Spacecraft Charging Considerations and Design Efforts for the Orion Crew Module

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I. Introduction

The Orion Crew Module (CM) is nearing completion for the next flight, designated as Exploration Mission 1 (EM-1). For the uncrewed mission, the flight path will take the CM through a Perigee Raise Maneuver (PRM) out to an altitude of approximately 1800 km, followed by a Trans-Lunar Injection burn, a pass through the Van Allen belts then out to the moon for a lunar flyby, a Distant Retrograde Insertion (DRI) burn, a Distant Retrograde Orbit (DRO), a Distant Retrograde Departure (DRD) burn, a second lunar flyby, an Earth Insertion (EI) burn, and finally entry and landing. All of this, with the exception of the DRO associated maneuvers, is similar to the previous Apollo 8 mission in late 1968.

In recent discussions, it is now possible that EM-1 will be a crewed mission, and if this happens, the orbit may be quite different from that just described. In this case, the flight path may take the CM on an out and back pass through the Van Allen belts twice, then out to the moon, again passing through the Van Allen belts twice, then finally back home. Even if the current EM-1 mission doesn't end up as a crewed mission, EM-2 and subsequent missions will undoubtedly follow orbital trajectories that offer comparable exposures to heightened vehicle charging effects.

Because of this, and regardless of flight path, the CM vehicle will likely experience a wide range of exposures to energetic ions and electrons, essentially covering the gamut between low earth orbit to geosynchronous orbit and beyond. National Aeronautical and Space Administration (NASA) and Lockheed Martin (LM) engineers and scientists have been working to fully understand and characterize the vehicle's immunity level with regard to surface and deep dielectric charging, and the ramifications of that immunity level pertaining to materials and impacts to operational avionics, communications, and navigational systems. This presentation attempts to chronicle these efforts in a summary fashion, and attempts to capture the results of that work as they pertain to the electrical and avionic systems on-board the Orion CM.

II. Work in this Area for EFT-1

A. Initial Efforts

LM, the prime contractor for the Orion vehicle, derived their baseline vehicle electrostatic charging requirements from the governing Orion Program document [MPCV 70080]. These requirements were originally taken largely from International Space Station (ISS) legacy, and, thus, primarily reflected operations in a Low Earth Orbit (LEO) or Middle Earth Orbit (MEO) environment. LM sub-contracted with ElectroMagnetic Applications, Inc. (EMA), to perform certain electromagnetic analyses for the vehicle. Among these was an analysis of vehicle charging expected to occur during the Operational/Experimental Flight Test 1 (EFT-1) of the Orion vehicle. LM's contractor, ElectroMagnetic Applications (EMA), published a charging analysis using the Nasa/Air force Spacecraft Charging Analysis Program 2K (Nascap-2K) in October of 2011. This work used known vehicle design and material characteristics, used a classic single Maxwellian distribution per a worst-case Geostationary Earth Orbit (GEO) environment definition, and employed values for n_e, T_e and n_i, T_i ,synthesized from multiple sources. Very high magnitudes of surface potential on the vehicle were predicted, as high as 22kV.

The NASA Electromagnetic Environmental Effects (E^3) group at Johnson Space Center (JSC) reviewed the analysis, and determined that the levels were excessively high in comparison to design guidelines contained in standard reference documents [NASA TP 2361, NASA-HDBK-4002, NASA-STD-4005 NASA-HDBK-4006].

A Technical Interchange Meeting (TIM) was organized in February of 2013 in Denver, CO, at the EMA facility. Personnel from LM, EMA, JSC E^3, and Marshall Space Flight Center (MSFC) Natural Environments were invited to participate. In preparation, JSC E^3 developed a revised set of electrostatic charging requirements, and asked MSFC Natural Environments to review them. The TIM was very successful, with a very good exchange of information and philosophy, resulting in LM and EMA agreeing to re-perform the charging analysis using more specifically applicable data, including a better set of electron and ion density and temperature data embodied in Aerospace corporation Electron model 8/Aerospace corporation Proton model 8 (AE8/AP8) and other applicable models, and specific trajectory information for the test flight.

B. Second Report and Subsequent Response

Ultimately, a second report was filed for EFT-1 resulting from the TIM discussions and agreements. While improvements were realized in this second report, some technical issues remained unresolved to the full satisfaction of all NASA parties. A detailed memo was released by MSFC [Parker, 2014] highlighting remaining areas of concern. Clearly it was essential to readdress the analyses performed for EFT-1, accounting for the observations contained in the MSFC memo, as well as major design changes to the vehicle to be implemented after the EFT-1 mission. To facilitate these efforts, a Working Group (WG) was formed with members from the E^3 Group at LM Denver, EMA, the JSC E^3 Group, and the MSFC Natural Environments Branch. The WG would eventually grow to some 24 members, including representatives from the NASA Engineering Safety Center (NESC), Ames Research Center (ARC), Glenn Research Center (GRC), and Utah State University.

