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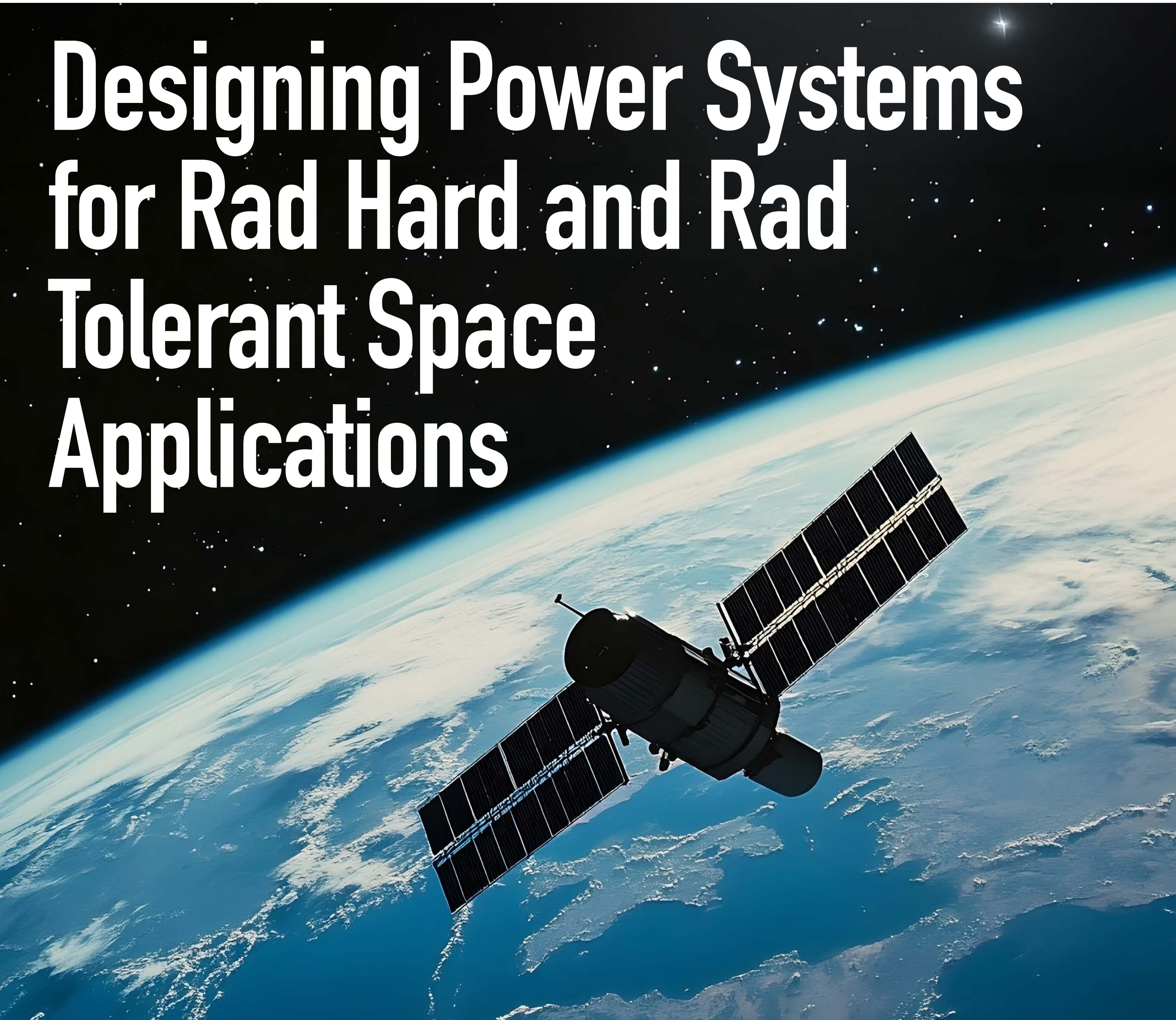
Designing Power Systems for Rad Hard and Rad Tolerant Space Applications



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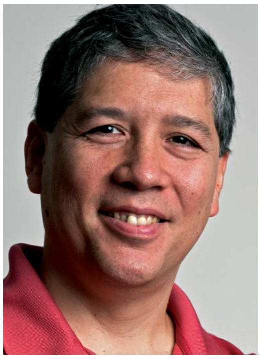
Designing Power Systems for Rad Hard and Rad Tolerant Space Applications

SPACE, THE FINAL FRONTIER, introduces the adventures of the starship Enterprise. It was a futuristic romp around the galaxy where spaceships abound and most of the technology was a hand wave away. In the real world, creating solutions that work in space, from satellites to space vehicles, requires hard science and engineering to provide reliable electronics needed for space applications. One thing that these systems demand is power, and designers must contend with everything from electromagnetic interference (EMI) to radiation. Designing and testing radiation-hardened systems that can meet power density requirements is doable.



Bill Wong
Editor,
Senior Content Director, Editor, Electronic Design & MWRF

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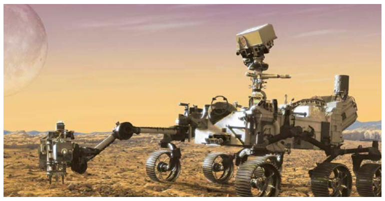


Credit: NASA/Desiree Stover

CHAPTER 1:

How Do You Counter the High-Radiation Environment of Space?

PAUL MORRIS, VP of the RF and Communications Business Unit, *EnSilica*

This article examines the mitigation techniques that allow space equipment to cope with ionizing solar radiation.

It's an understatement to say that launching equipment into space isn't cheap. Even with costs dropping in recent years, the cost of a satellite and its launch can still be anywhere between $10 and $400 million. Indeed, a geomagnetic storm in February 2022 is estimated to have caused approximately $50 million of damage to SpaceX's low-Earth-orbit (LEO) communication satellites. Weather-monitoring satellites cost approximately $290 million.

And that's before maintenance costs, with component failure requiring either in-space repair or causing the entire system to be written off. In short, all equipment must incredibly reliable and be able to withstand the extreme environment.

Chip and system engineers essentially face three key differences when creating orbit-based rather than ground-based equipment.

The first is temperature, with equipment needing to be protected from extreme (150°C) fluctuations and an operational level maintained. The second is the vacuum.

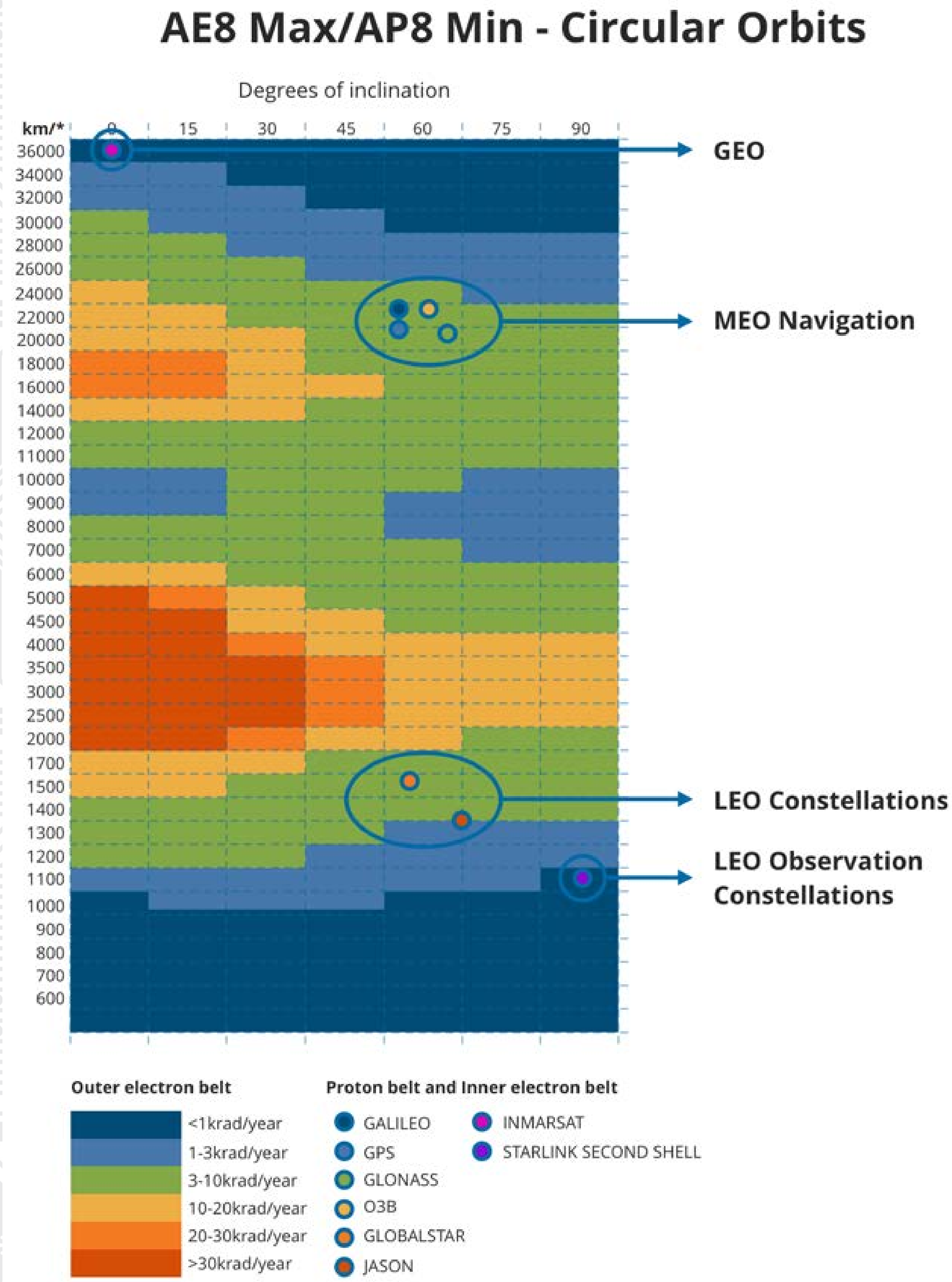
Collectively these create a different cooling effect than on the ground, relying solely on thermal radiation rather than air convection. This requires slightly different calculations for heat dissipation. It also creates issues with moisture, which gets into the package on the ground and then seeps out of the package once in orbit, potentially delaminating the package from the board. Thus, a separate qualification is needed to make sure that you don't have trapped moisture in the package before launch.

These two issues are relatively straightforward to mitigate through packaging and insulation. The third (and arguably more challenging) difference encountered by electronic components in space is radiation.

Radiation Encountered

The magnetosphere of the Earth concentrates particles into two main belts *(Fig. 1)*. The lower belts mostly consist of protons, and the upper belts being mostly electrons, with most of these particles coming from the sun via solar wind / solar flares. Any remaining particles come from cosmic radiation from other galaxies.

While it's difficult to replicate the full test environments on Earth—to generate some of these particles would require in the region of giga electron volts—these belts are at least very well understood and were being studied by NASA since the start of its space programs. Depending on the equipment's orbit, it will pass through these belts at different rates.



1. Van Allen belts in the Earth's magnetosphere, adapted from European Space Agency (ESA) data. The Y axis is orbit height to 36,000 km (geostationary satellite); the X axis is angle of inclination of the orbits (0-90 degrees). EnSilica

Anything that's operating in a polar orbit, such as a spy satellite, will be crossing through the concentrated radiation belts on a regular basis and need protection from a higher radiation dose. Whereas LEO satellites operate at 1,000 to 1,500 km and thus undergo lower levels of radiation.

