INTERNATIONAL SPACE STATION SPACECRAFT CHARGING HAZARDS: HAZARD IDENTIFICATION, MANAGEMENT, AND CONTROL METHODOLOGIES, WITH POSSIBLE APPLICATIONS TO HUMAN SPACEFLIGHT BEYOND LEO

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ABSTRACT

In this paper, we present an overview of how the International Space Station (ISS) safety engineering methodology directed to controlling extravehicular activity (EVA) crew electrical shock hazards, caused by ISS spacecraft charging, has evolved over the past 25+ years. Long-term measurements of ISS charging severity and frequency-of-occurrence, combined with detailed probabilistic analysis of EVA electric shock-circuit completion, led to a change in hazard control methodology. The requirement for two-fault tolerant EVA shock hazard control during all EVAs was replaced with a less operationally burdensome and risky EVA shock hazard detection and warning process. The applicability of event probability-based detection-and-warning processes to human spaceflight charging hazard control beyond low-earth orbit (LEO) is also considered.

1. BACKGROUND AND INTRODUCTION

ISS floating potential probe (FPP) and ISS plasma contactor unit (PCU) emission current measurements made during the years 2000 and 2001 demonstrated that the severity and duration of ISS charging events were far less than predicted by worst-case pre-flight estimates [1-4], though considerable uncertainty remained about how the hazard environment might change as ISS assembly continued.

Spacecraft-charging-driven dielectric breakdown arcing of external thin dielectric surfaces was recognized early on as the specific event causing possible hazardous outcomes affecting avionics, touch temperature of surfaces subject to EVA crew contact, and EVA crew electric shock. However, by the end of 2002, avionics effects were shown to be negligible and only the EVA hazards were still subject to active control by the ISS program. Both positive and negative ISS Floating Potential (FP) values can be EVA shock hazard causes [5,10]. Negative FP values may cause dielectric breakdown of exposed thin anodic films on the Extravehicular Mobility Unit (EMU) completing a potentially hazardous circuit through the EMU suited crew person. This is achieved by dielectric breakdown arc plasma discharging charged dielectric surfaces overlying negatively charged conducting structure [5]. Positive FP values cause collection of electron current by exposed conducting surfaces on the EMU suit and associated EVA tools. The collected current can then flow through the EVA crew person to the positively biased ISS structure. The subject hazards become possible only when electrically conducting EMU components contact ISS conducting structure, and charge is passed across the EVA crew person's body (specifically, the heart and voluntary muscle spasms).

To reduce the uncertainty in estimates of ISS charging severity as ISS construction continued, the ISS program installed a Floating Potential Measurement Unit (FPMU) on ISS during 2006 to quantify hazard severity and frequency of occurrence [6]. The FPMU measures both ISS floating potential (FP), defined as ISS conducting structure voltage measured relative to the surrounding ionospheric plasma, as well as ionospheric electron temperature (Te) and density (Ne), the most important natural environmental parameters in ISS charging models. FPMU data were validated against comparable ground-based and satellite measurements of Ne and Te [5,6]. FPMU measurement campaigns are ongoing as a key part of the EVA shock hazard detection and warning process.

Between 2006 and 2014, thousands of FPMU measurements demonstrated that hazardous ISS charging environments occur only infrequently, but not infrequently enough to ignore, largely because extremely low solar activity led to observed ionospheric densities that were too low to cause hazardous charging. Historically low solar activity during the deep solar minimum following solar cycle 23, continuing, through the weak maximum of solar cycle 24, and expected to continue through solar cycle 25 contributed to that outcome [7, 8]. However, unanticipated increases in solar activity, or specific space weather events, e.g. coronal mass ejections and associated geomagnetic storms, can lead to increased ionospheric densities that are potentially hazardous. The ISS spacecraft charging detection and warning process identifies possibly hazardous conditions before they occur and advises ISS management in time to activate EVA shock hazard controls as needed [5].

Motional electromagnetic force (motional EMF, aka magnetic induction) also contributes to ISS FP via high-speed flight through the earth's geomagnetic field. The magnitude of the effect depends on the orientation of the ISS structure with respect to the velocity vector and the geomagnetic field lines, and maximum FP voltages occur at high latitude when ISS is operating in the nominal flight attitude, where the 100-meter truss is perpendicular to the velocity vector. Small positive FP voltages (~+10V) are generated at one truss tip and larger negative FP voltages (~-40 V) are generated at the other [5].

Operation of payloads or system equipment that either collect or emit charged particles from ISS, such as experimental electric propulsion systems as well as photovoltaic or thermoelectric arrays with exposed metallic circuit elements, can also affect ISS FP. Devices emitting charged particle beams, without neutralization, can drive ISS FP to unacceptable values.

When operating, the ISS plasma contactor units (PCUs) emit current as needed to control ISS FP [1-6]. ISS carries two active PCUs enabling single-fault-tolerant ISS floating potential control. However, ISS safety requirements mandate two-fault-tolerant hazard controls for catastrophic hazards. Somewhat risky and burdensome ISS vehicle operational hazard controls provide the third hazard control when needed.

Replacing a hazard control process requiring two-fault-tolerant hazard controls for all EVAs with a detection and warning process is possible if and only if it can be demonstrated that, through a combination of in-flight measurements, ground based testing, and probabilistic analysis, the following criteria are true:

1) The probability (P1) of hazardous FP values (both positive and negative) on ISS is nominally low.
2) Space weather events and/or vehicle configuration changes leading to hazardous FP values on ISS can be identified with sufficient lead-time to enable activation of controls or rescheduling of the EVA. In addition, the expected frequency of occurrence of hazard control activation or rescheduling of EVAs must be acceptably small.
3) The probability (P2) of completing the EVA crew-hazard shock-circuit during any EVA is low.
4) The net probability of an EVA crew shock event, Ps, as a function of P1 and P2, is small enough for the ISS Program to accept the residual risk when EVA is conducted without any active hazard controls.

