Lunar Power Distribution & Power Conditioning

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Lunar Surface Innovation Consortium (LSIC)

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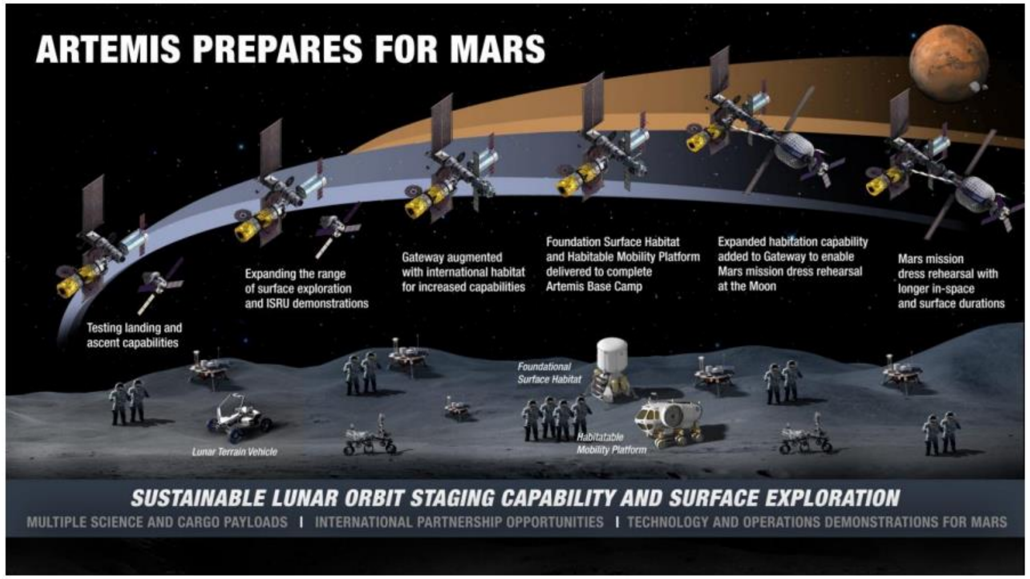
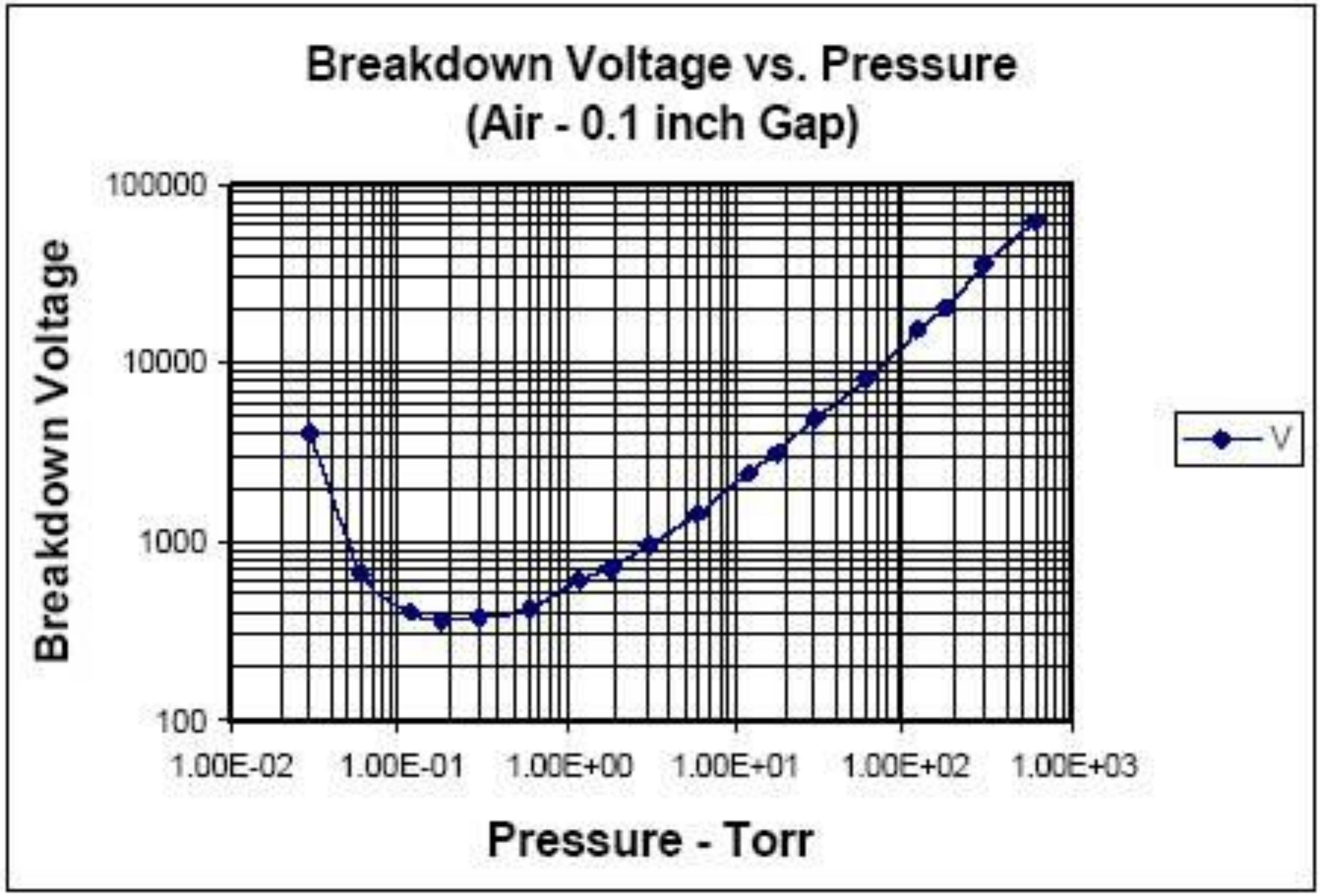
FSP Background

