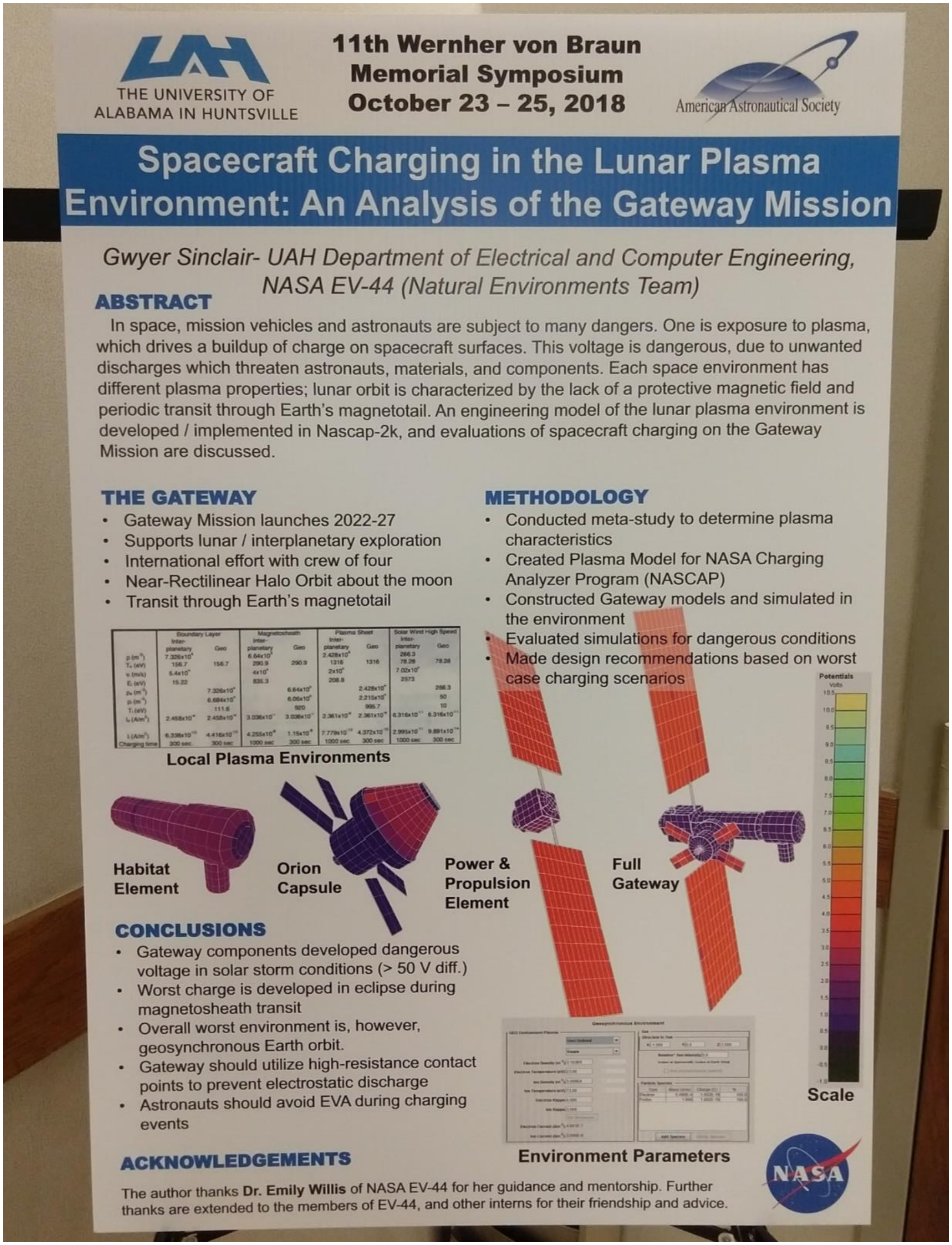

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Spacecraft Charging in the Lunar Plasma Environment: An Analysis of the Gateway Mission

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ABSTRACT

In space, mission vehicles and astronauts are subject to many dangers. One is exposure to plasma, which drives a buildup of charge on spacecraft surfaces. This voltage is dangerous, due to unwanted discharges which threaten astronauts, materials, and components. Each space environment has different plasma properties; lunar orbit is characterized by the lack of a protective magnetic field and periodic transit through Earth's magnetotail. An engineering model of the lunar plasma environment is developed / implemented in Nascap-2k, and evaluations of spacecraft charging on the Gateway Mission are discussed.