In the following sections of this paper, we present the analysis and supporting data demonstrating that statements 1-4 above are true. Note that in the hazard analysis presented below we treat P1 and P2 as independent random variables. P1 is very low and supports a detection-and-warning risk acceptance process instead of hazard controls because of unusually low solar activity during the past two decades, driving unusually low ionospheric densities at ISS operating altitudes. If solar activity, and hence ionospheric densities, were more typical of those observed during the 20th century, the detection and warning process would likely not be acceptable. It should also be noted that nominal ISS operations very seldom place the high voltage PV array wings in a configuration that maximized electron collection.

In this paper, we address only EVA electric shock hazards caused by ISS spacecraft charging processes. We do not address the more conventional electric shock hazards resulting from EVA galvanic contact with electrical power system conductors carrying voltage and current.

ISS spacecraft charging environments and physical mechanisms are radically different from those encountered at higher altitudes in Earth's magnetosphere and in cis-lunar and interplanetary space. ISS charging is driven by voltages generated by ISS itself, specifically the operation of the photovoltaic power system in sunlight and/or the motional EMF resulting from high-speed flight of ISS conducting structure through the geomagnetic field [5]. The internally generated voltages drive collection of ions and electrons from the relatively low-temperature, high-density ionospheric plasma that is ever-present at ISS operating altitudes [9]. Collection of ions and electrons (current collection) generates the ISS FP [1-5]. The magnitude of the FP determines the voltage drop across exposed dielectric material, as well as current collection by exposed conductors, determining the character of ISS spacecraft charging hazards [10].

The much-reduced strength of the geomagnetic field at higher altitudes and in cis-lunar space, combined with the absence of a natural ionosphere makes ISS-like charging mechanisms largely negligible [11]. Energetic charged particles (primarily energetic electrons), sunlight/photoemission, and secondary electron emission are the most important natural factors affecting spacecraft charging in magentospheric and cis-lunar environments beyond LEO [12]. However, spacecraft utilizing electric propulsion systems generate a local artificial ionosphere and current collection from that artificial ionosphere may lead to ISS-like spacecraft charging processes [5].

2. CRITERIA 1: THE PROBABILITY (P1) OF HAZARDOUS FP VALUES ON ISS IS SMALL (ESTIMATING P1)

The ISS Space Environments team performs an annual review of ISS FPMU FP measurements for possible exceedances of the negative and positive FP potential thresholds that were determined during the ISS EVA safety process.

The negative ISS FP EVA safety threshold (-45V) was established early in the ISS Program based on laboratory testing performed at NASA MSFC, with an additional safety factor applied, and concurrence from the ISS safety community [10].

The positive potential threshold was established based on a current threshold (derived from the possible positive FP of exposed conductive ISS surfaces, ionospheric density and temperature, and the possible EMU suit exposed conductive current collecting area) with collaboration/input from the ISS medical specialists on allowable current values [10].

To establish the probability (P1) of hazardous FP values on ISS, the historical database of FPMU measurements was reviewed and used to quantify the number of exceedances. These values were provided to the ISS Safety community for concurrence and the Probabilistic Risk Assessment (PRA) team for input in their analyses. As these values provided a basis for the plasma hazard process, the ISS space environments team continues to monitor FPMU data for exceedances by reviewing the ISS floating potential, densities, and temperature measurements annually.

Figure 1 shows a table listing the number of exceedances by year. The exceedances are shown for the truss tip (Tip), solar array rotary joint (SARJ), and centerline (Center) locations on the ISS truss. The fractional time of exceedances (exceedances compared to total measurement time) is used to establish the probability (P1) that is provided to the ISS PRA team.

For the annual assessment review of the negative potential exceedances, the following process is utilized: (1) Calculate floating potential values at locations other than the FPMU install site using the Lorentz equation (VxB)·L where L is the position vector relative to the FPMU of the point of interest, V is ISS velocity, and B is the value of the geomagnetic field at the point of the orbit). For the FPMU 128 hz (high time resolution) data we calculate FP at both truss tips (port and starboard), the solar array rotary joints (SARJs), and the vehicle center.

(2) Scan the data for exceedances of the - 45.5 V safety threshold at either of the truss tips, SARJs, and vehicle center.

(3) Record the data for the exceedances that meet the following criteria: (a) PCU off, (b) Exceed -45.5 V at either truss tip, either SARJ, or vehicle center.

