Aerospace Corporation Space Power Workshop
26-29 April 2022

On the Moon to Stay
NASA's Technology Goals for Lunar Surface Power

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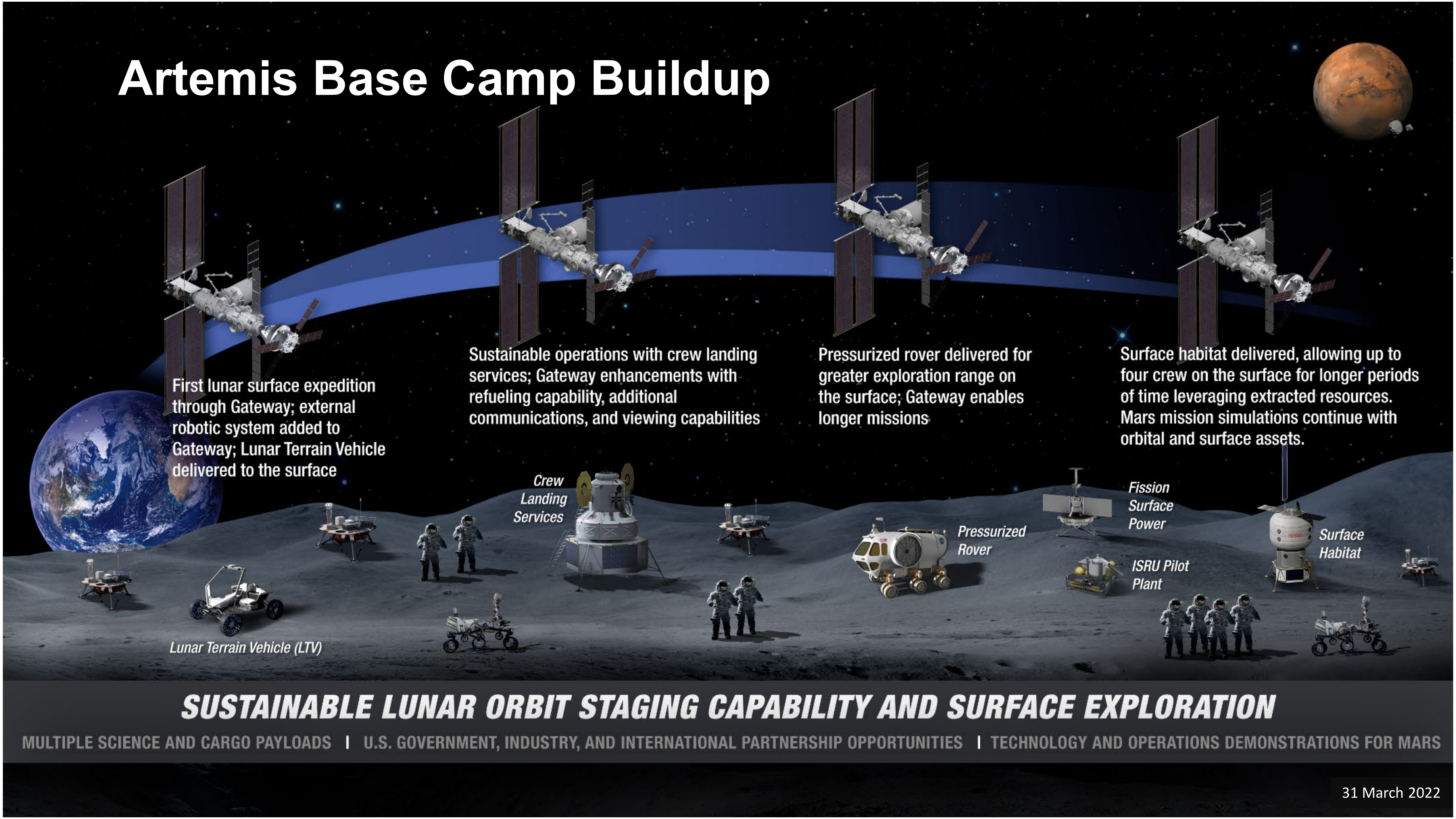
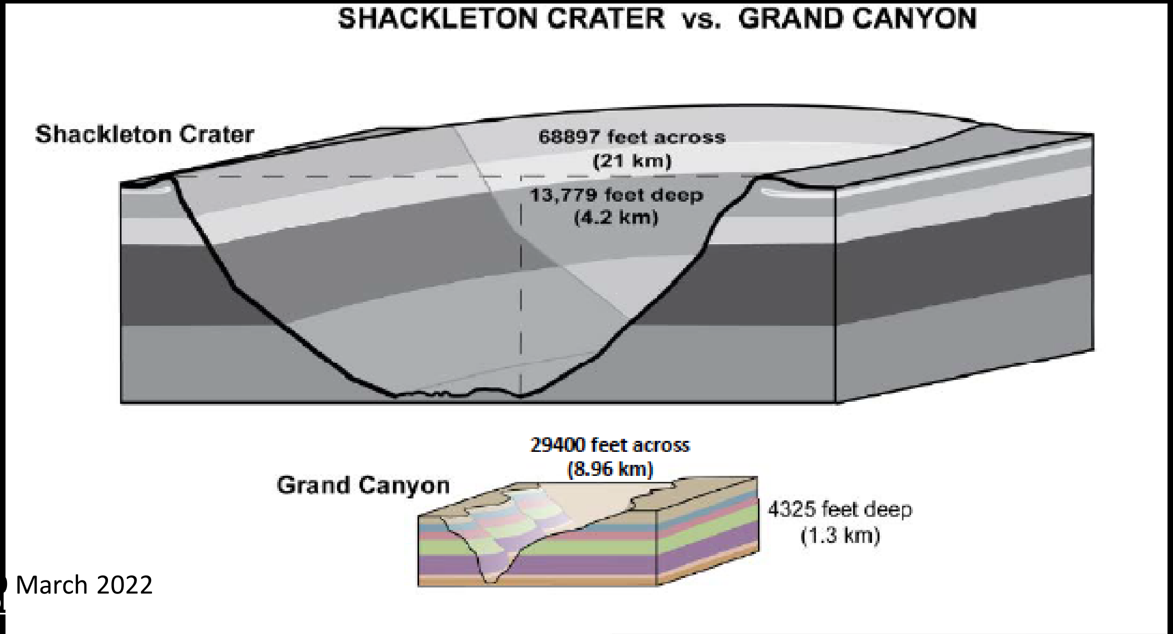
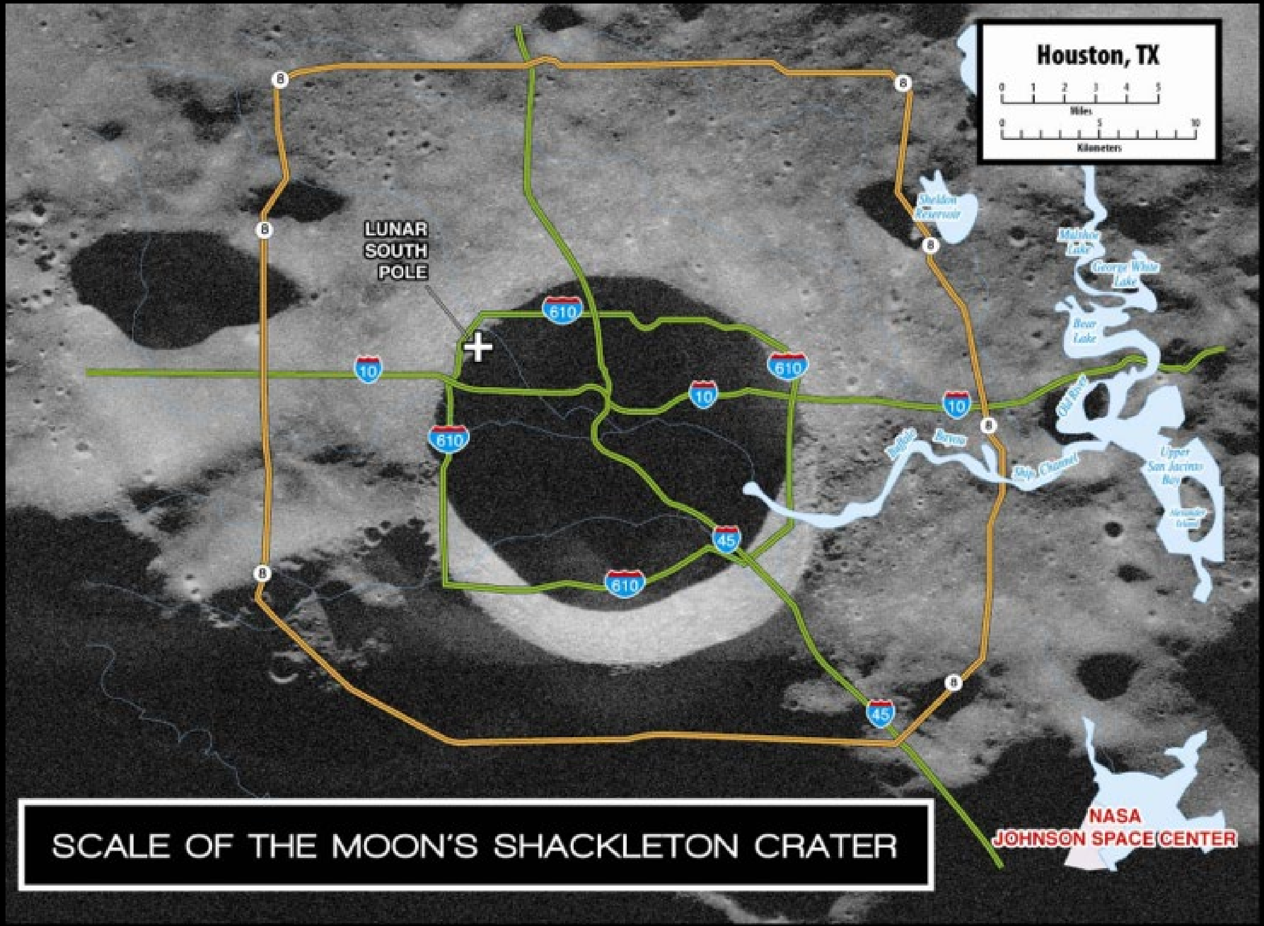
31 March 2022


