Challenges of a Lunar Surface Electrical Power Grid

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NASA's Moon To Mars Strategy and Objectives Development

Plan for the Moon

NASA's Moon To Mars Strategy and Objectives Development:

Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

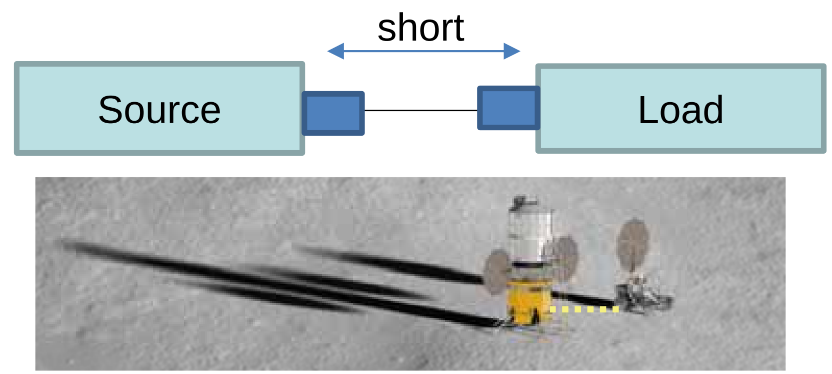
LI-1: Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

Surface Power Grid Concept: Early stages

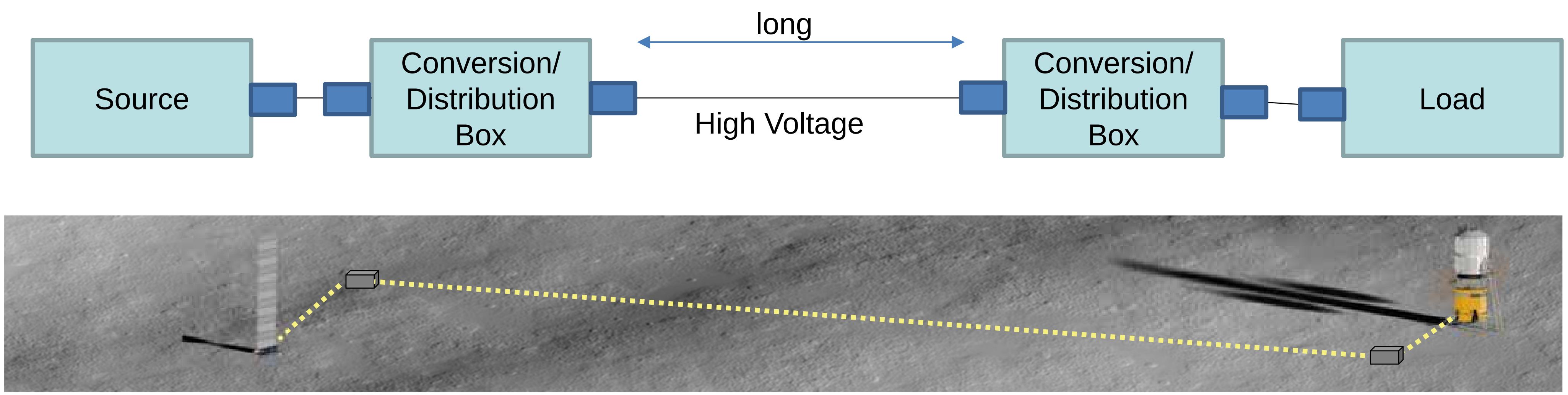
- **The initial Lunar missions will not involve many separate surface elements and will not require a complicated power grid or microgrid.**

No Grid

Short distance connections between surface assets.