- NASA seeks to return humanity to the moon in semi-permanent lunar base
- FSP explored deployment of a nuclear reactor power generation system to the moon
- The reactor and all subsystems must be capable of autonomous operation for ten years
- FSP examined two power conversion systems (PCS)
  - Stirling engines
  - Brayton engines



MOSFET Limitations in Space

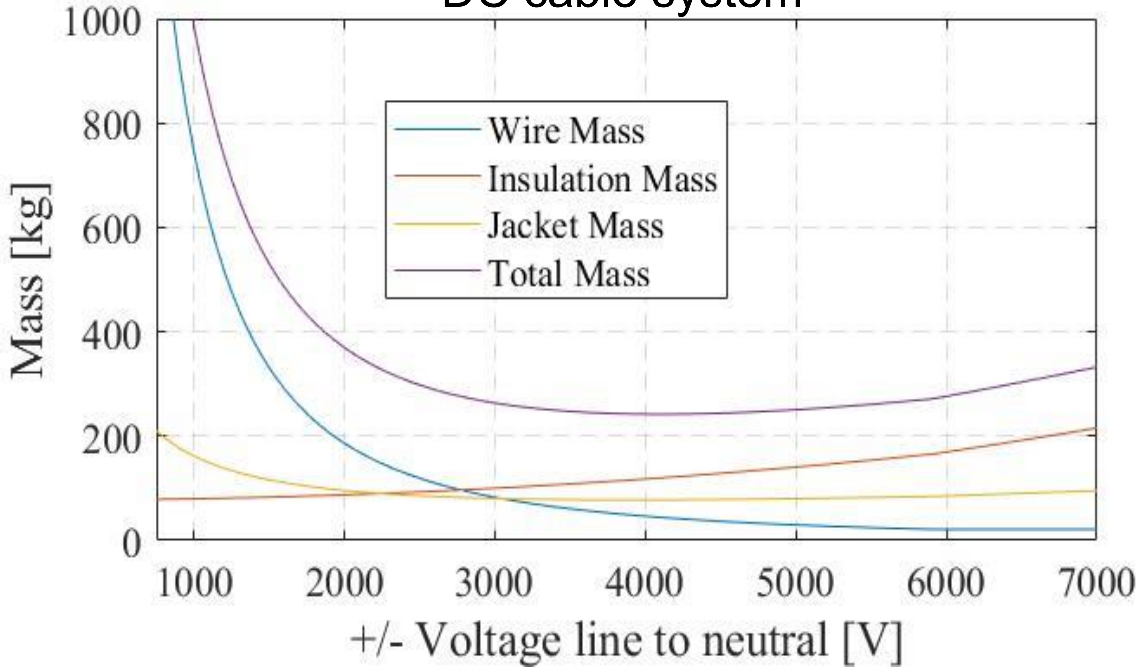
- MOSFETs are critical switching devices, required for power management and distribution (PMAD) hardware
- MOSFETs can fail due to TID radiation, SEE radiation, thermal environment, or Paschen breakdown (arcing between component conductors)
  - TID, Paschen breakdown issues, and thermal issues can be solved with engineering
  - SEE cannot be shielded
- Space-rated MOSFETs have been limited to 120VDC operation
  - Space station uses 120VDC