Artemis Base Camp Buildup
First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface
Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities
Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions
Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.
Crew Landing Services
Fission Surface Power
Pressurized Rover
ISRU Pilot Plant
Surface Habitat
Lunar Terrain Vehicle (LTV)
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION
MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS
31 March 2022

Shackleton Crater

- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings





Artemis Base Camp Zone

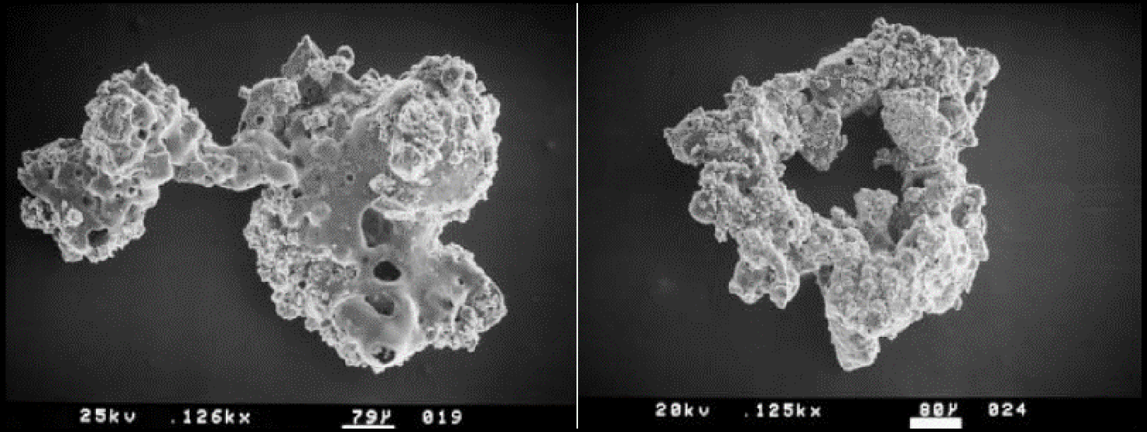
Lunar Surface Environment

Dust and Thermal Extremes are challenges in general.

Lunar Surface Temperatures

-173 C to 130 C
(-250 C in Permanently Shadowed Regions)

Lunar regolith (incl. lunar dust) is angular, abrasive, irregular in shape, small in particle size, and adheres to surfaces



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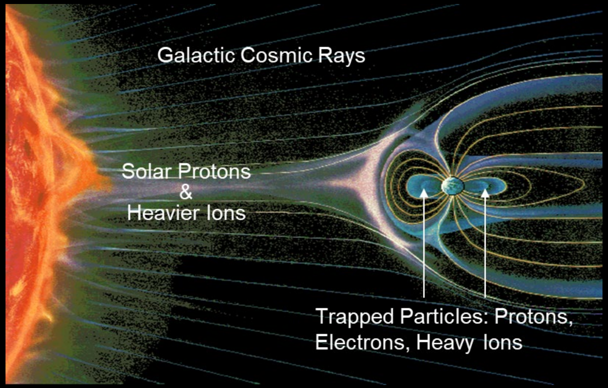
Lunar Surface Environment

RADIATION is the more difficult problem, particularly for semiconductors

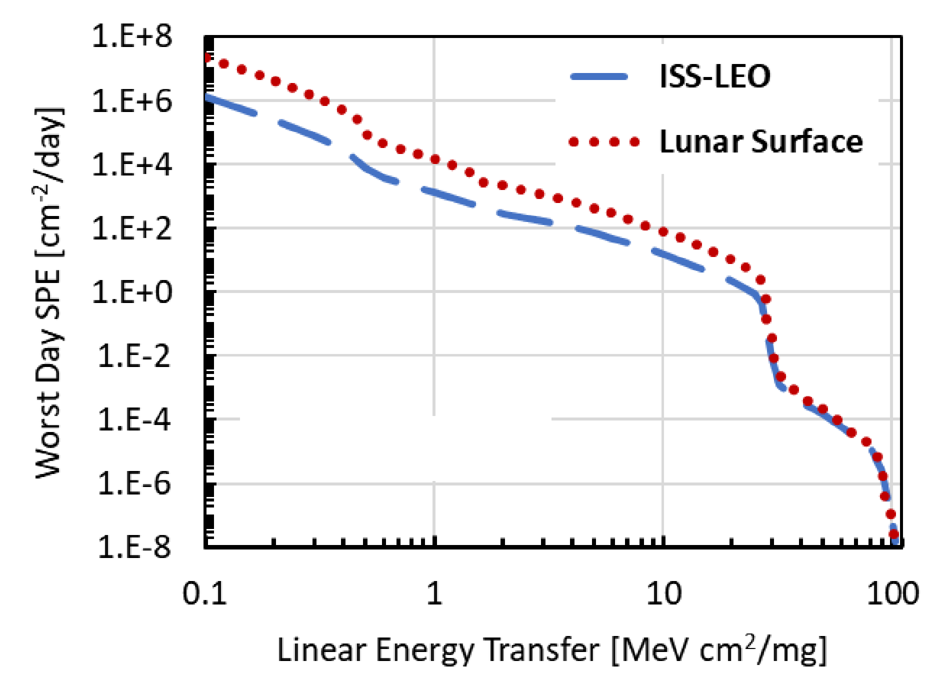
Total Ionizing Dose

Orbit	~1-year TID (2.5 mm Al) krad(Si)
Jovian	1000
GEO	150
Lunar Orbit	4
Lunar Surface	2
ISS LEO	2
Earth Surface	< 0.001



Single Event Effects

"Achilles' Heel" of Wide Band Gap Materials



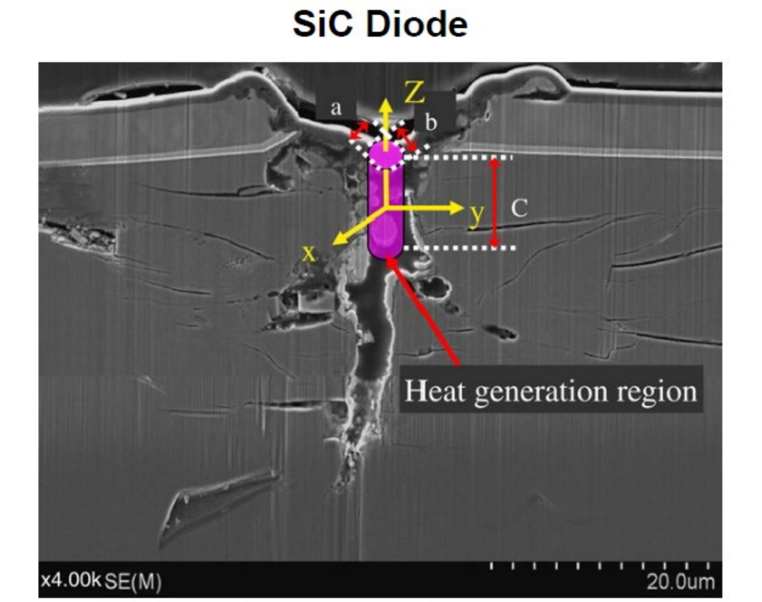


Image: Shoji, et al., © (2014) The Japan Society of Applied Physics, used with permission.