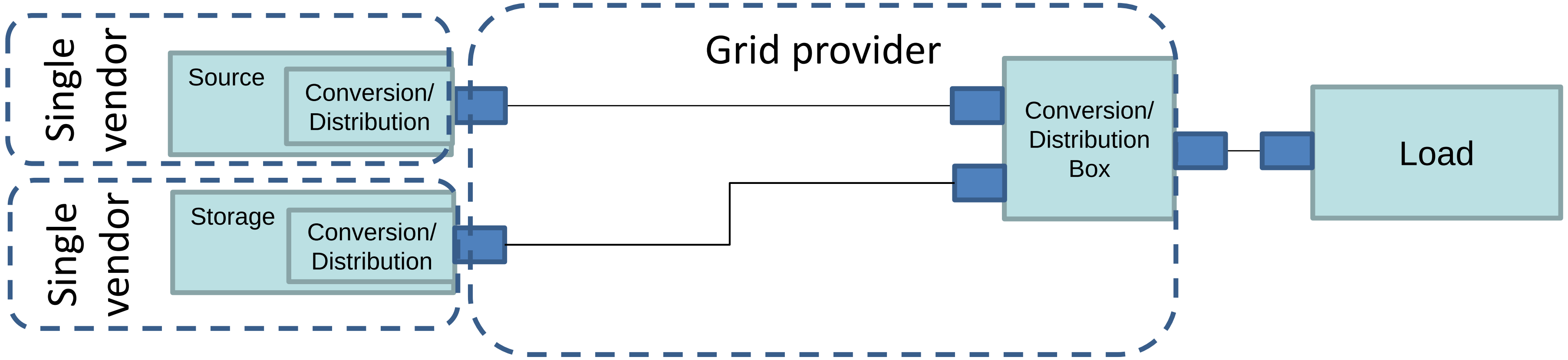


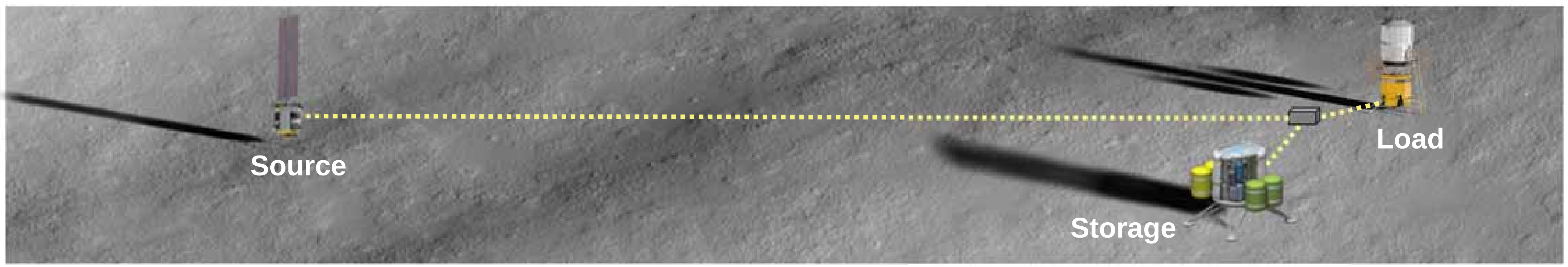
Minimum Viable Grid



Surface Power Grid: Interoperability

As surface elements are added, more vendors will get involved, and interoperability will become important.





Note: Here the grid has progressed beyond the “minimum viable grid” to one where connections matter. The details of what connects to what would be up to the grid provider.

Terrestrial Power Interoperability Examples

- **There are many examples of families of terrestrial electric power interoperability standards:**
  - Utility 50/60Hz
    - IEEE Std 1547: Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces
    - ANSI C84.1, Electric Power Systems and Equipment—Voltage Ratings (60 Hz)
    - IEC/IEEE 61850-9-3, Communication networks and systems for power utility automation
    - ANSI/NEMA WD 6-2002 (R2008) COTS connector dimensions. Only goes up to 600V
    - MIL-STD-TMS, Tactical Microgrid Standard
    - MIL-STD-1399 SECTION 300, PART 2 MEDIUM VOLTAGE ELECTRIC POWER, ALTERNATING CURRENT
    - IEEE Std 2030.9™-2019 IEEE Recommended Practice for the Planning and Design of the Microgrid
  - Military 400Hz
    - MIL-STD-704F AIRCRAFT ELECTRIC POWER CHARACTERISTICS
    - MIL-STD-1399 SECTION 300, PART 1 LOW VOLTAGE ELECTRIC POWER, ALTERNATING CURRENT (type II, III)
    - Others
  - DC
    - IEEE Std 2030.10 Standard for DC Microgrids for Rural and Remote Electricity Access Applications
    - IEEE Std 1709™-2018 Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships
    - IEEE Std 1899™-2017:Guide for Establishing Basic Requirements for High-Voltage Direct-Current Transmission Protection and Control Equipment
    - IEC60038: IEC Standard Voltages
    - Others
- **Some of these come close to what a Lunar Surface Interoperability standard would look like.**
- **The closer that a Lunar Surface standard comes to terrestrial standards, the easier to get vendors interested in using it.**

The Lunar surface grid will probably consist entirely of Solid state power converters connected to each other.

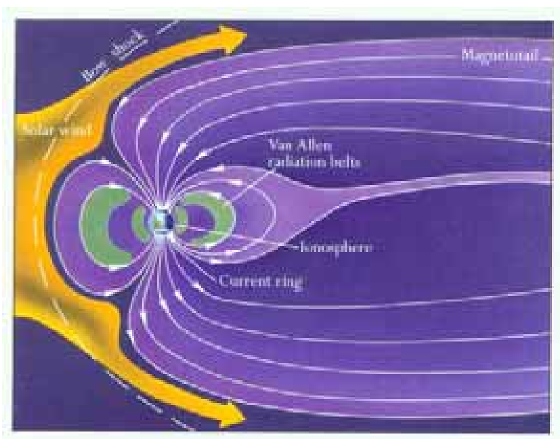
No directly connected rotating equipment, electrochemical, or photovoltaic is anticipated.

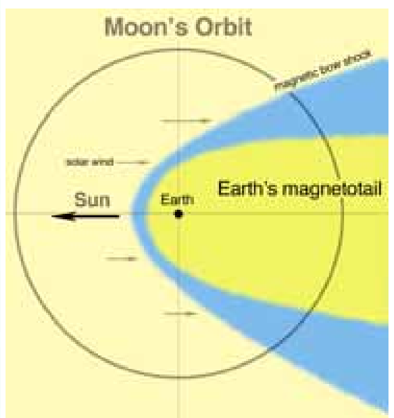
Grid Reliability and Converters

- **The reliability of a Lunar surface power grid hinges on the reliability of power converters**
  - High voltages (AC or DC) needed to transmit power over long distances.
  - Power sources on the Lunar surface not likely to produce high voltages natively.
  - Loads will not use high voltages directly, either.
- **The current state-of-the-art for converters does not have good high voltage components with radiation tolerance.**
- **There are two approaches:**
  - Converters are more radiation tolerant (reliable) at low voltages and can be combined with AC transformers to make a low frequency (50Hz to ~2 kHz) grid.
  - Low voltage converters can also be combined in redundant series arrays to get high DC voltages. This would allow a DC grid.
    - Terrestrial HVDC lines often use a similar redundancy scheme.
- **There is more to reliability than radiation tolerance (system reliability)**

Unique Challenge: Surface Electromagnetic Conditions

- **Is there a risk of Lunar equivalent to geomagnetic storms that have adversely affected terrestrial power grids?**
  - Yes.
    The Moon lacks Earth's ionosphere and resulting plasma currents. This may mean reduced Lunar effects.
  - Easy to avoid large conducting loops in a grid if we know that we need to.
  - More work needed: envelope situation and produce design guidelines.





