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# Graphene-based Energy Storage Devices for Space Applications

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# Energy Storage in Space

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- Desirable characteristics
  - High energy density
  - Stable, Reliable, Safe
  - Wide operating temperature
  - Rapid recharge

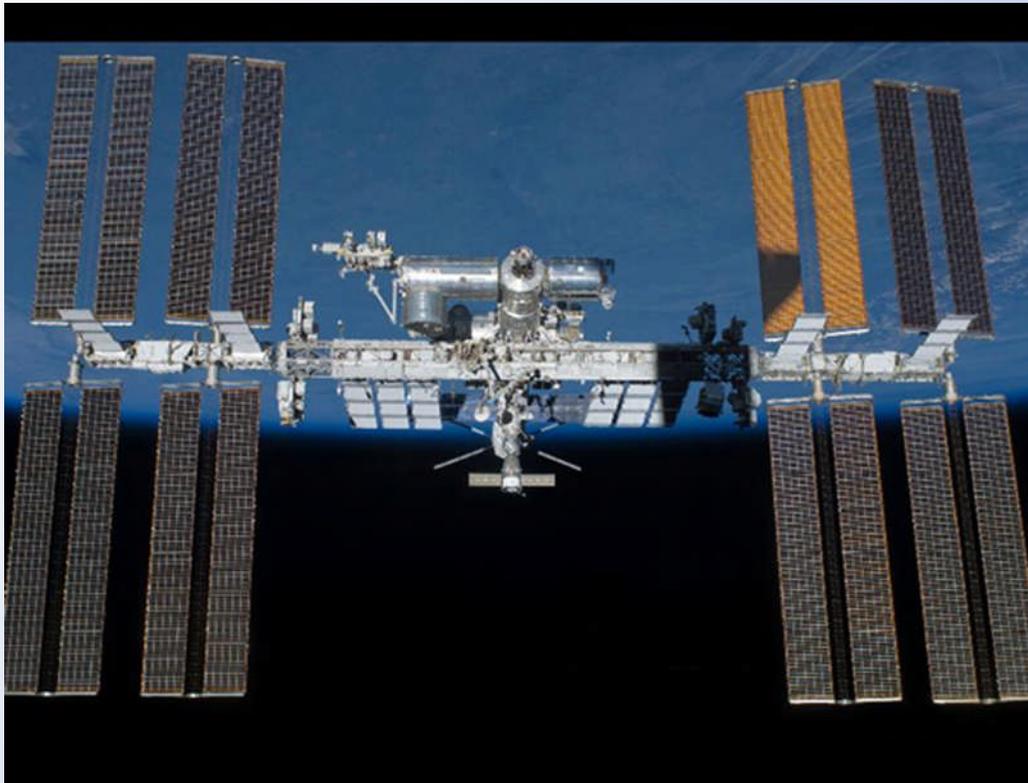




# Evolving Technology

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## International Space Station



Nickel-hydrogen (Ni-H<sub>2</sub>)

Charge-use cycle of  
90 minutes

Expected replacement to  
lithium in 2017

One lithium ORU to  
replace two nickel-  
hydrogen ORU's



# Evolving Technology

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## Curiosity/Mars Science Laboratory