THE GATEWAY

- Gateway Mission launches 2022-27
- Supports lunar / interplanetary exploration
- International effort with crew of four
- Near-Rectilinear Halo Orbit about the moon
- Transit through Earth's magnetotail

	Boundary Layer		Magnetosheath		Plasma Sheet		Solar Wind High Speed	
	Inter-planetary	Geo	Inter-planetary	Geo	Inter-planetary	Geo	Inter-planetary	Geo
ρ (m^{-3})	7.326x10[illegible]		6.64x10[illegible]		2.428x10[illegible]		266.3	
T_e (eV)	156.7	156.7	290.9	290.9	1316	1316	78.28	78.28
v (m/s)	5.4x10[illegible]		4x10[illegible]		2x10[illegible]		7.02x10[illegible]	
E_i (eV)	15.22		835.3		208.8		2573	
ρ_e (m^{-3})		7.326x10[illegible]		6.64x10[illegible]		2.428x10[illegible]		266.3
ρ_i (m^{-3})		6.684x10[illegible]		6.06x10[illegible]		2.215x10[illegible]		50
T_i (eV)		111.6		920		995.7		10
I_e (A/m^2)	2.458x10[illegible]	2.458x10[illegible]	3.036x10[illegible]	3.036x10[illegible]	2.361x10[illegible]	2.361x10[illegible]	6.316x10[illegible]	6.316x10[illegible]
I_i (A/m^2)	6.338x10[illegible]	4.416x10[illegible]	4.255x10[illegible]	1.15x10[illegible]	7.779x10[illegible]	4.372x10[illegible]	2.995x10[illegible]	9.891x10[illegible]
Charging time	300 sec	300 sec	1000 sec	300 sec	1000 sec	300 sec	1000 sec	300 sec

Local Plasma Environments

Habitat Element

Orion Capsule

Power & Propulsion Element

Full Gateway

METHODOLOGY

- Conducted meta-study to determine plasma characteristics
- Created Plasma Model for NASA Charging Analyzer Program (NASCAP)
- Constructed Gateway models and simulated in the environment
- Evaluated simulations for dangerous conditions
- Made design recommendations based on worst case charging scenarios

Scale

Environment Parameters

CONCLUSIONS

- Gateway components developed dangerous voltage in solar storm conditions (> 50 V diff.)
- Worst charge is developed in eclipse during magnetosheath transit
- Overall worst environment is, however, geosynchronous Earth orbit.
- Gateway should utilize high-resistance contact points to prevent electrostatic discharge
- Astronauts should avoid EVA during charging events

ACKNOWLEDGEMENTS

The author thanks **Dr. Emily Willis** of NASA EV-44 for her guidance and mentorship. Further thanks are extended to the members of EV-44, and other interns for their friendship and advice.

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August 3, 2018

Reviewed by NASA Mentor
Dr. Emily Willis
EV – 44

Emily Willis

Mentor Signature Here

Spacecraft Charging in the Lunar Plasma Environment: An Analysis of the Gateway Mission

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In space, mission vehicles and astronauts ate subject to a number of dangers. One is exposure to solar plasma, which can drive a buildup of charge on a spacecraft surface. This voltage can be dangerous, as it may lead to an unwanted discharge which threatens astronauts, materials, and electrical components. An engineering model of the lunar plasma is developed and implemented on a model of the Gateway, a proposed lunar station. The worst case scenarios for charging seem to remain in geosynchronous Earth orbit, though worse conditions may exist in yet-unstudied portions of the lunar plasma environment.