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POWER

The key commodity needed to exploit the Lunar Surface

Equatorial Illumination Limits

- Cyclical periods of 14 days illuminated, 14 days dark
- Consistent

Illumination

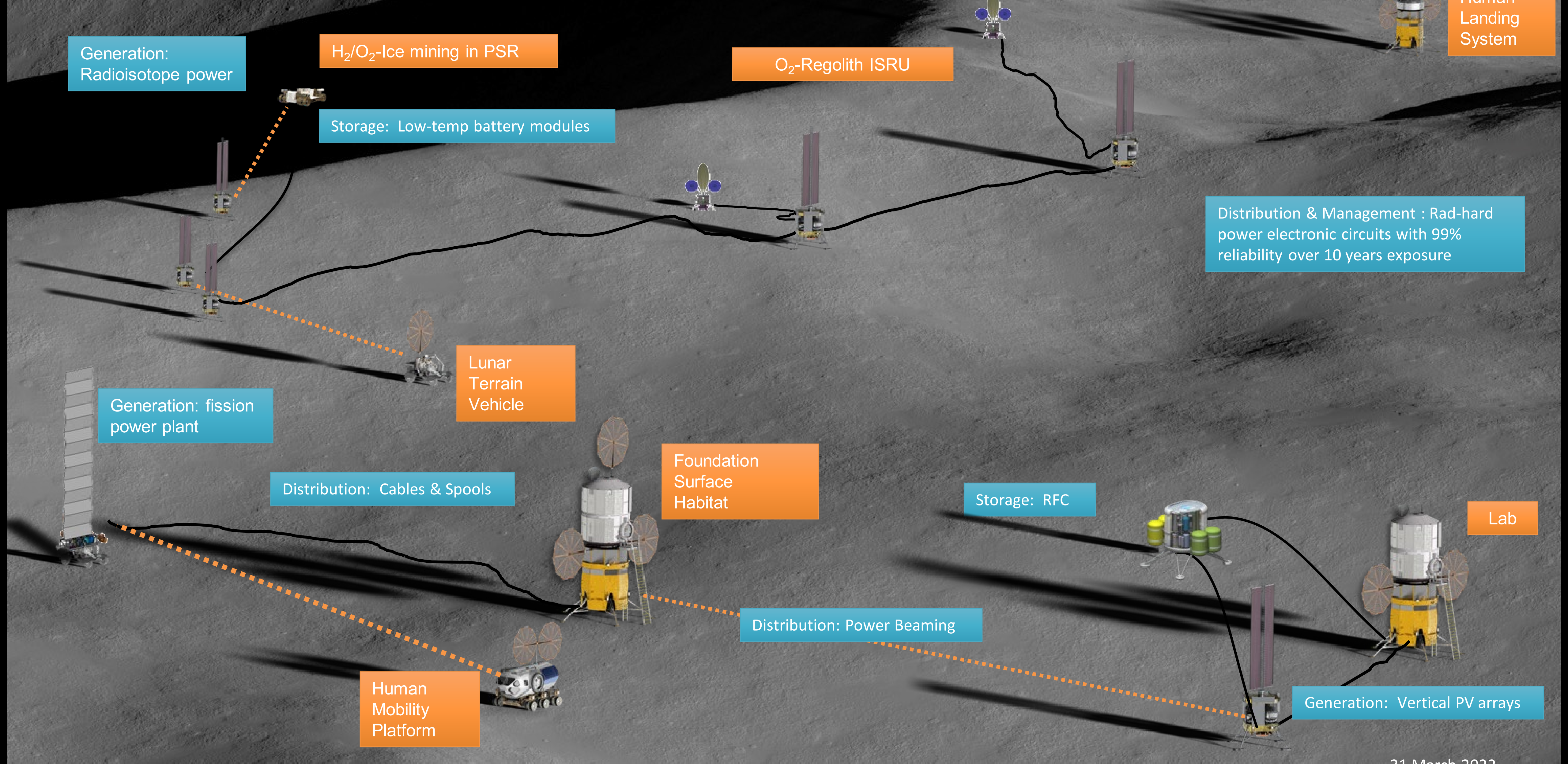
The scarce resource needed to produce power

Polar Illumination Limits

- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

90-Day Illumination Cycle at South Pole

Building Block Power Technology Options for Initial Artemis South Pole "Outpost" (2030+)



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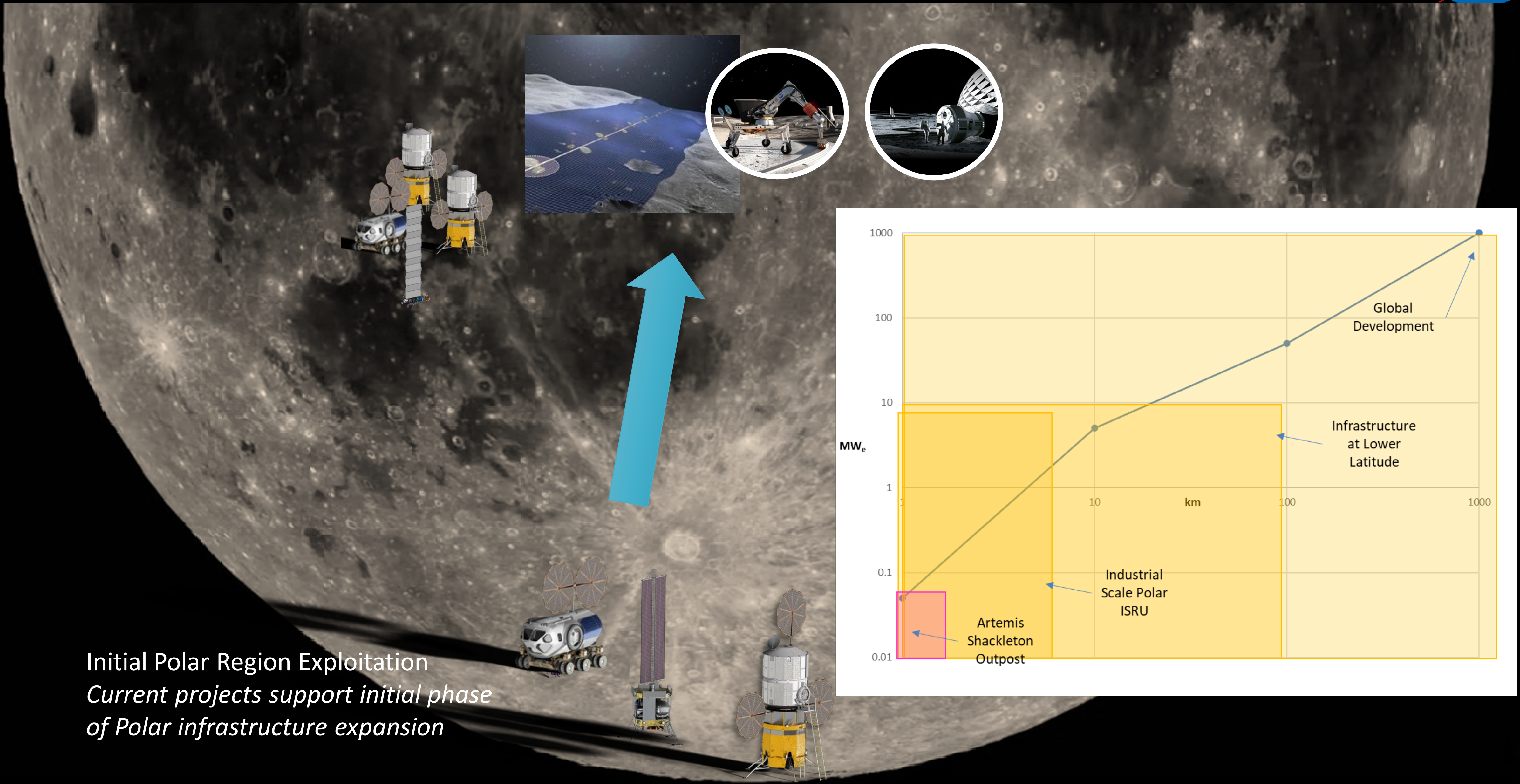
Ultimate Global Exploitation