Lithium

Charge-use cycle  
multiple times per day

Peak power demands  
exceed MMRTG power  
Source



# Graphene

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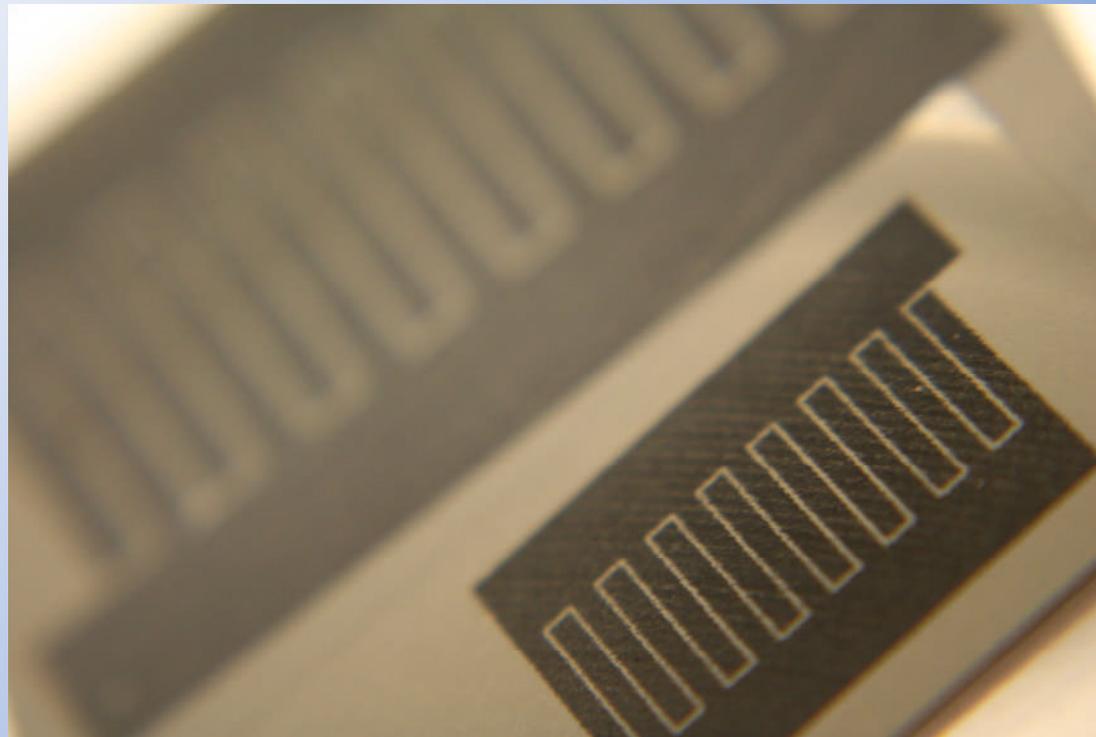
- High intrinsic capacitance
  - $21 \mu\text{F}/\text{cm}^2$
- Large surface area
  - $\sim 2,600 \text{ m}^2/\text{g}$
- Versatile
  - Grown on or transferred to a wide variety of substrates
- High temperature and chemical stability



# Laser Scribed Graphene

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- Use of laser to reduce Graphene Oxide
  - Exfoliates layers while removing oxygen
  - Result is a large surface of area of graphene crystals



Picture credit: Rachel E Cox, NASA

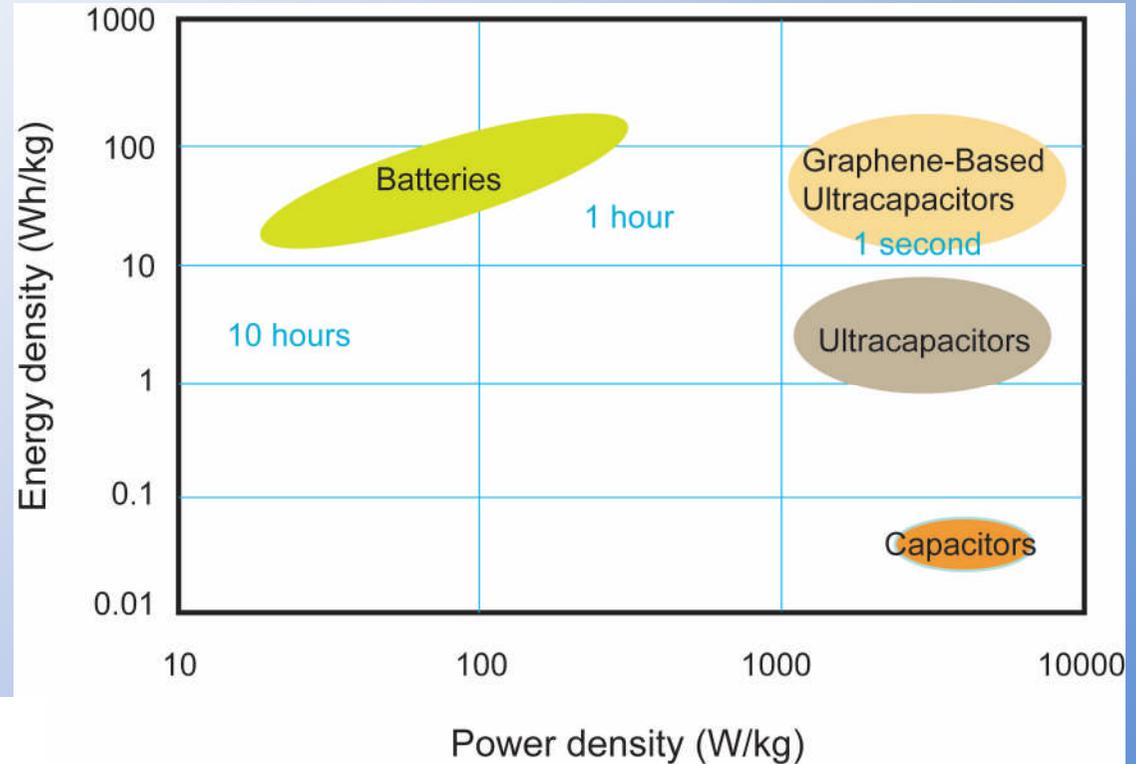


# Expected Performance

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Graphene-based ultracapacitors:

- High power densities
- High energy densities



supercapacitors



batteries



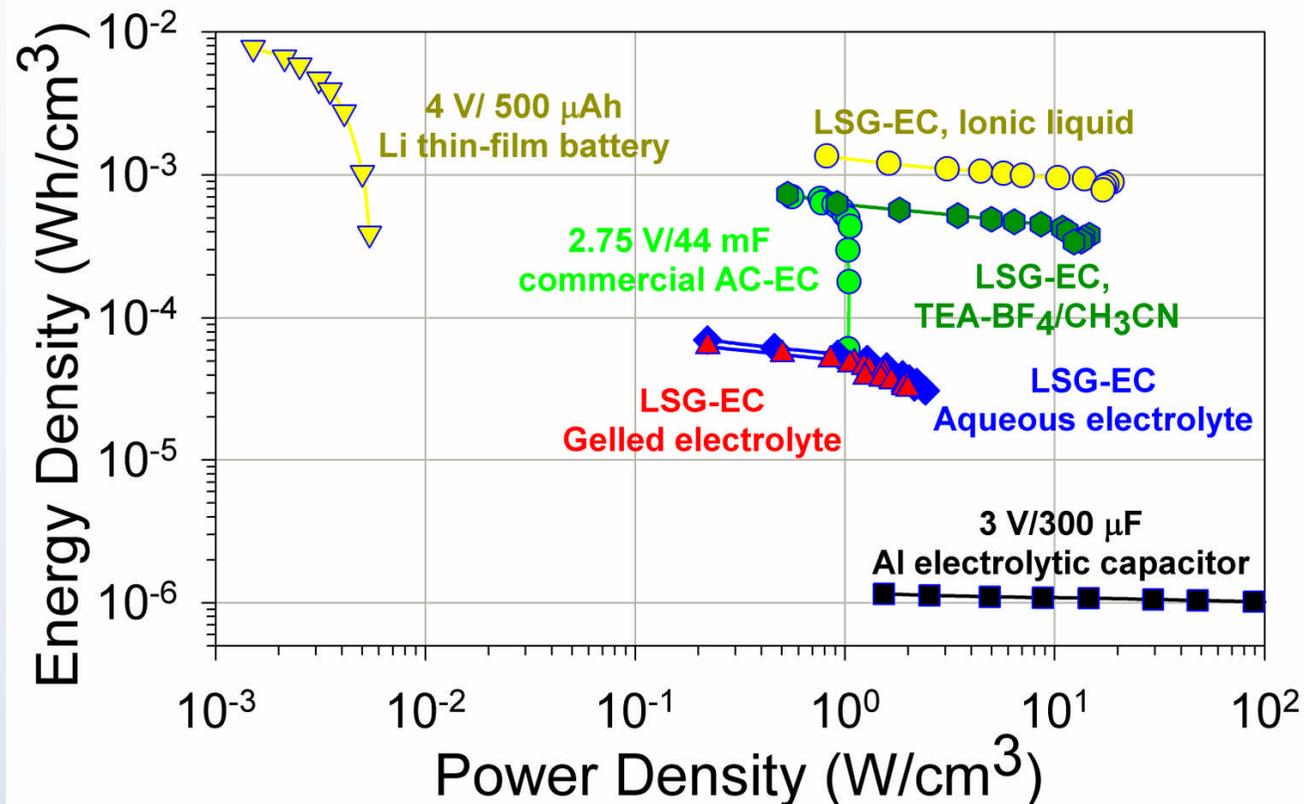
Energy and power density comparison for batteries, conventional ultracapacitors, and the expected performance of graphene-based ultracapacitors. Charging times are shown in blue.