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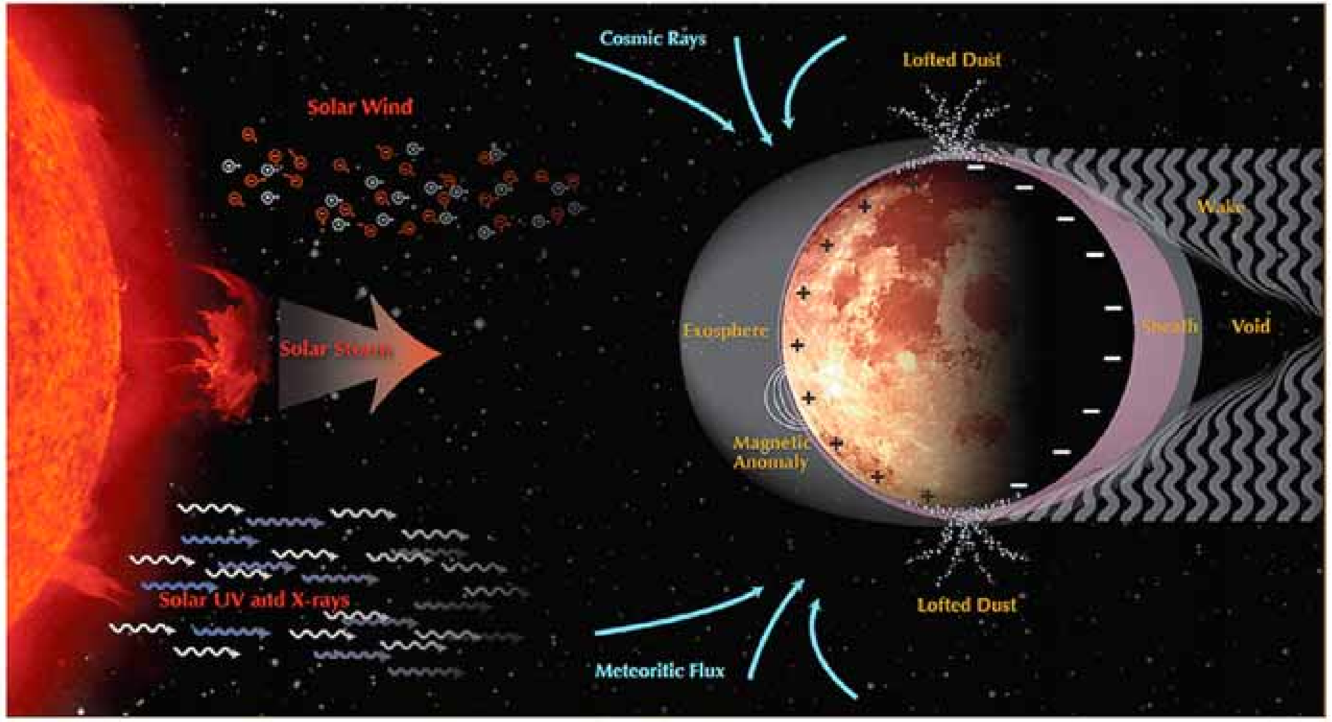
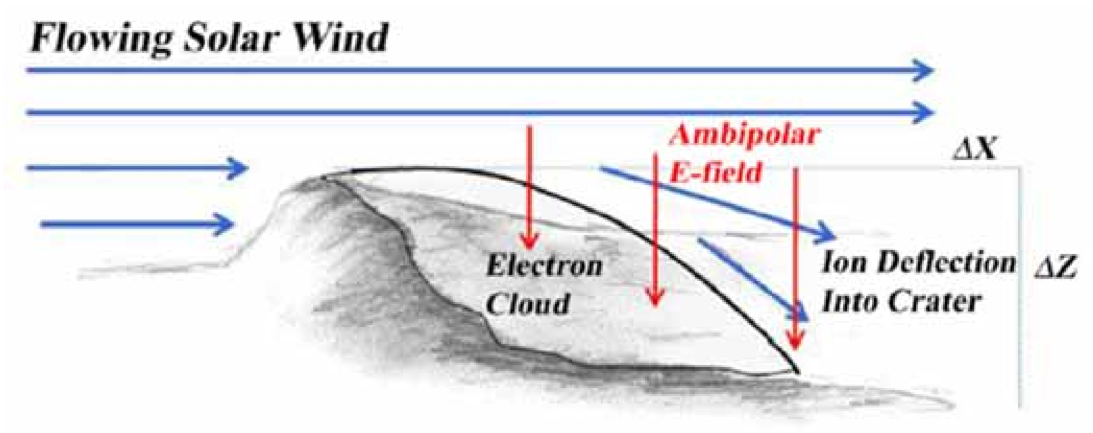


Solar-Storm/Lunar Atmosphere Model (SSLAM): An overview of the effort and description of the driving storm environment

W. M. Farrell,[1,2] J. S. Halekas,[2,3] R. M. Killen,[1,2] G. T. Delory,[2,3] N. Gross,[2,4] L. V. Bleacher,[1,2] D. Krauss-Varben,[2,3] P. Travnicek,[2,3] D. Hurley,[2,5] T. J. Stubbs,[2,6] M. I. Zimmerman,[1,2,7] and T. L. Jackson[1,2]

Unique Challenge: Surface Electromagnetic Conditions

- **The Lunar surface has plasma issues:**
  - Effects on surface assets not clear
  - Long conductive surfaces can couple to plasma (but Lunar plasmas less dense than LEO plasmas like ISS is exposed to).
  - Several people have been looking at this in the context of tribocharging of rovers and drills.
  - Most likely consequence is that individual surface equipment may develop static charge with respect to other equipment.
    - There are well known workarounds for this (aircraft fueling, etc).