	Total FPMU Measurement Time (sec)	Tip Exceedance (sec)	SARJ Exceedance (sec)	Center Exceedance (sec)
Year				
2006	9.6E+03	0	0	0
2007	5.2E+04	0	0	0
2008	1.3E+06	111	38	18
2009	2.4E+06	221	26	1
2010	2.3E+06	37	24	23
2011	3.8E+06	49	36	34
2012	3.4E+06	50	44	44
2013	9.7E+06	136	130	130
2014	9.4E+06	115	112	108
2015	9.3E+06	162	107	105
2016	6.7E+06	184	117	103
2017	1.2E+07	708	371	229
2018	8.7E+06	609	296	149
Sum (sec)	6.9E+07	2383	1300	943
Fraction of exceedances:		1/	1/	1/
		28818	52824	72792

Figure 1. Annual FPMU Data Review for Exceedances

For the annual review for positive potential exceedances, the following methodology is utilized to review for number of EVA hazard current exceedances, utilizing the current threshold and the following input parameters:

- PCU "in discharge" (on), and not in discharge (off) FPMU data,
- 50 Ω EVA crew body resistance (based on thoracic impedance measurements during defibrillation of human patients.),
- 0.4 m^2, and 0.1 m^2 EMU current collection areas (those areas on the EMU large enough to collect hazardous levels of current)

For those input parameters, the fraction of exceedances at both SARJ (inboard) and either Truss Tip were investigated for conservatism. (Note: it is likely the EVA would be performed on one side of the vehicle, not both sides). Values were found for exceedances for the limits of 0.1, 0.5, 1, 2, 3, 5, 10, 15, 25, and 35 mA. Exceedances are reviewed for Plasma Contactor Unit (PCU) both on and off, for locations including Truss Tip, and the Solar Array Rotary Joint (SARJ).

The 5mA EVA hazard current threshold for the positive FP hazard is of particular concern. The 5 mA value was determined by reviewing the ISS Medical Operations team's assessment of the physiological effects of different current levels. Medical operations determined that continuous direct current (DC) at 25 mA (or greater) could cause strong muscular contractions, possibly leading to bodily damage. Based on this data, the Safety team considered the severity of this level as catastrophic, due to possible bodily damage, and other events that could follow.

Continuous DC in the range of 6 to 12 mA may generate some involuntary muscle movement. The Safety team also considered this event to be at the catastrophic severity level because involuntary movements during an EVA may create hazards. Continuous DC in the range of 2 to 12 mA may generate an involuntary startle response. While it is believed that the full range to 12 mA may be acceptable for inadvertent contact, since the effect does increase with increased current levels, for conservatism, it was determined to apply a hazard threshold of 5 mA. It should also be noted that these physiological effects are associated with continuous DC and that it is expected that the positive potential hazard will be intermittent and short duration.

The annual review of the FPMU data is performed to validate that the exceedances remain in family with the values (P1) that were approved by the ISS Safety Review Panel (SRP) in connection with the acceptance of the detection and warning process.

ISS floating potential is driven by electron temperature (Te), density (Ne), motional EMF, the ISS Electrical Power System (EPS) (solar array operations/regulation) operations, payload operations (in particular, induced current from payloads), visiting vehicles (in particular, those with higher voltage solar arrays), and (rarely) auroral charging.

Te and Ne are important for spacecraft charging as they affect the current collected by the vehicle. The status of the ionospheric space weather, in particular solar activity/storms affects the density, in particular local density that can increase charging and currents. Motional EMF affects ISS charging because of the size of the ISS vehicle, in particular the length of the truss. For ISS, the two truss tips can be at very different potentials at high latitude, e..g, one positive, the other negative. So, one side of the vehicle can be collecting electrons, while the other collects ions. The space environments team includes the geomagnetic field and orbital location (latitude/longitude) and ISS flight attitude when evaluating ISS charging. In addition to the natural environment factors discussed, vehicle operations may also effect the vehicle FP (i.e. solar array regulation induced charging).

The ISS Space Environments team has identified, categorized, and actively tracks charging events in which the FP is more negative than -10V.. These charging events include: Auroral Charging, Eclipse Entry (EE) charging, Power on Reset (POR) charging, Regulation Event (RE), and Rapid Charging Event (RCE) charging.

Auroral charging is driven by high energy particles accelerated along the magnetic field lines. Rapid Charging Event (RCE) charging is due to the displacement current of the plasma sheath. For these events, the plasma density is too low to support a current. Eclipse Entry (EE) charging are small charging events as ISS enters eclipse and originate by the same mechanism as RCE events. Power on Reset (POR) charging events are due to the charging of a small capacitance in series with the frame and sheath (possibly the cover glass or kapton film in the Solar Array). Regulation Event (RE) charging events originate by the same mechanism as POR events; however, RE's also occur due to solar array operations.

Figure 2 shows a time history of these extreme charging events broken out by event classification over the period spanning from 2006 through 2018. Examining Figure 2, it is clear that EE and Auroral charging are not-dominant charging mechanisms. POR's occurred frequently over the period spanning from 2014 through 2016; however, Space Environments noted a rapid decrease in POR events following the Sequential Shunt Unit (SSU) Repair & Replace (R&R) EVA activity which occurred in January of 2016. RCE's and RE's are by far the most common charging mechanisms.

While the ISS Space Environments team monitors these extreme charging events to maintain general awareness of the ISS plasma environment, all of these anomalous charging event categories have been determined to be negligible contributors to the EVA shock hazard. This is true because: a) the majority of the charging event categories are short in duration (on the order of 2-3 seconds) relative to the time required for a shock hazard to persist (on the order of seconds or more, depending on potential). The exception to this are auroral charging events which can span several minutes. However, as

Figure 2 shows, auroral charging events which exceed a FP of -10V are exceedingly rare. Secondly, b) for all of these charging event types, the majority of the FP is supported by the plasma sheath, not the dielectric material. The significance of this as it relates to the EVA shock hazard will be discussed later in this paper.