Nomenclature

eV = Electron-Volts, commonly a unit of energy, unit of temperature in plasma physics
t = time (seconds)
ρ_e = density of electrons (number / m^3)
ρ_i = density of ions (number / m^3)
T_e = Temperature of electrons (eV)
T_i = Temperature of ions (eV)
V = Volts, a unit of electric potential
NASA = National Aeronautics and Space Administration
NRHO = Near-Rectilinear-Halo-Orbit
NASCAP = NASA/Air Force Spacecraft Charging Analyzer Program
ARTEMIS = Acceleration, Reconnection, Turbulence & Electrodynamics of the Moon's Interaction with the Sun
LOCATES = Lunar Orbital Charging Assessment Tool for Environmental Simulation
PPE = Power Propulsion Element

I. Introduction

Space plasma drives the majority of electrical interaction experienced by space vehicles. Plasma is sometimes described as a 'fourth state of matter', and it takes the form of a loose association of ions and free electrons. Solar plasma is in a state of *quasi-neutrality* when ejected from the sun, meaning that in a given volume one expects to find an equivalent number of positive and negative particles[1]. Due to the free movement of these particles, however, this description will not be valid for all environments. One such environment is a region in space nearest to the moon's anti-sunward face, called the wake. The moon's bulk blocks the solar wind from reaching the region behind it, creating an area of very low particle density. Quasi-neutral plasma on the edge of this empty region starts to accelerate into the wake, and the small, energetic electrons are quicker to fill the region. This effect is thought to cause the relative densities of electron and ion species to diverge in the wake.

This lunar environment is of particular importance to the NASA's mission to return to the moon with robotic and manned missions. Herein, the study of this plasma environment is discussed with relation to the Gateway outpost. Gateway is a lunar orbital vehicle which is planned to be constructed throughout the 2020's. The Gateway mission is interesting from a charging perspective due to its unconventional orbit and the solar-electric propulsion system. The orbit is classified as a NRHO which has a close lunar approach on one side and flies far from it on the opposite. In addition, the Gateway will orbit over the poles, becoming one of the first significant craft which plans to occupy that environment.

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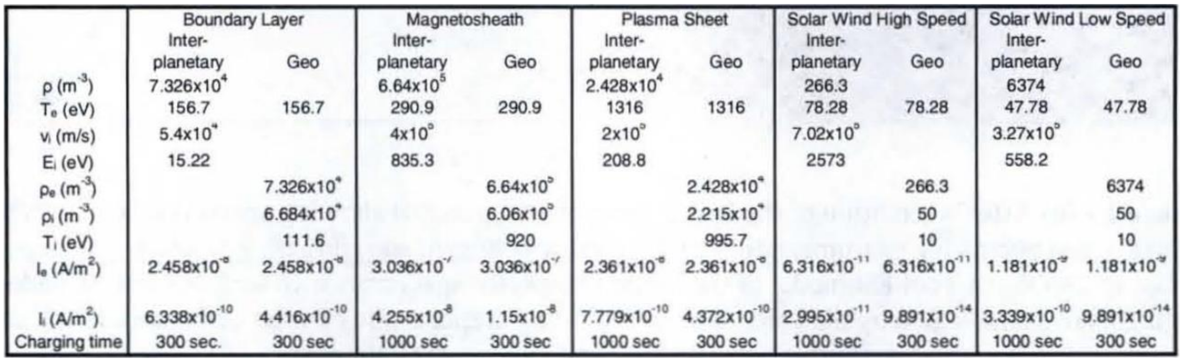
When the Gateway comes into contact with plasma (and other solar radiation), it will undergo *spacecraft charging*. This phenomenon occurs when a large number of high-energy electrons in plasma impact the surface of the craft. Sufficiently penetrating electrons pass into the material of the vehicle, eventually becoming lodged in place and driving the charge of the spacecraft more negative. Conversely, electrons with sufficient energy will impact and 'knock loose' electrons which are already inside the material. This is called *secondary electron emission*[1]. While other interactions do occur, the majority of plasma charging effects are due to these two electron impact interactions.