So, depending on these factors, a satellite can absorb between 1 and 10 kilorads per year. Therefore, we need to calculate the dose a satellite will receive during its lifetime.

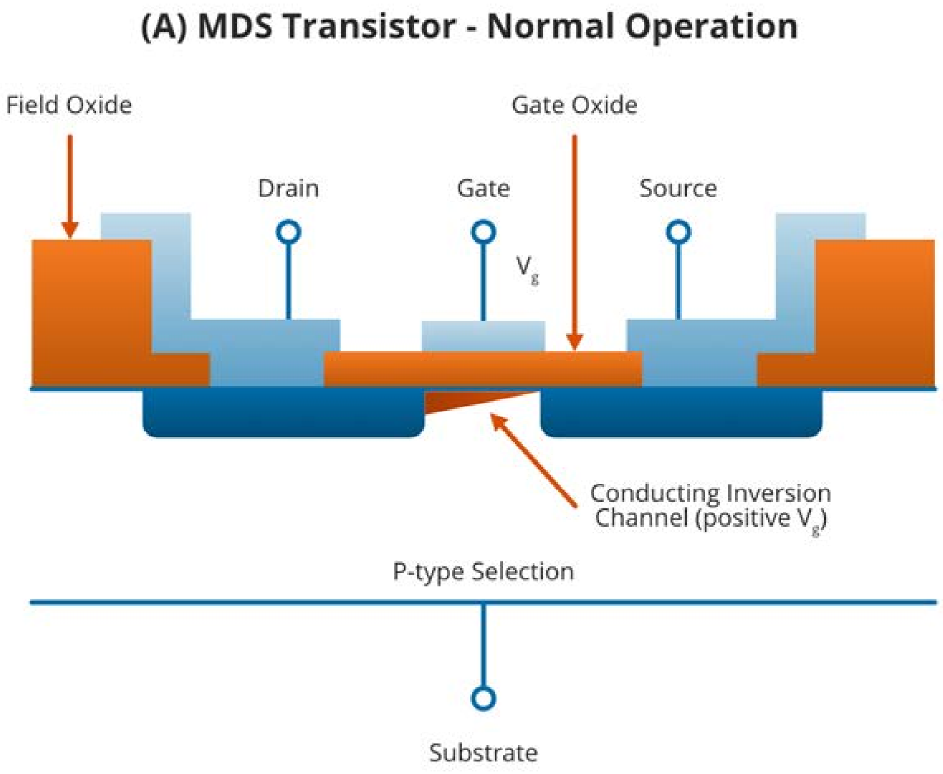
Effect of Radiation

In addition to dose, we need to look at the types of radiation and the damage they cause.

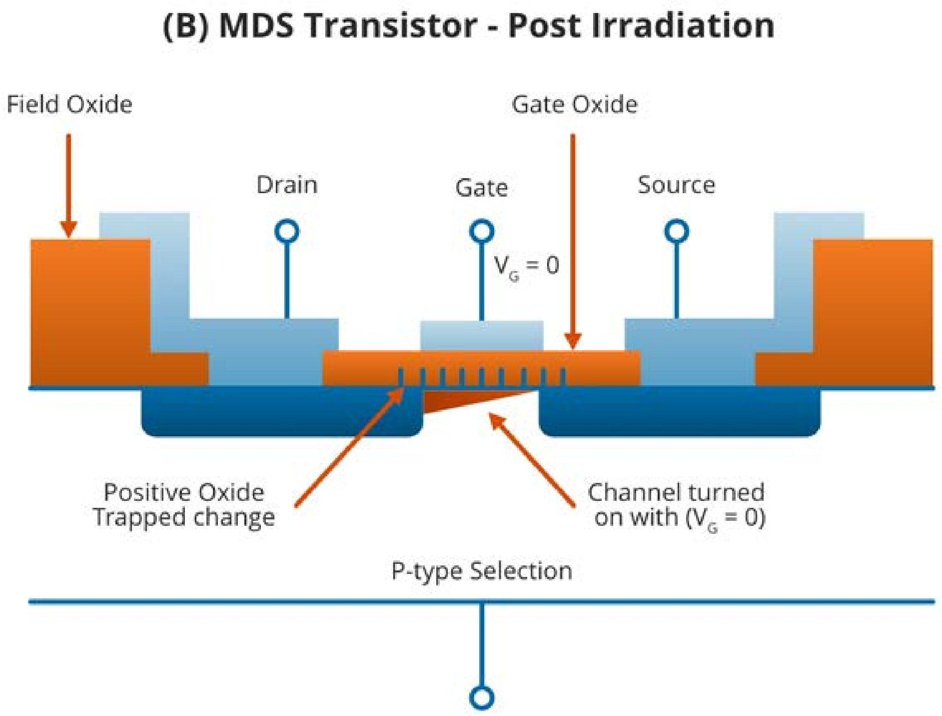
Let's first look at ionizing radiation (non-ionizing radiation is discussed toward the end of the article), which can come from protons or electrons. These particles strike the gate oxide of the semiconductor and cause damage through a build-up of charged particles in the MOSFET gates *(Fig. 2)*.

In a PMOS transistor, this increases the threshold voltage and makes it more difficult to turn on. Conversely, in an NMOS transistor, the opposite is true, making it turn on at a lower threshold.

And the probability of this happening is proportional to the size of the gate. Consequently, older process nodes tend to have a higher probability of radiation damage to the gate oxide.



(A) MDS Transistor - Normal Operation



(B) MDS Transistor - Post Irradiation

2. Shown is a standard (left) and damaged NPN transistor (right) with the two junctions and its gates in the sensor. The damaged transistor has a positive charge build up on the gates. EnSilica

In addition, in an analog design, you can get bandgap shifts, changes in bias current leakage side effects, and an increase in the 1/F noise.

Types of Events

There are two possible outcomes following an impact: a non-destructive or destructive event *(Fig. 3)*. A non-destructive event might be a single-event upset in a storage element, a soft error where the radiation causes a noise spike and changes a memory location from a zero to a one.

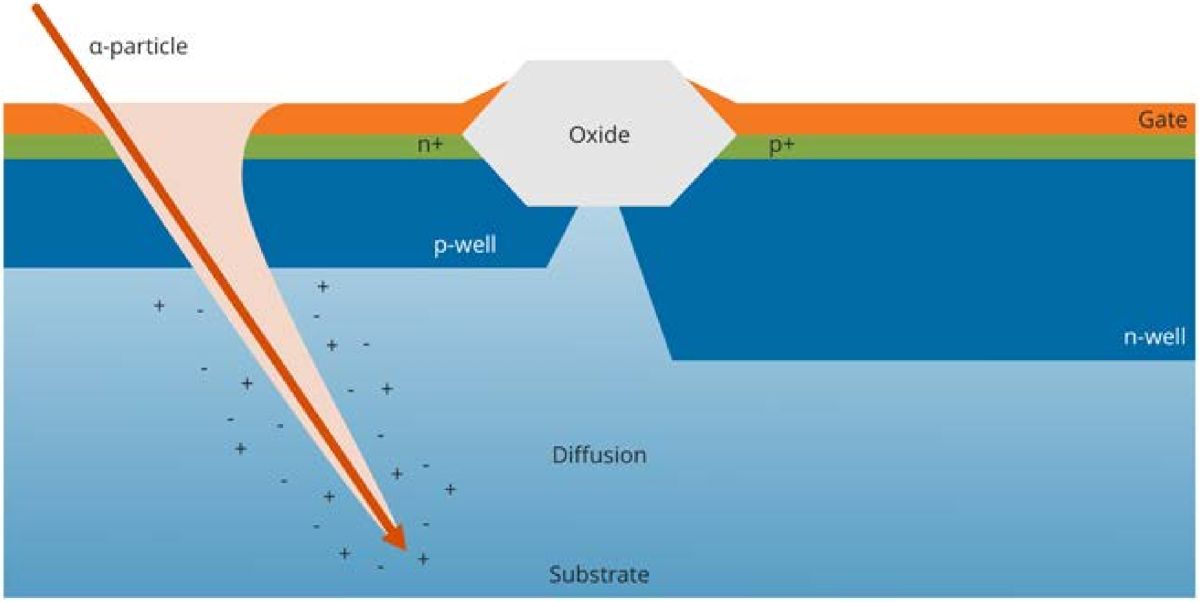
A destructive event might be a single-event gate rupture, which mostly affects power devices. Or, if the particle impact energy is high enough, it can also cause a single-event latch-up, which results in a device turning on permanently until a power cycle is undertaken. And depending on the device, this can be catastrophic.

Thus, you need to detect and protect the equipment against these events. We've looked at these single end events and their effects tend to come more from the heavier particles, creating electron hole pairs and a transient conduction path; flipping memory locations and flip-flops is a concern, too. And that tends to be how most of these things are tested: Placing a large memory on a device, radiating it, and then measuring the number of errors across the megabits of memory.

Latch-up is a separate test and you need to put in protections to detect power surges and read the ability to reset critical devices.

Mitigation Techniques

First is gate selection. For example, with a power transistor, which must



3. A simplified view of a semiconductor device following a particle impact with a conduction path created across the device.

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not switch on by accident, it's better to use PMOS than an NMOS.

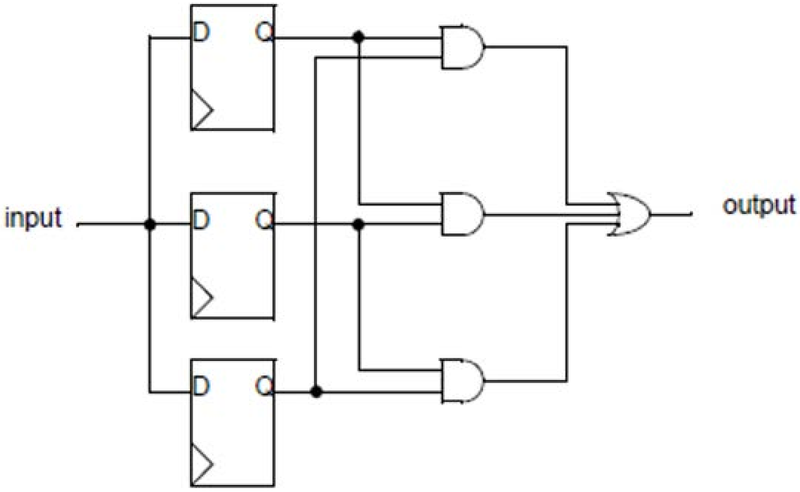
In addition, because the probability increases with size, there's some advantage in going to smaller process nodes, but that that does bring in other risks as well.

And there are specific design mitigation techniques such as avoiding gates with many inputs.

Beyond these basic steps, a host of other specific mitigation techniques target both single-event upsets and single-event latches.

Noteworthy among these is the triple-redundancy flip-flop *(Fig. 4)*. This (and its multiple variants) often has been used in the aerospace industry, as it offers the best possible protection against single-event upsets.

But there are disadvantages that prevent the triple-redundancy flip-flip from being used throughout the design: It's going to triple the size of your solution and increase power demands from the whole system. But they should be deployed in critical areas where you've got key



4. The triple-redundancy flip-flop has been used by the aerospace industry to mitigate against single-event upsets. It offers the best protection, but there are disadvantages.