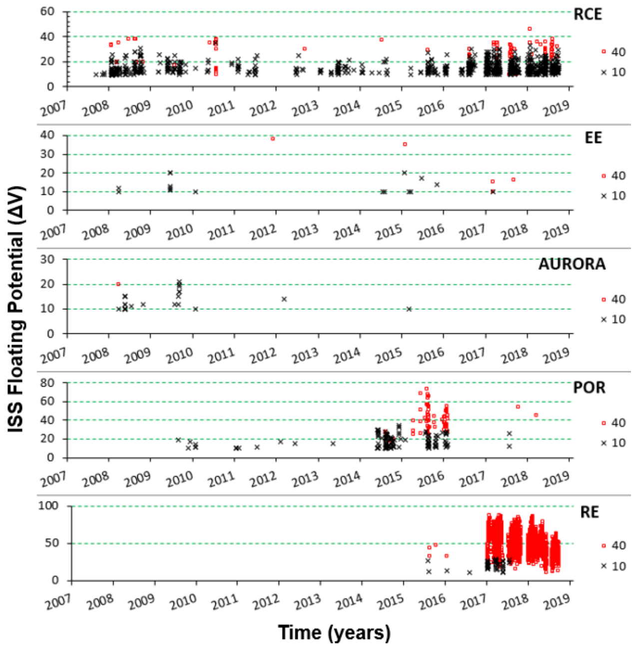

Figure 2. FPMU Data Review: Time history of extreme charging events by type (late CY 2006 to Dec. 2018). Black X's indicate an FP spike greater than 10V. Red rectangles indicate an FP spike greater than 40V.

It should also be noted that for the survey of exceedances, as shown in Figure 2, all the exceedances are included (e.g., short duration, etc…), for conservatism, in the determination of the probability (P1) of hazardous values. While all exceedances are included, the short duration, intermittent charging processes add conservatism, however, their individual contribution to the P1 value is limited because of their short durations and infrequent occurrence.

The ISS space environments team utilizes a spacecraft charging model of ISS, the Plasma Interaction Model (PIM), to estimate vehicle charging based on the ionospheric environment electron density and temperature from FPMU on-orbit measurements (for post-event comparisons), and the IRI (International Reference Ionosphere) model (for predictions) [13,14]. The output of the model is vehicle charging that is compared against the FPMU floating potential data. Figure 3 shows the FPMU measurements and PIM calculations on a 45 degree scatter plot at ISS on-orbit eclipse exit (when the vehicle translates from eclipse to insolation and the solar arrays become charged). Eclipse exit is expected to be when some of the highest solar array driven charging occurs. As can be observed, the model does not capture the events observed in the lower right of the plot.

The events in the lower right quadrant of Figure 3 have been identified as rapid charging events (RCE), as discussed earlier. The FPMUmeasures the floating potential from the plasma, across the sheath, and across the dielectric to the vehicle structure. The plasma hazard risk is primarily driven by the potential across the dielectric, not the sheath. The potential across the sheath is discussed in Hartman, et. al., 2018. The ISS charging model (PIM) has been developed to calculate the potential across the dielectric, as that is the hazard, and to simplify the calculations required to model the potential over the ISS orbits. [13,14]

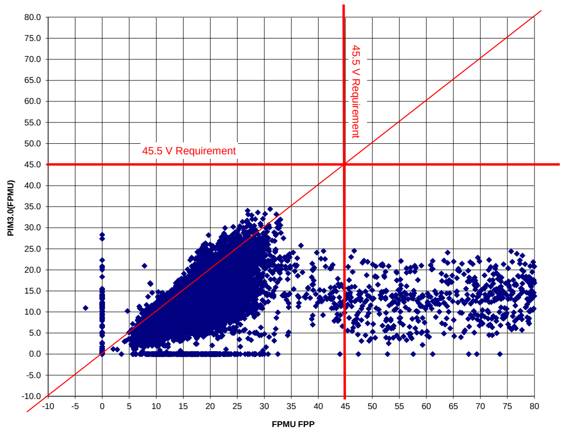

Figure 3. 45 Degree Scatter Plot Comparing FPMU Measurements and PIM Calculations at Eclipse Exit for all Ne (Scatter Plot @ FPMU location, PIM3.0, 10/02/2017)

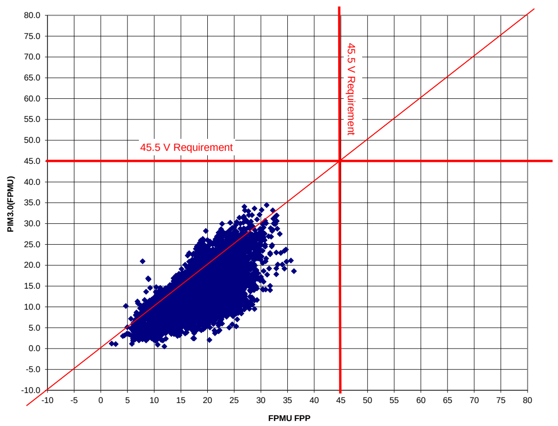

Figure 4. 45 Degree Scatter Plot Comparing FPMU Measurements and PIM Calculations at Eclipse Exit for Ne > 5E10 m^{-3} (Scatter Plot @ FPMU location, PIM3.0, 10/02/2017, remove rapid events)

Figure 4 is similar to Figure 3 and shows the FPMU measurements and PIM calculations on a 45 degree scatter plot at ISS on-orbit eclipse exit. For Figure 4, the rapid charging events have been removed from the plot.

Note that the PIM model overall under prediction has also been primarily attributed to the potential being calculated across the dielectric, while the on-orbit measurements include the sheath [13]. Figure 5 shows a plot of the delta voltage across the anodized aluminum (blue) and the sheath (orange). As can be seen in the figure, the potential drop across the sheath can be significant. However, the EVA shock hazard is dependent upon the potential across the dielectric material only. Therefore, these extreme, short-duration charging events not captured by PIM contribute negligibly to the overall EVA shock hazard.