Initial Polar Region Exploitation

Current projects support initial phase of Polar infrastructure expansion

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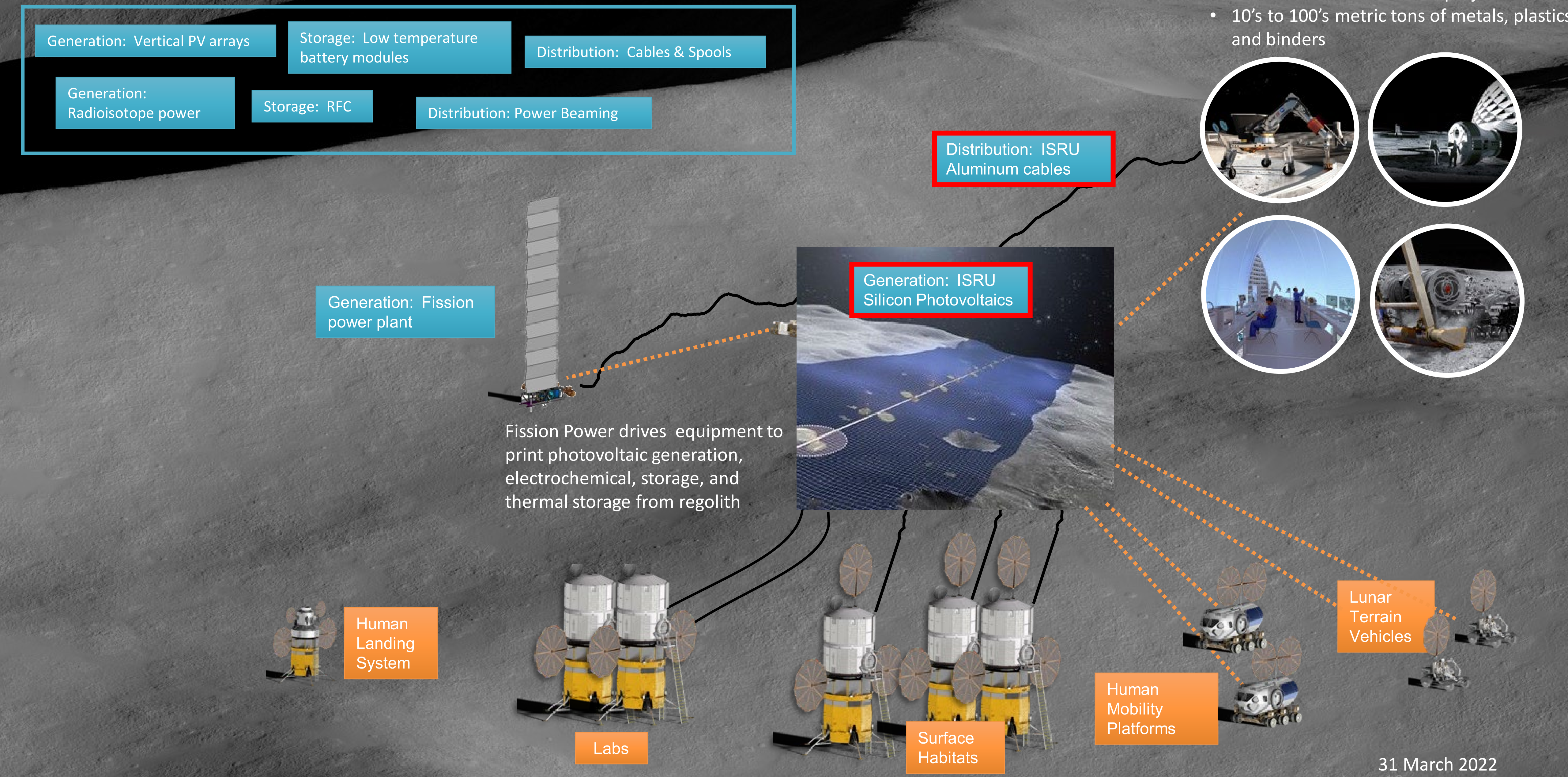
Polar Building Block Power Technologies Can Bootstrap Generation, Storage and Distribution at Lower Latitudes (2040+)

- Landing pads and protective structures
- 100's to 1000's metric tons of regolith-bas[...] feedstock for construction projects
- 10's to 100's metric tons of metals, plastics and binders



ADVANCED POWER SYSTEMS SUPPORT MULTIPLE STRATEGIC OUTCOMES AND REQUIRE SUPPORT

Primary outcome supported: "Sustainable power" under "LIVE" thrust.
Secondary outcome supported: "Platform Technologies" under "EXPLORE" thrust

Go *Rapid, Safe, & Efficient Space Transportation*	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live *Sustainable Living and Working Farther from Earth*	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore *Transformative Missions and Discoveries*	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries.

Led by Advanced Propulsion PT TX 2.0

Power PT
TX 3.0 Power and Energy Storage

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Envisioned Future - *LIVE*

Sustainable Living and Working Further from Earth

Developing sustainable power sources and other surface utilities to enable continuous Lunar and, ultimately, Mars surface operations.

Power Generation

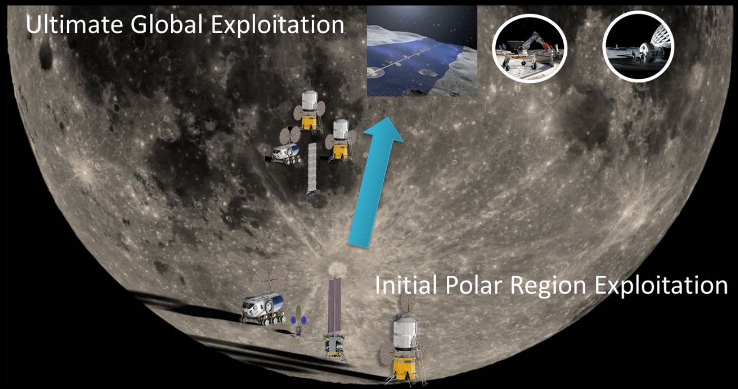
- Up to 50 kW_e-class modular Earth-sourced Photovoltaic Arrays for Lunar Polar surface outposts and ISRU prospecting/production plants.
- 40 kW_e-class mobile Fission Power Systems to support Lunar Polar operations, bootstrap a global Lunar surface power grid to support Lunar industrialization at lower latitudes, and support Mars surface exploration

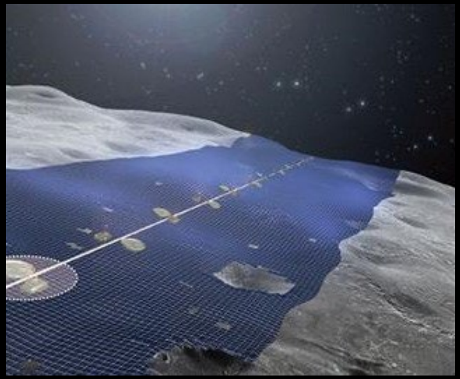
Energy Storage

- Up to 50 kW_e-hr Secondary Batteries for mobility
- Up to 1 MW_e-hr Regenerative Fuel Cells for Polar Outpost/ISRU energy storage
- Large scale energy storage systems gathered from Lunar-sourced minerals

Power Distribution

- 1000 V, radiation-hard, high reliability power electronics
- Up to 10 kW_e–class low mass Cables and spools for multi-km power distribution grids
- Up to 10 kW_e-class Power Beaming for up to 5 km line-of-sight.
- High power, long distance transmission lines printed from Lunar-sourced aluminum.





John.h.scott@nasa.gov All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Envisioned Future: Gaps to Close to Enable Outcomes

LIVE: Sustainable Power

	Gap	Polar Ice Mining	Polar Regolith O_2	Global Regolith Mining
A	**Mobile Fission Surface Power**	●	●	●
B	**Reliable, Rad-Hard Power Electronics***	●	●	●
C	**Transmission Cable Systems**	●	●	●
D	**Photovoltaic Arrays**	●	●	●
D	**Long Life, Grid-Scale Secondary Energy Storage**	●	●	●
E	**Wireless Power Transmission***	●		●
E	**Dynamic Conversion for Radioisotope GPHS***	●		
E	**Low Temperature Secondary Battery Modules***	●		
F	**CH_4/O_2 Primary Fuel Cell Power**			

** Also supports "EXPLORE: Platform Technologies"*

Needed for:
- Polar Ice Mining (blue)
- Polar Regolith O_2 (red)
- Global Regolith Mining (green)

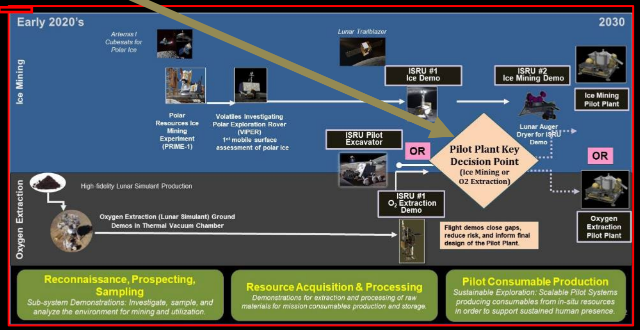
"Killer App" for highest priority LIVE gap closures is support to industrial-scale Lunar ISRU production and construction in the early 2030's at the South Pole and expansion toward the equator 2035+

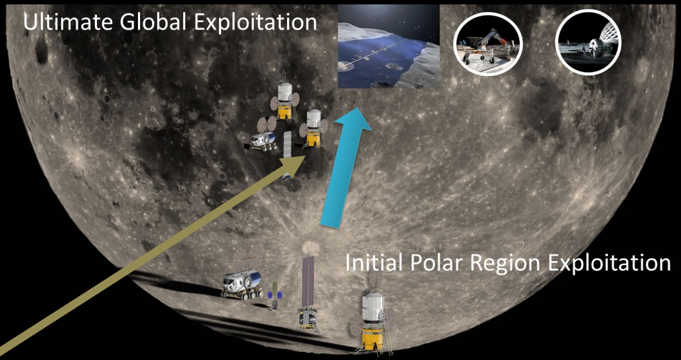
- *Mission architects need to know what capabilities will be available when*

Overall sustainable power gap priorities are affected by a key decisions related to Lunar resource extraction:

- ~2026: Will initial industrial-scale capability at the South Pole focus on ice mining in PSRs or extracting oxygen from regolith in insolated regions?
- ~2030's: Will power demand away from the Pole grow beyond the capability of Earth-launched assets?