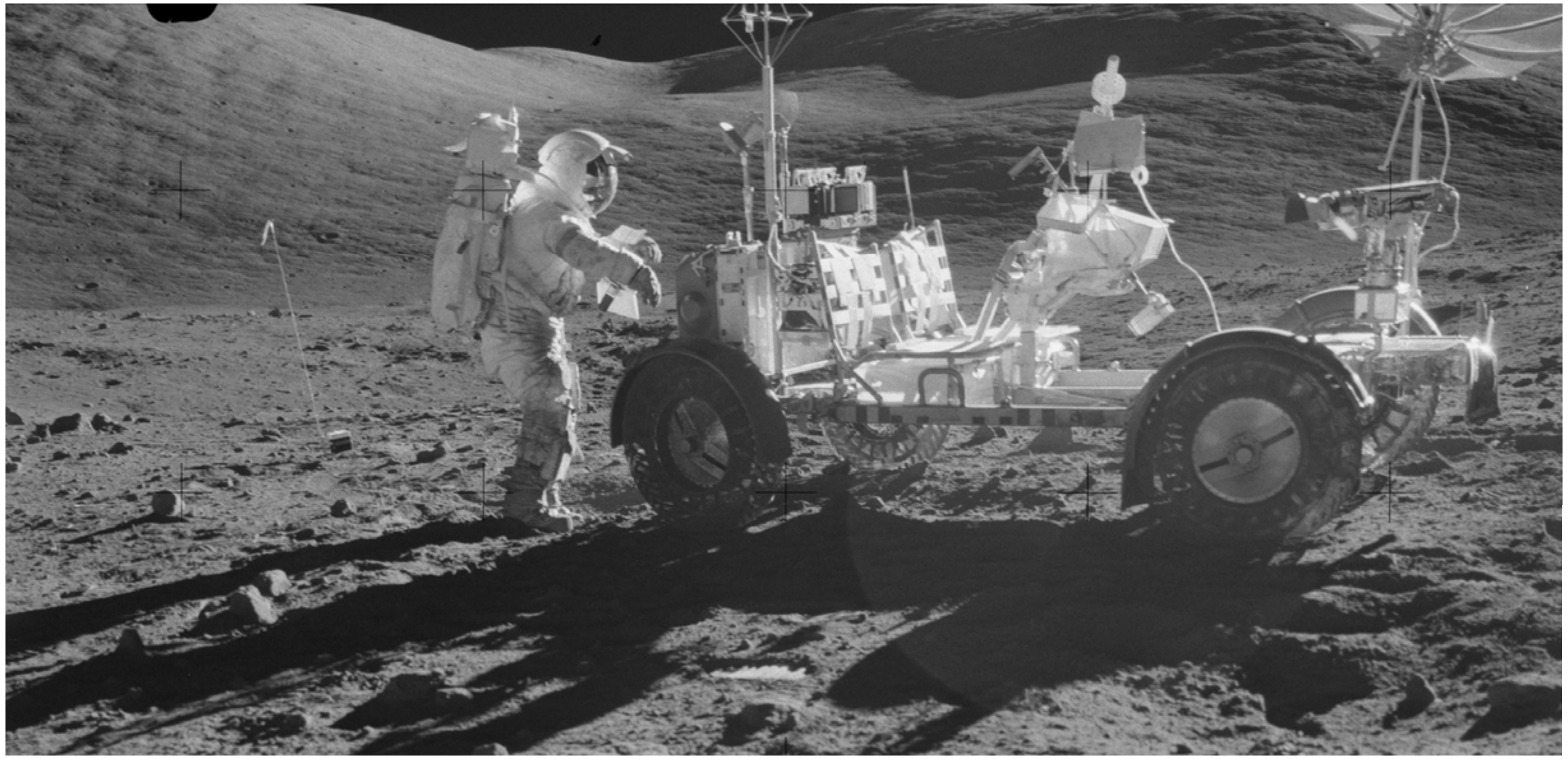
Farrell, W. M., et al. "The lunar photoelectron sheath: A change in trapping efficiency during a solar storm." *Journal of Geophysical Research: Planets* 118.5 (2013): 1114-1122.

Unique Challenge: Lunar Dust

Lunar Dust proved to be a significant and dangerous hazard on previous Apollo Moon missions.

Apollo 17 photo AS17-134-20453

NASA/TP-2006-213726 The Apollo Experience Lessons Learned for Constellation Lunar Dust Management



Apollo 17 photo AS17-136-20759 https://history.nasa.gov/alsj/a17/

The Apollo science equipment was set up to avoid the use of connectors that would be connected during an EVA, so there is not a lot of direct Apollo evidence that dust will be a problem with connectors.

Unique Challenge: Lunar Dust Tolerant Connectors

- **Unmated connector contacts and insulating surfaces will be exposed to Lunar dust during operations.**
- **Problem is much harder than keeping dust out of mated connectors.**
- **Lunar dust is more like you dropped the connector in the dust but don't get to clean it off before plugging it in.**

- **Three factors:**
  - Mechanism (locking, sliding, sealing, etc)
  - Current path (contact resistance)
  - Voltage standoff (contaminant on insulation)

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There is a MIL-SPEC dust test (MIL-STD-810 510.7) but it is unclear how useful its results are for assessing lunar hardware.
NASA is assuming that the unique properties of Lunar dust mean that there is no useful overlap.

Connector dust tolerance

Dust tolerance approaches:

- Keep dust away from conventional aerospace contacts with limited wipe-off:
  - KSC devices: DTAU, other connectors
  - Honeybee Robotics connector

Dust Tolerant Automated Umbilical (DTAU)
Gabor J. Tamasy, Robert P. Mueller and Ivan I. Townsend III