II. Methodology

The central goal of this research was to determine the worst-case charging scenario that the Gateway could expect to experience in lunar orbit. The question was attacked in a four-step process. Firstly, the characteristics of the lunar plasma environment should be researched by a review of literature, previous models, and measured data. Secondly, the path of the Gateway had to be understood, in order to determine the amount of time spent in each region of lunar space. Next the Gateway itself was modelled using NASCAP's Object Toolkit. Finally, NASCAP was used to integrate the previous steps into a simulation of the charge over the spacecraft.

A. The Lunar Plasma Environment



	Boundary Layer		Magnetosheath		Plasma Sheet		Solar Wind High Speed		Solar Wind Low Speed	
	Inter-planetary	Geo	Inter-planetary	Geo	Inter-planetary	Geo	Inter-planetary	Geo	Inter-planetary	Geo
ρ (m^{-3})	7.326×10^{4}		6.64×10^{5}		2.428×10^{4}		266.3		6374	
T_e (eV)	156.7	156.7	290.9	290.9	1316	1316	78.28	78.28	47.78	47.78
v_i (m/s)	5.4×10^{4}		4×10^{5}		2×10^{5}		7.02×10^{5}		3.27×10^{5}	
E_i (eV)	15.22		835.3		208.8		2573		558.2	
ρ_e (m^{-3})		7.326×10^{4}		6.64×10^{5}		2.428×10^{4}		266.3		6374
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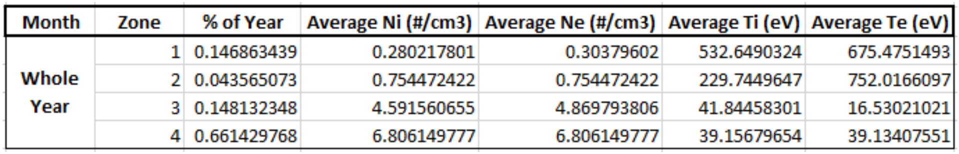
T_i (eV)		111.6		920		995.7		10		10
I_e (A/m^2)	2.458×10^{-6}	2.458×10^{-6}	3.036×10^{-7}	3.036×10^{-7}	2.361×10^{-6}	2.361×10^{-6}	6.316×10^{-11}	6.316×10^{-11}	1.181×10^{-9}	1.181×10^{-9}
I_i (A/m^2)	6.338×10^{-10}	4.416×10^{-10}	4.255×10^{-8}	1.15×10^{-8}	7.779×10^{-10}	4.372×10^{-10}	2.995×10^{-11}	9.891×10^{-14}	3.339×10^{-10}	9.891×10^{-14}
Charging time	300 sec.	300 sec	1000 sec	300 sec	1000 sec	300 sec	1000 sec	300 sec	1000 sec	300 sec

Table 1. Environmental Parameters from Mathematical Model. [3]

Due to the relative rarity of lunar missions (as compared to earth-orbit and interplanetary), there have been few previous efforts to study and describe the lunar plasma environment. A few such efforts give conflicting reports, representing the updating and re-codifying of previous knowledge. The most recent model, when used in conjunction with current standards from EV44's DSNE[2], give a reasonable picture of the lunar plasma environment. In addition to these environmental models, a corpus of real flight data (from the ARTEMIS mission) was available. With reference to the work of Kylie Sullivan, the most extreme plasma events were identified and recorded for use in later simulation.



Month	Zone	% of Year	Average Ni (#/cm3)	Average Ne (#/cm3)	Average Ti (eV)	Average Te (eV)
Whole Year	1	0.146863439	0.280217801	0.30379602	532.6490324	675.4751493
	2	0.043565073	0.754472422	0.754472422	229.7449647	752.0166097
	3	0.148132348	4.591560655	4.869793806	41.84458301	16.53021021
	4	0.661429768	6.806149777	6.806149777	39.15679654	39.13407551

Table 2. Environmental Parameters from ARTEMIS Data. [5]

The moon's plasma environment is largely defined by two electromagnetic processes – the forming of a lunar wake, defined by low density and high energy particles, and the passage of the moon through Earth's magnetotail[4]. The magnetotail gives rise to highly unpredictable plasma events, as the structure of the tail itself is not consistent. High-energy plasma may be caught by Earth's magnetosheath and travel in any direction along its magnetic 'surface', while other plasma is completely trapped by the Earth's magnetic field. This uncertainty remains an issue for the planning and development of lunar missions.