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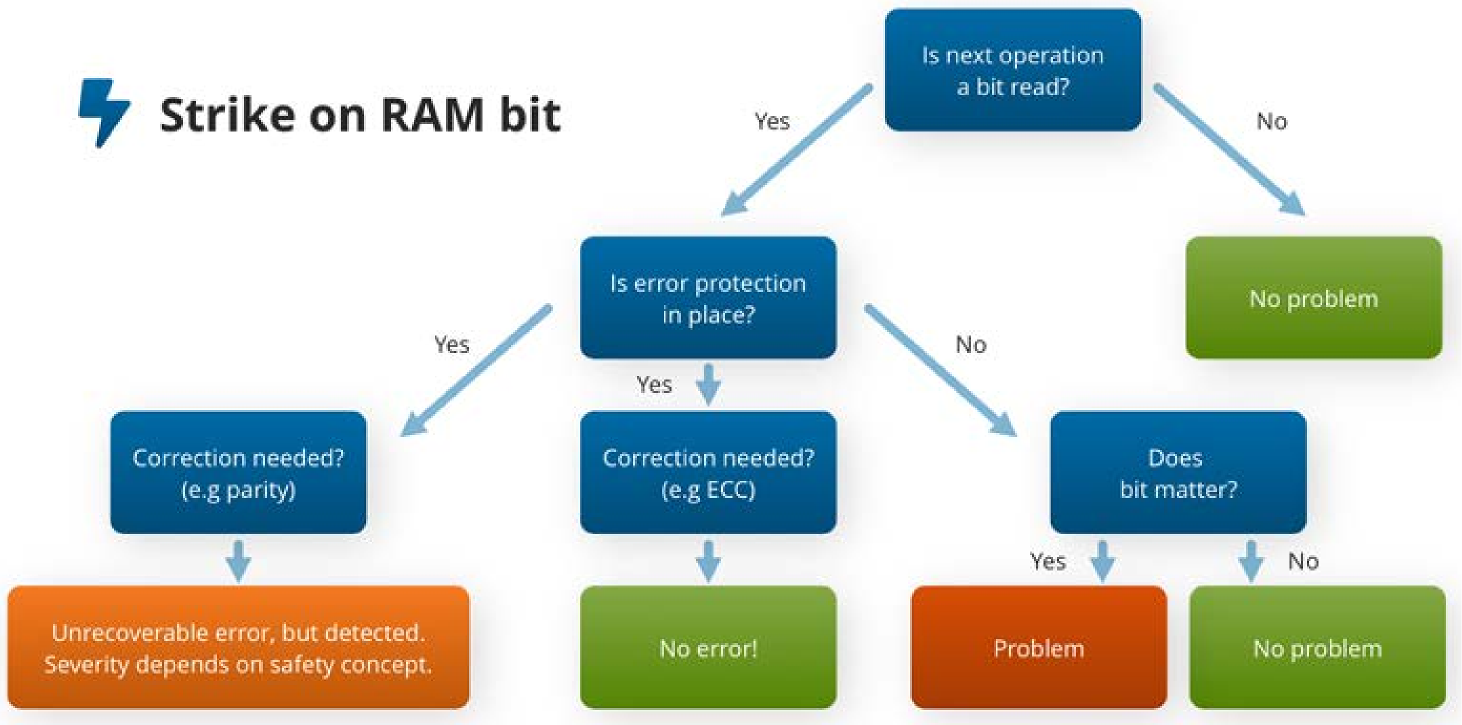


5. Error detection and classification following a strike on RAM. EnSilica

decisions being made.

To avoid a glitch on a clock causing the same error to propagate through, it's also possible to jitter or defer the clocks to each of the flip-flops so that they're all completely independent. The downside for this method is that it doubles the safe faults rate.

Finally, you could have a fully redundant system with separate microprocessors where the results are compared. And only when there's a majority of votes is the output allowed to be used to decide. Again, this is an expensive solution.

In short, the mitigation technique employed will depend on the criticality of the component and the likelihood of a destructive event affecting it.

Predicting and Fixing Software Errors

After an incoming particle strikes RAM, the problem depends on whether the next step is a read or write. If you're going to be reading that data, you've got a problem. And if the next operation is a write, then the error is going to be cleared. So how do you predict what's going to happen?

It's completely interdependent to the software operation of the system. And, of course, you can put in memory refresh strategies to try to keep your memory clean.

Taking this a few steps further, for some functions—where the data isn't critical to the function—you can ignore it and carry on.

For more critical elements, you could deploy error correction code (ECC) to give you error protection, with the ECC built into the memory *(Fig. 5)*. It should be stated that you will not always have enough correction parity to fix every error. However, even in this case, such an approach will still be able to detect an error, alerting you to a problem and preventing you from proceeding with certain actions or functions at critical stages.

Additional steps that can be taken include the implementation of cyclic redundancy checks into communication channels; or setting the state machines' Hamming distance to be greater than 1, which will avoid accidental flipping into another state.

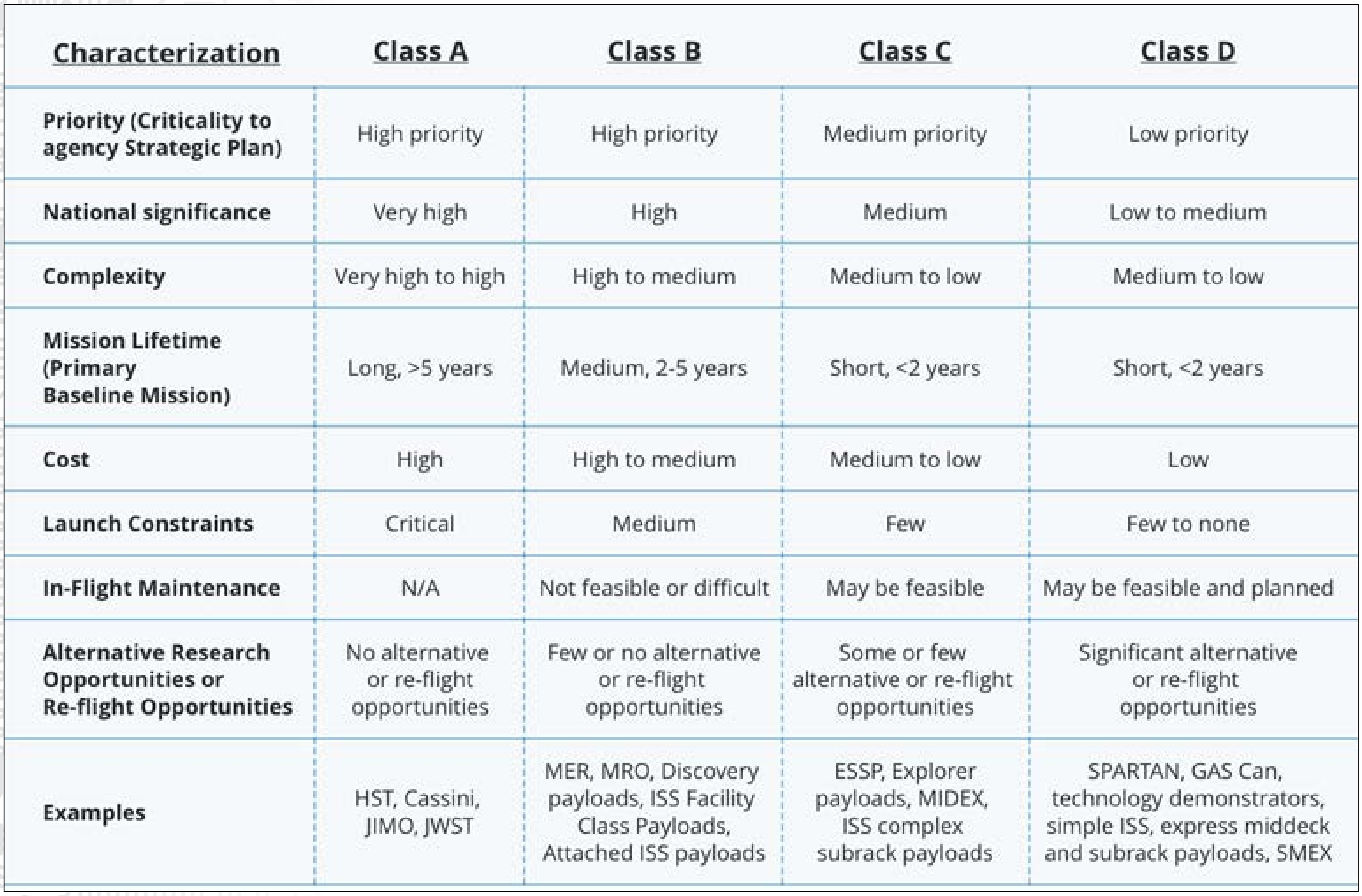
Beyond that, it's possible to run software self-test procedures, as well as have the hardware check on the software and the software check on the hardware. Of course, there are external watchdogs, too, as we have in embedded systems. Finally, a remote-control-based internal clock monitor or safety clock can be recovered from a PC.

Coping with Non-Ionizing Radiation

As alluded to above, there are also effects from non-ionizing radiation. Displacement damage leads to more gradual effects, with bits of the silicone structure becoming damaged over time and leakage that causes decreased gain in bipolar transistors.

This effect has been documented in satellites, notably with CMOS imaging sensors becoming damaged over time. In this case, the component might need replacement at some point, or the use of larger devices to create spare pixels and extend the life of the satellite.

Again, a host of mitigation techniques can be deployed, including the incorporation of some form of redundancy or ECC into the system. On the analog side, it's advisable to



Characterization	Class A	Class B	Class C	Class D
Priority (Criticality to agency Strategic Plan)	High priority	High priority	Medium priority	Low priority
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission Lifetime (Primary Baseline Mission)	Long, >5 years	Medium, 2-5 years	Short, <2 years	Short, <2 years
Cost	High	High to medium	Medium to low	Low
Launch Constraints	Critical	Medium	Few	Few to none
In-Flight Maintenance	N/A	Not feasible or difficult	May be feasible	May be feasible and planned
Alternative Research Opportunities or Re-flight Opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities
Examples	HST, Cassini, JIMO, JWST	MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads	ESSP, Explorer payloads, MIDEX, ISS complex subrack payloads	SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX

6. Is your component space-qualified? EnSilica monitor the voltage and current carefully—if there's a latch-up, you can more easily detect it and shut things down quickly.

And silicon layout plays a crucial role. Here on Earth, there's always a push to put the metal tracks closer and closer together with each generation, with designs taking them to the absolute limits of what the technology can support. However, for electronics designed for use in space, it's advisable to increase the separation of the critical node to give greater protection.

So, is Your Chip Space-Qualified?

Can you use something off the shelf? It's a little (lot) more difficult than that, and the answer, of course, is "it depends." NASA has tried to define four classes: A,B,C, and D *(Fig. 6)*. These depend on the mission and its lifetime. For example, the James Webb Space Telescope is Class A *(see opening image)*.

Conclusion

The ionizing radiation that electronic components will undergo in space can cause significant damage if it's not considered from the beginning of their design.

Several mitigation techniques can be deployed. However, cost and size limitations prevent them being used throughout a system. Thus, careful cost vs. risk analyses must be performed when developing the system as a whole.

**The opening image of the James Webb Space Telescope is credited to NASA/Desiree Stover.*

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Courtesy of Getty Images

CHAPTER 2:

Board-Level Qualification Testing for Rad-Hard MOSFET Packaging

ANDREW POPP, International Rectifier HiRel Products (IR HiRel),
an *Infineon Technologies company*

For Defense Logistics Agency (DLA) QPL qualification, high-reliability rad-hard MOSFETs undergo extensive screening and quality-conformance testing to ensure that devices perform to specification in the harshest environments, sometimes for 15 years and longer. Both the U.S. and European communities have developed specifications detailing quality conformance testing sequence.