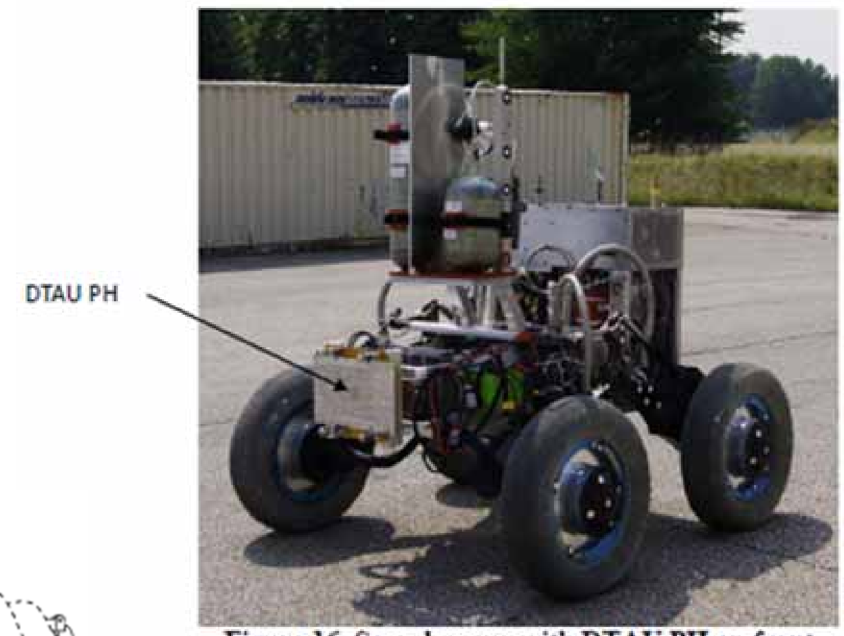


Figure 16. Scarab rover with DTAU PH on front

Figure 13. Chariot Rover with the DTAU AH

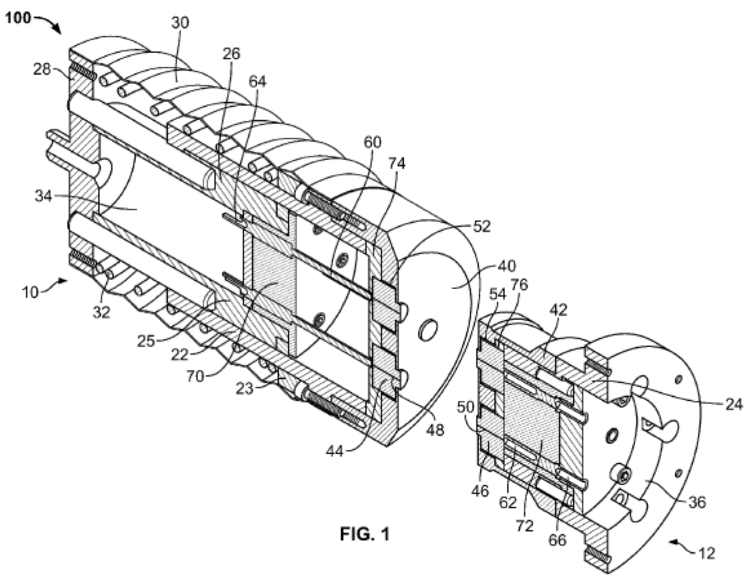
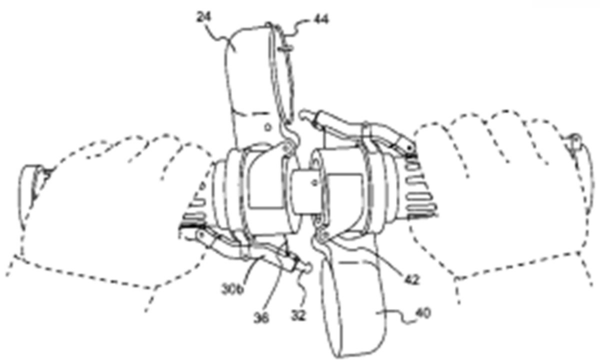


FIG. 1

Patent US 8,011,941


Patent No: 9,431,778

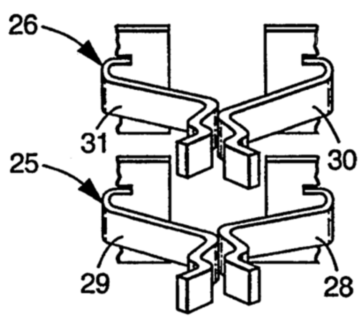
KSC-TOPS-11

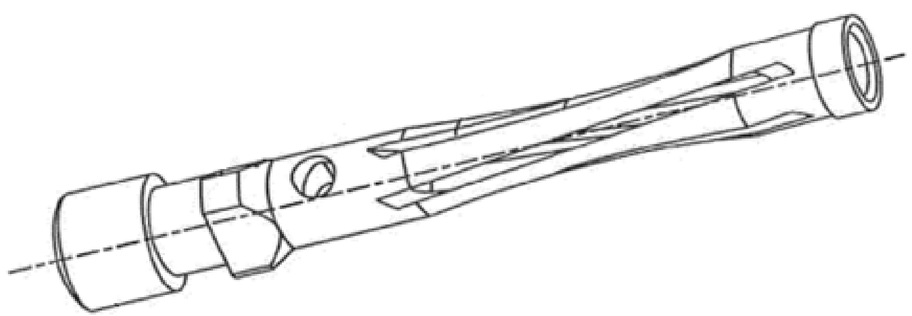
Dust tolerant connector contacts.

- Self wiping electrical contacts
- High normal forces between contacts
- Path for dust leaving