NASCAP models plasma using a probabilistic distribution, which can take one of many forms. Where possible, a kappa distribution (characterized by have more extreme values than a Maxwellian or 'bell' curve) with a value of 3.5 was used[6].

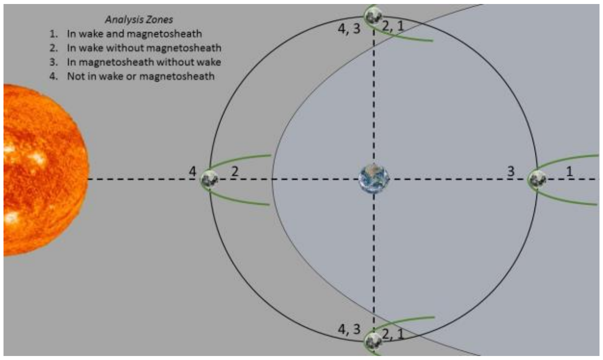


Figure 1. Lunar Regions.

B. Studying the Gateway's Orbit

The most highly-charged plasma regions present no threat if the craft does not travel through them, or spends minimal time traversing them. Once high-danger zones had been identified (such as orbiting through an eclipse or a bodies' wake), Gwyer Q. Sinclair created a tool to study how much time would be spent in these regions. LOCATES graphs the four-body problem of the Sun-Earth-Moon-Gateway system. The program plots regions eclipsed by bodies, and their wake in the solar wind. To facilitate graphical output, LOCATES was developed and implemented in Processing, a Java variant language which is optimized for visual-output programming. In addition to showing the location and trajectory of the Gateway, LOCATES measures the percentage of time spent in each of the following zones[1]:

A. In both the Lunar Wake and Earth's Magnetosheath
B. In the Lunar Wake but not the Magnetosheath
C. In the Magnetosheath only
D. In the solar wind (no obstructions)

Predictions made using LOCATES are comparable to previous estimates and measured data. Future developments to the tool are being made to plot the exact location of a lunar satellite, in order to match plasma events to specific regions of space and time.

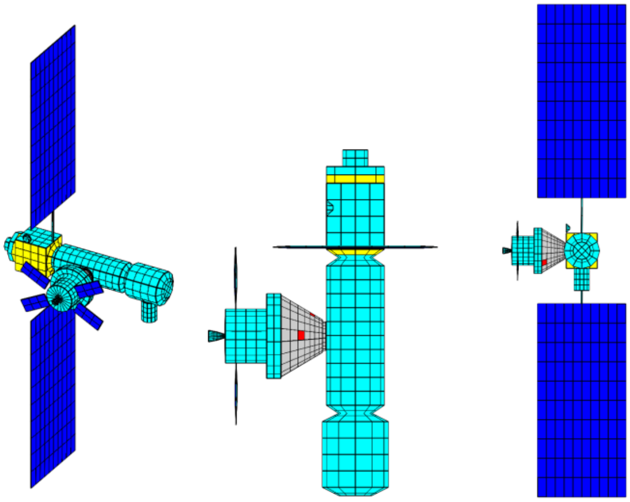


Figure 2. Views of the Assembled Gateway Model.
(Left to right- 'Isometric', 'Top', and 'Front' Views)

C. Gateway Object Modelling

The Gateway project is in the planning stages. Past presentations and initial proposals were reviewed to determine the possible configurations for the Gateway. While proposals varied between contractors and within NASA, they all suggested three base elements which could be considered the 'core' of the Gateway. These include the PPE, the Habitat Element, and the crewed Orion Spacecraft.

The PPE is the workhorse of the Gateway, and will be the first element to be constructed and placed into orbit. The PPE features large solar collection arrays (in dark blue on Figure 2), and utilizes Solar Electric Propulsion, a rarity in missions of this size or purpose. This propulsion element will allow for stationkeeping and orbital transfers, allowing the Gateway to move to different locations to perform its science objectives. The PPE is expected to be similar in construction to recent satellite busses from NASA's contracting partners, and representative materials were used. These included an anodized aluminum body, reflective conductor wrapping, and high efficiency fold-out solar cells.

