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Dr. Steven Koontz

>>DR. GARRISON: Can I have everyone's attention? I want to introduce our speaker today and also, I want to make a couple quick announcements especially students taking the 4372 course. You guys, in about two weeks you will have your presentations in here, your final presentations to the class and so I'm going to need everyone to email me the title of your presentations as soon as possible so that I have all of those and once you email me your title, I will email you back information on any of the reports I'm missing from you guys. That way you know everything is squared away and if you do have a report that I show is missing, then you know to get it to me before the end.

So I want to introduce our speaker today. This is Steven Koontz, who is at NASA Johnson Space Center as the ISS system manager for space environment. He has a background in chemistry, analytical chemistry, but we are not holding that against him today.

He went to -- got degrees from University of California Berkeley and University of Arizona. Also he has won several awards from NASA including the NASA Exceptional Service Medal, the Astronaut's Personal Achievement Award, Rotary Stellar Award Nominee for two years, NASA Johnson Space Center's Director's Commendation Award and the NASA Silver Achievement Medal.

So today he's going to be talking about spacecraft charges and it is an interesting problem because you will hear it involves a lot of things that you learn about in (inaudible), but it is in a different environment because the space center is definitely (inaudible) not.

>>DR. KOONTZ: Well, it is in a sense and this will not seem like an academic physics lecture. This talk was originally prepared and presented to the NASA Engineering Safety Council at one of the series I did. It is kind of interdisciplinary and a lot of jargon.

The fact that hazard appears three times on the cover page should tell you that has to do with safety reliability and mission success.

So summary. Hazard cause is the accumulation of electrical charge on spacecraft and spacecraft components produced by the spacecraft interactions with space plasmas, energetics particle streams, solar UV photons and free electrons and photons typically drive these processes and the spacecraft can do it itself with electrical propulsion and ion guns and other gadgets that are fun.

Hazard effects are radiated and conducted status noise in spacecraft avionics. Some things can happen that I'll show later, but when you move out beyond LEO, an Orion vehicle making contact with one of them is at 400-volts and one at 0-volts can be interesting and it is something to avoid.

For years, NASA has put first contact resistors on spacecraft even if you don't need them but whether or not that works depends on how rapidly the spacecraft is charging verses how rapidly the resistor -- you get your big jolt any way when the metals make contact.

The best way to control this hazard is through safe and verified design. A lot of spacecraft destroyed in the 70's and 80's while everyone was figuring out how this works and if you take advantage of lessons learned to date and familiar with NASA and DOD standards on this subject, spacecraft will survive most of the time. If you blow it off because you have schedule and budget problems, you might find other things blown off later in the program. Basically material selection, grounding and bonding practices, electromagnetic interference and electromagnetic compatible and potentially hazard configurations derived during acceptance testing is how it is done and works for 15 years without a problem.

Unfortunately, people don't know what the requirements are, and we have had cases where that is done, and it slips through the cracks and you will see an example of which a billion-dollar spacecraft was destroyed by failure to do that. People say the space environment destroys spacecraft and I maintain it really doesn't. The design and operations team did by ignoring the environment up front.

It is 100% human error but that's just me. It looks that way to me. You can use in-flight operation hazard controls and at the end of the day, you want to test like you fly and fly like you test to the extent possible. Aerospace Corporation keeps going on about this, but in many cases, you really have to compromise on that ideal.

Presentation outline, we will summarize spacecraft charging processes and look at a simple charging and discharge current and materials and configuration and operations effects and compare internal and external charging and look at the charge balancing equation that quantifies all of this. And then we will about space plasmas and energetic particles. We will look at some examples like how it charges in an otherwise benign controlling environment because it is PV array and its size that selects current from the ionosphere.

We will look at auroral electron charging and that's the precursor to see how things are out in GEO and cislunar and interplanetary environments. Space weather has a lot to do with this. All the way to Mars. Space weather generated by solar activity is going to change your charging environment and there will be days when you are going to need a lot of protection against that, even though it is benign most of the rest of the time.

Last, we will look at a particularly interesting example of what happens if you ignore all of that and design, development and test and that spacecraft didn't even last a year in orbit.

Why do we care about this? Safety reliability and mission success is why we care about this. The table on the upper right gives the number of anomaly records compiled by Aerospace Corporation up to 2001. You can see internal charging and surface charging contribute almost as much as single event effects and meteoroid and debris impacts.

More recent study sorts out 85% of the failure is to human error and as I indicated before, I think the rest are really human error. It isn't often that the environment exceeds your design environment and you get hit any way but that can happen.

The most common hazard effects of the spacecraft charging hazard cause are avionics system failures and anomalies, electric power, and surface performance property degradation. They are in a high-risk charging environment and surface arcing is causing their PV arrays to lose power much more rapidly than anticipated as a result of contamination of the arcing events.

And even increased attitude control propellent usage just because the surface arcs can be propulsive. That's led to early emission for some communication and military satellites.

Without putting too fine a point from it, if you are 6 months out from earth and you lose your electrical power system, everybody dies so we can't let that happen.

Spacecraft charging.  Any process that produces an electrical potential or voltage difference between the spacecraft and the surrounding space and environment, absolutely charging.  As well as voltage differences between electrically isolated parts of the spacecraft. We call that differential charging.