In the U.S., DLA's MIL-PRF-19500 and MIL-STD-750 govern the quality conformance testing sequence performed on discrete MOSFET semiconductors manufactured to JANS or JANTXV levels. In Europe, ESA's ESCC 5000 is the standard for discrete semiconductors, hermetically sealed, and die.

These tests are performed at the chip or package level, per applicable standards. In real life, rad-hard MOSFETs are mounted to boards for use in subsystems, such as DC-DC converters, intermediate bus converters, motor controllers, and others. Yet PCB-level performance testing is not required by DLA or MIL standard. That's why with our newest package designs, International Rectifier HiRel (IR HiRel) developed a series of board-level qualification tests to provide even greater levels of assurance to our customers.

> **High-reliability rad-hard MOSFETs undergo extensive screening and quality conformance testing to ensure that devices perform to specification in the harshest environments.**

Packaging for Higher Reliability

In space-rated power electronics, reliable attachment of surface-mount hermetically-packaged MOSFETs to PCBs has dogged space system designers for years. Material differences, specifically coefficient of thermal expansion (CTE) mismatch of the board and surface-mount power package, can make it difficult to maintain reliable solder joints between the PCB and SMD package. CTE mismatch also makes it challenging to preserve the sealed integrity of a hermetically packaged silicon power MOSFET.

IR HiRel developed the SupIR-SMD package as a way to overcome the issue of CTE mismatch between a power semiconductor and PCB. Designed for direct-to-PCB surface-mount attach, SupIR-SMD enables the shortest thermal conduction path to help optimize power system efficiency. Standard qualification for new devices housed in SupIR-SMD is JANS level per MIL-PRF-19500.

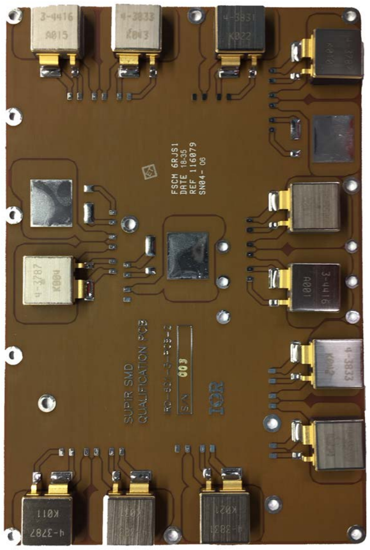
Typical applications range from space exploration vehicles to communications, navigation, and observation satellites, and more. These vehicles may fly at low Earth, geostationary, or highly elliptical orbits, or interplanetary, deep space missions. While the flight environments may differ greatly, we know that each space program must be evaluated vis-à-vis its mission profile needs, including, but not limited to:

-Reliability
-Radiation tolerance
-Environmental stresses
-Expected mission lifecycle

Beyond that, space electronics must withstand tremendous forces from the launch environment itself. Extreme shock and vibration, ESD discharge, vast temperature swings and more…high-reliability electronics are designed to endure much harsher conditions than COTS parts were ever meant to face. IR HiRel's rad-hard silicon power MOSFETs undergo extensive testing at the chip or package level per the applicable standard(s) to ensure performance to specification in the harsh space environment. In this case, it is typically qualified to MIL-PRF-19500 JANS level.

The goal of PCB-level test procedures is to validate the package design integrity through next-level assembly and environmental testing operations. Broadly speaking, these board-level protocols include:

-Random vibration
-Mechanical shock
-Temperature cycling
-Post-test inspection for fine and gross leak, and cross-sectioning of solder joints



Sequential Qualification Tests

For example, to qualify the SupIR-SMD package at the board-level, we mounted several packages in various orientations and positions on a representative PCB. With polyimide glass fiber as the board material, per IPC 4101/411, the PCB had eight layers and an overall board thickness of 1.8 mm. Using SN63Pb37 solder and RMA flux, we attached components to the PCB. The solder stencil was 8 mils thick, with a 90% ratio of opening to pad size.

Prior to testing, we inspected the whole assembly according to IPC-J Standard, Space Addendum2. Then we subjected the board to random vibration, mechanical shock, and temperature cycling. In order to proceed through each stage of mechanical stress tests, the assemblies had to remain failure-free.

Random Vibration

The random vibration test simulates spacecraft launch and Grms (root-mean-square acceleration) that the electronics must endure. We tested in accordance with ECSS-Q-ST-70-38C3, with the test level increased to 40 Grms. Note that this standard includes by reference test conditions outlined in ECSS-Q-ST-70-08C4. Based on IR HiRel's space power electronics experience and our customer needs, increasing the test conditions more accurately reflects what parts actually face in launch settings. This is also closer to MIL-STD-883J5 Test Method 2026, Condition 1J, which requires 36.6 Grms.

Our test setup vibrated the SupIR-SMD board assemblies in three dimensions, up to 40

Test characteristics	MIL-STD-883J TM2026 condition 1J	ECSS-Q-ST-70-08* Table 13-3, launcher applications	ECSS-Q-ST-70-08* Table 13-4, non-launcher applications		IPC-TM-650 Test condition F	IR HiRel PCB board-level parameters
			Perpendicular to PCB	Parallel to PCB		
Power spectral density	1.0 g^2/Hz	+3 dB/octave (20 – 60 Hz) 0.27 g^2/Hz (60 – 100 Hz) -6 dB/octave (1000 – 2000 Hz)	+6 dB/octave (20 – 100 Hz) 1.0 g^2/Hz (100 – 500 Hz) -6 dB/octave (500 – 2000 Hz)	+6 dB/octave (20 – 100 Hz) 0.5 g^2/Hz (100 – 800 Hz) -3 dB/octave (800 – 2000 Hz)	0.008 g^2/Hz (0 – 10 Hz) +3 dB/octave (10 – 75 Hz) 0.06 g^2/Hz (75 – 2000 Hz)	+6 dB/octave (20 – 100 Hz) 1 g^2/Hz (100 – 1000 Hz) -3 dB/octave (1000 – 1500 Hz) -6 dB/octave (1000 – 2000 Hz)
G_{rms}	36.6	20	28.5	27.1	10.9	39.9
Duration	15 minutes/axis	5 minutes/axis	5 minutes/axis		15 minutes/axis	5 minutes/axis

*ECSS-Q-ST-70-38C includes by reference test conditions outlined in ECSS-Q-ST-70-08C, as summarized here.

Test characteristics	MIL-STD-883J TM 2002.5 condition B	ECSS-Q-ST-70-38C	IPC-TM-650 TM 3.8 A condition E	IR HiRel PCB board-level parameters
Peak acceleration (G)	1,500	Should "meet the intended mission with margin"	1,000	1,500
Pulse duration (ms)	0.5		0.5	0.3
Shocks/axis	5		3	3
Total shocks	30		18	18

Grms for five minutes in each dimension, which exceeds the ECSS standard. For comparison, IPC-TM-6505 test condition F is the closest equivalent to these ECSS and MIL-STD-883 standards, but far less intense, with a required test level of only 10.9 Grms.

Mechanical Shock

The mechanical shock test simulates the sudden and extreme accelerations or decelerations caused by launch sequence engine separations. As a baseline reference, we started with MIL-STD-883J4 Test Method 2002.5, Condition B, which is part of IR HiRel's usual package-level qualification for MOSFETs. We also considered ECSS-Q-ST-70-38C5, which specifies that shock levels should "meet intended mission with margin." IPC-TM-6506 Test Method 3.8 A, Condition E is similar to the MIL standard, but less intense, specifying a peak acceleration of 1,000 Gs with three shocks in each direction per axis and a pulse duration of 0.5 ms.

For our PCB-level tests, we subjected the SupIR-SMD assemblies to a minimum of 1,500 Gs peak acceleration for 0.3 ms, shocking them in positive and negative directions each in X1, Y1, and Z1 directions. With six shocks per axis, we performed 18 shocks in total. These test parameters are in line with our global customer requirements for standard space equipment.

Temperature Cycling

This test simulates the extreme operational temperatures space electronics must withstand in flight. We subjected the SupIR-SMD assemblies to the thermal cycling based on ECSS-Q-ST-70-38C (-55 to 100°C). Specifically for the board assemblies, we applied 500 temperature cycles from -55 to 100°C with a maximum 10°C/minute ramp and a minimum 15-minute dwell time at each extreme, which is more intensive than specified by the standards for package qualification.

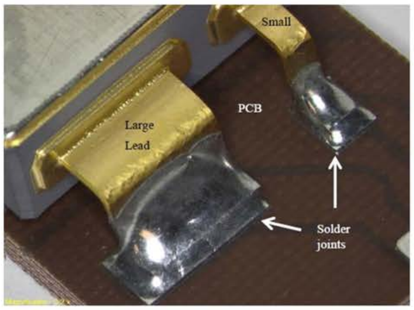
These parameters are similar to IPC-9701A7, but with an increased dwell time and decreased ramp rate. MIL-STD-750F for package qualification isn't directly comparable to either the ECSS or IPC standards which both use a test condition from -55 to 100°C, whereas MIL-STD-750F specifies -55 to 85°C. ECSS-Q-ST-70-38C and MIL-STD-750F standards also specify fewer number of cycles, 200 and 20, or as specified, respectively.

Cross-section Inspection of Solder Joints

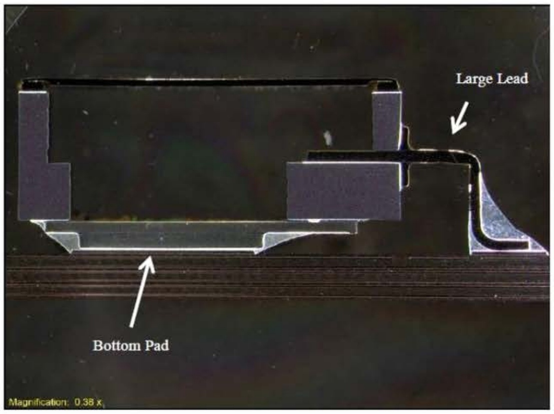
After completion of these tests, we cross-sectioned the assembly solder joints in accordance with ECSS-Q-ST-70-38C, which specifies requirements for qualification of PCB technology. Pass criterion for this test is that cracks in the solder shall not exceed 25% of the lap connection in the critical zone. There shall also be no cracks in the ceramic. Since the ECSS standard doesn't allow for any ceramic cracks in SMD devices, it is stricter than the MIL-STD-7508 Test Method 2071 and MIL-STD-883 Test Method 2009 alternatives.

Test characteristics	MIL-STD-750F TM 1051 condition A	ECSS-Q-ST-70-08C*	IPC-9701A Test condition 5 NTC=B	IR HiRel PCB board-level parameters
Temperature range	-55°C – 85°C	-55°C – 100°C	-55°C – 100°C	-55°C – 100°C
Ramp rate	≤ 15°C/minute	≥ 10°C/minute	≥ 20°C/minute	≥ 10°C/minute
Minimum dwell time	10 minutes	15 minutes	10 minutes	15 minutes
# of thermal cycles	Minimum 20, or as specified	200	500	500

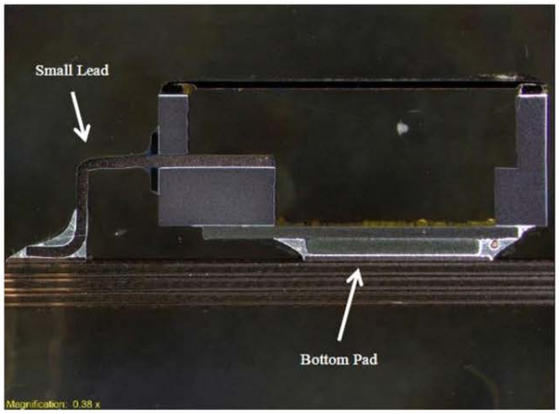
*ECSS-Q-ST-70-38C includes by reference test conditions outlined in ECSS-Q-ST-70-08C, as summarized here.