The Habitat Element has the highest variability among the studied proposals. Some companies proposed clones of International Space Station habitation elements, which others presented fully inflatable modules. A representative design was chosen, and modeled in NASCAP. This habitat element uses an anodized aluminum material for the majority of its construction, shown in light blue on Figure 2. Should another design be chosen, different charging effects should be expected.

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[1] Note that the *Bow Shock* and *Plasma Sheet*, two structures in Earth's Magnetosphere, were not studied. This is due to their relatively small size, unpredictable nature, and the lack of a corpus of data.

Finally, the Orion Capsule was rendered in NASCAP. The Orion capsule has already been designed, and the NASCAP model was created to be as similar to it as possible. The Orion capsule has propulsion and a solar array, which drive charging effects. In addition, accurate physical information was released to use in the design of Orion's material properties. The Orion capsule features prominent dielectric surfaces, where antennae and instruments break the conductive shell. These are shown in red on Figures 2 and 3. This causes interesting charging effects. The full detail of the craft could not, however, be replicated in NASCAP's Object Toolkit, due to computing restraints.

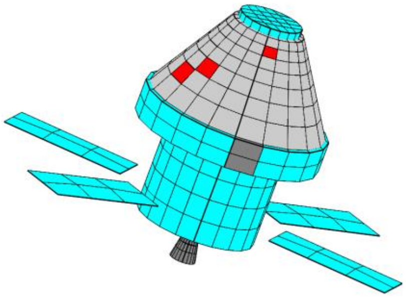

Figure 3. Isometric View of the Orion Model.

D. Simulations

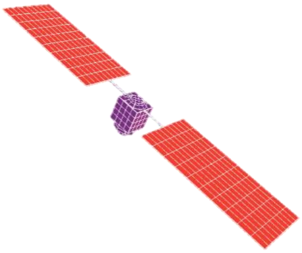

Figure 4. PPE Charging.
(Mathematical model)

After creating an environment definition and modelling the Gateway in the Object Toolkit, NASCAP was used to simulate the charging effects in various Gateway configurations. NASCAP uses measurements of $\rho_{e,}$ ρ_i, $T_{,e}$, and T_i (referred to as Environmental Parameters*)* to generate a plasma cloud and study the interaction with surface materials on the spacecraft model. First, each element was individually tested, in all of the environments defined in *Part B* above. This was done to determine the danger of electrostatic discharge during the assembly of the station, where each element is charged individually before docking. Next the fully-assembled station was simulated in each environment. The intention was to discover the worst charging levels the Gateway could expect to reach, and this was accomplished by using the most extreme observed plasma events.

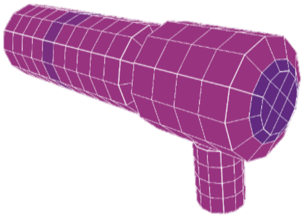

Figure 5. Habitat Charging.
(Mathematical model)

III. Results

Throughout the course of the project, newer and more updated data continued to be tested with the Gateway model. At no point did a reliable data source exhibit the kinds of dangerous charging levels which are observed in geosynchronous orbit. In the ARTEMIS data which was studied, notable periods of high-temperature plasma often seemed to coincide with periods of low density. A general condition for charging to be really serious is that both of these measures have to be high.

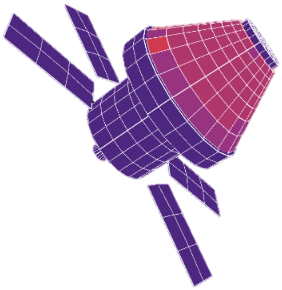

Figure 6. Orion Charging.
(Mathematical model)

The environmental analysis yielded an estimated amount of time in each lunar region:

A. In both the Lunar Wake and Earth's Magnetosheath: ~15%
B. In the Lunar Wake but not the Magnetosheath: ~ 5%
C. In the Magnetosheath only: ~15%
D. In the solar wind (no obstructions): ~65%

This analysis was completed using LOCATES, and compared against estimations made by Kylie Sullivan, based on data from the ARTEMIS mission. In each environment, local average Environmental Parameters were calculated, and the times when serious extremes occurred were studied and used in simulation. An important finding from the tool is that the rarest major environment, Zone B, still occupies about 5% of the Gateway's orbit. With a total orbital period of about 252 hours, this is still a significant portion of time, and enough to experience the full charge development of that zone.