III. Working Group Efforts moving forward for EM-1 and Subsequent Missions

The WG moved forward with a systematic approach to determine what aspects and characteristics of design needed to be examined, what sort of requirements changes, if any, might be needed, and ultimately what sort of data would be needed to close on the design.

EMA began to carefully catalogue the numerous materials used in the vehicle design, the locations and interfaces of these materials, and the electrical bonding between them (if any). See Fig. 1 for a graphical example of these considerations. In the middle of this activity, it became known that thermal considerations were becoming a major design driver for the outer mold line surface design, and in particular, the use of various types of tape to cover the thermal protection materials. Some tapes were of course better thermally than others, some tapes had previous flight experience on Apollo, some did not, and so forth.

Of course, no one had any idea what the electrostatic performance of these tapes might be, complicating the process of determining the potential for either surface charging, deep dielectric charging, or both. Adding to the mix of materials for consideration was the makeup of the solar array panels being developed by the European Space Agency (ESA), a design with long-standing satellite performance in GEO from the ESA perspective, but no history from the NASA perspective for LEO or MEO applications.

Further considerations were given to expected flight trajectory, orbital altitudes, environments exposures, and so forth. See Fig. 2 for a representative EM-1 flight trajectory. Note that no specific considerations have been given to date for the proposed EM-2 flight path, seen in Fig. 3, but it is believed that an EM-2 configuration that mimics an EM-1 configuration that will be able to satisfy applicable E^3 requirements will be acceptable for the EM-2 mission, and subsequent mission profiles that are similar in nature and scope.

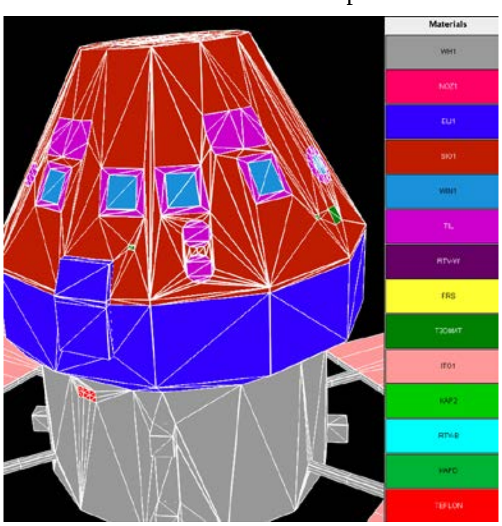

Figure 1. Graphical example of materials mapping on the Orion CM.

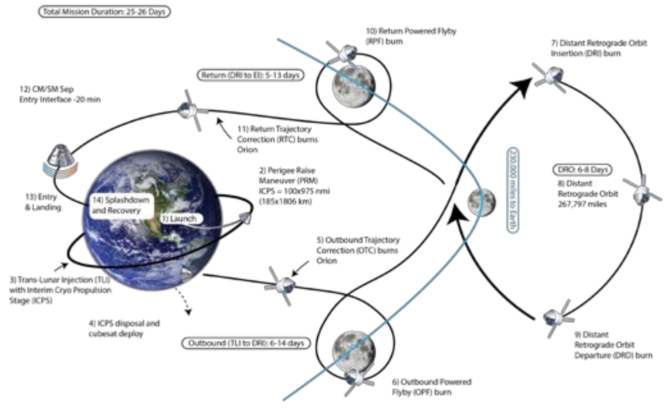

Figure 2. Representative flight trajectory for EM-1.

IV. Working Group Closure

As might be expected, a great deal of work has been accomplished by a great many people towards closure of this activity, and as suggested, it has attracted the attention of a large number of experts in the area who share varying aspects of the physics involved in this design problem. Rather than attempt to detail the work step by step, it seems best to simply summarize where the WG is at the present time.

In order to close this activity, further analysis is required per MPCV 70080 E3 Requirements, caused primarily by the use of non-conductive surface materials and ungrounded internal insulating materials exposed to GEO conditions. Standard tools for analysis that have been employed to date include Nascap-2k to address surface charging and NUMerical InTegration (NUMIT 2.0) used to study the charging and discharging characteristics of dielectrics. Both tools require material properties specific to plasma interactions as inputs. In order to inform this work, selected material testing was completed by Utah State University in December 2016. In addition, both Nascap-2k and 1-D simulation analyses performed by EMA using NUMIT 2.0 with the EM-1 ascent mission trajectory (additional to and expanded beyond that performed for EFT-1) was completed by EMA in February 2017.