The electrical potential differences result from the separation of positive and negative charges in the spacecraft, space flight environment, are both with accumulation of an excess on one charge on some specific location.  Current balance equations will let you quantitate that and let's summarize the determining factors now.

Flux and kinetic energy of high energy charged particles, anything above 30-kilovolts or 10.  Local space plasma density and temperature as in earth's ionosphere.  The solar wind -- causing a geomagnetic storm moving across the planet and even space spacecraft motion relative to the local space plasma and magnetic field.

It is one piece of metal going through the field at 1.8 (inaudible).  We see a lot of it. During charges and discharging, currents flow through various parts of the spacecraft and can break things.  Simple resistor capacitor charging circuits can give you a feel for how this works and you need to remember the conductors and dielectrics charge and discharge in different ways.

Spacecraft charging isn't magical but many of my colleagues thought it looked that way and that's because I have drawn a resistor capacitor circuit here, but these resistor and voltage sources are peculiar than what you see in the electronic lag.  It could be coming from (inaudible) interacting with magnetic fields over hundreds of millions of kilometers.

It is not a power supply on the bench. The selecting circuit by the vehicle depends upon the plasma sheath around the vehicle and the density it is in. When you really work the charge balance equation it does not have the visible R on it. You work with conductances and particle collection rates directly. This other resistance is the resistance of the plasma breakdown arc that appears when that switch closes. And that's kind of exotic too.

It also depends -- R2, being a discharge pathway can be a function of your active charging control equipment like a plasma contactor. That doesn't look like a resistor either. C is the easiest piece of all of that because it depends on vehicle configuration and simple capacitance equations.

It works well here and explains why.

I have been accused of trying to scare people with this and I am not really trying to scare people with this, but it is what happens when you take a piece of acrylic plastic and put it in the vacuum chamber and hit it with a few minutes with a one million electron volt electron beam. Then you -- it looks like nothing interesting has happened. You can pick this up and carry it around.

But you will notice the fellow who is about to do this is holding an insulated hammer and a rubber strip that doesn't conduct electricity. When he disturbs it, something interesting happens. It got erupted very quickly and still arcing after the first hit. We do encounter mega volt electrons and sufficient -- even 100 KEV electrons in the auroral zone and if this is an acrylic window on your spacecraft that isn't protected by a centimeter of quartz. Your window can do this occasionally and not going to work too well afterwards. If I'm depending on that window to keep the air inside, it is time to put the space suit on.

So spacecraft mission environment, materials, configuration and -- determines the concept of operations -- determine what's going to happen to your spacecraft with respect to charging.

Your spacecraft is also able to charge itself in a variety of different ways, especially if it as ion engines. The amount of metallic area on your spacecraft is important because that can help collect ions and help with the electron collection. Most important are the properties of the dielectric materials. Secondary electrons are not out of the solid when a high ion enters it. In the same environment, you can have one plastic at 200-volts and the other at a kilovolt.

Photo electron emission can screen surface charge off of spacecraft completely. Concepts that have charged to 30-kilovolts in ellipse come out and now it is at plus 10-volts and the adjacent is at -30 and interesting things can happen if you didn't design that out with static dissipative materials.

The capacitance, you can evaluate with these equations. The reason I put these down is to compare the pre-space capacitance with -- dielectric coating on the metal and the capacitance in that case is A over D. So if you have a thin dielectric coating on a large metallic object, your capacitance goes up at a magnitude or more. That means it stores more energy, but it also means that it takes a lot more time at a given current to get to a high voltage. We will see later the space charges maybe to 18 to 20-volts in an environment that charges DOD -- defense (inaudible) satellite to 2-kilovolts. It's the capacitance difference and the limited exposure.

Electron kinetic energy is the primary importance. There have been a couple of papers about proton charging, but it is not convincing that's important yet. Maybe a problem there. A lot of protons of high energy. We most usually do it as a single radiation event problem; surface charging 5 to 50-kilovolts. Surface to internal charging transition is 50 to 100. Internal charging is greater than 100 KEV. Bear in mind that the rule of thumb about space radiation environments, there is always a power law. You have a lot more at low kinetic energy than high. That means you got a big surface charging threat and a big internal charging threat, long before you have any kind of single event threat from the protons. Electrons don't do single events.

The practical range of convergence for GEO and cislunar is .1 to 3 MEV and you need about .1 to .3 centimeters of shielding at some time to keep that stuff off of your printed circuit boards.

Here is the range plot that tells you, for example, how much aluminum it takes to stop a 1 MEV electron and it turns out to be about a centimeter. We will put it up here. The protons aren't doing much until we are way out beyond 200 MEV, 300 MEV and then they take over as the electrons fall off.

And this little cartoon is supposed to give you a feel for what's going on with the various processes for surface charging and internal charges. Internal charging, the electrons come right through your spacecraft and military reconnaissance vehicles, and that kind of thing, don't have a lot of shielding mass because you have to keep them light enough to launch.

So that means if some electrons get through and into your printed circuit board or that ungrounded piece of metal you forgot to ground, you will have electronic static discharge on the PC board and metal traces from the ungrounded piece of metal that will destroy your avionics.

Outside on the skin, we are picking up electronics from the plasma and the sunlight is removing electrons that were picked up. The same kind of thing is happening with the metal, but if you end up with a big voltage difference between your dielectric and piece of metal, you can have an arc and many of those are recorded and have done damage.