Slide courtesy of UCLA, Kaner Laboratory



# Comparison of LSG, AC, Thin-film Li

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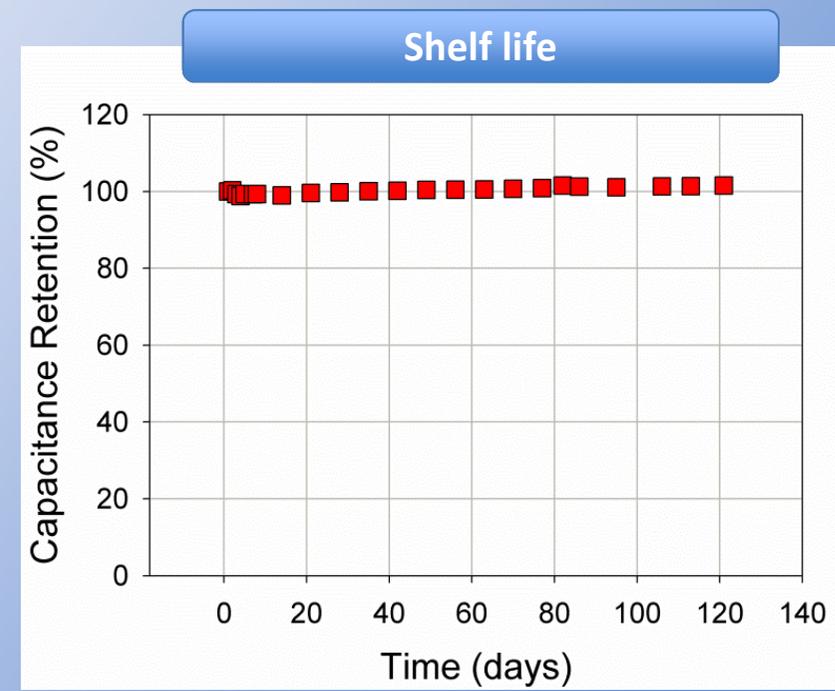
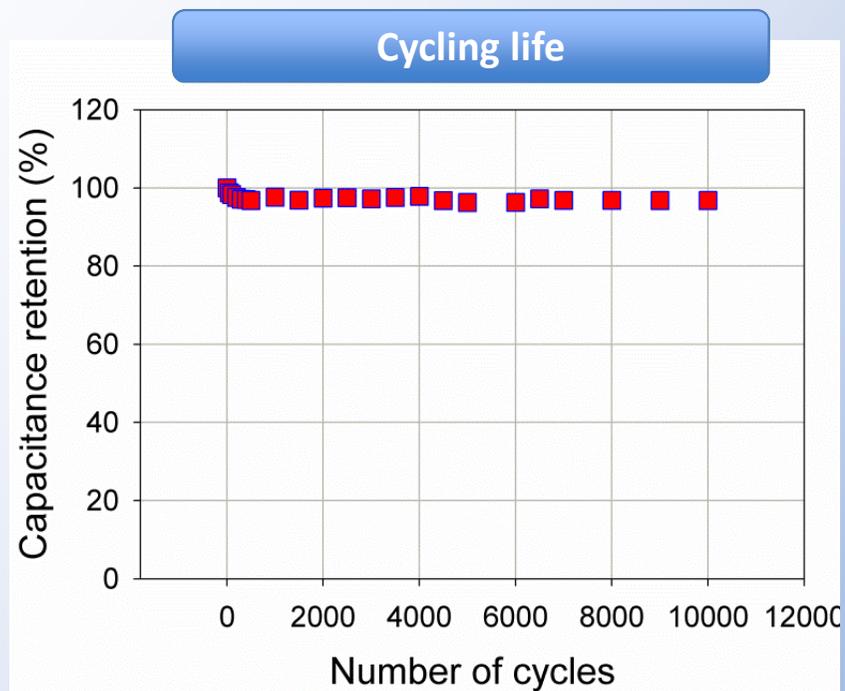
- The plot shows the energy density and power density of the stack for all the devices tested (including current collector, active material, electrolyte and separator).
- Additional features: flexible, lightweight, current collector free and binder free

Slide courtesy of UCLA, Kaner Laboratory



# Cycling and Shelf-Life

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# Current Work

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- Increased surface area
- Conductive substrates
- Better electrolytes
- Operating voltage primarily a limitation of the electrolyte
- Ionic liquids can offer exceptionally high thermal stability to 200°C [Kolmulski *et al.* 2004]