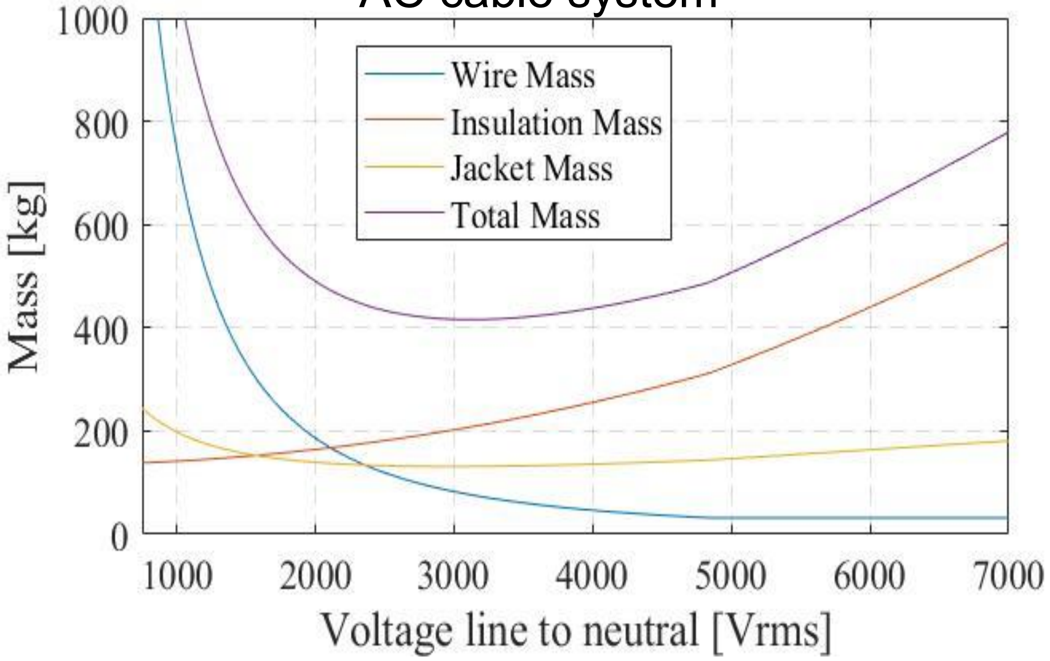
AC vs. DC Power Transmission

- Trade Study performed to analyze AC vs. DC power transmission
  - Cable sized for transmission of 43 kW a distance of 3 km with 95% efficiency
  - Cable power loss limited to 0.7 W/m
  - Fission Power Mass estimates: 1689 kg/10 kW core power conversion, 2691.4 kg/10 kW
- AC and DC mass comparable for transmission lines, slightly favoring DC