ISRU Pilot Plant Key Decision 2026: Ice Mining vs. Regolith O_2





Global power grid planning: 2030

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Gap A: Fission Surface Power

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.2.1, 3.1.4.1

Definition: No multi-kW_e-scale power sources have been developed to be capable of providing sun-independent, mobile power on the Lunar or Martian surface. Such power is needed not only to supplement solar power for sustainable operations on the Lunar pole but also to bootstrap the printing of power system components from Lunar regolith as infrastructure expands toward lower latitudes.

SOA: Though fission reactors have been operated on Earth land and sea for many decades, no reactors have been operated in space since the Soviet Topaz I (~5 kW_e) flight in 1988. The Soviet TOPAZ II development unit (~6 kW_e) was briefly ground tested in the US in 1994. A space fission reactor development unit (~ 1 kW_e) was tested in the US in 2018.

CURRENT INVESTMENTS

NASA:

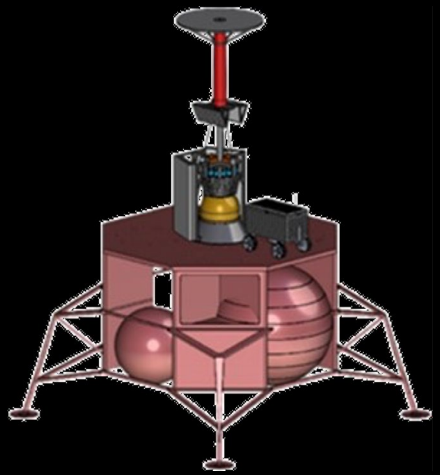
- Energy Conversion
  - *SBIR/STTRs (Stirling, Brayton, ATEG, Heat Ex, Radiators)*
- Radiation Shielding
  - *SBIR (materials)*
- Systems
  - *TMD (FSP)*
-

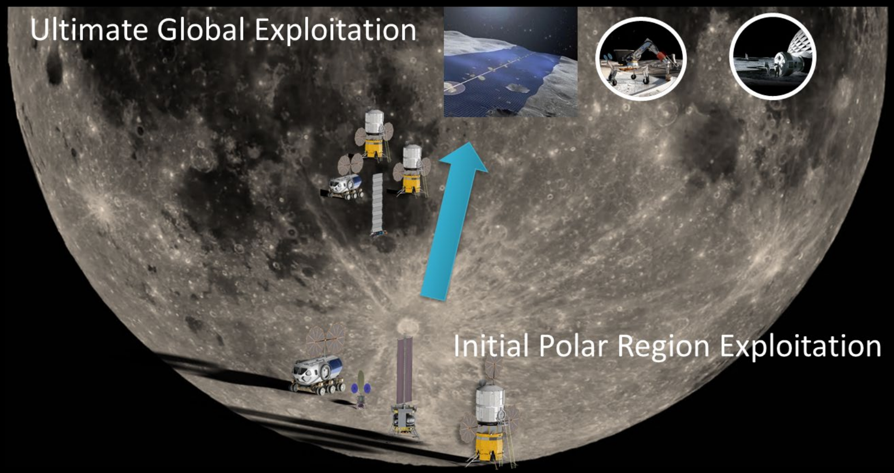
OGA

- Nuclear fuels
  - DoE SMR
  - DoD Project Pele

CLOSURE:
Bring to TRL 6 a 40 kW_e-class mobile fission power system suited for the Lunar polar environment in time to support a TDM on the Moon in 2028. Lower power (e.g., 10 kW_e) units may be developed for Mars.

CLOSURE PLAN:
- Complete NASA TDM FSP Project





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Gap B: Reliable, Rad-Hard Power Electronics

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.1, 3.3.3, 3.3.4

Definition: SOA power management and control electronics do not provide sufficient reliability and durability to support full scale ISRU operations in the Lunar Pole thermal, dust , and radiation environment and are not maintainable in that environment. Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the 2030s

SOA: Power electronics of sufficient reliability for current missions are at TRL 9 for near Earth, geosynchronous, and deep space missions at <200 V.

CURRENT INVESTMENTS

NASA:

- Materials:
  - *SBIRs (SiC, Ga_2O_3, shielding)*
  - *LuSTR grant (SiC)*
- Circuitry and Devices
  - *SBIR (switches)*
  - *STTR (controller)*
  - *LuSTR grant (router)*
  - *GCD TP (Apogee RPCD)*
  - *GCD TP (TYMPO)*
  - *GCD TP (BDPA)*
  - *GCD TP (MIPS)*
- Dust compatibility
  - *GCD (LO-DuSST)*

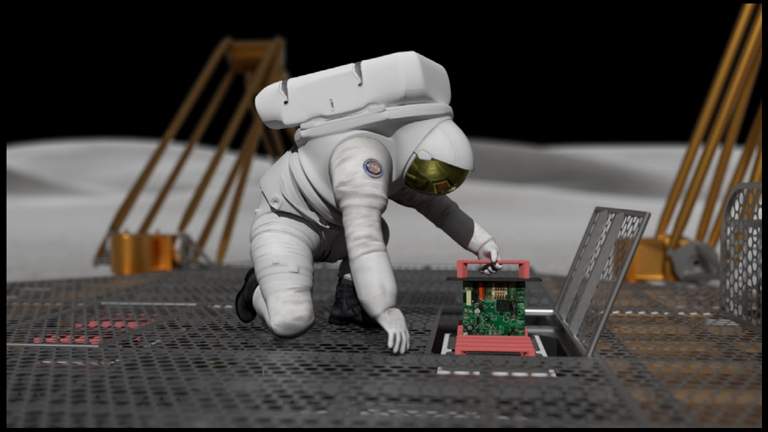
OGA (DoD & DoE):

- Materials & Devices

CLOSURE:
Bring to TRL 6 by 2030 a suite of power management, control, and regulation circuits & software operating at up to 1000 V and at maximum specific power and which are maintainable in the Lunar dust environment and 0.99 reliable for 10 years in the relevant Lunar radiation and thermal environments and in the Lunar hard vacuum and Mars atmosphere environments.

CLOSURE PLAN:

- LuSTR or ECF project for integrated subsystem (material, device, circuit) reliability modeling
- GCD efforts to bring optimized suite of circuits with dust tolerant connectors to TRL 6
- TDM project to demo circuits and software on CLPS and/or for ISRU Pilot plant(s) in 2030



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Gap C: Transmission Cable Systems

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

DEFINITIONS:
CA: SOA Earth-sourced power cables and load connection and deployment systems do not provide capability at specific power and dust-tolerance levels sufficient to support power distribution among Lunar pole surface elements. Flight-qualified technologies for cables, connectors and deployment spools are not optimized for the Lunar polar environment.
CB: The technology required to print long distance (100's of km) on the Lunar surface from locally-sourced aluminum has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

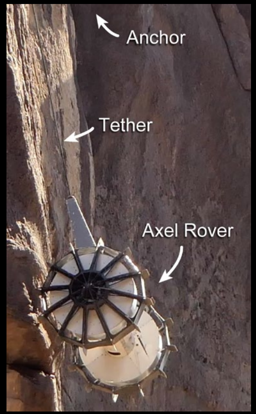
SOA: Cables, dust-tolerant load connection systems, and cable deployment systems for the Lunar surface have been developed only to the "bench-top" level.