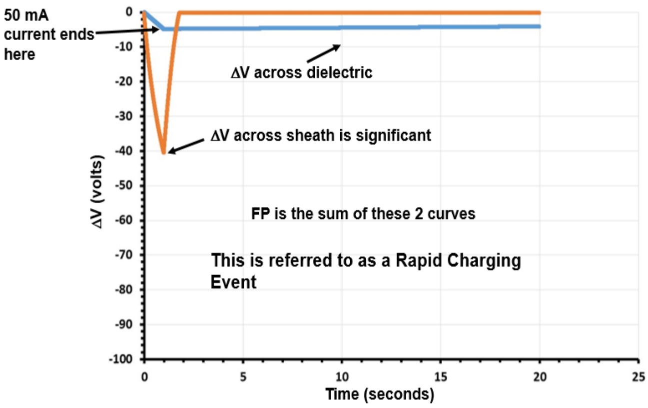

Figure 5. Plot of the ΔV across the anodized aluminum (blue) and the sheath (orange) when solar array current is 50 mA for 1 second and the Ne is 1e10 m-3. (Figure as shown in Reference [13])

3. CRITERIA (2): EVENTS LEADING TO HAZARDOUS FP VALUES ON ISS CAN BE IDENTIFIED WITH SUFFICIENT LEAD-TIME TO ENABLE ACTIVATION OF CONTROLS OR RESCHEDULING OF THE EVA

A detection and warning approach was developed to support the ISS EVA Program shock hazard control process. The process is described in Figure 6, The Plasma Hazard Monitor and Notification Criteria and Process.

For each EVA, the ISS Flight Operations Team submits a Short-Term Plasma Forecast Request document three weeks prior to an EVA. At this time, the FPMU is activated for data gathering. This data is used daily to determine the present state of the environment and track any changes in the ionospheric environment and ISS FP value in the weeks leading up to the EVA.

The ISS space environments team monitors for Coronal Mass Ejections (CME) and high-speed solar winds with Co-rotating Interaction Regions (CIRs) starting 2 weeks prior to a planned EVA. (For a contingency EVA within two weeks, the team starts monitoring for CMEs and CIRs at the time. a need for an EVA is identified.

The ISS Space Environments team performed a study of the possible effects of space weather events/storms on ionospheric density, as those effects may affect ISS vehicle charging. Based on that study, it was determined that a CME may increase the ionospheric variability by approximately 2-sigma (variability) [15].

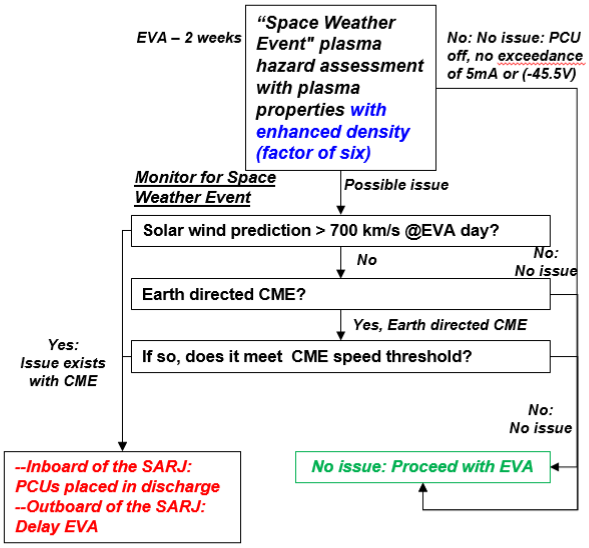

Figure 6. Plasma Hazard Monitor and Notification Criteria and Process

To account for the effect of possible space weather events/conditions that have been found to increase P1 such as solar storms (CMEs, coronal holes) and high-speed solar wind, the Plasma Interaction Model (PIM) is run for a Ne enhancement of a factor of 6 for CMEs and a factor of 2 for high speed solar winds to calculate possible space weather effects on the vehicle and crewmember during the EVA. If the Floating Potential does not break the -45.5 V requirement and the DC current does not exceed 5 mA then a space weather event is not a concern and will not affect the EVA. If these thresholds are broken then further monitoring of CME and solar wind speeds on a daily basis prior to EVA is required, and the ISS Program is notified (via the Vehicle Integrated Performance and Resources (VIPER) console in the Mission Control Center (MCC) Mission Evaluation Room (MER)), as soon as the event is identified to adjust the ISS hazard controls accordingly.

An initial forecast is provided to the Flight Control Team approximately 2 weeks prior to the start of the

EVA. The forecast includes an assessment for the EVA location (inboard, outboard), for the present plasma environment (based on FPMU data), and for the planned EVA solar array plan. Loss of Attitude Control (LOAC), is also considered.

The final forecast is provided at 24 hours prior to the start of the EVA. If there is a prediction of exceedances, the ISS Flight Control Team Console notifies the ISS Program of a Significant Plasma Hazard Space Weather Event.

The ISS PRA team and Space Environments team also reviewed the probability of a space weather event occurring on an EVA day to confirm that it would not occur so often as to be unmanageable. The ISS Space Environments team provided the PRA team with the expected number of space weather days of concern per year (~7). With the number of EVA days per year (~10 EVA days/yr), the ISS PRA team estimated that there may be 1 space weather event of concern every 6 years occurring on an EVA day that may require the ISS Program to review and make a determination.