DC cable system



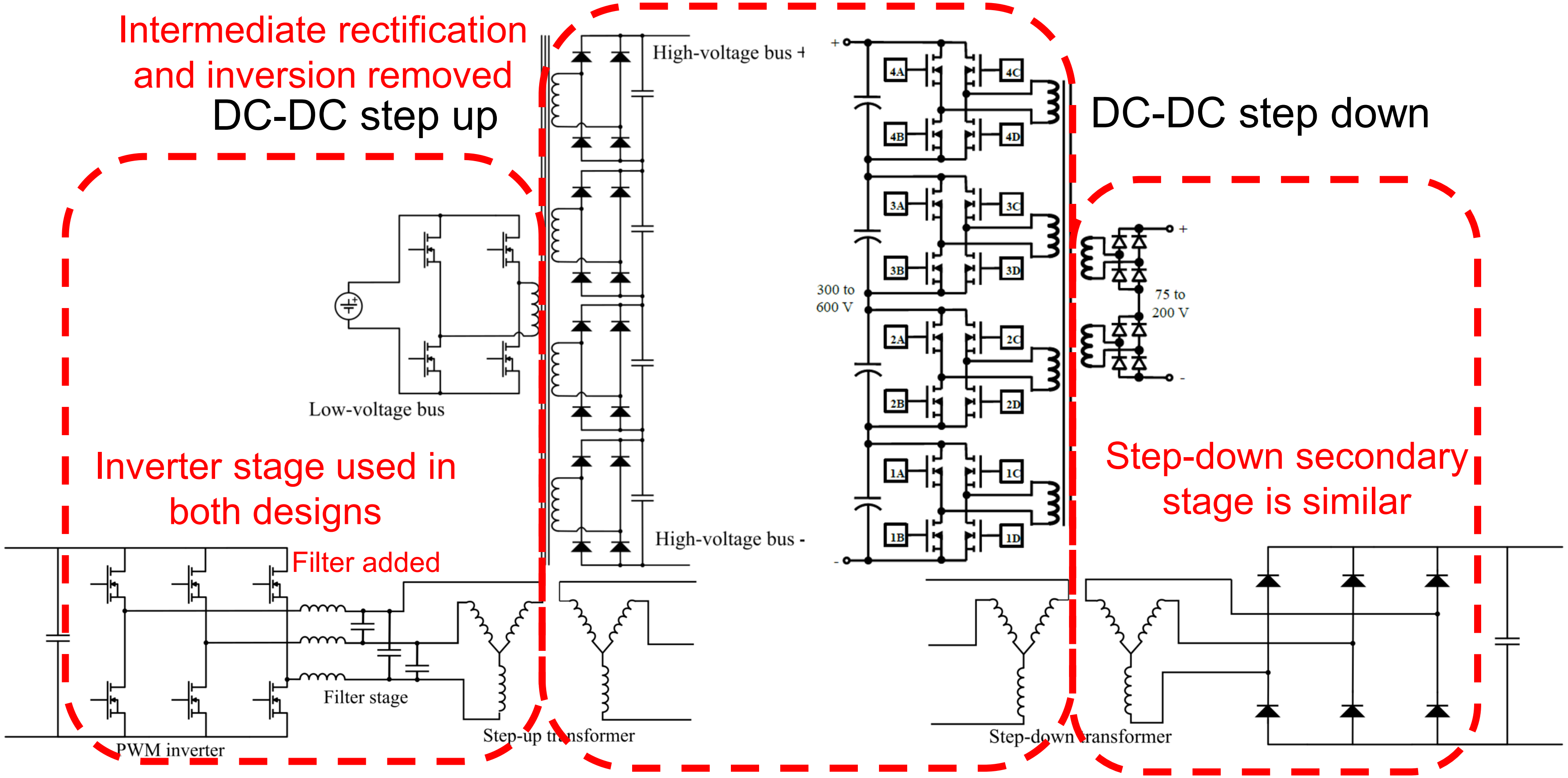
AC cable system



1) Christopher Barth, PhD and Pike, David. LUNAR POWER TRANSMISSION FOR FISSION SURFACE POWER. Cleveland : NASA Glenn Research Center, 2022.
2) Trade Studies Report - Nuclear Fission Power System, Document No.: NFP-RPT-0017, May 14th, 2020 version

AC vs. DC Power Transmission

- Input and output stages are similar for both designs
- Intermediate rectification and inversion are removed for AC
- **DC requires more parts & higher risk of system failure**



DC-AC step up   AC-DC step down (6-pulse can be implemented)

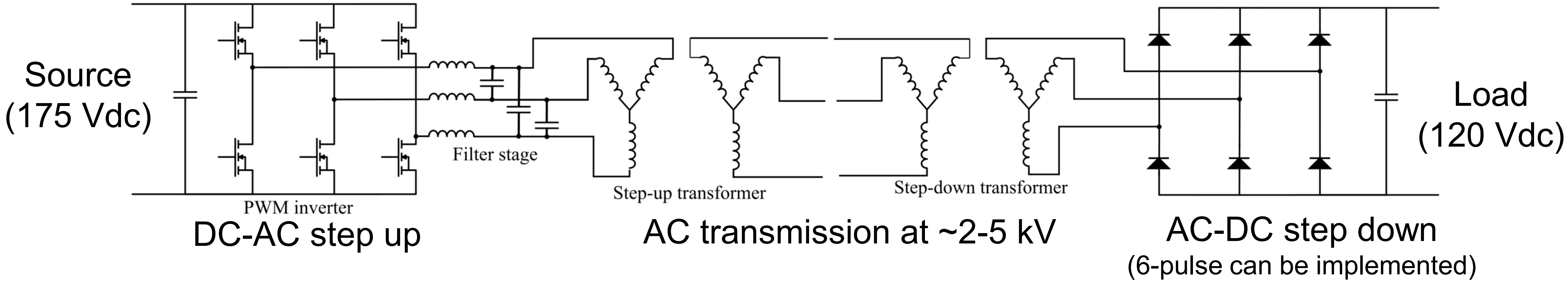
Auto Balancing Series Stacked converter (ABSS)

- Inherent isolation
- $\# \ Active \ Switches = 4 * ceiling\left[\frac{Vdc}{Vsw}\right]$
  - 24 switches rated at 175 V = 1050 V
  - 6 levels required for 175 V switches and 1 kV bus
    - 250 V switches derated to 175 V

1) Christopher Barth, PhD and Pike, David. LUNAR POWER TRANSMISSION FOR FISSION SURFACE POWER. Cleveland : NASA Glenn Research Center, 2022.
2) ABSS: https://www.techbriefs.com/component/content/article/26140-lew-19172-1a