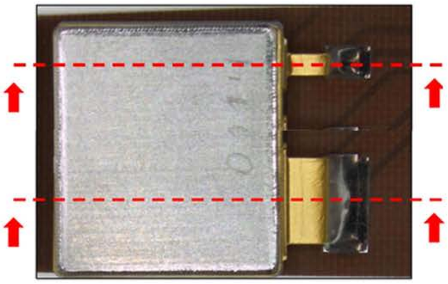
SupIR-SMD close up view of large & small lead solder joints



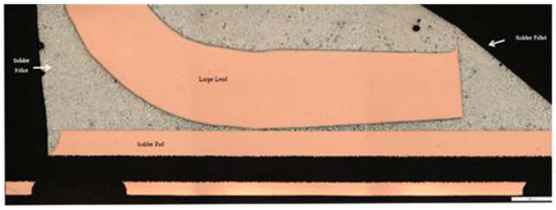
SupIR-SMD package cut view, one side, large lead (0.38x magnification)



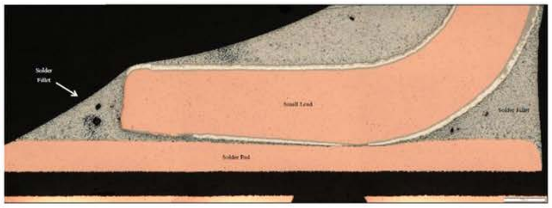
SupIR-SMD package cut view, one side, small lead (0.38x magnification)



SupIR-SMD cross section plane & direction of cuts, large & small leads



SupIR-SMD cross section of large lead



SupIR-SMD cross section of small lead

#	Test	Conditions
1	Random vibration	ECSS-Q-ST-70-38C with test level increased to 40 G_{rms} (MIL-STD-883, Test Method 2026 1J requires 36.6 G_{rms})
2	Mechanical shock	ECSS-Q-ST-70-38C (1,500 G, 0.3 ms) MIL-STD-883, Test Method 2002 3x in positive and negative directions each in X1, Y1 and Z1 directions 6 shocks per axis, 18 shocks total
3	Temperature cycling	ECSS-Q-ST-70-38C (-55°C to +100°C) Ramp not to exceed 10°C/minute Dwell minimum 15 minutes at each extreme 500 cycles
4	Cross-section of solder joints	ECSS-Q-ST-70-38C Cracks in solder shall not exceed 25% of the lap connection in the critical zone

Conclusion

Satellite manufacturers worldwide use hi-rel DC-DC converters, and board-level tests subject the power semiconductors to the same rigors expected during space flight lifetime. While there are no mandated industry standards for this type of testing, best-practice board-level protocols should either comply with or exceed the test conditions selected as baselines. We strongly believe this proactive approach and added level of qualification gives a high degree of assurance.

Silicon-based technologies remain a trusted choice for use in high-reliability space applications. With its proven heritage, performance, robustness, and well-known screening and reliability standards, pushing to greater levels of test acceptance helps extend that confidence to next-generation silicon platforms.

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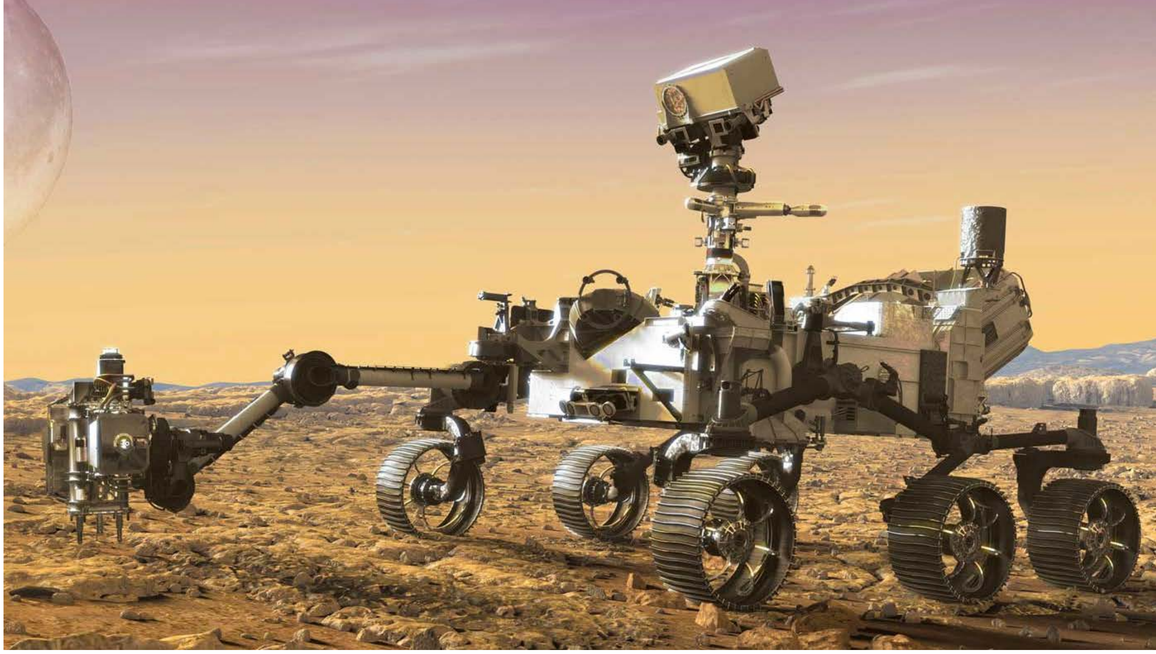
Designing Power Systems for Rad Hard and Rad Tolerant Space Applications



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CHAPTER 3:

Achieving Power Density for NASA Aircraft and Mars Rovers

STEVE TARANOVICH, Contributing Editor

From panels to arrays, solar energy—backed by battery power—may be the best solution to power management for satellites.

In 2019, small spacecraft with a mass under 180 kg made up almost 7% of all mass launched into orbit. And 63% of spacecraft under 600 kg had mass less than 180 kg—47% of those were CubeSats. Since 2013, CubeSat flights have nearly doubled.

Dedicated SmallSat launch capabilities also create easily available and expanding opportunities to demonstrate new technologies and systems. Powering these satellites is a challenge and power density is crucial.

Beyond the SmallSats, the International Space Station (ISS) and the Mars Rovers face challenges for sustained power, too. Again, power density is a critical issue in these applications. How can designers achieve power density as well as a viable source of power in space for such spacecraft?

The Solution: Solar Energy

Electrical power systems (EPS) encompass electrical power generation, storage, and distribution in the spacecraft. The EPS is a critical and fundamental subsystem that usually comprises up to one-third of total spacecraft mass and volume. Power-generation technologies can include photovoltaic (PV) cells, solar panels and arrays, and radioisotope or other thermonuclear power generators. In this article, we will discuss solar-panel and -array storage that usually will be in the form of either single-use primary batteries or rechargeable secondary batteries.

Power management and distribution (PMAD) systems help provide power control to spacecraft loads. PMAD can take a variety of forms and is frequently custom-designed to meet specific mission requirements. EPS design engineers target a high specific power or power-to-mass ratio (Wh/kg) when selecting power generation and storage technologies to minimize system mass impact. The volume is more likely to be the constraining factor, especially with nanosatellites. High power density also is crucial in these systems; a typical value is 90 to 110 W/m^3.

The information described in this article isn't intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for the ISS, Mars Rover, and small spacecraft subsystems. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated.

Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of the described technology. There's no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

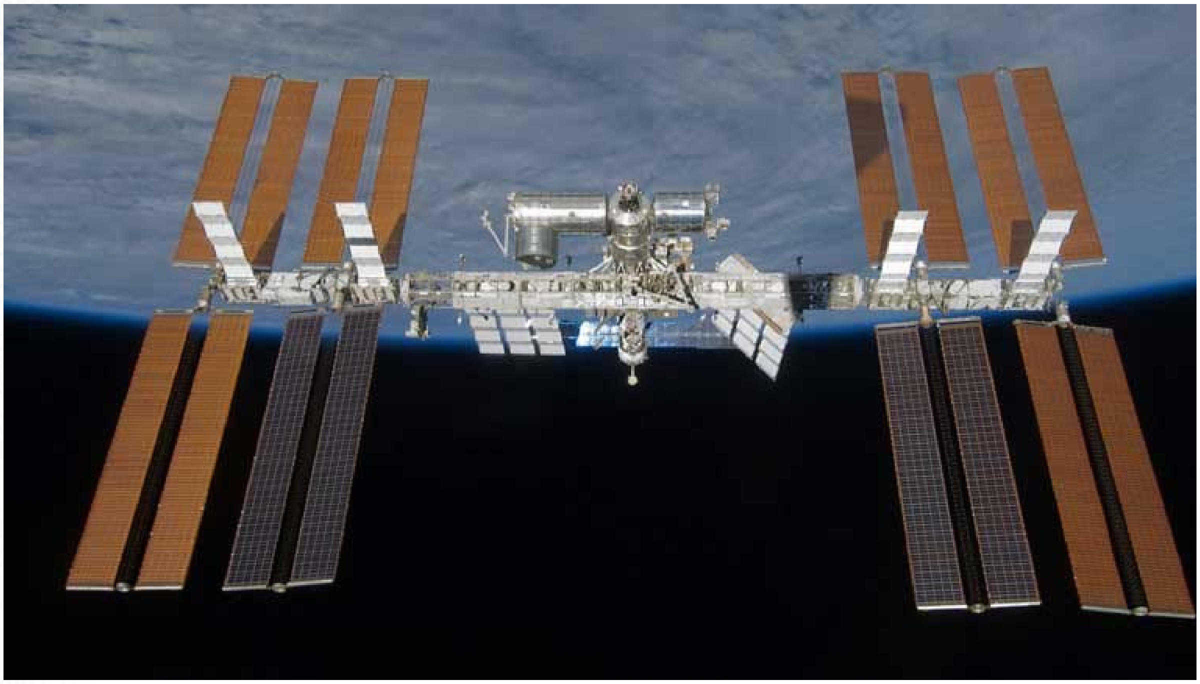
International Space Station (ISS)

The ISS orbits 220 miles above the Earth and needs quite a bit of power to support life and power all ISS systems such as light, breathable air, experiments, and so much more for the astronauts and mission specialists. Thus, power density becomes crucial on the ISS *(Fig. 1)*.

The ISS employs a Roll-Out Solar Array (ROSA) architecture, which is an innovative new solar-array design that uses high strain, one-piece, composite slit-tube booms. The stored strain energy of the booms enforces the deployment actuation, and the booms provide the array's deployed structural stiffness and strength.

When the orbiting station is in sunlight, 60% of the direct-current (DC) electricity from the solar arrays charges the station's batteries. However, there are times when some or all of the solar arrays find themselves in the shadow of Earth or the shadow of part of the ISS itself. Thus, of course, many of those arrays aren't collecting sunlight. Therefore, batteries power the ISS when it's not in the sun *(Fig. 2)*.