# Future Work

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## RASSOR



Regolith Advanced  
Surface Systems  
Operations Robot

Regolith includes dust,  
sand and rock

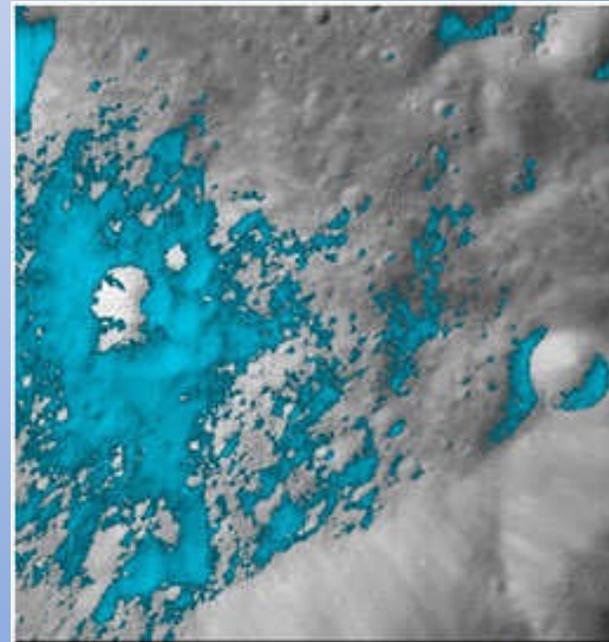
High power robotics  
designed to extract  
compact and icy regolith  
frozen mixtures



# ISRU

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- In-Situ Resource Utilization (ISRU) is the identification, acquisition, and utilization of in-situ resources whether they be naturally occurring or man-made.
- This lunar crater image from the M3 mapper shows water-rich minerals in blue.