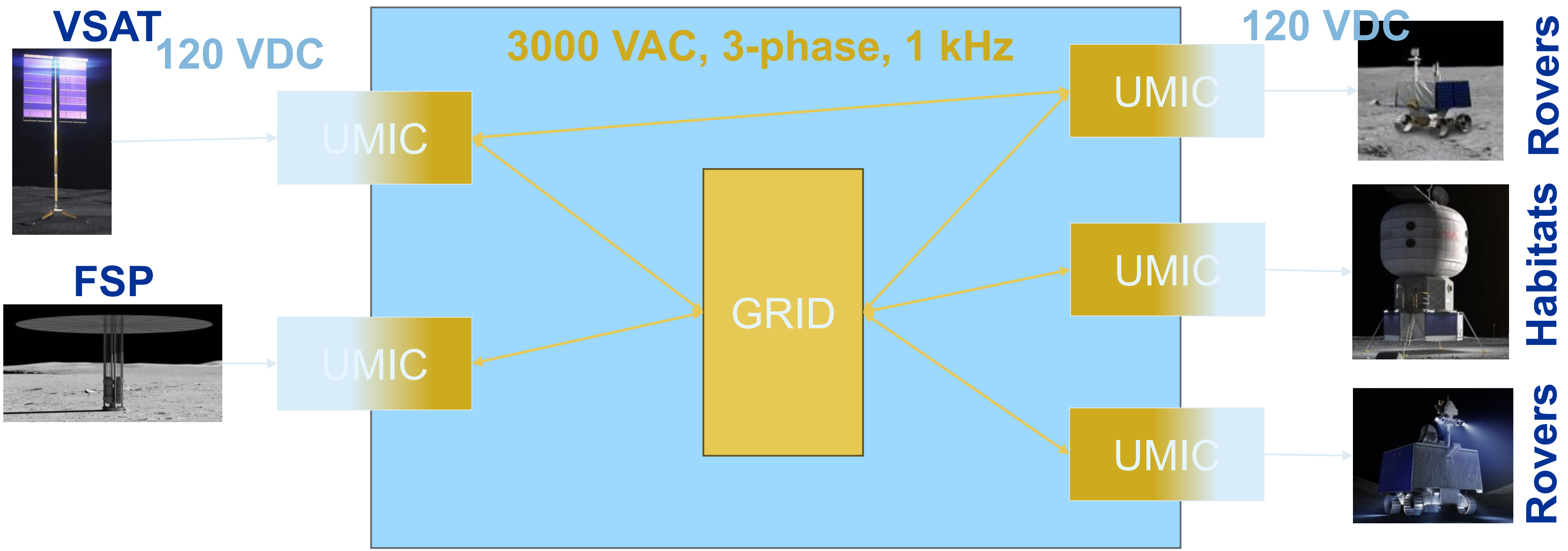
AC vs. DC Power Transmission

- **Simplifies voltage step-up and step-down**
  - AC transmission allows use of existing flight-rated switches without stacking (175 Vdc)
  - Eliminates the need for high voltage capacitors
- **Modest frequency (1-5 kHz) AC transmission options have been proposed and preliminarily evaluated [1-3]. AC and DC system masses are comparable.**
- **AC transmission voltage can be easily changed (by changing turns on transformer) based on distance without changing power electronics**
- **Additional work is in process at GRC to evaluate cable insulation degradation under AC transmission**



1) K. J. Metcalf, "Power management and distribution (PMAD) model development," NASA Contractor Report CR-2011-217268, Boeing Corporation, Canoga Park, CA, Nov. 2011 (118 pages)
2) K. J. Metcalf, R. B. Harty, and J. F. Robin, "Issues concerning centralized vs. decentralized power deployment," NASA Contractor Report CR-187121, Rockwell International, Rocketdyne Division, Mar. 1991 (120 pages)
3) T. Kerslake, "Electric power system technology options for lunar surface missions," Tech. Rep. NASA TM-2005-213629, NASA Glenn Research Center, Cleveland, Ohio, Apr. 2005

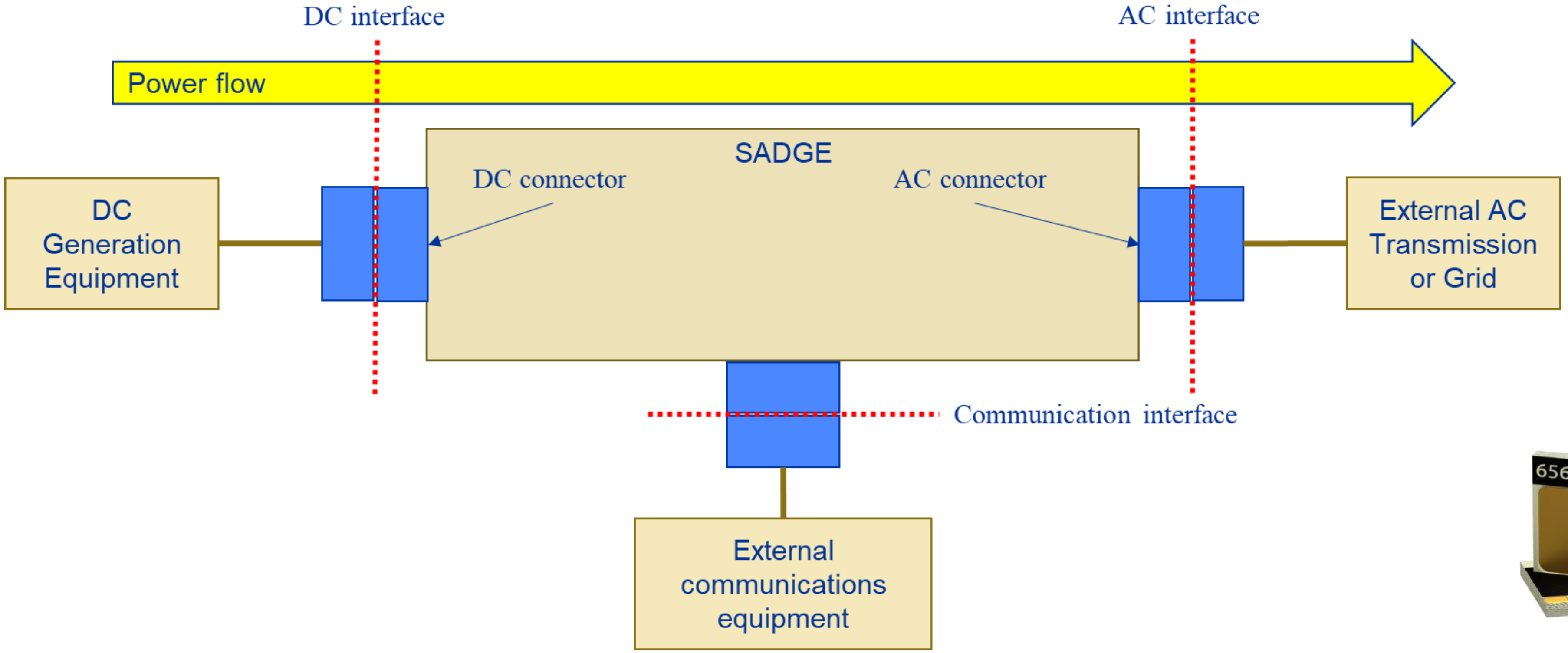
Universal Modular Interface Converter Concept