TIP FOR FORCING CONTACTS TO WIPE AGAINST EACH OTHER

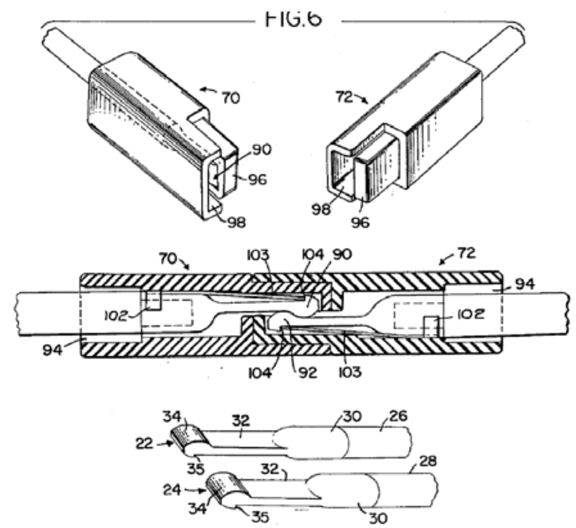
Patent Number: 5,378,164



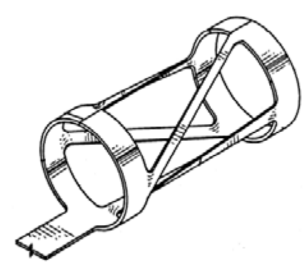


EP2882044A

“self-cleaning”:
thick silver plated contacts wipe each other



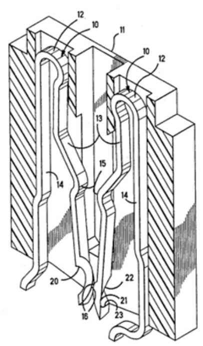
Patent US 3,091,746



Patent US 5,326,289

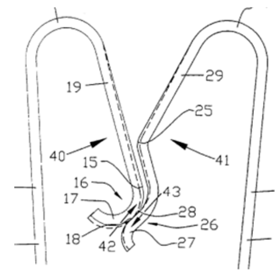
ELECTRICAL CONNECTOR WITH SHORTING CONTACTS WHICH WIPE AGAINST EACH OTHER

Patent US 5,277,607



Patent US 6,102,746

ELECTRONIC MODULE SOCKET WITH SELF-CLEANING SHORTNG CONTACTS
Patent US 5,533,907



Connector dust tolerance: Voltage

- Surface contamination is a well-known problem on terrestrial high voltage connectors.
- Looking for dust tolerant insulator materials or geometry (long creepage distance)

Issues (gaps)

- Effect of lunar dust on vacuum flashover on connectors.
- Effect of temperature range on insulators (electrical and physical).
- Effect of radiation on insulators (Total Ionizing Dose).

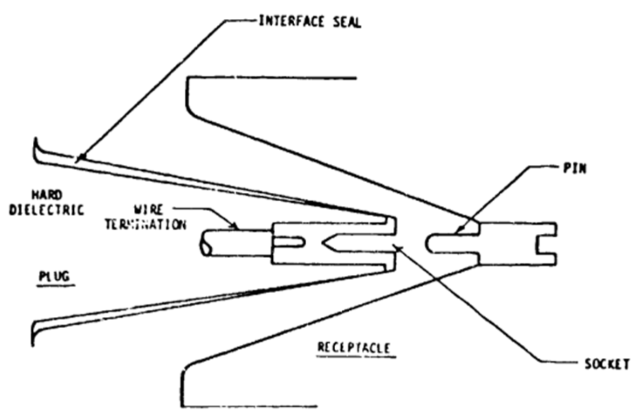
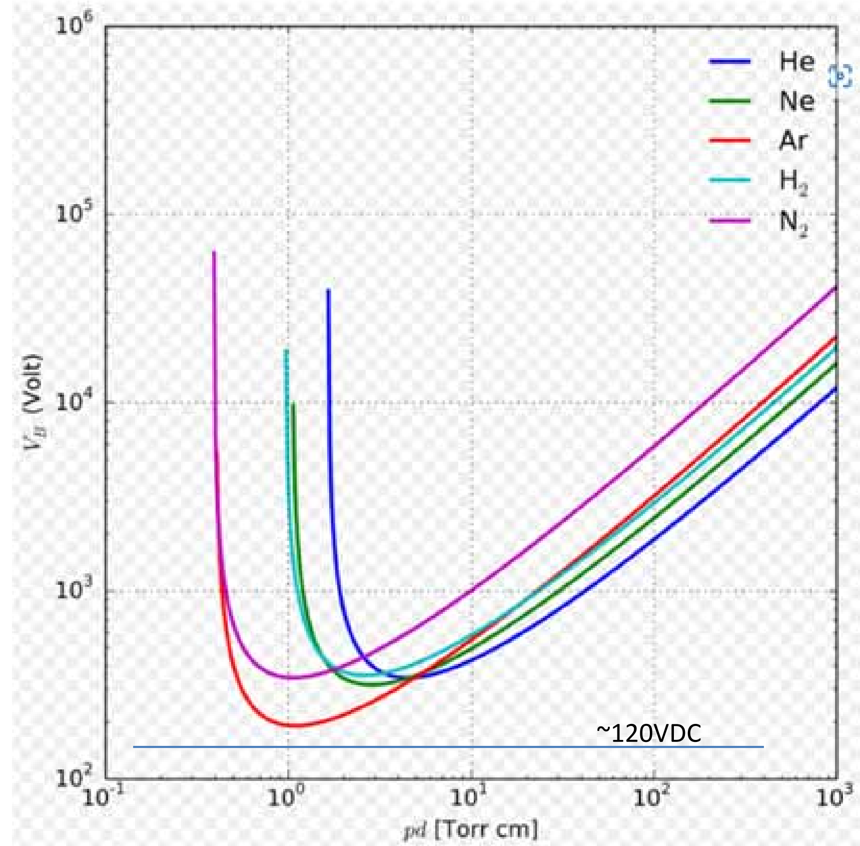


FIGURE 47. HIGH VOLTAGE CONNECTOR

From: AFAPL-TR-76-41 High Voltage Design Guide For Airborne Equipment

Figure 22. Partial discharge of the flat plate model with d=120 mm, σ_s=50 mg/cm^2.

W. Sima, Q. Yang, G. Ma, C. Jiang, L. Wu and H. Cheng, "Experiments and analysis of sand dust flashover of the flat plate model," in *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 17, no. 2, pp. 572-581, April 2010, doi: 10.1109/TDEI.2010.5448114.



https://en.wikipedia.org/wiki/Paschen%27s_law#/media/File:Paschen_curves.svg

Connector dust tolerance: High voltage contacts

Small high voltage contacts in 38999 type connectors.