4. CRITERIA (3): PROBABILITY (P2) OF COMPLETING THE EVA CREW-HAZARD SHOCK-CIRCUIT DURING ANY EVA IS LOW

The ISS PRA team performed an assessment to determine the probability of completing the EVA crew-hazard shock-circuit during EVA. To support this assessment the ISS PRA, space environments, safety, medical, and VIPER teams met to review EMU electric shock circuit pathways and galvanic contact probabilities that had been determined previously by specialists. Figure 7 shows the identified external EMU surfaces reviewed.

Based on that meeting the ISS PRA team agreed to obtain and review surveys of video records of galvanic contact between the EVA crew metallic suit parts and ISS conducting structure elements. The video survey were provided by the suit manufacturer, Hamilton-Sundstrand.

This survey provided the basis for the probability of completing the circuit. An assumption was also made, based on human factors, that a galvanic contact on the exterior of the EMU was likely to also result in a simultaneous electrical contact with bare metal on the inside of the EMU.. The ISS PRA team also considered suit modifications, and operational procedures that had been implemented to mitigate the concern. In particular, the ISS Program implemented EVA tool modifications (electrical isolation of the tool caddy) to lower the exposed conducting area.

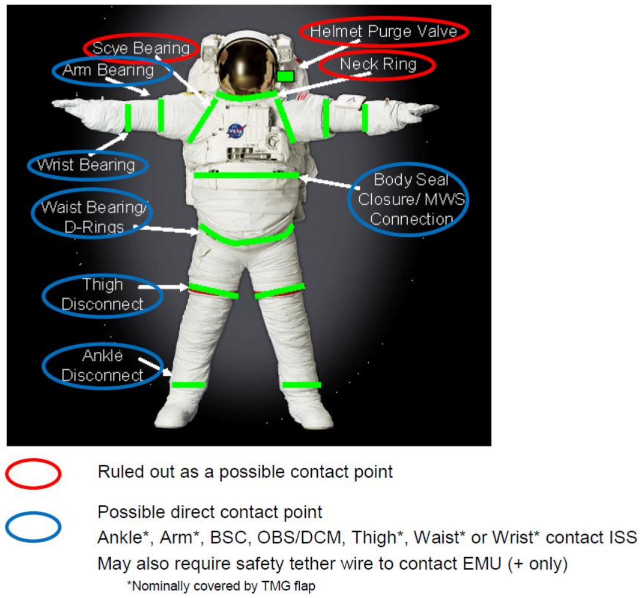

Figure 7. External EMU Surfaces

For conservatism the contact probability is used for both cases, the negative ISS FP and positive ISS FP hazards. Both hazards are classified as catastrophic hazards. The control points for both hazards was discussed previously in this paper.

To perform the PRA assessment, a discrete event simulation was developed to model EVA plasma shock events. Fault trees, a more traditional PRA modelling methodology, capture the probability of events occurring over time but not when they occur. In this case it was important to model not only the rate at which contacts occur but also their duration and time of occurrence. For an indirect continuity path to occur, multiple events that occur intermittently over a given time span must align (e.g. safety tether body contacts wrist bearing while also in contact with ISS structure, while safety tether wire is in contact with EMU).

A discrete event simulation models the operation of a system as a discrete sequence of events occurring at particular points in time. This simulation sampled contact times and durations for each indirect continuity path (for each crewmember), and then compared those samples to check for overlap.

Figure 9 shows a representation for the probability (P2) of completing the hazard circuit/contact. The figure shows the results for mean (1/290), 5th percentile, and the 95th percentile.

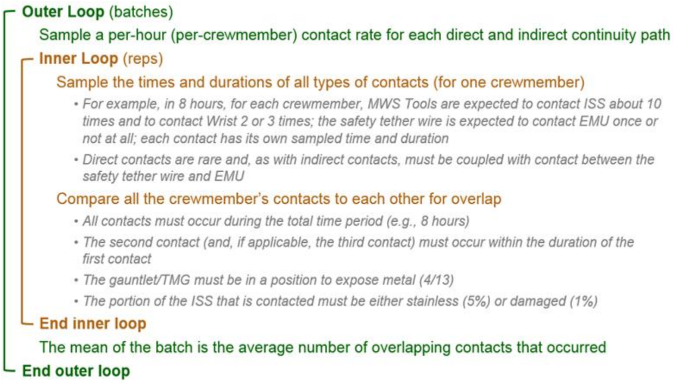

Figure 8. Discrete Event Simulation Logic

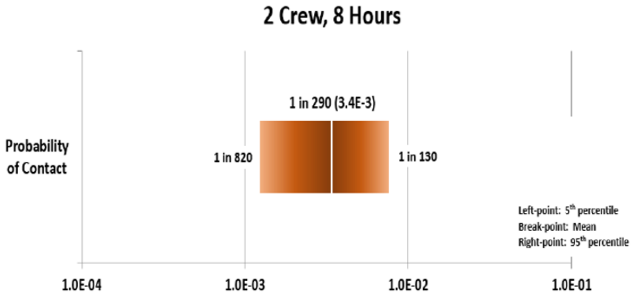

Figure 9. Probability of Completing the Hazard Circuit/Contact (P2)

5. CRITERIA (4): NET PROBABILITY OF AN EVA CREW SHOCK EVENT, Ps IS SMALL ENOUGH FOR THE PROGRAM TO ACCEPT THE RESIDUAL RISK WHEN EVA IS CONDUCTED WITHOUT ACTIVE HAZARD CONTROLS

5.1. Ps = F(P1,P2) SPACE WEATHER AND THE DETECTION AND WARNING PRODUCT

Once the likelihood of contact was established, the hazardous scenarios were constructed and their probabilities calculated.