This is a specific example of what it looks like for a space station if, as was suspected before, we can pick up enough PV array charging to charge up those big pressure charge modules which are huge capacitors and the dielectric breakdown is through that thin metal coating on the aluminum spacecraft.

Active electrons are collected by the ISS PV arrays. All conductors want to do is rearrange charges to null out any externally applied electro static or magnetic field. So we have ions come in to try to null that out and that produces a huge voltage gradient across that. If the voltage is high enough, it turned out to be between 60 and 160-volts per station, depending on how long you let it cook before you see the arc. Time dependent dielectric breakdown is important. Then you get a big arc and a lot of damage locally and a lot of electromagnetic noise and that's acting like a plasma contactor. That's what that looks like when you do it in a test chamber.

This scale, that's about 14 centimeters. These are all arcs produced when a huge, high-speed storage capacitor was charged to that metal plate. The huge storage capacitor and this was arcing pretty regularly every few minutes in the test chamber and that doesn't look too bad and it isn't. Nobody was really worried about that because our EMI/EMC designed grounding and bonding all of that effectively inside the space station. Fortunately, this hasn't happened at all. We have not seen it happen on orbit and we will explain why later.

However, we have seen other things happen on orbit and if your PV array is powered and you get one of these dielectric breakdown arcs, so it can conduct a hot wire, a ground wire or a solid at two different voltages, the power from the power supply feeds the arc and it gets bigger and this happens. Then you can lose your PV array and various people have in the past.

The current balance equation I was referring to earlier, the voltage is the voltage of the spacecraft. We are not referring to explicitly, in this simple tutorial toy model about the kinetic energy of the incoming particles, but at equilibrium the total current to the surface is 0. You will collect electrons more easily than ions and the surface goes negative until the collections are equal and then we are done. Remember, at earth's orbit, at 1AU from the sun, you can get about 10 to the -9 amps/centimeters squared. So if your charging current -- the electron current is a lot less than 10 to the -9 amps, you will not see much charging. That's fine but the part of the spacecraft not at the sunlight might be at 30-kilovolts.

We will have a look at earth's Ionosphere. This is a map and a bunch of little dots and the little dots are (inaudible) stations. They are vertical transmitters that sound the ionosphere and determine that altitude of the maximum density region. Looking up, the first maximum density region you see and the -- effectively the electron density because the critical density is proportional. So we can look and see how that is doing today by doing that I hope.

Maybe, maybe not. There it goes. Okay.

So this is the maximum electron density number, the critical frequency and that's the altitude we see the critical frequency. We have planetary coverage except over the oceans and we plan to use this -- if we lose our FPMU for safety and (inaudible). You see this peculiar structure? That's called the (inaudible) anomaly and we pick up a lot of charges on that. Oops. I think I shut off the talk. There it is. Thank you.

We've also used this facility in the past without actually having to pay for it. That's the Millstone Hill Astronomy Observatory and ion (inaudible). It goes through the ionosphere and you need a really big dish to receive the very weak scattered return signal, but that gives you density and temperature profile for the entire ionosphere above you. Albeit, at one location; Millstone, Massachusetts.

As I will show you later, we verified some of our instruments on station that we fly over this and compare their measurements with ours.

Moving away from LEO, everything gets interesting and this cartoon is designed to give you a feel for that and the fact there are a large number of spacecraft working in this environment that have not been destroyed by spacecraft charging. I think we learned something from 1979 or before when we were losing spacecraft a lot.

This cartoon obviously isn't to scale, but the reason I like to show it to people is to reinforce the idea that when the moon is full as viewed from earth, you are in a GEO synchronous charging environment. This is not benign anymore like the solar wind. When there is a geomagnetic storm, you get one out here and we have spacecraft observations to that effect. Now that we are planning to put a -- hopefully put a man-attended platform around the moon with international partners and fly Orion over there and we have to remember that with Apollo, we never went to the moon when viewed fully from earth. That's for thermal surfaces. You don't want to be on the moon when it is fully illuminated from the sun. It is really hot.

This gives you an idea of how all that works. You may have heard something about reconnection. That's a -- we are about to get a geomagnetic storm from a reconnection of that. You may have heard something after the August solar eclipse last year about reconnection events being a reason that the solar corona was much hotter than anyone thought it should be because a lot of energy is stored in those magnetic field structures that get released by the reconnection. You just saw a bunch of electrons get fired at earth, same time a bunch got fired downwind and if the moon happens to be there, it gets the electrons too.

Now, I have been talking about plasmas and energetic particles and there is not much to say about energetic particle streams except in space they are usually isotropic.

Plasmas are something that a lot of people aren't familiar with and it is an ionized gas that conducts electricity and it has a number of charged particles in a particular Debye length or shielding length is greater than 1 and a shielding length is much less than the length of whatever system you are dealing with.

Maxwell-Boltzmann equation applies to all of this. The particles and ions are -- that's why you pick up more of them and your surfaces charge negative.

Some other important properties are the plasma frequency. That's how the ion -- the Digisons work. And the fact that this sheath around the spacecraft contributes to the capacitance is a really big deal and contributes to some of the peculiar phenomena that we see on station. When we do charge to high dangerous voltages, albeit very briefly, and that's not a hazard that we don't need to control it, but we need to put that on the command.

