Power Generation and Energy Storage

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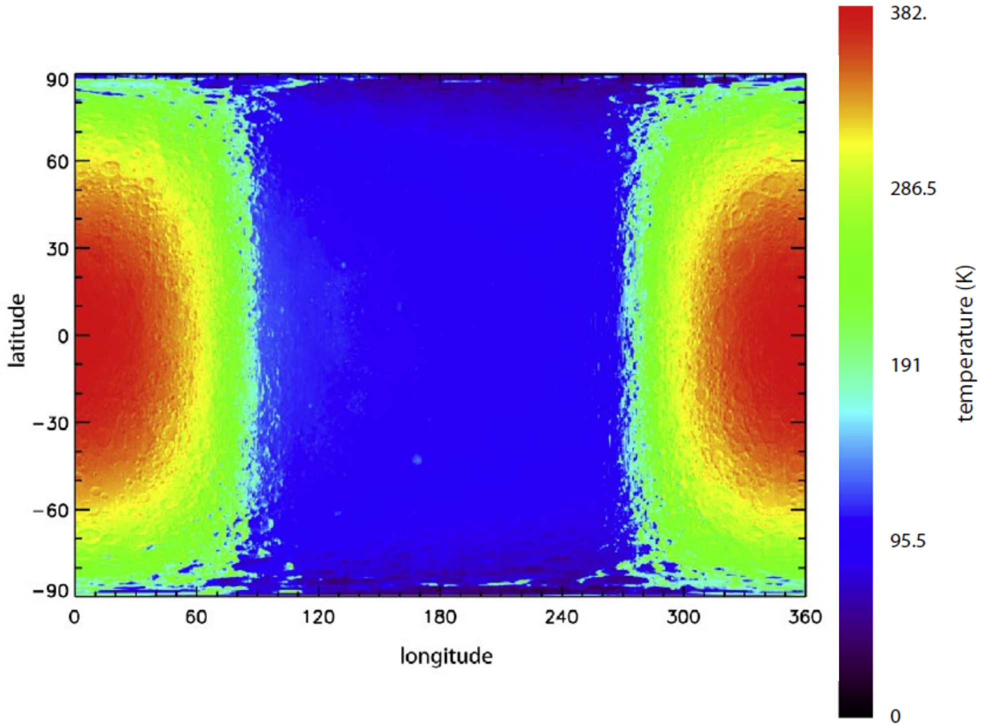
Powering Lunar Surface Missions

Challenges

- Diurnal Temperature Extremes
  - Increases degradation on components
  - Reduces efficiency of many Power Technologies
  - May require Active Thermal subsystems to maintain operational temperatures
- Dust and Charging
  - Dust coverage reduces Solar Panel and radiator effectiveness
  - Electrostatic charging may induce different voltage potentials for multiple lander missions
- Power Distribution
  - Vacuum and Low thermal conductivity of the Lunar regolith limits the amount of heat that can be removed from power distribution networks

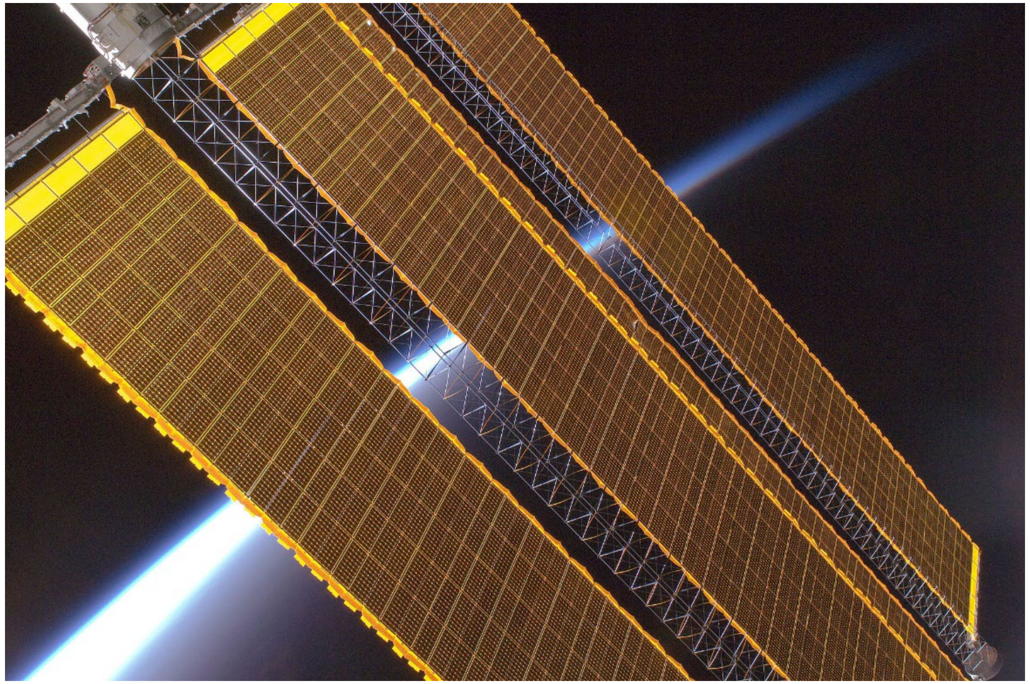


Power Generation

Solar Cells, Panels, and Arrays

- Mature Technology - Flight Proven
- Scalable to match required power generation
- Long lunar day allows for extended operations and energy storage charging time

- Long Lunar Nights require Energy Storage
- Extreme temperatures reduce efficiency and increase degradation
- Requires articulation to maximize effectiveness
- Dust accumulation reduces efficiency