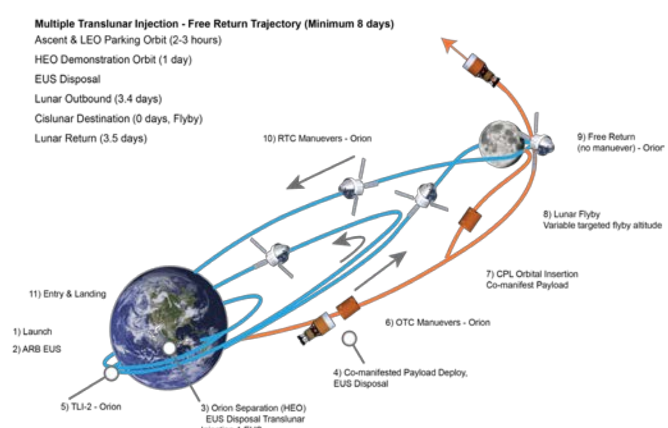

Figure 3. Current Proposed EM-2 flight trajectory

Note that Nascap-2k results from this effort were based on a GEO storm-time environment. This is the worst environment that Orion could encounter as defined in the Design Specification for Natural Environments (DSNE).

Based on the measured data and the analyses performed, surface and internal charging simulations indicated several materials do not meet the requirements for MPCV Plasma Vehicle Charging Control as documented in MPCV 70080. In these efforts, materials found likely to charge to levels that could result in surface arcing (greater than 500V differential voltage) included SiOx coated tape covering the tile on the backshell, uncovered tile near windows and antennas, Kapton on the solar arrays, Room Temperature Vulcanizing (RTV) sealant, 3DMAT patches surrounded by SiOx tape, Beta Cloth (modeled as Teflon) on the service module, and CM windows.

Specific areas of concern defined by the group included arcing of any of the above materials able to couple into electronics or produce emissions that interfere with sensitive antenna connected receiverss; arcing of the SiOx tape, thermal protective tile, and Beta Cloth that could cause damage to materials and loss of thermal protection; or arcing of windows that could cause damage to the window.

Solar array plasma interactions, associated testing, and analysis are being coordinated by GRC. The results of this charging analysis specific to the solar arrays have been passed on to GRC to support their efforts.

In order to satisfy the E3 requirements, testing and analysis must be done to show that electrostatic discharges do not cause undesirable or intolerable Thermal Protection System (TPS) contamination or damage leading to degradation of thermal protective capability, or undesirable or intolerable electromagnetic interference, upset, or permanent damage to avionic or electrical systems.

Materials that require additional testing for surface charging impacts include SiOx tape, thermal protective tile, RTV, 3DMAT, Beta Cloth, and windows. Materials that require testing for internal charging impacts include SiOx tape, windows, and 3DMAT providing thermal protection on small patches on backshell. The Program has been apprised of these recommendations informally, with formal work to proceed in the near future.

V. Summary

This effort started some 6 years ago, and has been gathering steam and interest since that time. It has served to not only establish an excellent foundation of knowledge of the Orion CM design as it pertains to immunity to the effects of the various regions of the earth's plasma environment, including the Van Allen belts, but it has also brought together a diverse and multi-talented team of experts across the Agency with a correspondingly diverse set of technical expertise and historical background. This has resulted in a very thorough and comprehensive examination of the Orion CM design, and solid recommendations going forward to bring the vehicle's design into final compliance with the existing Program E^3 requirements while also ensuring that other equally important aspects of the design, such as thermal protection, are not violated or sacrificed.

Acknowledgments

While it is true that an increasing number of people are engaging in this activity, the author would like to acknowledge Linda Parker, Joe Minow, and Emily Wilson, of MSFC; Larry Lallement of LM; and Bryon Neufeld of EMA; for significant enabling contributions to this effort over an extended period of time.

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MPCV 70080, "Cross Prograsm Electromagnetic Environmental Effects (E3) Requirements Document"

NASA TP 2361, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects"

NASA-HDBK-4002, "Mitigating In-Space Charging Effects - A Guideline"

NASA-STD-4005, "Low Earth Orbit Spacecraft Charging Design Standard"

NASA-HDBK-4006, "Low Earth Orbit Spacecraft Charging Design Handbook".

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