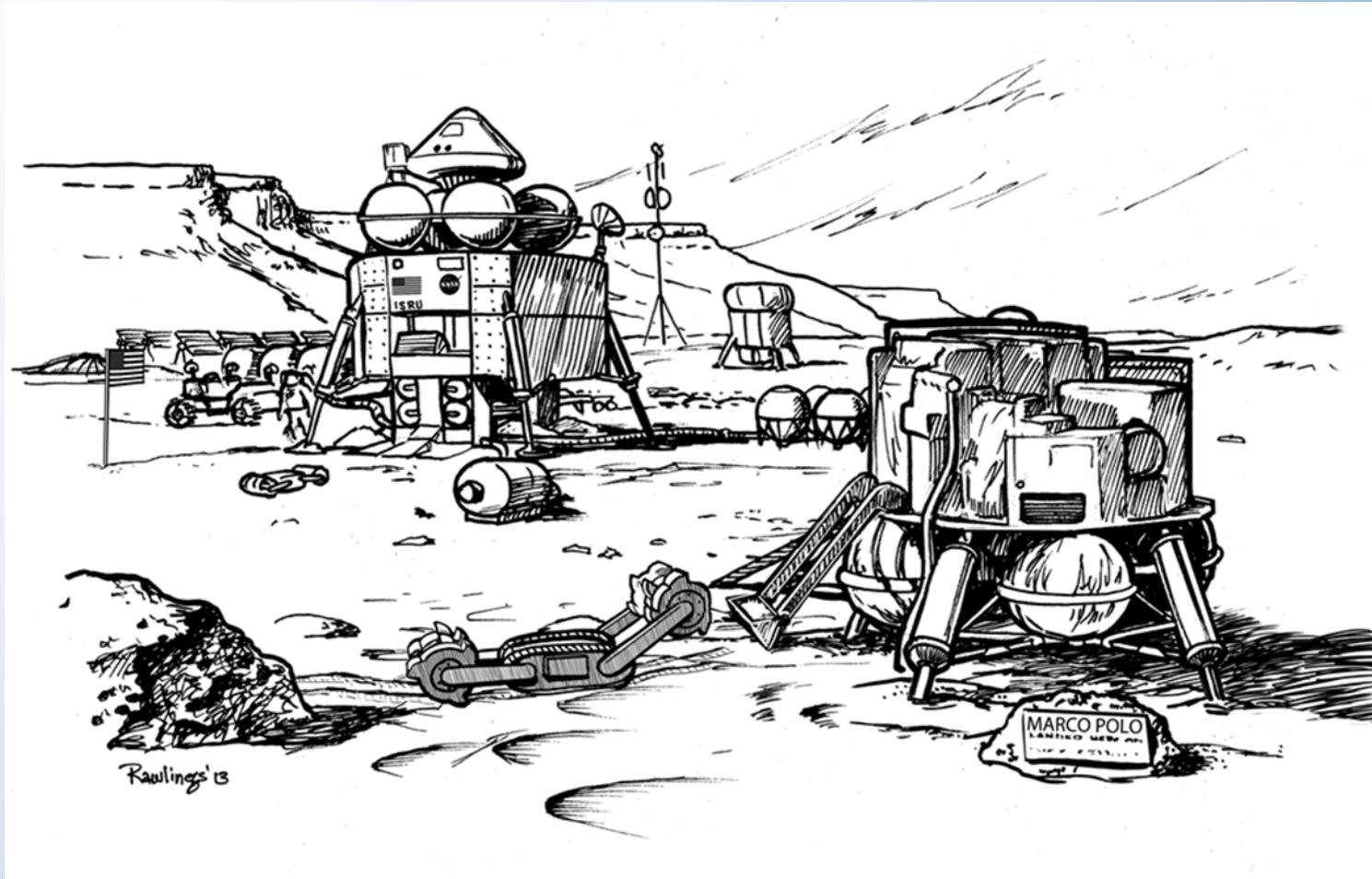


(Image: NASA/Brown University)



# End-to-End ISRU

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Excavation, collection and processing for methane/oxygen bipropellant



# Application to Space

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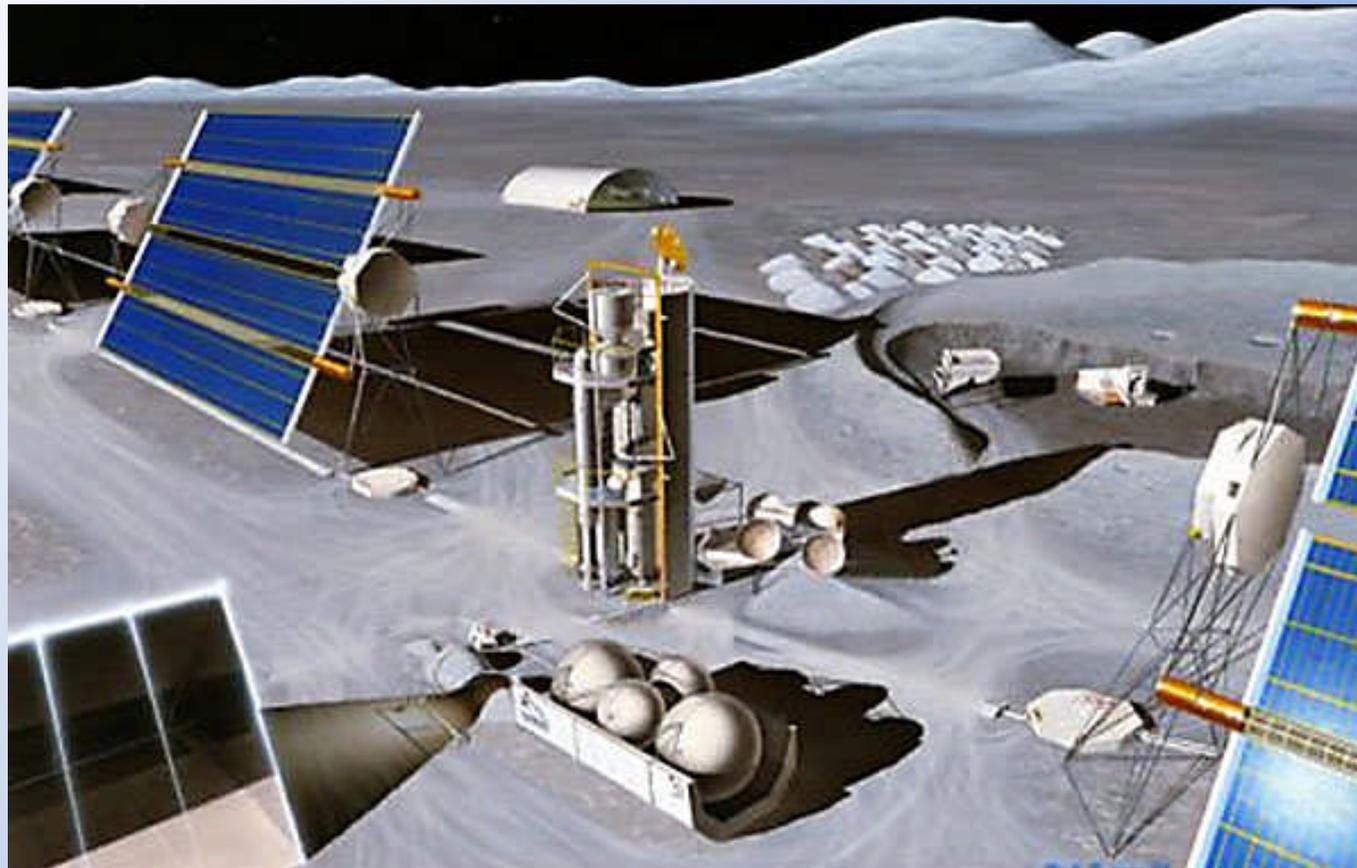
- Higher power density will enable a new class of operations
- Potential for much wider temperature operation: carbon melting point (4900K)
- Increased safety-margin due to reduced fire and toxicity risk
- In-situ resource available from regolith or waste stream