CURRENT INVESTMENTS NASA:

- Cable & Spooling system
  - *SBIR*
  - *PCC (WOTM)*
  - *GCD TP (TYMPO)*
- Connector
  - *GCD TP (UFPC)*
  - *GCD (Lo-DuSST)*

GAP CA CLOSURE:

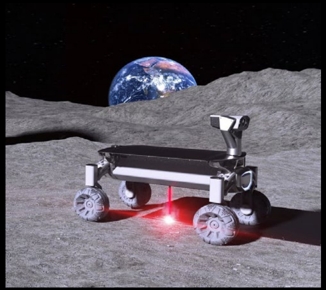
Bring to TRL 6 by 2030 an electrically insulated transmission cable, spooling, and load connection systems that can be unrolled and deliver power point-to-point with 0.99 reliability at 1000 V (source and load) and at 10 kW_e scale in the Lunar polar dust, MMOD, and thermal environments (both insolated and PSR), losing no more than 3% per km and at maximized delivered power per unit of cable system mass.



Closure Plan:
- Further SBIR and ESI efforts for load connection and cable/spooling systems
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate components (cable/spool, connectors, proximity charging) on CLPS

GAP CB CLOSURE:

Bring to TRL 6 by 2035 MW_e, 100 km-scale power transmission systems, printed on the Lunar surface from Lunar-sourced aluminum and with minimal material brought from Earth.



Closure Plan:
- STRG and SBIR efforts for Lunar aluminum mining and conductor printing
- GCD efforts to bring integrated, printed power conductor systems to TRL 6 by 2035
- TDM project to fly and operate power conductor production equipment on the Lunar surface by 2037

Gap D1: Photovoltaic Arrays

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.1

Definition:
D1A: SOA Earth-sourced solar array blankets do not provide sufficient durability or scale to support full scale ISRU production in the Lunar Pole thermal, dust , and radiation environment. Flight-qualified technology for deployment towers and reflectors is not optimized for gathering sunlight low on the horizon as at the Lunar poles.
D1B: The technology required to print photovoltaic arrays on the Lunar surface from Lunar silicon has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Photovoltaic arrays (<200 V) and deployment mechanisms suitable for LEO operations are at TRL 9. Vertical array deployment mechanisms for Lunar gravity are at a benchtop level of development. Large 10's kW_t-scale reflectors/mirrors are at a concept-level of development. Large scale, surface-level photovoltaic arrays, at a GW_e scale and printed from Lunar-sourced silicon, are at a very early stage of conceptual development.

CURRENT INVESTMENTS

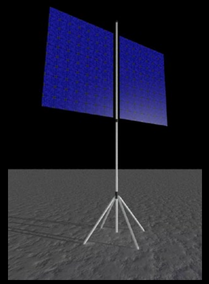
NASA:
- Earth-sourced PV Blankets:
  - *SBIR (composite Blanket)*
  - *GCD ACO (FSAP)*
  - *CLPS (PILS)*
- Earth-sourced Deployment Structures
  - *SBIR*
  - *STRG (BYU)*
  - *GCD (VSAT)*
- Earth-sourced Reflectors
  - *none*
- Dust compatibility
  - *GCD (LO-DuSST)*
  - *GCD ACO (DMFlex)*
- Lunar-sourced PV blankets
  - *None*

OGA (DoD & DoE):
- Earth-sourced PV Blankets

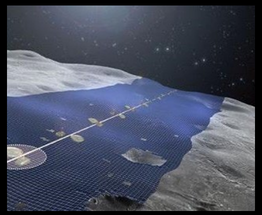
Gap D1A CLOSURE:
Bring to TRL 6 by 2030 50 kW_e-scale photovoltaic arrays, deployed vertically or horizontally (with reflector towers), providing power at >200 V at 200 W_e/kg BOL and exhibiting no more than 10% degradation over ten years in the Lunar polar environment (including shadowed periods). Deployment solutions must maximize effective low-horizon insolation within limits of specific power.

Closure Plan
- SBIR efforts for rad-hard photovoltaics, blanket, and reflector/concentrator designs
- GCD efforts to bring optimized blankets (with concentrators, dust tolerance, and rad-hardened PV) to TRL 6
- Continue GCD VSAT Project
- TDM project to fly 10 KW_e-scale VSAT or reflector tower to support PSR prospecting in ~2025
- TDM project to fly ~50 kW_e arrays to support pilot plant ops in 2030

Full-Scale Polar Power Demand Assumptions	kWe
Outpost Module	10
Initial Full-Scale O_2-from Regolith (7 t/year system - Carbothermal	15
Initial Full-Scale Ice-Mining , Rim (10 t/year system)	46
Initial Full-Scale Ice-Mining, in PSR (10 t/year system)	22



Gap D1B CLOSURE:
Bring to TRL 6 by 2035 GW_e-scale photovoltaic blankets, printed horizontally on the Lunar surface from Lunar-sourced silicon and with minimal material brought from Earth.



Closure plan
- STRG and SBIR efforts for Lunar silicon mining and PV array printing
- GCD efforts to bring integrated, printed PV generation systems to TRL 6 by 2035
- TDM project to fly and operate PV production equipment on the Lunar surface by 2037

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Gap D2: Long Life Grid-Scale Secondary Energy Storge

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.2

Definition:
D2A: **Eclipse-period support of industrial scale ISRU production facilities and a crewed outpost at the Lunar pole will require Earth-sourced, large-scale, long life, maintenance-free electrical energy storage** at a MW_e scale.
D2B: Expansion of Lunar infrastructure toward the Equator will require large scale electrical and thermal energy storage sourced from Lunar regolith..
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: For Earth-sourced, electrical energy storage, H_2/O_2 Primary fuel cells are nearing TRL 6/7 at a 1 kW_e-scale with ~5000-hour operating life. High pressure electrolyzers of similar life and scale will be at TRL 5 at completion of NASA STMD's RFC project. Electrical and thermal energy storage sourced from Lunar regolith, such as metal-oxygen flow batteries and thermal "wadis", remain at only a conceptual level of development.

CURRENT INVESTMENTS

NASA:

- PEM Primary and Regen FC
  - *GCD ACO (AARC)*
  - *GCD ACO (AMPES)*
  - *GCD ACO (LFC-Blue Origin)*
  - *GRC (RFC)*

DoD NUWC:

- PEM Primary FC
  - *Various (SNC, Teledyne)*

Gap D2A CLOSURE:

Bring to TRL 6 by 2030 a H_2/O_2 regenerative fuel cell energy storage system in up to MWh_e and 10 kW_e increments with maximum specific energy and maintenance-free life in the Lunar polar environment of 50,000 hours and 500 charge/discharge cycles.

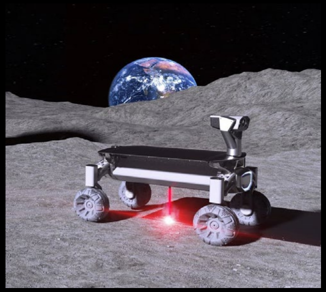
Closure Plan

- LuSTR or STRG effort for reliability/life modeling
- SBIR efforts for highly durable membranes and fluid components
- GCD project for ultra-long life RFC system
- TDM project to fly ~10 kW_e RFC to support Outpost and ISRU pilot plant operations in 2030

Full-Scale Power Demand Assumptions	kWe
Outpost Module	10
Initial Full-Scale O_2-from Regolith (7 t/year system – Carbothermal	15
Initial Full-Scale Ice-Mining , Rim (10 t/year system)	46
Initial Full-Scale Ice-Mining, in PSR (10 t/year system)	22

Gap D2B CLOSURE:

Bring to TRL 6 by 2035 GWh_e-scale secondary flow batteries formed from Lunar-sourced chemicals and large-scale thermal wadis printed from sintered regolith.



Closure plan

- STRG and SBIR efforts for mining Lunar minerals suitable for secondary electrochemical batteries and for sintering of regolith for thermal energy storage
- GCD efforts to bring integrated electrical and thermal energy storage systems to TRL 6 by 2035
- TDM project to fly and operate energy storage equipment on the Lunar surface by 2037

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Gap E1: Wireless Power Transmission up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

Definition: ISRU ice mining operations in PSR (from prospecting to full-scale industry) will require power transmitted from insolated regions to mobile assets in the PSR interior.

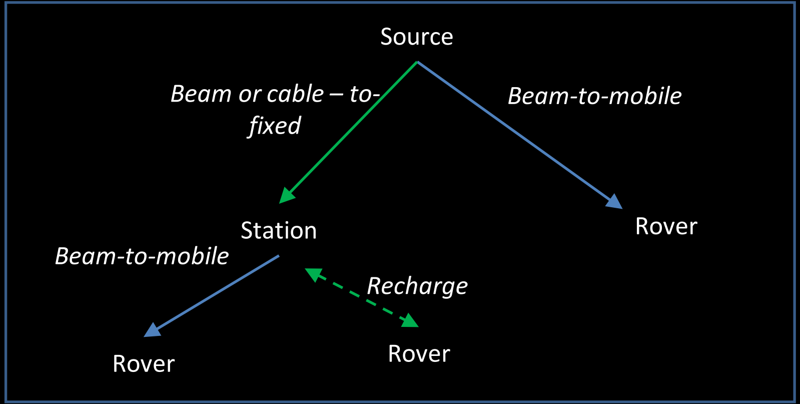
SOA: Subscale wireless power transmission systems have been developed to the bench-top level. Relevant pointing mechanisms have been developed for terrestrial applications.