In the case of EV crew hazardous exposure to shock due to negative potential, the crewmember must be at a location on the ISS truss with a negative floating potential, and the EMU must make electrical contact with ISS (either directly or indirectly). As stated earlier, crew electrical contact with the EMU interior is assumed. Achieving these two events simultaneously results in the EV crewmember becoming a ground to space for whatever charge has accrued on the ISS dielectric surfaces. Combining the likelihood of a negative floating potential in excess of `45.5 V (as described in Figure 1) with the likelihood of galvanic contact (as described by P2 (Criteria 3)) results in a probability of hazard occurrence of less than 1E-7 for an 8-hour EVA.

As stated earlier in the discussion of P1, EV crew hazardous exposure to shock due to positive potential was given a threshold 5 mA. In order for the electrical circuit to be completed, several events must occur simultaneously. As with negative potential, the crewmember must be at a location on the ISS truss with a positive floating potential, and the EMU must make electrical contact with ISS (either directly or indirectly), resulting in simultaneous electrical contact between the crew and the EMU interior (assumed). In addition, the exposed bare metal of the EMU must be collecting charge from the ionosphere, and the overall circuit impedance must be low enough to allow a harmful current level (i.e. 5 mA). Conditions worsen if the safety tether housing has also been collecting charge and makes non-grounding contact with the EMU during contact with ISS.

It is assumed that the non-grounded exposed bare metal of the EMU will be collecting charge from the ionosphere (as will the crew member's safety tether housing). What remains is the likelihood that the crew member makes direct or indirect (via a tool) contact with the positively charged ISS, possibly while in contact with the additionally charged tether housing, thus discharging the various EMU and housing surfaces through the crew member's body to the ISS structure. Combining the likelihood of an environment capable of creating a 5 mA exceedance (as described by P1 (criteria 1), varied by distance from the ISS truss centerline) with the likelihood of galvanic contact (as described by P2 (Criteria 3)) results in a Ps that is also varied by distance from the ISS truss centreline. With the PCUs off, the mean likelihood of EV crew exposure to this positive potential hazard is 1 in 34,000,000 inboard of the SARJ; 1 in 11,000,000 outboard of the SARJ; and 1 in 290,000 at the truss tip, for an 8 hour EVA.

Note that this is considered a conservative assessment, given that only part of the EVA would be conducted outboard of the SARJ and EVAs are nominally planned for approximately 6.5 hours in total duration. Also, note that the mean likelihood for all locations with PCUs on is worse (greater), since PCUs were not designed to control or mitigate a positive potential hazard.

Figures 10 and 11 show the results of the assessment for two locations, at the ISS truss Tip and 35 m from the vehicle centreline, with the PCU off. The results for the positive shock hazard are shown with the green boxes. Results are shown for multiple current levels. For the ISS Program, the 5 mA threshold has been selected, and is indicated with the red arrow. The results for the negative shock hazard are shown at the bottom of the figure with the blue box. For reference only, the overall EVA Loss of Crew (LOC) risk for the crew is shown with the red box.

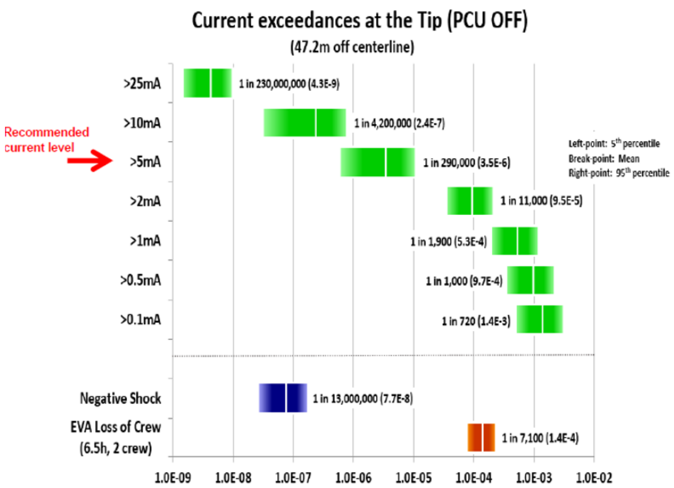

Figure 10. Probability of Positive Shock (8 hour EVA, 2 crew) (Truss Tip, PCU Off)

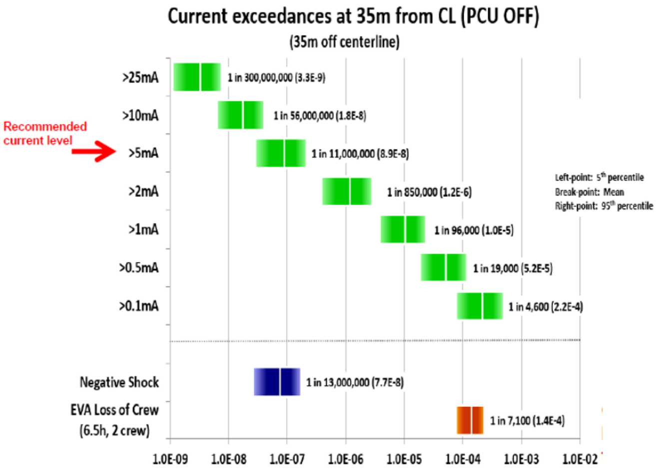

Figure 11. Probability of Positive Shock (8 hour EVA, 2 crew) (35 m from Vehicle Centerline, PCU Off)

The results of this assessment for the net probability of an EVA crew shock event (Ps) and the detection and warning process has been presented to and accepted by the ISS Program, and the safety community, and supports the decision for EVA on ISS without active hazard controls.