NASA astronauts Mike Hopkins and Victor Glover went on a spacewalk on February 1st, 2021 to complete a multi-year effort replacing the aging nickel-hydrogen batteries on the



1. This image shows the ISS orbiting Earth while solar arrays capture sunlight for power. (Image: NASA)

2. NASA astronauts completed a multi-year project to upgrade batteries on the ISS. (Image: NASA)

ISS with new lithium-ion models. The upgrade is finally complete.

ISS Solar Array Facts

- Together the arrays contain a total of 262,400 solar cells and cover an area of about 27,000 square feet (2,500 square meters)—more than half the area of a football field.
- A solar array's wingspan of 240 feet (73 meters) is longer than a Boeing 777's wingspan, which is 212 feet (65 meters).
- The space station's electrical power system is connected by eight miles (12.9 kilometers) of wire.

Photovoltaic cells, or solar cells, are made from thin semiconductor wafers that produce electric current when exposed to light. The light available to a spacecraft solar array, also called solar intensity, varies as the inverse square of the distance from the sun. The projected surface area of the panels exposed to the sun also affects generation and varies as a cosine of the angle between said panel and the sun.

Limitations to solar-cell use include diminished efficacy in deep-space applications, no generation during eclipse periods, degradation over mission lifetime (due to aging and radiation), high surface area, mass, and cost.

SmallSat

To pack more solar cells into limited volume in SmallSats and NanoSats, mechanical deployment mechanisms can be added, which may increase spacecraft design complexity, reliability, and risk. Achieving high power density is crucial.

Small satellites usually have a range of power requirements from as little as a watt or two to a few kilowatts. Small low-Earth-orbit (LEO) nanosatellite and microsatellite power-system designs will be more challenging due to space/weight constraints.

While single-junction cells are cheap to manufacture, they carry a relatively low efficiency, usually less than 20% (they're not included in this article). Modern spacecraft designers favor multi-junction solar cells. These are made from multiple layers of light-absorbing materials that efficiently convert specific wavelength regions of the solar spectrum into energy, thereby using a wider spectrum of solar radiation.

The theoretical efficiency limit for an infinite-junction cell is 86.6% in concentrated sunlight. However, in the aerospace industry, triple-junction cells are commonly used due to their high efficiency-to-cost ratio compared to other cells.

CubeSat

CubeSats are a kind of "kit" form of a SmallSat in a standard form factor:

- 1 kg, 10- × 10- × 10-cm cube = 1 unit = 1U
- Designers may combine basic units to form larger CubeSats (e.g., 3U, 6U, higher)

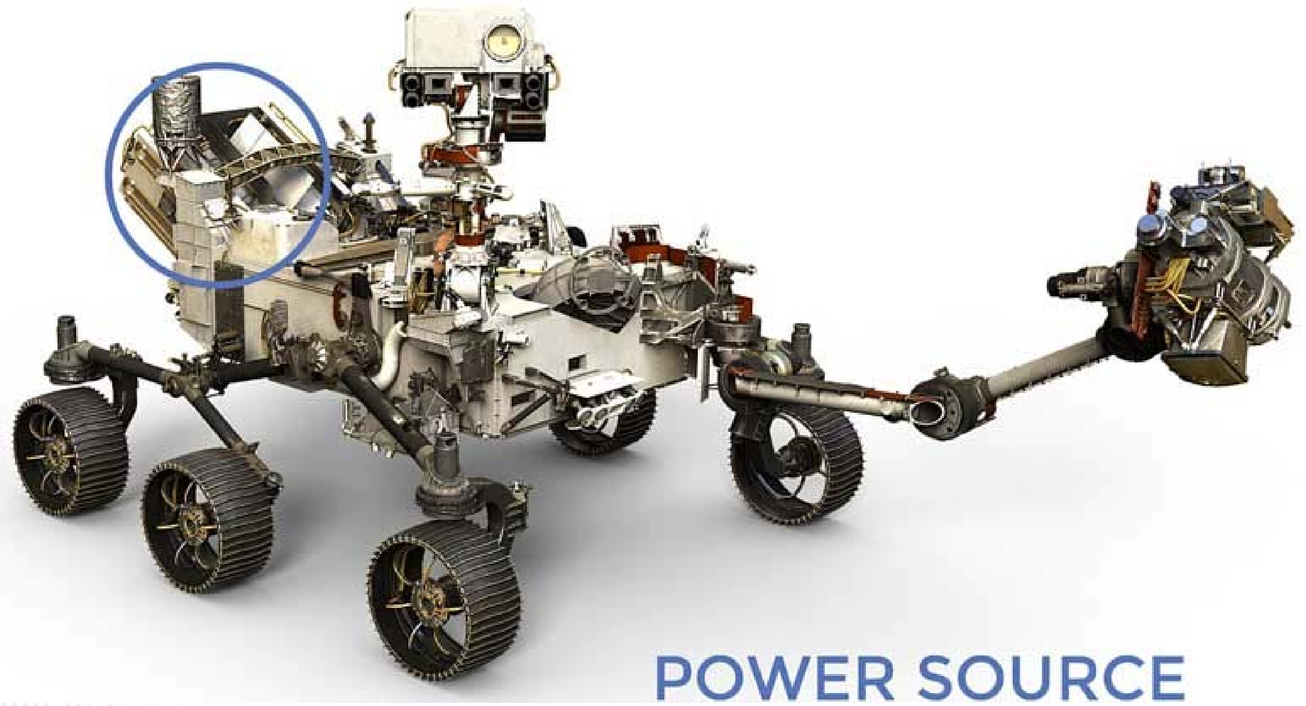
Nanosatellite

Nanosatellites are any satellite weighing less than 10 kilograms.

Solar-power generation is the predominant method of power generation on any small spacecraft. As of 2020, approximately 85% of all nanosatellite-form-factor spacecraft had solar panels and rechargeable batteries. Again, here, high power density is a necessary goal.

Mars Perseverance Rover

The Perseverance's main power system is a plutonium radioisotope called a "Multi-Mission Radioisotope Thermoelectric Generator" (MMRTG). This power system produces



3. The Mars Perseverance Rover radioisotope power system is circled in blue. (Image: NASA) a solid flow of electricity using the heat of plutonium's radioactive decay as its "fuel." The Rover subsystems are the flight computer, motor control, radar, and mission instrument suite. These subsystems get their primary power from the MMRTG. They're followed by the integration of high-reliability space-grade MOSFETs, ICs, and other lower-power control products that ensure reliable operation to these systems in the harsh space environment on Mars.

This power system charges the Rover's two primary lithium-ion batteries. An important role of the heat from the MMRTG is to keep the Rover's tools and systems at their optimum operating temperatures. The MMRTG has a 14-year operational lifetime, which provides a significant reserve for the Mars 2020 prime mission duration of 1.5 Mars years (three Earth years)

The power density of the Mars Perseverance Rover cylindrical power supply is 110 W/(Pi × [0.64 m diameter/2]^2 × 0.66 m height) = 517.87 W/m^3 *(Fig. 3).*

Summary

One of the primary components for NASA spacecraft is the solar array, and the EPS and PMAD systems round out the general architecture for most types of spacecraft. Batteries also are part of spacecraft design—when the spacecraft is periodically blocked by the sun, batteries will continue to power the vehicle and its systems.

The ISS has a full complement of solar arrays, while small satellites typically use solar power as their main source of power. Designers must achieve as high a power density as possible in these architectures.

The Mars Rovers, particularly the last two—the Curiosity and Perseverance Rovers—have a unique power architecture based on radioisotopes with plutonium as the main power source. Rechargeable lithium-ion batteries are called into temporary action when Rover activity demands peak and exceeds the radioisotope main generator's steady normal output. Once again, high power density is a necessary goal for designers.

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CHAPTER 4:

ISS Power-Density Plans: Now and into the Future

STEVE TARANOVICH, Contributing Editor

> **The International Space Station, which has survived for more than 20 years, will be gone in 2031. NASA looks to go the commercial route for the next station as it concentrates more on space exploration.**

After two decades, what is NASA planning to do after the present International Space Station (ISS) is decommissioned in about 2030?

The ISS is about the size of a professional football field. Its bigger modules as well as smaller components were delivered via 42 flights to complete the ISS assembly (37 on U.S. space shuttles and five on Russian Proton/Soyuz rockets).

In 2014, the ISS's power generation consisted of eight solar arrays that provide an average of between 84 and 120 kW of power. However, a few of the solar arrays are more than 20 years old—they were originally designed for a 15-year service life. They're now showing signs of degradation and are gradually getting less efficient over time. And the many complex science experiments being performed by the ISS astronauts are pushing the power requirements to the limit.

To keep up with the station's power needs, the electrical systems on the ISS have continuously been upgraded. Excursions to the ISS in 2019 replaced batteries in the main systems. In 2022, new arrays needed to be added via a set of spacewalks.

In 2023, NASA astronauts installed roll-out solar arrays to enhance the existing eight main solar arrays. These added arrays will produce more than 20 kW of electricity, increasing power production by 30% over the ISS current arrays.

Then in 2024, NASA announced it had selected SpaceX to develop a "deorbit vehicle" to perform the task. The present space station will be deorbited in 2031.

International Space Station: The Future

Looking forward, NASA plans to transition the operations in low Earth orbit (LEO) to commercially owned and operated destinations to secure their continued access to indispensable research and technology development. In late August 2024, NASA received about 12 proposals for a new space station from quite a diverse group of companies. Estimates are that proposals came from such companies as Axiom Space, Bigelow Aerospace, Boeing, Lockheed Martin, and Space X.