Gap E1 Closure:

Bring to TRL 6 by 2030 a wireless transmission system delivering power at up to ~10 kW_e scale from a 1000 V source in either an isolated region or a PSR to a mobile load in a PSR, losing no more than 75% source-to-load over 5 km and at maximized delivered power per unit of system mass.

Closure Plan:

- Further SBIR efforts for beaming and pointing mechanisms
- ~100 W_e subscale demos may support CLPS applications.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 PSR ice mining demo, 10 kW_e for 2030 PSR Ice Mining pilot plant



PSR Distribution/Storage Trade

CURRENT INVESTMENTS

NASA:

- Power Beaming
  - *SBIR*
  - *PCC (WOTM)*
  - *LuSTR grant (UCSB)*

DoD:

- Power Beaming
  - *Various*
- Pointing Mechanisms
  - *Various*

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Gap E2: Dynamic Conversion for Radioisotope GPHS in 500 W_e Increment

Thrust: **EXPLORE**
Outcomes: **Develop vehicle platform technologies supporting new discoveries**
Taxonomy Elements: **3.1.2, 3.1.4**

Definition: A key strategic mission for NASA's Science Mission Directorate (SMD) is an understanding of the distribution of resources in the permanently shadowed regions of the Lunar South Pole. A multi-100 W_e, sun-independent power source is required for mobility assets to conduct through prospecting in the 2026 timeframe. Smaller power sources (~100 We) required for CLPS-class science exploration missions in PSR

SOA: The current MMRTG can deliver ~125 W_e BOL from ^{238}Pu General Purpose Heat Sources (GPHS).

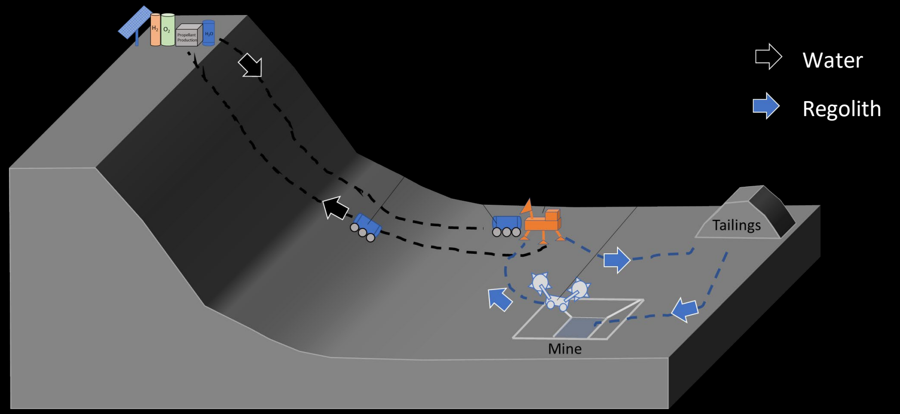
CURRENT INVESTMENTS NASA/DoE:

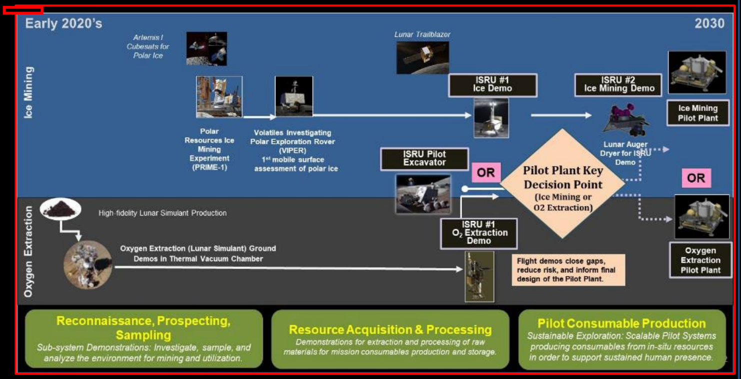
- SMD RPS program
  - *DRPS Project*

CLOSURE:
Bring to TRL 6 by 2024 a 500 W_e-class radioisotope power source with Stirling conversion from the ^{238}Pu GPHS.

CLOSURE PLAN:

- Accelerate SMD's DRPS project





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Gap E3: Low Temperature Secondary Battery Modules up to 50 kWh_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations

Taxonomy Elements: 3.2.1

Definition: The principal challenge from Artemis for battery technology is mobility energy storage for ISRU operations in PSRs. SOA (Li-ion) batteries lose 75% of their room temperature (295 K) capacity when operating at 235 K. Battery modules that can deliver SOA 295 K performance in a 70 K environment can thus increase specific energy for batteries in PSRs by well over a factor of three. Such performance might be achieved with a combination of cells developed to perform better at lower temperatures, improved insulation/thermal management hardware, and supplemental radioisotope heat sources.

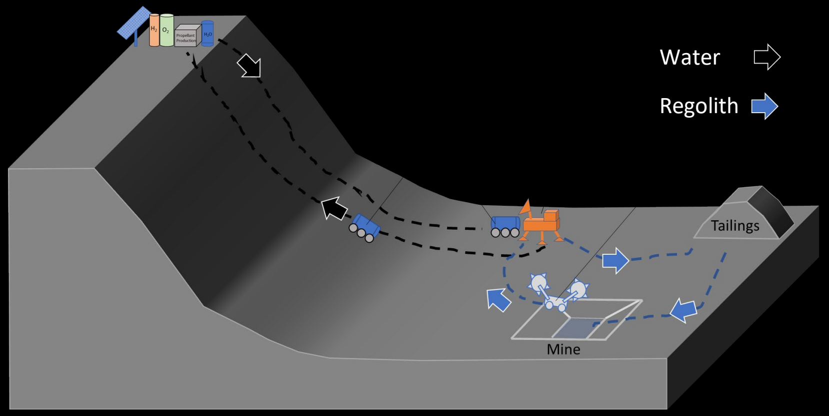
SOA: Li-ion battery modules at 50 kWh-scale can deliver ~500 cycles at 150 Wh_e/kg at 290 K. Insulation and active thermal management hardware are required to maintain the cells in this temperature range when operating in colder environments.

CURRENT INVESTMENTS

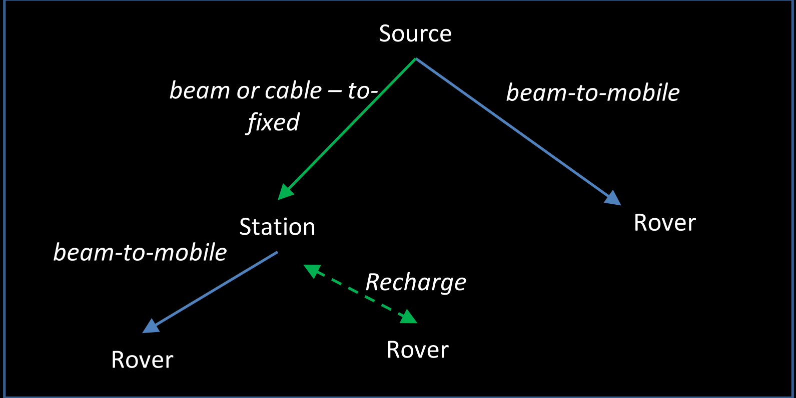
NASA:
- Cells
  - *ECF (various)*

CLOSURE:
Bring to TRL 6 by 2030 a 50 kWh-class battery module with capability to provide greater than net* 150 Wh_e/kg specific energy at 1 kW_e discharge for 500 cycles in a 70 K environment and to survive with full operational capability after long-duration cold soak at 70 K.
**net of module insulation, extra heat sources, or extra cells to feed heaters.*

CLOSURE PLAN:
- Further SBIR efforts for cell development, thermal management systems, and supplemental (e.g., radioisotope) heat sources.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 ice mining demonstration



PSR Distribution/Storage Trade



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Gap F: CH_4/O_2 Primary Fuel Cell Power up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.2

Definition: Primary power from LO_2/LCH_4 reactant storage may be the mass-optimal solution for certain Lunar/Mars mobility assets and Landers

SOA: Air/Natural Gas Solid Oxide Fuel Cells are in common terrestrial use up to ~50 kW_e scale. Multi-kW_e-scale Jet Fuel/O_2 power plants tested by USN NUWC in operational configurations. NASA and vendors have tested LO_2/LCH_4 SOFC 1 kW_e-scale in breadboard configurations.