5.2. HOW DOES THE ISS PROGRAM MANAGE THE EVA SHOCK HAZARD WHEN Ps IS UNACCEPTABLY LARGE?

In the event of exceedances and high Ps, the ISS Program has hazard control options available. For EVAs inboard of the SARJ (without the positive potential hazard), in the event of a significant space weather event, the two PCUs can be placed in discharge. This option is only single-fault-tolerant for the negative potential hazard and doesn't control +V EVA hazard (this hazard has been found to be minimal and acceptable for inboard the SARJ) but for little or no added operational risk.

For EVA outboard of the SARJ, if there is a high value of Ps, in the event of a significant space whether event, the ISS Program maintains the option to defer the EVA until the event passes.

6. RISK TRADE DISCUSSION – TWO-FAULT-TOLERANT HAZARD CONTROL SYSTEM AT ALL TIMES VS. DETECTION AND WARNING APPROACH

The ISS safety process requires that catastrophic hazards are two fault tolerant controlled, so that two faults can occur, and the hazard would still remain controlled.

The ISS Program has two PCUs on the vehicle that can be utilized to control the FP (floating potential). However, the two ISS PCUs are only single fault tolerant so a third operational hazard control is needed to meet the safety requirements for catastrophic hazards.

Options for providing a third hazard control have been investigated in the past. These included: wake pointing of photovoltaic (PV) arrays, EPS management (shunting/ regulation) of the solar arrays, and changing the vehicle attitude (with the truss long axis parallel to the velocity vector). Each of these options introduces additional operational risk, and/or planning complexity. Wake pointing arrays reduces available power for operations and planning, as does solar array shunting/regulation. Changing the vehicle attitude requires approval/certification for the attitude and operational planning. In addition, controls for the negative potential hazard do not solve the positive potential hazard. Therefore, risk acceptance is still needed in the case of motional EMF +V hazards.

The detection and warning approach requires no active hazard controls when Ps is small enough, which has been the case most of the time during the past several years. Therefore, conditions leading to increased Ps are detected before the EVA and conventional hazard controls can be activated as needed, minimizing EVA risk. In addition, not implementing EVA shock hazard controls when the hazard is absent eliminated difficult to quantify operational risk.

6.1. VALIDATION AND ISS PROGRAMMATIC APPROVAL OF THE DETECTION AND WARNING APPROACH TO EVA SHOCK HAZARD CONTROL

The detection and warning approach was approved through the ISS Program acceptance process that included team level technical specialist, Program Office technical forum, safety panel, and ISS Program board approvals.

Considerations with the approval included the possibility of the loss of the on-orbit FPMU data availability. The FPMU data ensures that the vehicle is still operated within the expected floating potential values. A study was performed to develop a backup procedure for collecting ionosphere data in the event of the loss of FPMU data to produce the plasma hazard forecast.

IRI Real-Time Assimilative Mapping (IRTAM) was selected as a viable alternative data source. IRTAM is an ionospheric model that uses real time measurements from ~70 digisonde instruments that provide continuous near real time measurements of key ionospheric parameters. It is used in the same manner as FPMU data in conjunction with International Reference Ionosphere (IRI) model to provide Ne and Te values to produce the forecast. The Space Environments team worked with University of Massachusetts at Lowell (UML) Space Science Lab to obtain access to the IRTAM data to support the back-up methodology, to be used in the case of FPMU failure in the days leading up to an EVA. [15]

7. THE APPLICABILITY OF PROBABILISTIC SPACECRAFT CHARGING HAZARD ASSESSMENT AND CONTROL METHODS TO HUMAN SPACEFLIGHT BEYOND LEO

The ISS Space Environments team has developed an EVA Shock Hazard Detection and Warning Process that meets the criteria for acceptance by the ISS Program, as discussed in this paper. The general approach does have applicability to future human spaceflight missions as risk trades will need to be performed to support mission success. The approach allowed the on-orbit FP (floating potential) and ionospheric measurements to be compiled into input data that the PRA team could then use to generate the probabilistic spacecraft charging data required by the ISS Program management to support their decisions.

For future missions, the spacecraft charging risks will be different. In the case of the cis-lunar environment, the vehicle-charging environment will include higher electron temperatures, with a greater contribution from secondary electron and photo-electron emission.

For missions that pass through the Van Allen Belt, GEO, and Geo tail environments, the vehicles will be subjected to much higher electron energies for the duration of the transit (5, 12, 16-12). The geo tail spacecraft-charging environment is similar to but less severe than the GEO environment. Earth’s moon resides in the Geo tail environment whenever the moon is near full as viewed from earth (21-23). Solar energetic particle events can also produce spacecraft charging environments in cis-lunar space (24)

Designing spacecraft specifically for the more severe charging environments beyond LEO will be the best approach. However, when the material selection does not support that approach, spacecraft charging assessments and hazard analysis will be required. Those charging assessments will need to consider the requirements, and possible approaches to quantify the data that can support the Program’s risk trade decisions. The frequency of occurrence and severity of expected charging environments will need to be quantified to determine whether or not a detection and warning approach to managing spacecraft charging hazards will be acceptable in cis-lunar space beyond LEO.

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