What do these plasmas look like? The gas discharge, which is high-density audio and hot, well, it is not a space environment concern unless you understand that -- looks this way inside your ion engine or your all-effect engine and a small object in this plasma charges to about -10-volts.

The ionosphere, a small object is going to be a volt or two at most. Up in the magnetosphere in the GEO belt and (inaudible) orbit, we have low densities and moderate density so that at night or in shadow, your structures can go to -10, where anything negative will be 10 positive unless you have static dissipated surfaces and we even that out.

The solar wind itself is completely behind. We only have problems outside of the magnetosphere or issues, if we're in the geotail or there is a coronal mass ejection going by or a solar particle in process. Then it gets interesting and very magnetosphere-like.

One charged particle environment of particular interest, since we fly through them all of the time, is the auroral charging environment. This gives you a feel for what that charging particle environment looks like. Electron kinetic energy is 100 KEV and flux is from 10 to the 2 to 10 to the 6 electrons per square minute, centimeter per second for SR EV. This over here is a distribution in contrast to these where the EV doesn't appear and that means that say at 1 MEV here, we have this many particles of energy equal to or greater than that number. We are adding it up.

So that's your worst case charging environment suggested for design by our ultra conservative friends at JPL and that's the NASA solar minimum model. And that model is going to probably be replaced by AE9 as soon as we think it is ready for prime time, which we don't think it is yet.

Over here you can see a comparison of the GEO environment. The map environment, which is a lunar phasing departure trajectory and the higher orbit environment which is basically elliptical out to just under GEO.

Look at your flux. 10 to the 5, 10 to the 6, 10 to the 7, and you have enough energy out here and it is all bigger than your threshold for worrying about internal charging. Notice these are 10-hour averages and instantaneous occurring are small. 10 centimeters -- this is the internal flux for centimeters per second. That's a 10-hour average and it fluctuates a lot and it really gets ugly when you are in the radiation belt, but you don't stay there very long, and you don't operate there. You pass through as quickly as possible.

I like to see this slide because some of my colleagues are convinced that solar particle events are a charging environment. Look at the electron kinetic energies and look at the particle flux. Yes, it is. It can get you into a GEO situation.

This was from the ACE spacecraft in October or November 2003. This became that (inaudible) storm that Canadian children found so interesting because of the auroral.

Now another useful tool from our ultra conservative friends at JPL, this is a map of your surface charges risk as a function of your latitude and altitude. GPS vehicles operate where I put the white arrow right now, which is one reason they are parking on the surface a lot and contaminating the PV arrays and losing power faster than anyone thought they would.

The other interesting feature here is that all the way out at 100,000 kilometers, halfway to the moon, at 0 degrees latitude as viewed from earth, we still have a high-risk environment. Isn't that interesting?

Otherwise, everything is kind of moderate, medium or no issue unless where you are in the space station going every day where this high latitude passes. Something else to mention about that. Garret and Whittlesey, this is available free of charge at that link. JPL is giving it away.

This is an internal charging threat map which looks a little different. This is described in terms of orbital -- GEO synchronous is right there. You can see where the protons and electrons are. Once again, GPS satellites operate in here.

Let's do a simple example that shows you how to use a current balance equation. I don't have an audio-visual aid here, except this one. Imagine this was a simple PV array. It has a length and a width. In sunlight, the cells have a voltage and we will make it 160-volts in the example. And it is connected on its negative end. I want to be able to calculate flooding potential as a function of position along this. Can I do that? Yes, because I have made a simple geometry that lets me cheat basically.

At steady state, the ion and electron currents will be equal. The expression for the ion current and electron current can be put into a ratio and you can cancel things and you end up with this. Let me point out the difference that makes this work the way it does.

Remember (inaudible) equation applies. We have a temperature and the heavy things are going slower than the light things. The velocity of the electrons just as kinetic speed is higher than the orbital velocity of the spacecraft. So they are coming in from every which direction, as fast as they can.

The ions in contrast are being picked up at space station orbital velocity because they are not going fast enough to do that. Then you ask, why don't the electrons come into the back side too? Well, they try to, but they separate from the ion and that creates another field and slows down the electron and speeds up the ions a little and you still have a wake behind the wave. Can't pick up any charge back here if your velocity vector is that way.

So I just do the ratios and that's just the volts and the expression for the collection of particles with some velocity, VE, on a flat surface.

Then you do the ratio and it turns out only about 20% of that whole length is collecting electrons. The rest is collecting ions to balance the charge. When I do this, I can calculate -- it is just arithmetic. The voltage is a function of one end to the other. The negative end is -130 and the positive is about plus 30. Most of the wing isn't collecting electrons at all because it is too negative.

That's what a lot of folks or some people thought would happen to the station early on and this calculation does work for a number of satellites that meet this key criteria, exposed metallic PV cell interconnects and collection buses. There is metal that can collect the electrons around.

This doesn't work on ISS at all. Why?

Well, that's because we buried the interconnects between the cells and the current collection buses and dielectric. The only way ISS can collect electrons from the ionosphere is around the solar cell coverslip edges on the edge of the solar cell. That's why we're not seeing very much from the PV array rings, smaller than originally anticipated. And the 10 contactor units are way too much gun for this. That's why we don't use them much or at all anymore.

