics of the EMU in the plasma environment. The other factors involving the amount of exposed conducting surface, the probability of contact with the wrist or tether are the responsibility of a NASA team. The assessment of that probability is an active area of interest of the NASA and contractor teams assigned to the hazard assessment.

NASA Medical Operations is presently involved in a major effort to assess the human body impedance and the physiologic thresholds for electric shock at the low voltage under the wet conditions encountered in the EMU. Animal model studies can be used to understand physiologic effects at the neurologic and cellular level. Most of the physiologic effect is a subjective experience of the human mind during the stressful EVA activity. It can only be investigated scientifically using humans. An experimental protocol subjecting a human cohort to electric shock is constrained by ethical considerations and proceeds slowly and with caution.

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