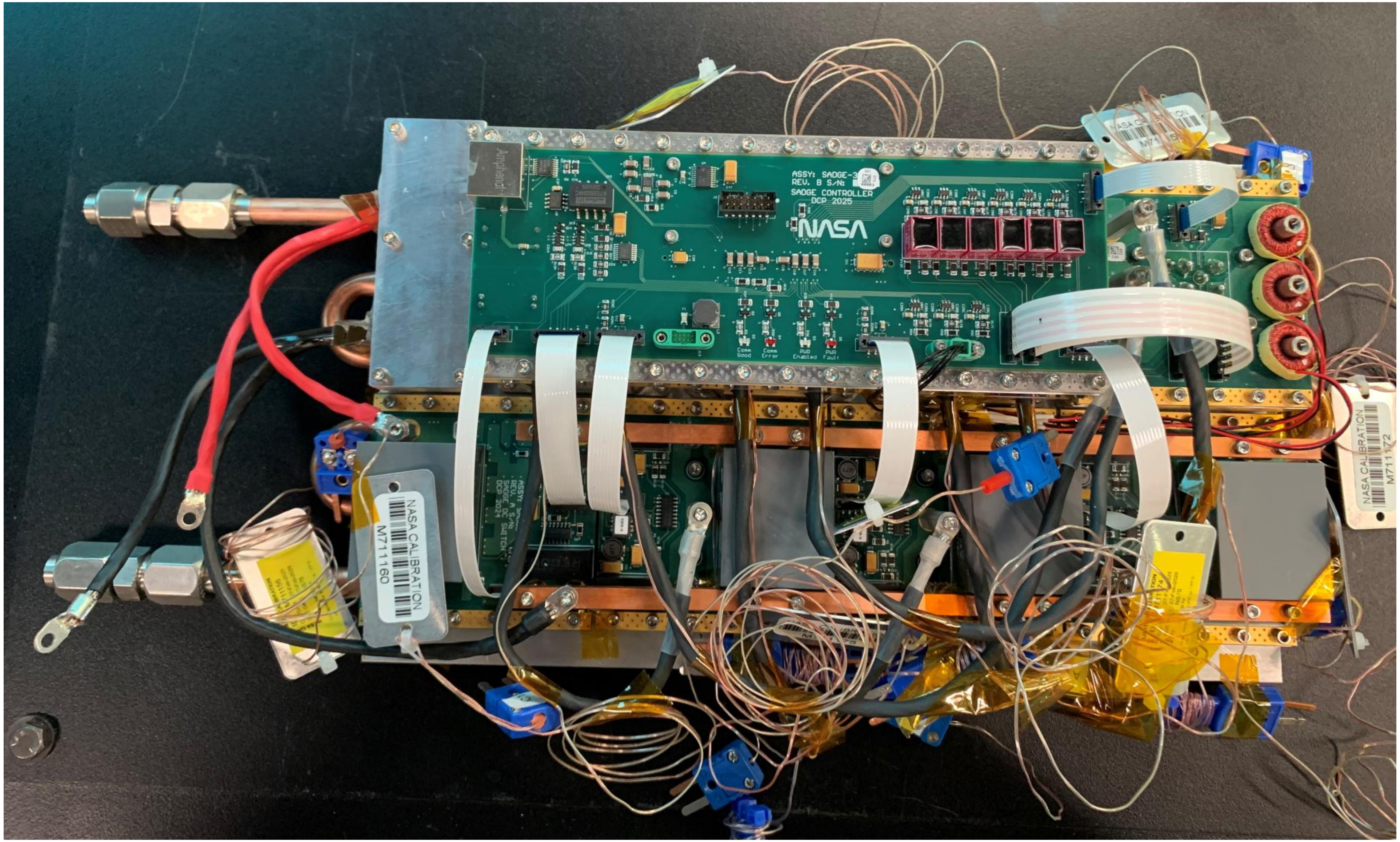
- The UMIC enables long-distance power transmission and a power grid
  - Connects power sources and loads together over-long distance and allows for a power grid as the system evolves.
  - Source and loads design to current 120 VDC and 28 VDC power standards

Standardized Adapter for Dedicated Generation Equipment (SADGE) Operating Parameters