- More like what Aerospace is used to.
- Dust testing is planned

Series	Hi/Mate™
Voltage Rating	13.5 kVDC
Current Rating	4 A

Inserts in place of standard 12 AWG contacts

0.72”

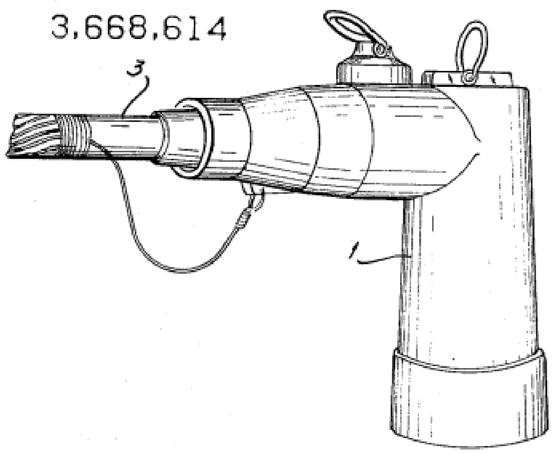
Connector dust tolerance: Terrestrial MV connectors

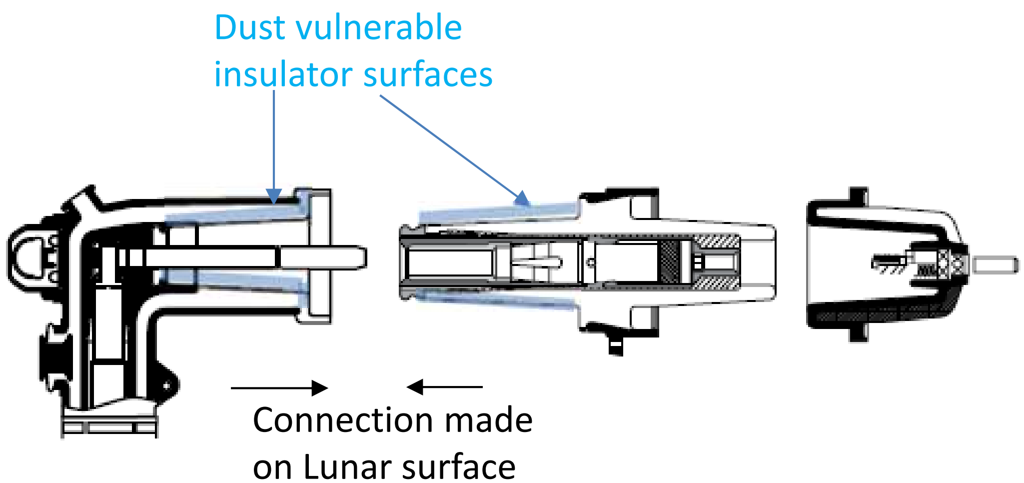
Terrestrial MV (Medium Voltage) connectors:

- Used by utilities.
- Reasonably tolerant to dirt (based on talking to vendor engineer)
- May have materials issues (rubber, grease)
- Really big

Can 35kV connectors be derated down to 3 kV and tolerate some amount of dust?

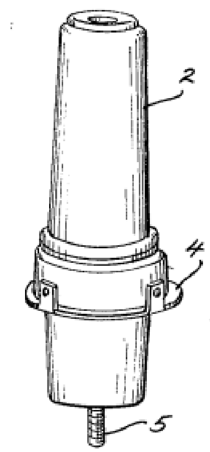
Perhaps same geometry possible with other insulator materials.





From Cooper Power Systems Specifier’s Guide

35kV 600A Deadbreak connector:



Unique Challenge: Temperature range

Standard high voltage materials, such as silicone rubber, do not perform well at extremely low temperatures.