# The Vision

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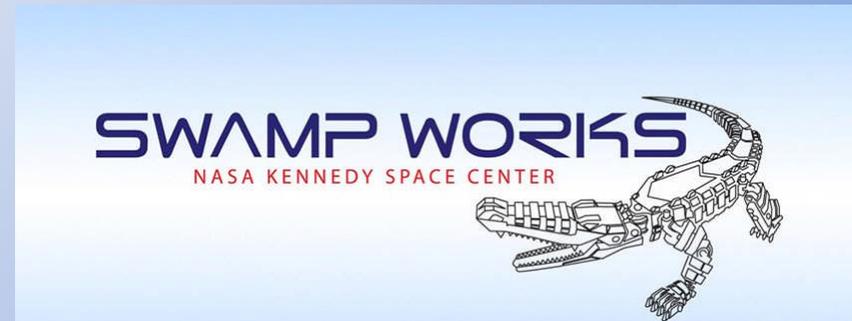
- Every exploration plan calls for a sustainable exploration architecture.





# Contributors

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BACKUP



# Current Missions

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## Hubble



Nickel-hydrogen (Ni-H<sub>2</sub>)

Charge-use cycle of  
97 minutes

Reliable

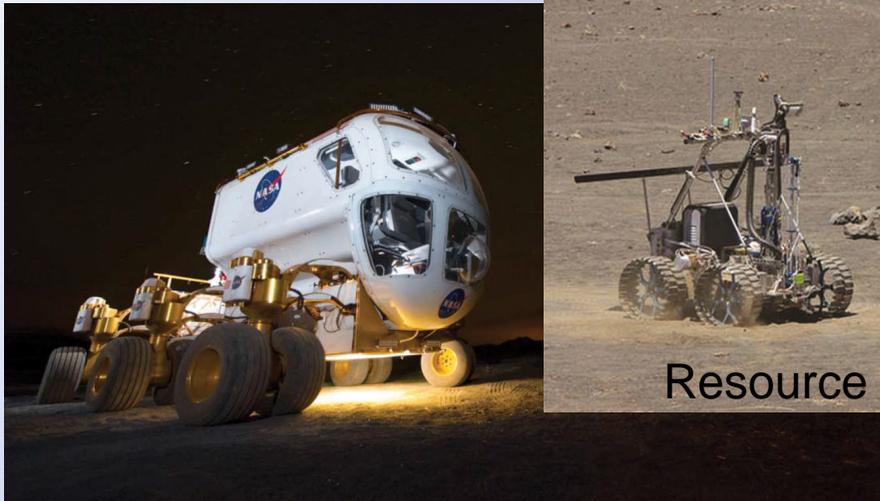
Deep discharge capability



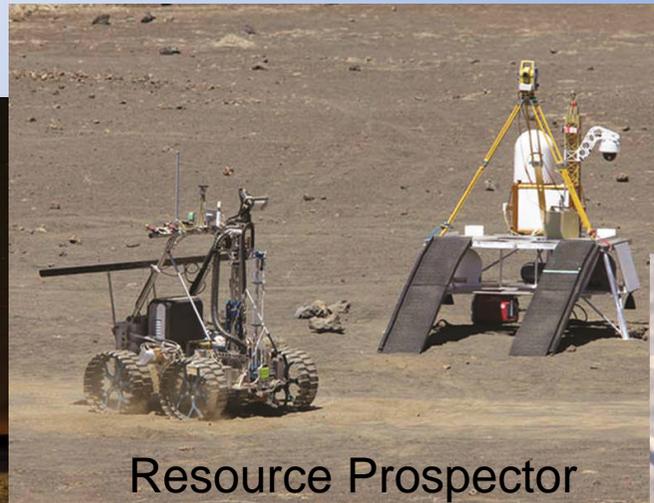
# Potential Future Missions

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- Future missions will require higher energy and power density to enable:
  - High power robotics
  - In-Situ Resource Utilization (ISRU)
  - Exploration