- 300 VDC to 3 kVACrms, 3 phase, 1 kHz, >3 kW
- GaN MOSFET (GS-065-060-5-T-A) can only be used to 300 V
- Redesigned UMIC based on the higher DC input voltage and unidirectional power flow
  - Similar control scheme; only change based on single direction power flow
- Design raises DC input as high as possible with current part limitations without stacking bridges



SADGE


ASSY: SADGE-3
REV. B S/N:
SADGE CONTROLLER
DCP 2025
NASA
NASA CALIBRATION
M711160
NASA CALIBRATION
M711172

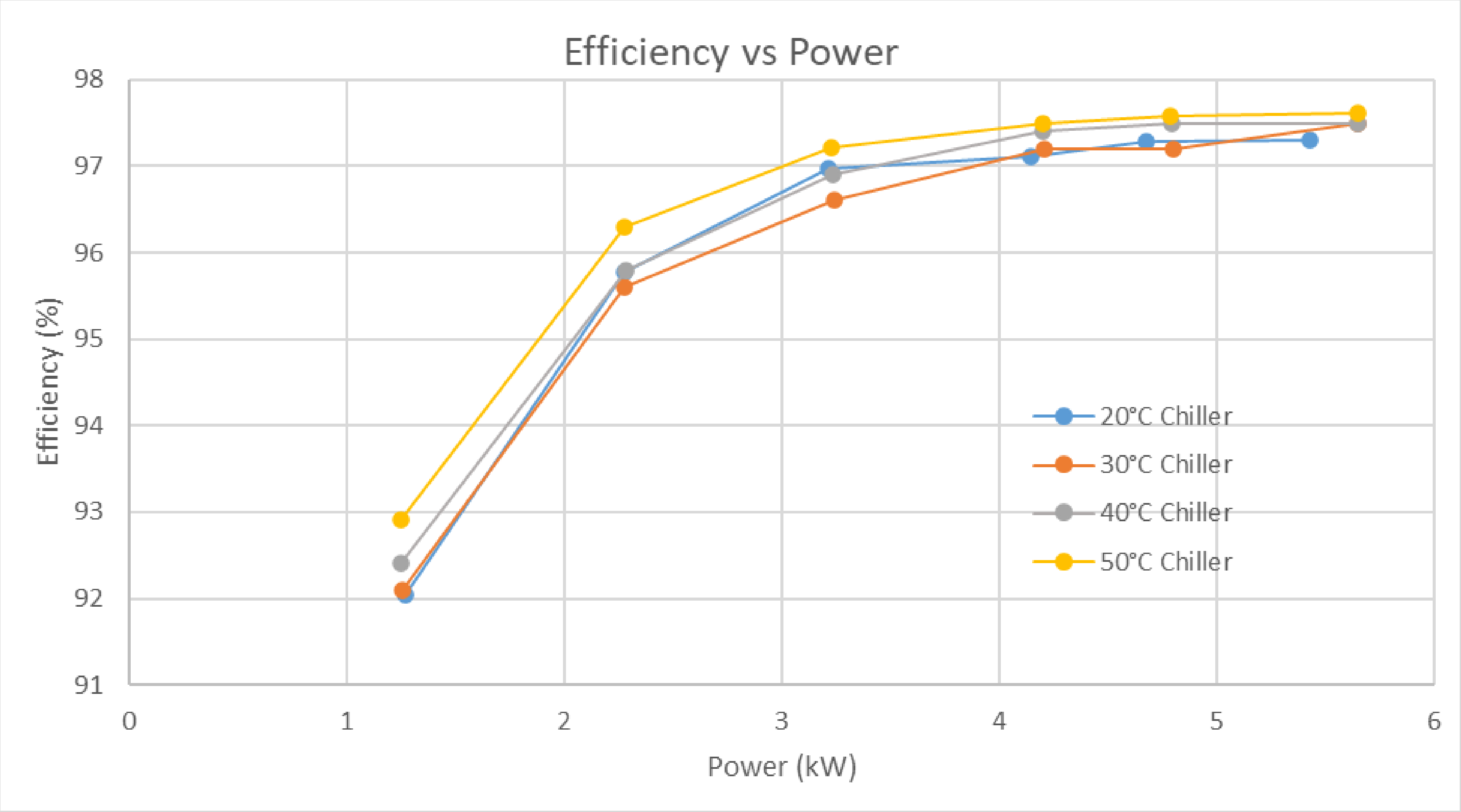
Testing Results

Test Voltage

300 VDC

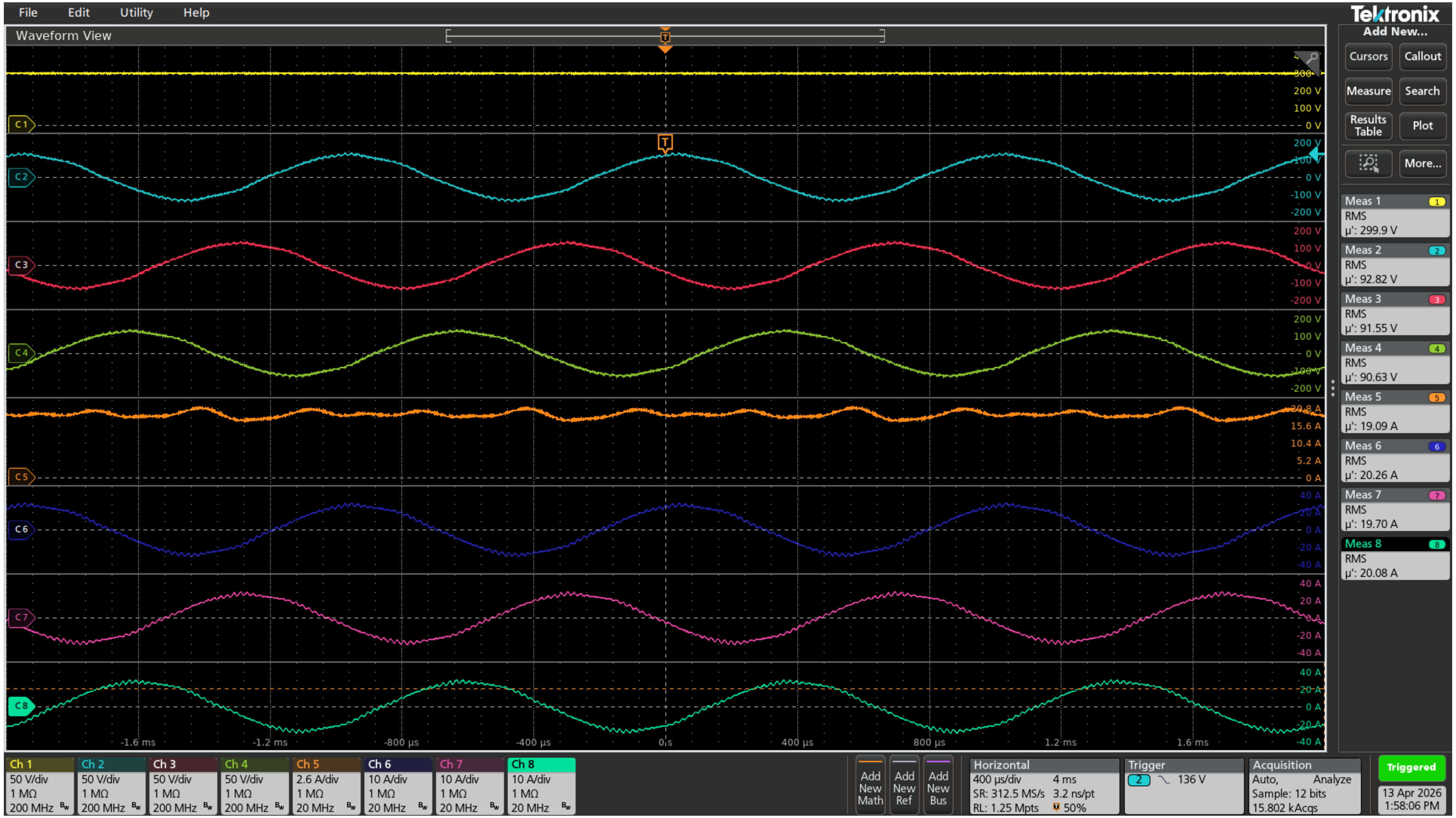
Efficiency @ 5.65 kW

97.6 %



- Tested at 300 V up to ~5.5 kW at 50 °C chiller setpoint
  - ~70 °C MOSFET-to-baseplate delta consistent across all load levels likely exceeds flight margins

Performance: 5.5 kW, 300 V, 50 °C Chiller



SADGE oscilloscope capture, 5.5 kW, 50 °C chiller setpoint

Conclusion

Successes

- Operated at 5.5 kW in vacuum at 50 °C baseplate
- Achieved ≥ 97.5 % efficiency at 5.5 kW

Issues

- ~70 °C MOSFET temperature rise above baseplate requires thermal management improvement
- MOSFET discontinuation (GS-065-060-5-T-A) mandates new component selection
- Further technology maturation required
  - Input/output filtering
  - Switching optimization
  - Switchgear

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Lunar Environmental Challenges

- Radiation environment: cosmic rays, solar wind, solar flares; comparable to in-space environment (similar degradation expected to GEO)
- Temperature extremes: -173 to +127 C near the lunar equator and down to -247 C inside the craters and cold traps
- Large thermal gradients that may occur across an asset during sunrise and sunset
- Dust: jagged crystalline, can be expelled at high velocity on landing/takeoff
- Topographical: uneven surfaces, craters, high slope areas, low density surface dust
- Variations in conditions based on equatorial, polar, or permanently shadowed areas. Design solutions for the lunar south pole may not be acceptable as operations move towards the equator
- Hard vacuum: with no atmosphere, components will off-gas and functionality may be affected or compromised completely
- Insulating lunar regolith: unlike the earth, the moon is non-conductive, meaning that terrestrial grounding conventions may not apply
- Component reliability: harsh environment will likely degrade components