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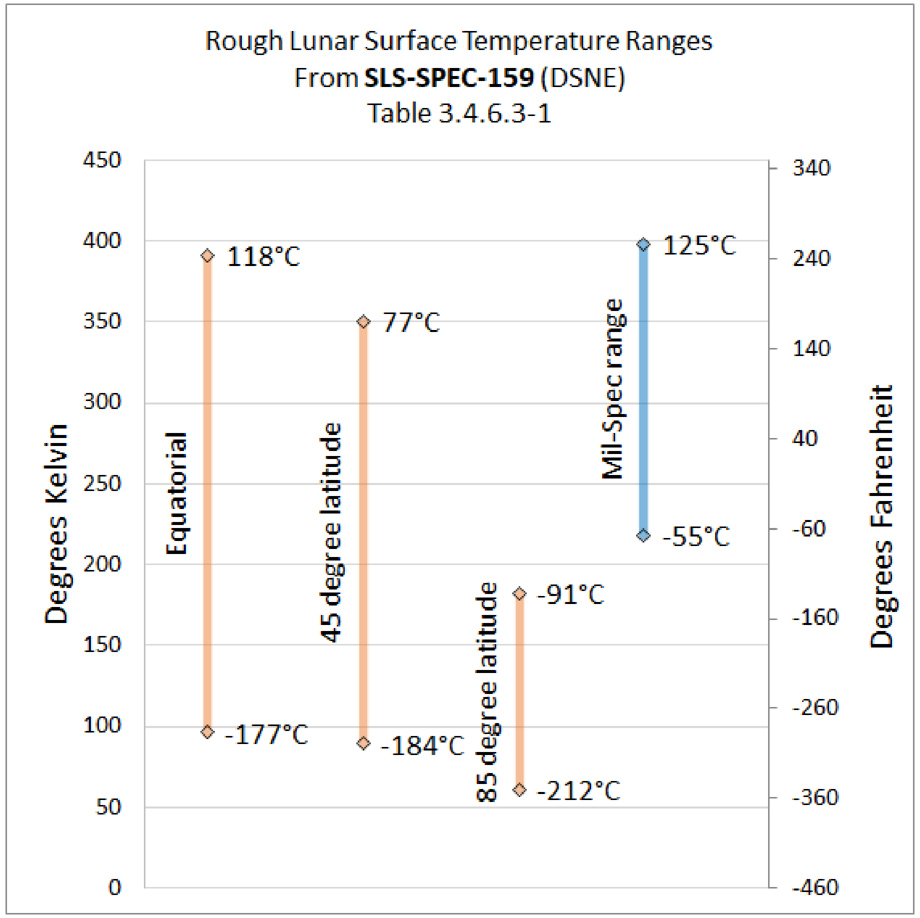
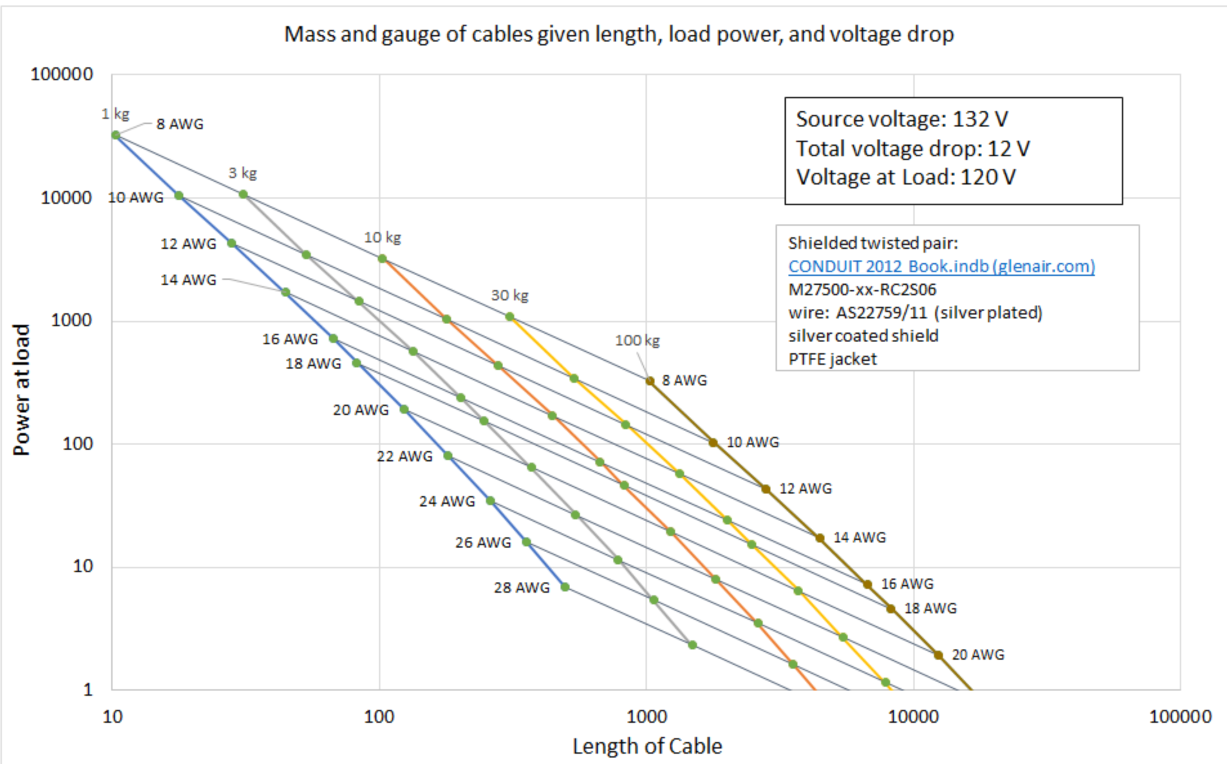


Unique Challenge: Mass and volume

- **Mass is a perennial Aerospace challenge.**
- **In one sense, the threat is that we will be driven to low mass solutions that do not scale well.**
- **Maximum spool size is also a limitation**



Analysis by F. Davies

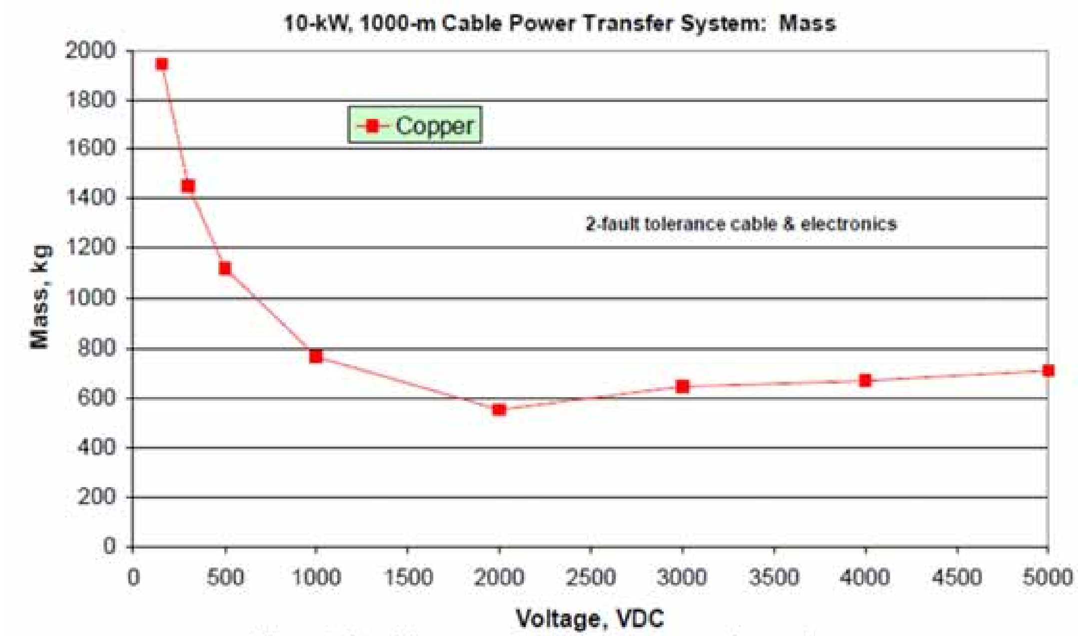


Figure 13.—Mass versus DC cable operating voltage.

NASA/TM-2007-215041 Lunar Surface-to-Surface Power Transfer
Thomas W. Kerslake