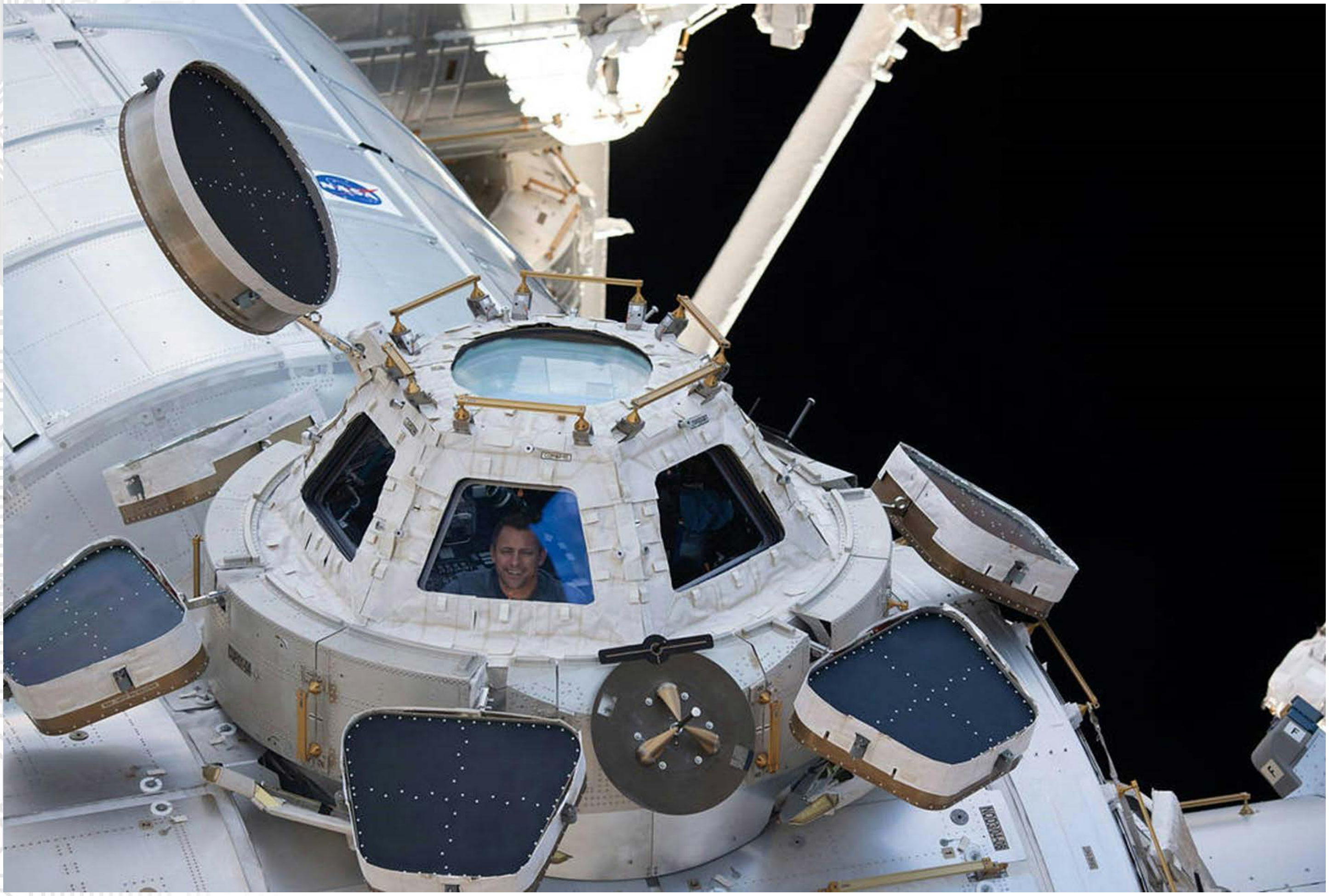
NASA seems to be interested in a commercial space station, as the present operating cost of the ISS is around $4 billion dollars each year. NASA would rather venture to the Moon again and then later to Mars. Thus, NASA plans to buy commercial space station services a la carte to save about $30 billion.

NASA has already begun awarding contracts worth hundreds of millions of dollars to companies that are able to develop new space stations. These possibly could turn into small research laboratories or even destinations for space tourists, maintaining humanity's presence in orbit around the Earth.

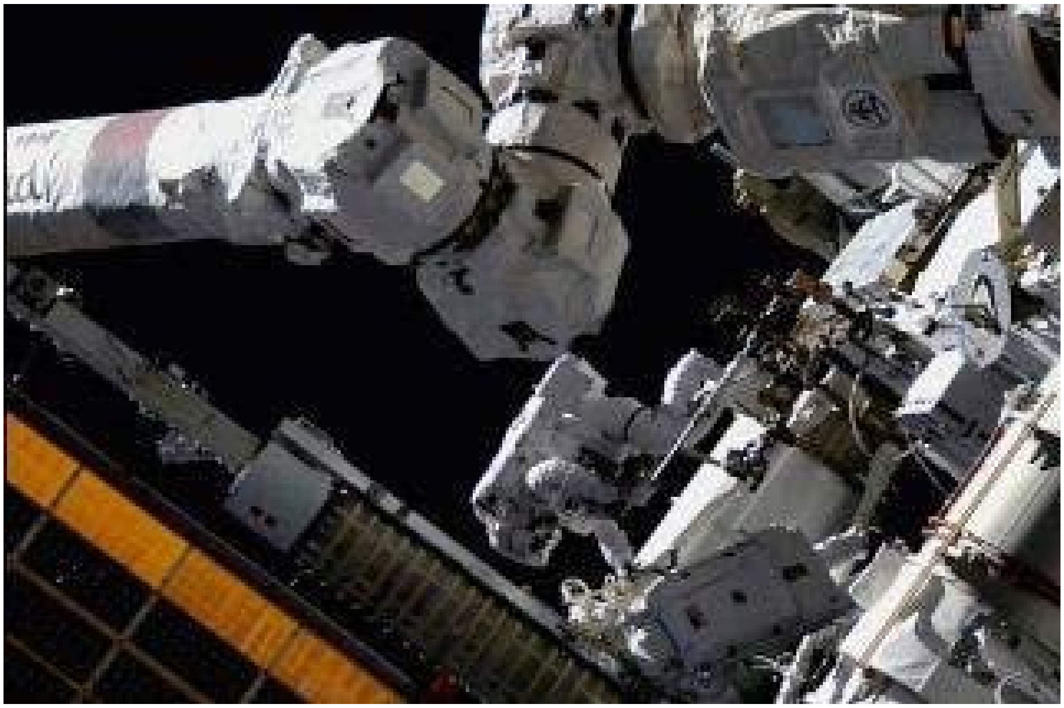
Axiom Space has been transporting paying astronauts on SpaceX rockets. In 2025, the company wants to begin attaching modules to the ISS. These may eventually be detached to form its own station that will be able to be rented out to paying customers.

Why Astronauts Need a New Space Station

A new space station must have updated research facilities with the latest, state-of-the-art laboratory equipment along with a much cleaner environment. Cabling and networking



1. NASA astronaut and Expedition 68 Flight Engineer Josh Cassada looks through one of the seven windows in the ISS cupola (the International Space Station's "window to the world"). NASA



2. NASA astronaut Warren “Woody” Hoburg (who can be seen in the center, partially obscured, with red stripes on the astronaut’s space suit legs) is holding on to an ISS roll-out solar array (iROSA) as he grasps the end of the ISS Canadarm2 robotic arm. Also shown is Stephen Bowen, an Expedition 69 crewmate, preparing the solar array’s mounting bracket at the bottom of this image during the spacewalk on Thursday, June 15, 2023.

NASA TV

must be behind the panels so that it will be easier for lab technicians to easily move around in the space, maybe in LEO.

Most of the electronic components on the ISS are bulky. In the present ISS, there’s only one small inflatable module. That structure flies up, collapses, and later expands as it fills with air once attached to the primary structure of the station. It will literally blow up like a balloon. Astronauts are looking at multiple elements of a new space station becoming inflatable.

Axiom Space is developing a new space station with windows in the crew quarters—essentially an astronaut’s window to the world. The ISS will also have a cupola that astronauts can pop their head and shoulders into and take in 360-degree views of space, in addition to being able to look down at the Earth. Actually, the cupola is so large that the astronauts can float their entire body in the area and have an experience like floating in space *(Fig. 1)*.

What are Roll-Out Solar Arrays?

The latest technology for the new ISS solar arrays is a larger version of the roll-out solar array (ROSA).[4,5]

ROSAs provide an alternative to existing solar-array technologies. These compact arrays are far more affordable. They offer autonomous capabilities that will enhance a wide spectrum of scientific and commercial missions, beginning with LEO and ultimately

3. NASA astronaut Nick Hague along with Roscosmos cosmonaut Aleksandr Gorbunov are part of NASA's SpaceX Crew-9 mission, which launched Sept. 28, 2024. SpaceX

leading to interplanetary travel.

The ROSA rolls up like a carpet to be stowed before launch, making it more easily transportable while maintaining a large surface area. In addition, ROSAs are scalable and modular as deployable space systems (DSS), created with a flexible design that would help to meet various mission requirements. ROSAs can also be scaled down for small satellite applications or made incredibly large for deep space missions.

Two NASA astronauts deployed the sixth, and possibly the last (on June 9, 2023), upgraded solar-array-mounted outside of the International Space Station. This increases the ISS's power-supply bank while tying an American spacewalk record *(Fig. 2)*.

After 5 hours and 35 minutes, the spacewalk ended at 2:17 p.m. EDT as the re-pressurization of the Quest airlock began. Astronauts Nick Hague and Aleksandr Gorbunov performed this task *(Fig. 3)*.

The next ISS is in the proposal stage right now. NASA's Commercial LEO Development Program is planning to support the development of commercially owned and operated LEO destinations, from which NASA, together with other customers, will be able to purchase services and stimulate the growth of commercial activities in LEO.

As commercial LEO destinations (CLDs) become available, NASA plans to implement an orderly transition from the current ISS operations to these new CLDs.

A Commercial Turn to the Next ISS

The ISS, launched in 1998, will extend to 2030. The present ISS has a complete power system that generates 100 kW power (30 kW available for research activities). Volumetric power density is approximately 3,300 kW/m^3. The total estimated volume needed for the ISS is about 0.022 to 0.027 m^3.

Shifting of LEO operations to the private sector will enable efficiencies in the long term, enabling NASA to shift resources toward other key objectives. With the introduction of CLDs, NASA should gain efficiencies from the use of smaller, more modern and efficient platforms as well as achieve a necessary commercial approach to meet the agency's needs in LEO.

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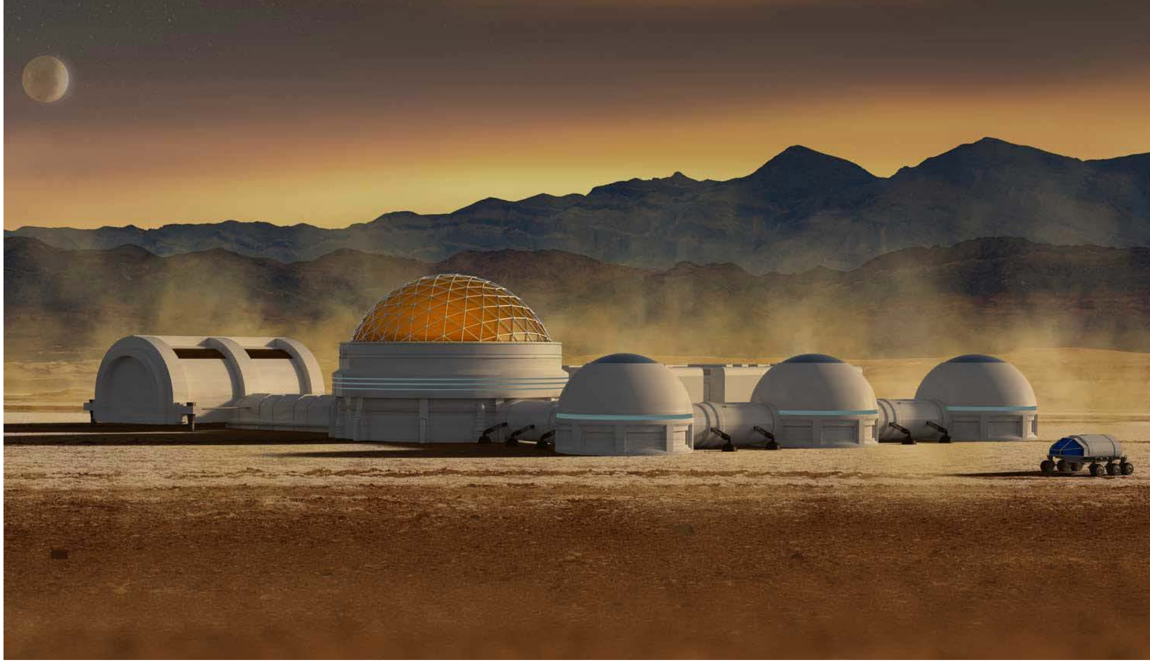

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CHAPTER 5:

Moon Mission: Powering the Lunar Surface

STEVE TARANOVICH, Contributing Editor

We're going back to the Moon, but more electrical power is needed to live there. NASA and selected companies will develop technologies to enable long-term exploration.