So the steady state assumption is also not valid given the size of the ISS, as a capacitor, which is greater than 10 to the 9 Pico farads. We do have a detailed model and not one of these toy calculations that Boeing developed, and we are doing good, accurate predictions.

Now something else is going on however. Any division to PV arrays collecting electrons, albeit a lot fewer than we thought we are flying through a magnetic field at 7.8 kilometers per second and that looks like this. The graphic at the lower right shows the station at high latitude. I don't know what latitude that picture really is, but we will pretend it is a 56-6 north.

The region B vectors are going into the page. That is the south geomagnetic pole near the north geographic pole and vice-versa. So your field lines operate the way you expect for that.

Using the same simple arithmetic we used for the PV array and using 50-volts, which is tip to tip voltage difference along the 100-meter truss at high altitude, we calculate that the negative end is -42 and the positive is plus 8 and we see something very close to that. Bear in mind that this motional EMF depends on orbital velocity and it is 0 at GEO because you are not moving relative to the field anymore.

When you learn a lot of -- we learned a lot using our floating potential measuring unit which is right here. It is inside that red circle. Very early after it was deployed, we got some over flights from Millstone Hill when the radar was operating and doing what they call (inaudible) to study ionic properties.

The red and blue circles are the density of electrons and temperature of electrons. Millstone Hill was reporting and the lines you see here is what the FPMU was reporting. So we are making good measurements compared to a completely different method for doing that.

We followed up in with orbital differences from the DOD. You can see with the progression line that (inaudible). The agreement is remarkably good there too. We have confidence in our instrument by validating against two independent measurements.

Now the best graph speaks volumes and we can spend a lot of time talking about it, but this is for the plasma contractors off. The starboard tip is doing that. And -- they get a little bit positive when the starboard tip is very negative, and the port tip is a little bit positive. You saw that in the drawing beforehand. Superimposed on these magnetic motional EMF voltages are these peculiar spikes and the maximum solar array driven charges we have ever seen. Collecting electrons around the edge of the coverslips can give you up to 45-volts on a day when you have that kind of temperature and density.

When we turn the PCU's on, it goes flat. We have our magnetic conduction happening, but it is shifted because the plasma contactors are clamped out to 10-volts negative. But the structure is still that -- picking up motional EMF anyway and collecting electrons so that the two ends are up and down but the PVA array charge is completely suppressed.

Then we saw something different. Operating -- when our electrical power system folks were doing efficiency measurement on those big 160-volts wings, when they did a full wing unshunted, we saw big voltage spikes that lasted a few tenths of a second. That's the subject of forward work, but I will mention that the charging and relaxation time is on the order of milliseconds to seconds. And the relaxation time is dependent on ionospheric density.

So if I got 160 to 300-volt wing on my gateway platform and not running an artificial ionosphere and I do a shunt, we don't know what's going to happen, but it looks like it could be an issue, safety thing. We don't necessarily want to -- that could be on the "don't do it" command list possibly if it turns into a problem.

But we believe there are a couple of different approaches to explaining this, but the one I found most satisfactory came from one of my Boeing colleagues and it is displacement current. Remember the capacitance shielding thickness contributes to the capacitance of the entire structure and when you do abrupt voltage changes, displacement current leads to big voltages that are transient like that.

So where else might we encounter ionospheric plasmas in magnetic fields like those we experience in the space station? The inner-solar system? Probably not. Mercury is the only planet with a magnetic field and it is only about 1% as strong as earth's. The moon, Mars, Venus, and main belt asteroids are insignificant global magnetic fields. Cold, dense ionospheric plasmas are Venus and Mars. If I don't -- I don't need one, I fly higher.

There is one other place I mentioned in passing that many don't expect and that is surrounding your high thrust interplanetary transport with electronic propulsion. It is making its own when engines are running. If the EPS -- the electrical power system is photo voltaic, which it will be until we get smart and invest in space nuclear power, we can expect high spring voltages for efficiency and very large PV arrays. There are other questions to consider here. We can learn something from what we have seen on the station.

How much PV array driven spacecraft charging can I expect when the electric engines are operating? Well, I operate PCU's when I operate electric engines. So the electric engine doesn't charge, so I have a PCU operating and if they are collecting electrons, it doesn't matter.

So if I am operating neutralizers with the thruster, no problem. What happens to the vehicle floating potential when the high voltage strings are unshunted? We don't know but it looks like it could be a problem. What happens if the electric engine neutralizers degrade or fail? Well, they operate at 300-volts and if you had partial failure or degradation of your thruster beam neutralizers, you can get 100-volts on your vehicle for a while.

Now using nuclear power reduces this risk, but it doesn't eliminate it because thermoelectric power conversion units look like array strings. They can still collect current from the plasma but given that this is only happening with electric propulsion, which is probably going to be -- I say high thrust -- compared to chemical, obviously not, but compared to traditional or electrical engines, yes. You have to increase the available power, so you can get your delta V into a practical window for human space flight.

You don't have three years to do this. You have a few months. They operate at a lower impulse and higher power and makes the wing bigger and drives you to reactor events.

The reason that the gateway platform is being used as a departure point -- I am sure that you have heard that lower orbit is halfway to anywhere in the solar system. Well, as it turns out halfway isn't far enough. And that (inaudible) lunar orbit you are more than halfway to

Mars. So that electrical propulsion system can get you there and back in a couple of years.