Space Exploration Vehicle (SEV)



Resource Prospector

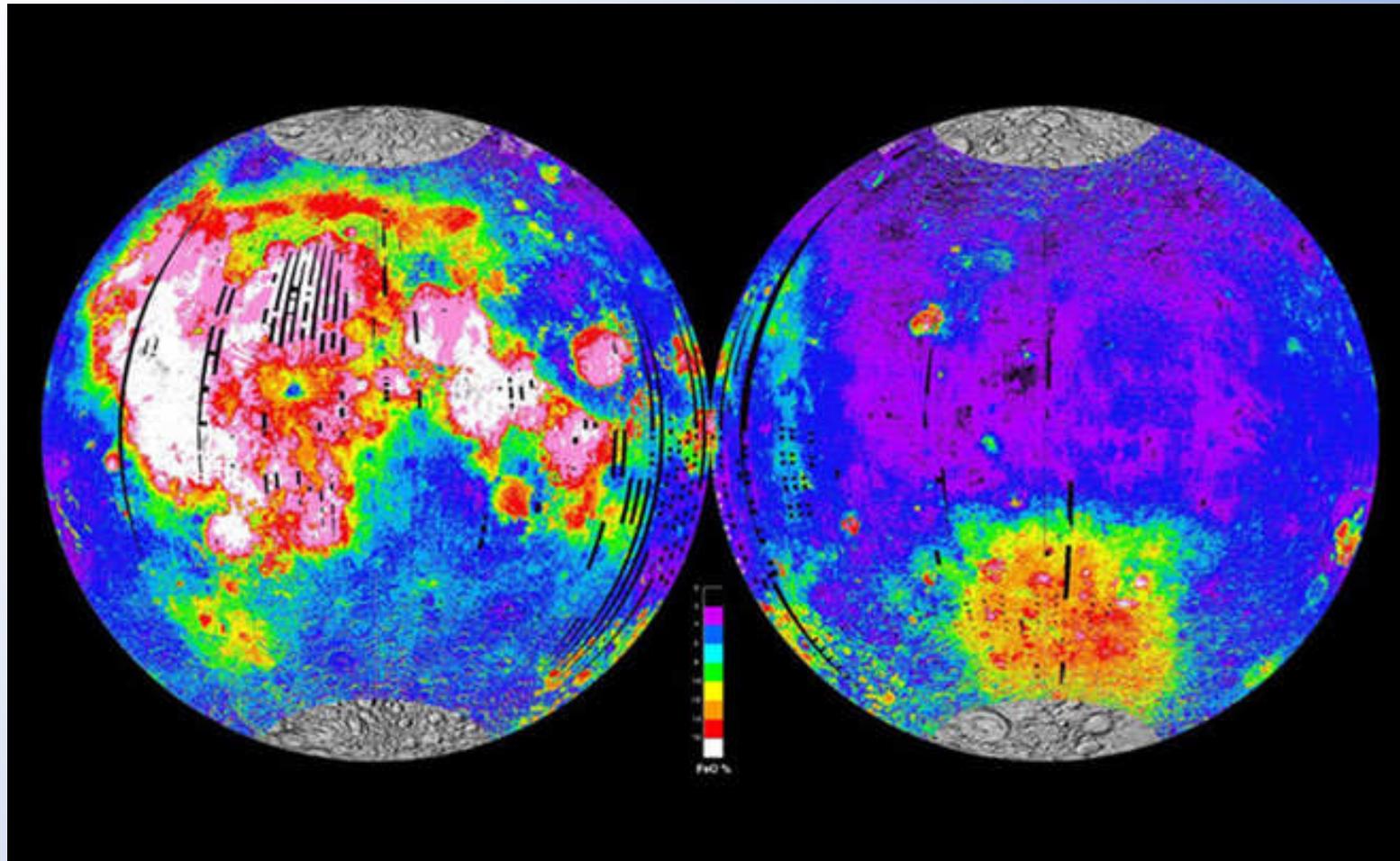


RASSOR



# ISRU

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Global map of the iron concentration on the lunar surface  
Black (0%) to white (16%). (Source: NASA/Clementine)