CURRENT INVESTMENTS

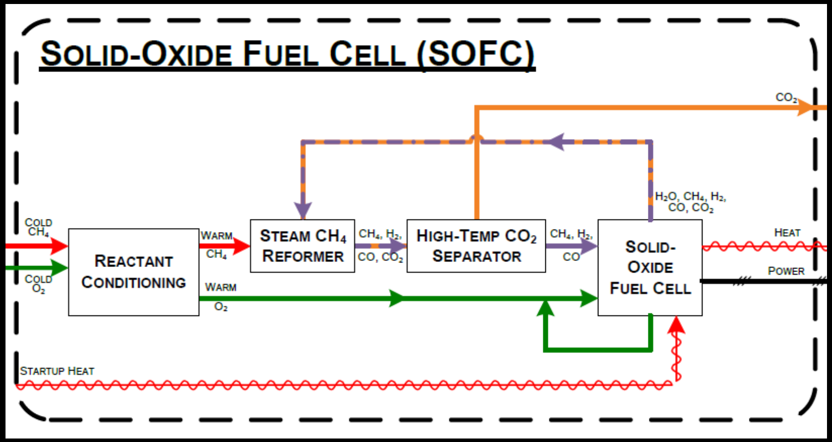
NASA:

- SOFC
  - *SBIR Ph 3 (Precision Combustion)*

CLOSURE:
Bring to TRL 6 LO_2/LCH_4 primary fuel cell power generation systems in up to 10 kW_e increments with maximum specific energy and maintenance free life in the Lunar polar or Martian environments of 10,000 operating hours

CLOSURE PLAN:

- Further SBIR efforts for cell development and thermal management systems
- GCD project to bring full-scale system to TRL 6



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Envisioned Future - *EXPLORE*

Transformative Missions and Discoveries

Vehicle platform technologies supporting new discoveries

POWER GENERATION

- Low Irradiance, Low Temperature (LILT) photovoltaic arrays operating at > 300 V and providing > 8 W/kg EOM in Jovian orbital environment
- LILT photovoltaic arrays operating with red-shifted spectrum at 750 K and 90 atm (e.g., Venusian surface mission)
- Improved efficiency/durability thermoelectric power conversion for ^{238}Pu GPHS
- Chemical or wind power generation operating at 750 K and 90 atm (e.g., Venusian surface mission)

ENERGY STORAGE

- Primary battery storage surviving to 35 K and operating (high rate) at 200 K with specific energy >200 Wh_e/kg. (e.g., Lunar PSR mission)
- Primary battery storage operating at 750 K and ~10 W for 3000 hrs. (e.g., Venusian surface mission)
- Passive thermal control at low mass for secondary batteries(2)

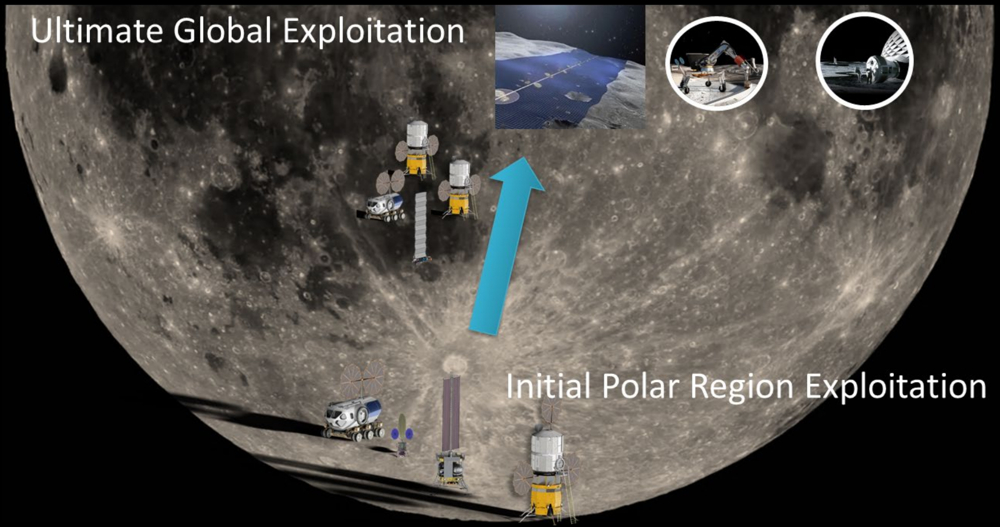
POWER DISTRIBUTION

- Reliable, Rad-hard power electronics for extreme (e.g., Jovian) radiation and high temperature (e.g., Venusian surface) environments(1)
- Beamed power at ~100 W_e-scale (3)

(1)Possible augmentation to closure of LIVE Gap B: Power Electronics.
(2)Probable inclusion with closure of LIVE Gap E3: Low Temperature Secondary Batteries
(3)Probably inclusion with closure of LIVE Gap E1: Wireless Power Transmission

Conclusions

- The immediate focus is on advancing TRL for power system components brought from Earth, defining performance which surface system architects can assume when designing sustainable exploration systems for the Moon and Mars.
  - The future priority should be advancing the technology to manufacture power system components from In-situ Lunar resources, with such systems bootstrapped with power systems brought from Earth.
- Continuation of several mid-stage investments is required to drive toward achieving desired outcomes.



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Lunar Surface Innovation Consortium (LSIC)

Nationwide alliance of universities, commercial companies, non-profit research institutions, NASA, and Other Government Agencies with a vested interest in our nation's campaign to establish a sustained presence on the Moon.

LSIC Objectives include:

- Identifying lunar surface technology needs and assessing the readiness of relative systems and components
- Making recommendations for a cohesive, executable strategy for development and deployment of the technologies required for successful lunar surface exploration
- Providing a central resource for gathering information, analytical integration of lunar surface technology demonstration interfaces, and sharing of results.

Focus Groups (FG) are the primary means for consistent interaction with the LSIC Community. This includes:

- Establishing collaborative relationships among members via virtual monthly forums, quarterly virtual workshops, and LSIC member site visits
- Building community and developing talent
- Compiling member input and reporting outcomes and recommendations

If interested in further information, please visit lsic.jhuapl.edu


NASA
www.nasa.gov/spacetech

Acronyms

- ACO – Announcement of Collaboration Opportunity
- BPDA – Breakthrough Distributed Power Architecture
- BOL – Beginning of Life
- BYU – Brigham Young University
- CLPS – Commercial Lunar Payload Services
- DMFlex –Dust Mitigation for Flexible solar arrays
- DoD – Department of Defense
- DoE – Department of Energy
- DRPS – Dynamic Radioisotope Power System
- ECF – Early Career Faculty
- EOM – End of Mission
- ESI – Early Stage Innovation
- FC – Fuel Cell
- FSAP – Flexible Solar Array qual Protocols
- FSP – Fission Surface Power
- GCD – Game Changing Development program
- GPHS – General Purpose Heat Sources
- GRC – Glenn Research Center
- ISRU – In-situ Resource Utilization
- kW_e – kilo-Watt electric
- LEO – Low-Earth Orbit
- LILT – Low Irradiance, Low Temperature
- LO-DuSST – Lunar Occupancy Dust- Surface Separation Technologies
- LuSTR – Lunar Surface Technology Research
- MIPS – Micro-grid Definition and Interface Converter for Planetary Surface
- MMOD – Micro-Meteoroid and Orbital Debris
- NUWC – Naval Undersea Warfare Center
- OGA – Other Government Agencies
- PCC – Prizes, Challenges, and Crowdsourcing
- PEM – Proton Exchange Membrane (fuel cell)
- Ph - Phase
- PILS - Photovoltaic Investigation on the Lunar Surface
- PSR – Permanently Shadowed Region
- PT – Principal Technologist
- PV - Photovoltaic
- RFC – Regenerative Fuel Cell
- RPCD - Rad-hard Power Controller Development
- RPS – Radioisotope Power System
- SBIR – Small Business Innovation Research
- SCLT – System Capability Leadership Team
- SOA – State of the Art
- SMD – Science Mission Directorate
- SMR – Small Modular Reactor
- SNC – Sierra Nevada Corporation
- SOFC – Solid Oxide Fuel Cell
- STRG – Space Technology Research Grants
- STTR – Small Business Technology Transfer Program
- TDM – Technology Demonstration Missions Program
- TP – Tipping Point
- TRL – Technology Readiness Level
- TX – Taxonomy (area)
- TYMPO – Tethered power sYstems for in-situ lunar Mobility and Power transmisison
- UCSB – University of California, Santa Barbara
- UFPC – Ultra-Fast Proximity Charging
- US – United States
- USN – United States Navy
- VSAT – Vertical Solar Array Technology
- WOTM – Watts on the Moon