What that means is you have put the entire cost of -- instead of launching a whole bunch of propellants and you put the cost of all of this back onto your launch system and it works for people who worry about money, like me.

Now before flight, no one in the program really believed the station would ever fly through Aurora. And then on November 10th of 2000, Commander Shepherd -- stronger as we approached. A faint, reddish plasma layer was above the green field and topped out higher than our orbital latitude. It looks like that. If you've got green under you, some of the electrons that were headed that way to contribute to the green didn't make it and they ran into your spacecraft first.

We have seen that happen from time to time. This is an example of auroral charging on a European spacecraft. Number of events verses voltage, most small, but there are a few, 2 or 4-kilovolt events over this time period. And Australis -- Freja was designed so it did not have an issue.

Now, I'm going to go through another simple work example and this one is how auroral electron streams charge spacecraft using a very simple capacitance.

V is equal to G/C. V is the charge I need to make that voltage happen with that capacitance. So my charge is going to be what I can collect on the surface area of that spacecraft in 10 seconds if I've got a normalized current of 2 times 10 to the -5 amps to the metered squared. So I decide it is 30-kilovolts and the capacitor can charge to 30 but not more. And I'm reporting this as net current. The net current of the spacecraft is the auroral current minus secondary, plus photo electrons, plus ions and that's what happens when you do the arithmetic. It charges all the way to 30-kilovolts in less than 30 seconds.

I put a 10-dielectric film on it and the capacitance goes up and now only 2-kilovolts in the whole exposure time. Same thing for the dip.

Now the space station doesn't have a capacitance of a million Pico farads, so it charges to 13-volts we expect and the space suit only charges to 27 which is a good thing because several astronauts report having (inaudible) in an Aurora. How do you know you were in one? It was green and red, and I think I was outside in an Aurora. This is really able to knock that down in a big way.

What evidence do we have that this is all true? Well, in 2008 on day 86, the station went through a high latitude auroral event and they reported an increase of about 18-volts and both probes reported an increase in electron density at the same time because the auroral electron stream was ionizing the upper atmosphere more than usual.

ISS was in the auroral zone for 144 seconds but the actual arcs, the green things you see in the sky, were much shorter duration and about 12 seconds. But we observed 18 and you remember in the previous simple toy calculation, we got 13. Pretty good.

And the defense meteorological satellite program confirms that when we were on that flight path, we were in a region at a time when densities were above 2 times 10 to the -5 amps per metered squared along that flight path.

The reason we were charging -- the Freja station -- 30-kilovolt can go through 30-microns of chromic anodized coating. So we understand all of this.

And what does the DMSP itself do? Well, it charges various surfaces to much higher voltages depending on what the surface is made out of. The highest are Teflon and the frame is much -- the structure is much lower. Kapton doesn't charge as much as Teflon and they started getting static dissipated because that vehicle got damage but note that individual dielectrics and conducting structures charge differently.

How does it work for a spacecraft like this? It looks like a smaller capacitance with a common ground on one side.

Somebody said that we're not grounded (static). In fact, we are. The ionosphere is our ground, but it is a weird ground because it acts like a diode and it doesn't necessarily carry that much current unless you have a plasma contactor.

So (inaudible) is your local reference ground, even though you have a station -- a vehicle structure ground inside of the spacecraft that refers to your structure potential. So the potential is really measuring the spacecraft or whatever surface relative to that environment. I am treating that environment no matter how limited its ability to provide current as its local reference ground.

Now I showed you the geomagnetic storm before, but this is interesting because this drawing is to scale. The moon is way out here. Earth is way over here and isn't it interesting that we can get geomagnetic storms downwind from earth that you look like this, with electrons being fired at earth from the reconnection site and then out towards the moon, where it does interesting things that we need to make sure won't hurt us?

Now, why are we talking about the geo synchronous environment if we're going to go to the moon and Mars and the cislunar? Answer is kind of obvious. I'm going to be in it a few days every month or when the geotail is whipping around and I end up in it anyway.

Mars is less obvious, but the geo environment is widely considered to be a worst-case hot plasma and energetic particle spacecraft charging environment for the inner-solar system. Only Jupiter and Saturn are worse. So the natural environments definition for design specifications for Orion and gateway all use SLS-spec-159 with the geo synchronous charging environment. This defines the environment and doesn't tell you what to do about it.

But the Orion document does and calls out specific design requirements for static dissipative properties of surface coating, printed circuit boards, and thickness, and all of that.

So spacecraft functional verification to the SLS-SPEV-159 extreme GEO design environment by a test and analysis is going to be a requirement for those spacecraft or actually it already is.

Now there is something about surface charging in the GEO synchronous environment. I think I mentioned this already. The currents are lower than we see in the auroral environment, a lot lower. They are lower than the photo electron emissions, so if you are in sunlight and seeing this kind of current on your surface, you will charge positive anyway, 10-volts at most.

Spacecraft have complicated shapes and some of them can be in shade and some in sunlight, so we want static dissipative things because we want that before this shadow goes to -20 kilovolts. Static dissipative materials let you do that. If that current gets bigger, then maybe you need -- maybe you need to have an active detection of surface detection with -- on demand to create a static dissipative -- DOD and (inaudible) operators are using some of this now but not a lot.