NASA took "a second giant step for man," on July 25, 2023, opening the door for humans to "live off the land" on the Moon. It's awarding several contracts toward the construction of landing pads, habitats, and roads on the lunar surface, using nuclear power for energy.

The moon that NASA is striving to visit isn't the same moon that Neil Armstrong and other Apollo astronauts left behind some 50 years ago. Journeying to the Moon and returning to Earth was the first effort achieved during the Apollo era in the 1960s and early 1970s. Now, during the next phase, it intends to build a sustainable presence that will focus on the Lunar South Pole, where water exists in the form of ice.

NASA selected 11 U.S. companies to develop technologies that would support long-term exploration on the lunar surface, as well as in outer space for the benefit of mankind. The technologies will range from lunar-surface power systems to tools for 3D printing in outer space. This will expand industry capabilities to sustain a human presence on the Moon via Artemis, along with other NASA, government, and commercial missions.

In addition, NASA will lay a high-voltage power line that extends over a half mile across the lunar landscape.

Participating Companies in the Lunar Power Project

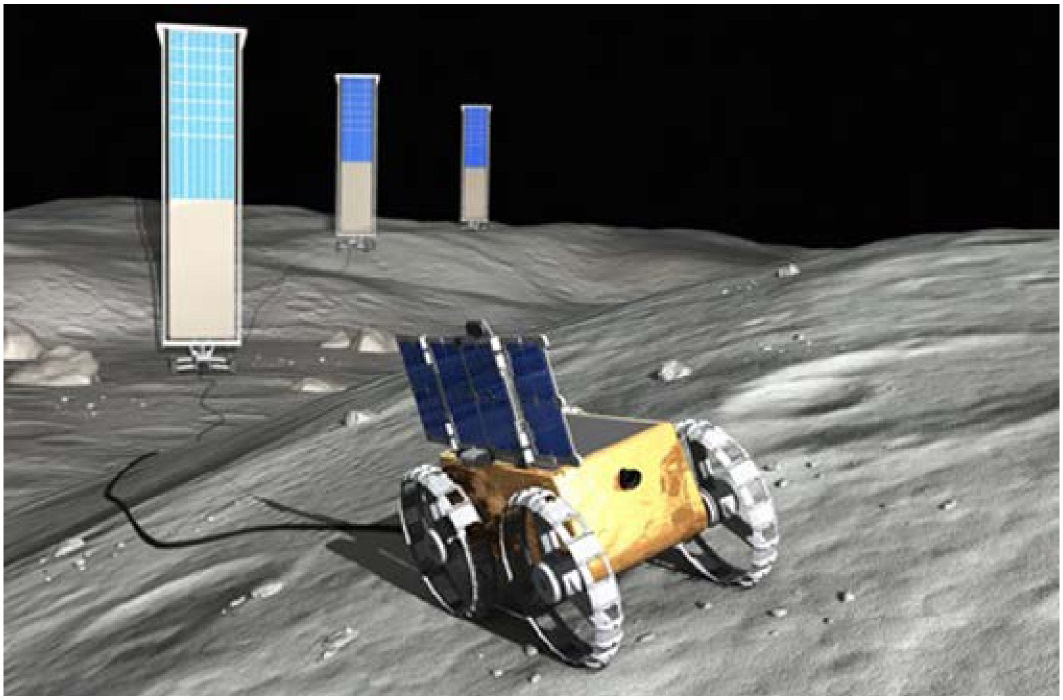
NASA has named some of the key technology companies related to providing power for the Moon. Two of those selected companies that will help provide power on the Moon are:

***Astrobotic Technology,** Pittsburgh, Pa., $34.6 million—LunaGrid-Lite: Demonstration of Tethered, Scalable Lunar Power Transmission.*

Astrobotic's proposal, selected by NASA, will employ advanced technology that can distribute power from devices on the lunar surface. This will be tested on a future lunar mission. The company's CubeRover will provide more than a half-mile (one kilometer) of high-voltage power line that can transfer power from a production system to a habitat/work area on the lunar surface *(Fig. 1).*

Astrobotic was also selected to deliver the VIPER to a lunar landing site close to the Nobile Crater (a 45-mile-wide [73 km] impact basin at the Lunar South Pole). The company chose SpaceX's Falcon Heavy rocket, a workhorse, to launch its Griffin lander that will carry the VIPER to the lunar surface *(Fig. 2)*.

The approximately $200 million commercial delivery arrangement enables Astrobotic to design and build the lander that will carry VIPER to the Moon. NASA would have developed this system for the original Resource Prospector mission, but it would have come at a much greater cost.



1. Here, Astrobotic's CubeRover unspools a cable to construct a power grid, initially by tying together solar-power towers and connecting those towers to power-hungry lunar equipment. John MacNeill

2. This is an artist's concept of the VIPER rover working in the lunar darkness. NASA/ Daniel Rutte

NASA also presented Astrobotic with a $34.6 million Tipping Point award for the development technology of its LunarGrid project that will produce energy via solar power.

***Blue Origin** of Kent, Washington, $34.7 million—In-Situ Resource Utilization (ISRU)-Based Power on the Moon.*

This company's technology may also make use of local lunar resources by extracting elements from lunar regolith to produce solar cells and wire that would be used to power work on the lunar surface.

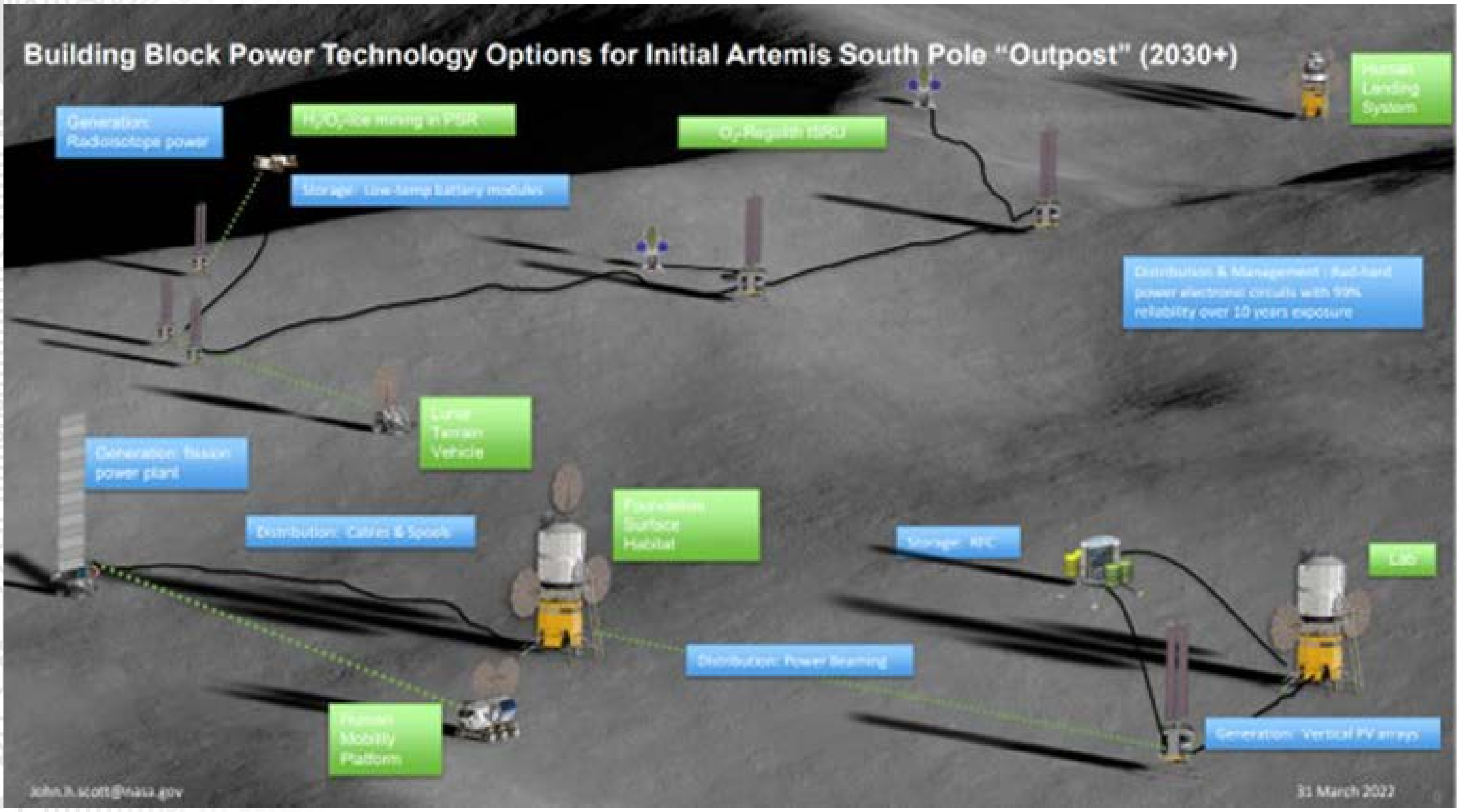
Blue Origin is also proposing "Blue Alchemist," an end-to-end, autonomous, scalable, and commercial solution that will be able to produce solar cells from the lunar regolith. The regolith is made up of dust and crushed rock on the Moon's surface.

This effort is based on a process known as "molten regolith electrolysis." This amazing breakthrough will be able to create unlimited electricity and power transmission cables anywhere on the lunar surface. The process will also produce oxygen as a byproduct for rocket propulsion and life support.

Power at the Moon's South Pole

After two Artemis test missions, two NASA astronauts—the first woman and the first person of color—will journey to the lunar surface in December 2025, beginning with the Artemis III mission. They will land where no humans have ever been before—the Lunar South Pole. This will be the ideal location for a future base camp thanks to its potential access to ice and mineral resources.

On the first few missions, the human landing system will double as a lunar habitat, offer-



3. These are some of the power technology options for the Artemis Lunar South Pole "Outpost" post-2030.

https://www.linkedin.com/in/john-scott-6339368/

ing life-support systems to support a brief crew stay on the Moon. Looking toward the future, NASA envisions a fixed habitat at the Artemis Base Camp, which will be capable of housing as many as four astronauts for a month-long stay *(Fig. 3)*.

The Moon's polar regions, especially at the South Pole, are areas that possibly contain water or ice. This discovery of polar water and ice could help provide both air and fuel as well as water for astronauts to drink. Once the water is processed, the oxygen may be able to produce vapor that could be used to supply a necessary part of the astronauts' breathable atmosphere. Water, once separated into hydrogen and oxygen components, might even be used as rocket fuel.

Landing at a location such as the South Pole site could help astronauts' long-term survival on the moon, and it may even lay the groundwork for boosting future teams farther out in the solar system.

Debra Needham, a planetary scientist at NASA's Marshall Space Flight Center in Huntsville, Ala., believes that the resources, when mined from the moon, could possibly reduce the need to launch resources from Earth. In turn, it would significantly reduce the cost of deep space exploration.

Summary

U.S. companies selected by NASA have the talent and resources to return astronauts to the Moon as a first step in developing sustainable exploration. Such scenarios would safely enable astronauts to escape from Earth's gravity, travel to the Moon, leave the Lunar orbit to travel down to the Moon's surface, and, most importantly, return home safely. All of this effort will lead to the ability to mine lunar water and other possible minerals, ultimately providing power for a sustainable, long-term lunar presence—and for man to explore not just the Moon, but Mars and beyond.

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