The simulation results in Figures 3-5 are representative of the worst case results from this study. A great number of small fluctuations are observed with each timestep, and the simulations cannot be run for every set of data. The author chose the most extreme Environmental Parameters to study. Each of these figures is colored according to the left-hand voltage scale in Figure 7, while Figure 9 corresponds to the right-hand scale.

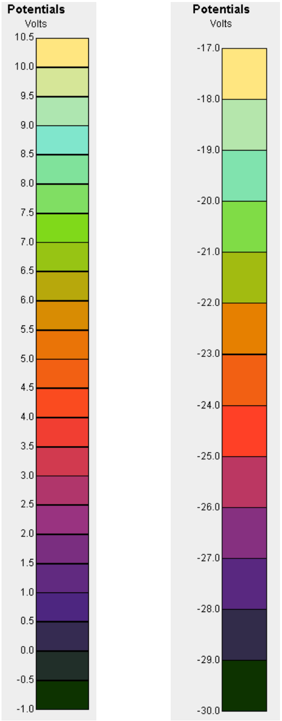

Figure 7. Voltage Scales.

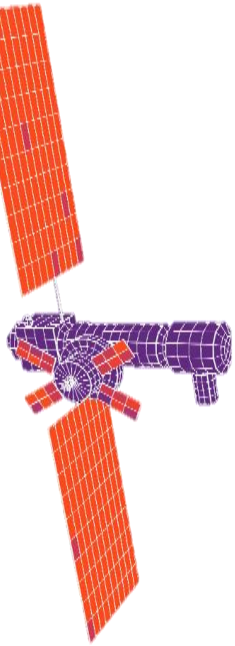

Figure 8. Gateway Charging.
(Mathematical model)

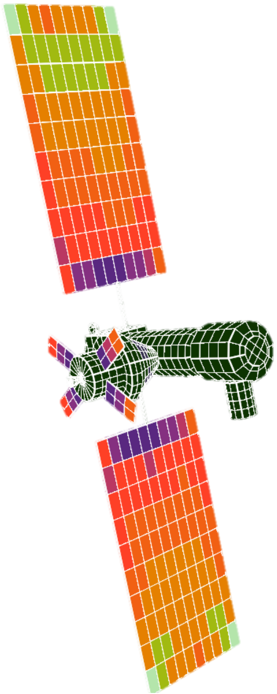

Figure 9. Gateway Charging.
(ARTEMIS data)

Numbers from the mathematical models did not yield dangerous charging conditions for the Gateway. In cooperation with Kylie Sullivan, Environmental Parameters from the ARTEMIS Mission were studied to find agreeance between the model and real data. ARTEMIS' data showed many discrepancies from the model, and when tested did yield more serious charging (see Figure 9). When high electron temperature coincides with high density, the spacecraft charging is driven to huge levels. This seemed to be rare occurrence, however, especially in the lunar wake where temperatures are highest. It seems that the wake region is only populated by a few very energetic electrons, and their low numbers limit the interaction with the Gateway.

This is not a comprehensive review; it is certain that more must be done to understand the lunar plasma environment. Of especially high concern is the behavior of the plasma in each lunar region. While we can guess at the rules which govern plasma movements, there are still many unknown mechanisms which can cause unexpected and potentially catastrophic failures.

Acknowledgments

G. Q. Sinclair thanks Dr. Emily Willis (EV44 - Natural Environments Branch, NASA) for her mentorship and advice, along with the rest of the EV44 team. Additional thanks are extended to the interns of EV44 for collaboration and friendship throughout this experience.

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