The other problem we have is deep dielectric charging and plasma contactors do no good because they are outside of the aircraft and I don't think you want to run one in your avionics box. In this case, dielectric time constant becomes a design driver because deep dielectric charging happens in timeframes in the order of hours to days. Primary spacecraft internal charges targets are insulators like clamps, wire insulations, circuit boards and electric connectors and arc tracking is one of your biggest threats for charging systems and power cables.

These are JPL and Aerospace recommendations looking at the permeability. Note that Kapton and Teflon are in the "don't use it" zone for good reason. And deionized aluminums are here. Kapton and Teflon are used successfully when they are with carbon black or (inaudible) to make them static dissipative.

Now the moon has no atmosphere capability of blocking solar wind or energetic particles so orbital spacecraft in the lunar surface are exposed to certain charging environments. Lunar orbiting surface charges threat environments including a few days on each side of a full moon plus whatever you pick up from the geotail and solar particle events and I should mention corona passage.

Lunar specter cislunar charging observation during the lunar surface event, the surface went to -4.5-kilovolts and spacecraft potentials to -100 to -300-volts. I showed you a table earlier where the shielding length was only a few meters and lunar prospector was a lot further away than that. So your question ought to be, how did they make that measurement? They made that measurement with an electron spectrometer. If it is 4.5-kilovolts relative to the spacecraft's spectrometer ground point, their aperture is only looking at lunar surface or some part of it. They can look at electrons coming in from the local environment and solar winds that are low energy and see how that changes their spacecraft.

Lunar prospector made the first observations of geotail current sheath region. Lunar surface potentials, even in sunlight where they have photo electron clean off and can go up to 100-volts negative where the spacecraft is between -40 and -80, which isn't so bad.

The Artemis and Themis have done the charger observations and produced the same thing. So the GEO design environment should cover the expected conditions because we are seeing that this cislunar environment is similar to GEO, even during particle events but less severe than we think.

However that is two spacecraft over a period of 20 years. I'm kind of thinking we can use some more data here, but we can proceed with reasonable confidence and safety by simply designing by the GEO.

I have mentioned space weather messing with us before and I'm going to go out again -- this is a hobbyist site, but it is useful in that you can go here and look directly at the solar wind. You can go here and look directly at the x-ray data. And you can buy dolls for your children if you like, that have flown on stratospheric balloons from California.

If I go down -- now, what do I want to do here. Okay. The real resource and that's where spaceweather.com gets all of its good stuff is here. You can look at coronal until SOHO dies -- until it dies which should be soon because it is 20 years old. You can look at the ghost proton flux and see, do we have an x-ray flare and is there a geomagnetic storm? What I want to show you is not the models in the report but the actual observations at GEO of the electron flux.

10 to the 3 particles per second squared. That's your alert condition for internal charging. These are greater than 2 MEV electrons and those are .8 which still do internal charging albeit (inaudible) and contribute to surface charging. I wonder where -- 10 to the 3 is the alarm one because it spends most of its time above the alarm limit. I have been watching it for 20 years now.

I recommend that you can see from the directory of the weather prediction center that this is a massive resource and it is worth your time if you are interested in this at all to go work through it and have a closer look.

Now, if an event happens that violates your design requirement, there isn't a lot you can do to save the vehicle for this kind of charging process. If you are worried about arc tracking on your PV arrays and you can shunt it and power down, but then again, your batteries are going to die pretty fast and that's loss of emission. That's why I emphasize that it has to be designed out.

It is designed out by becoming familiar with NASA and DOD standards and guidelines and preferred practices for managing spacecraft charging that captures the lessons learned from all of those spacecraft that died in the 70's and 80's. You can have a close look at the JPL voyager spacecraft charging design and verification process documented here and while that looks like the time and effort schedule that would make most managers crazy, if they hadn't done this, Voyager would not have survived the Jupiter and Saturn flybys.

If you are going to -- some way you are going to arc anyway, you want it to be harmless. Your spacecraft (inaudible). If your avionics system complies with these requirements, then nothing interesting will happen.

You can ask about active control during severe charging events if you expect that to happen and then you want a PCU or something like a plasma contactor unit, but they run on a lot of gas, so you don't want to run it continuously. So you want inaudible) that was built for DOD. Simple and small and remarkable, that it costs a million dollars per unit given its size, but it does.

>> (inaudible).

>>DR. KOONTZ: They were at risk for other charging events inside, the deep dielectric charges. So they didn't have solar arrays, but if you don't have solar arrays it doesn't mean you have high voltage cables. It didn't have it either and their concern was am I going to arc on my PC boards? Because at the time static dissipative PC boards didn't exist yet.

>> (inaudible).

>>DR. KOONTZ: Yeah. Say again.

>> (inaudible).

>>DR. KOONTZ: It was designed to survive the charging environment. It has a 1-centimeter titanium safe for its ionics because the total ionizing -- will kill parts in less than a year and a half, so that much shielding is to block the energetic electrons while removing the threat to the boards inside.

I think we need nuclear -- (Laughing). But that's just me. Nuclear electric (inaudible) would make everything so much simpler and that with -- launch at a reasonable cost, but I'm retiring soon so I won't worry about it.

Now, this is the story I was telling you earlier about ADEOS II. It was a billion or 2 billion-dollar Japanese operation package. Same as DMSP, kind of. On 20, October 2003 during a geomagnetic storm -- well, actually during an auroral event. I think that was a high velocity solar wind stream that caused that.

Something happened -- that was intended to power down to conserve energy. By 23:55 the satellite was dead. Further attempts to recover telemetry failed. A polar earth orbiting satellite with -- was attributed to interaction between the auroral electron plasma environment and the improperly grounded -- didn't hurt the wings and -- it was a twisted pair and wrong installation on them. The loss of ADEOS II investigation revealed that auroral charging of a polar satellite could cause serious failure, including total loss. Yeah, if you build it wrong.

And MM-OD impact could have done that too but there is more to this story in that those 50-volt wires were insulated with (inaudible) which was popular at the time because everybody was upset about Kapton arc tracking.

Well, in this configuration it was run 20 to 30 Centigrade over its recommended temperature. It was becoming brittle and it cracked. Now, that's what enabled the little arc on the ungrounded blanket, metallized plastic blanket, to start the arc track which killed the vehicle.

Without putting too fine a point on it, that configuration would have gone all by itself eventually. Look what you had to do to make this happen. You didn't ground the metal part of the structure. We used the wrong material and configured it -- shouldn't have gotten past PDR, much less CDR.

That's the end of my talk and unfortunately, without thinking about it, ended with a catastrophe story. Any questions?

>> (inaudible).

>>DR. KOONTZ: You have to get NASA to start funding nuclear power in space. They are doing a 10-kilowatt reactor development right now. So it is baby steps. You have a lot of public concern about this. I will say it is perfectly safe and people say, we have heard that before. It was funny. When I was at the first international gateway meeting, the Russians looked at this -- it would have to run at a kilovolt for efficiency because the conductor runs are so long, and they said, this is stupid. Look guys, we've got a one-megawatt space nuclear reactor in late development and we will give you a good price on it and nobody bid at the time, but this was four years ago when Russians were less unfriendly than they are now.

So you have to start building it. Frankly (inaudible) engine needs 1 to 10-kilo watts of something and let me mention why the Prometheus project was canceled.

Vice-President Dick Cheney decided it would be a cost-saving method to adapt submarine nuclear reactors to the Prometheus. They operate in the ocean, so you have cooling water and the only way you can dump waste heat is with a radiator and the radiator got so big it was the end of the Prometheus. That was 30-megawatts and it doesn't need to be that big and you have a problem going to Mars any time soon if your federal budget is clamped at 20 billion-dollars, less than and has been for four administrations.

I keep telling some of my colleagues about new technology to do this and that, and you don't need new technology. You need money. You need a budget and until that happens -- that's one of the reasons gateway has become attractive. Building a small man-attended space station that orbits the moon. The first time that was presented to the higher powers, they said, I don't want to build that.

Then they looked at the price tag on everything else and said yeah, space station around the moon with an international partnership and I want to buy that and then you can talk about Mars or whatever, but that's what I'm willing to pay for because the cost of everything, I'm not paying for that.

Political science. (Laughing).

>> (inaudible).

>>DR. KOONTZ: That's how electro dynamic tethers work. If you don't have a magnetic field, they don't work anymore.

>> (inaudible).

>>DR. KOONTZ: Well, your velocity is 0, so your tethers don't work anymore and around Mars and the moon, no magnetic field.

>> (not audible).

>>DR. KOONTZ: North orbit, electro dynamic tethers could work and actually HGTV fluid demonstrator -- and it surprised me that the safety review panel allowed it because it deployed its counterweight upward after HGTV separated from the station and that's the

configuration where the tubule breaks and then you have a collision.

So the Japanese had to (inaudible), if it breaks it can't get back to station altitude and then everybody was happy with it.

>> (inaudible).

>>DR. KOONTZ: I don't know the (inaudible) failure story. One of the earliest big charging -- spacecraft charging events was a defense communication satellite in the 70's. I mean it's communication system failed. Nobody knows why to this day. It is still there, and you can look up and see it as it flies over if you wish, but that got DOD really interested in spacecraft charging threats.

>> (inaudible).

>>DR. KOONTZ: Yeah. You can use tethers for propulsion. You can use tethers for orbit maintenance and you can use tethers to generate electricity, but energy is always conserved. So if you are generating electricity and using it, you are losing altitude. You have to do something to reboost.

If you are generating thrust, then you are using power and you are eventually going to have to recharge your batteries or find a power source to drive all that.

>> (inaudible).

>>DR. KOONTZ: Displacement damage. It also gets -- inside the spacecraft. That's driven mostly by protons and secondarily neutrons. So displacement damage, I mentioned DMSP poisoning itself with arcing contamination on PV arrays and that's because you expected decay rate of those arrays cannot be explained with displacement damage alone. Something

else has to be happen and the smoking gun evidence came from looking at the GPS.  There are antennas on these vehicles that were reporting signals that had to come from the spacecraft and not down there.  That turned out to be arcing signals and that's enough to explain contamination on the arrays.

>>   (inaudible).

>>DR. GARRISON:  Let's thank our speaker.  (applause).  If you haven't picked up your paper, it is up here in the front and also reminder, next week is our final talk -- public talk of the semester and (inaudible) from Lamont also talking about the International Space Station and I'm also -- after next week's lecture, I will give you final instructions for what is going to go on for the student presentations which are going to be the following week.