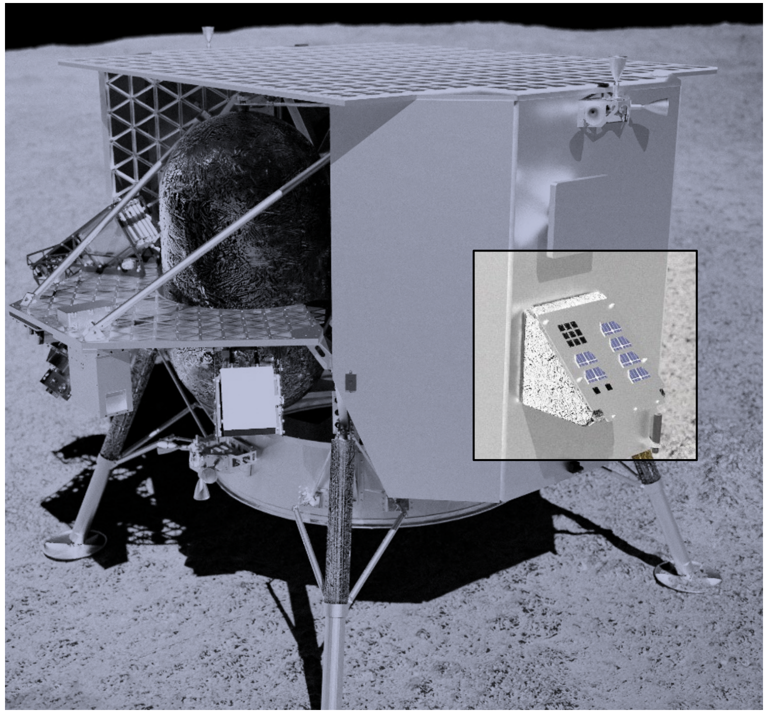


Power Generation

Solar Cells, Panels, and Arrays

Lunar Surface Challenges

- SOA Solar arrays are designed to be used on orbiting satellites
  - NASA's last use of solar arrays on the Lunar Surface was during the Apollo Missions
- Work is ongoing to determine the impact of the surface environment on current SOA Photovoltaics
  - The Photovoltaic Investigation on the Lunar Surface (PILS) payload will be launched on a CLPS Lander
    - PILS will test various SOA solar cells in the Lunar Surface Environment to verify photovoltaic performance and determine degradation effects caused by the dust and extreme temperatures

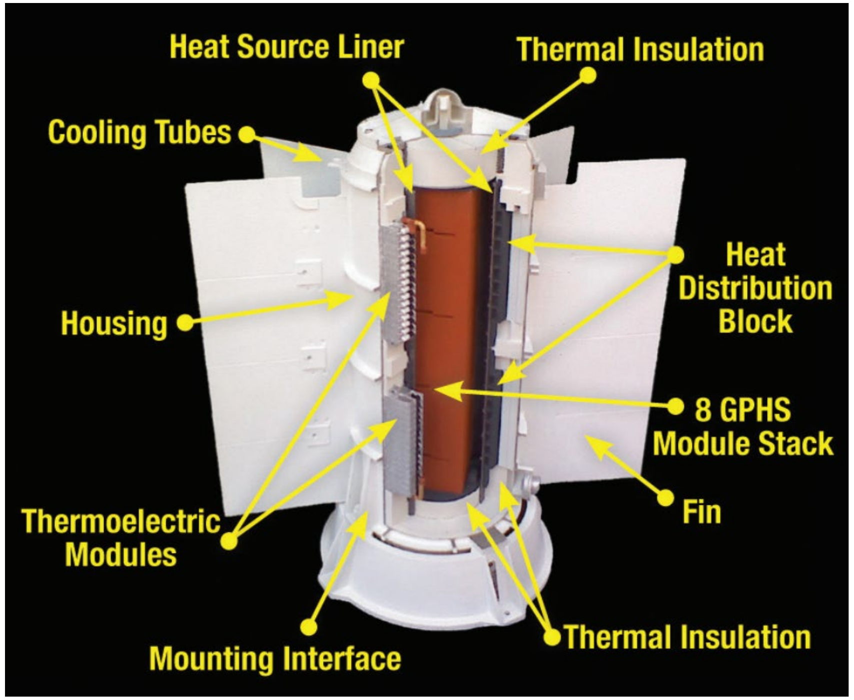


PILS payload on Peregrine Lander

Power Generation

Radioisotope Power Systems

- NASA RPS utilize the heat produced by the natural decay of Plutonium-238 to generate power
- Current systems use Thermoelectrics to convert heat into power
  - Dynamic Stirling system is currently in design, allowing for higher energy conversion efficiencies
- Lots of flight heritage on historical and current missions
- High Lunar Surface temperatures provide a challenging environment to reject heat
- Dust may limit radiator effectiveness
- Micrometeoroids and Ejecta may damage the RPS

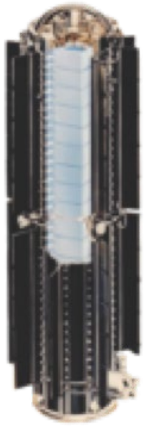


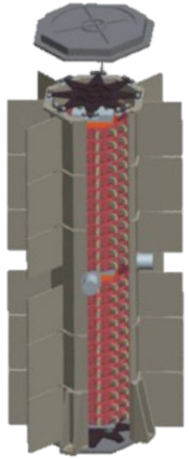
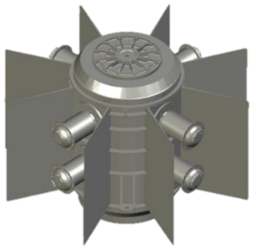
Cutaway View of an MMRTG

Power Generation

Radioisotope Power Systems

Performance Comparison



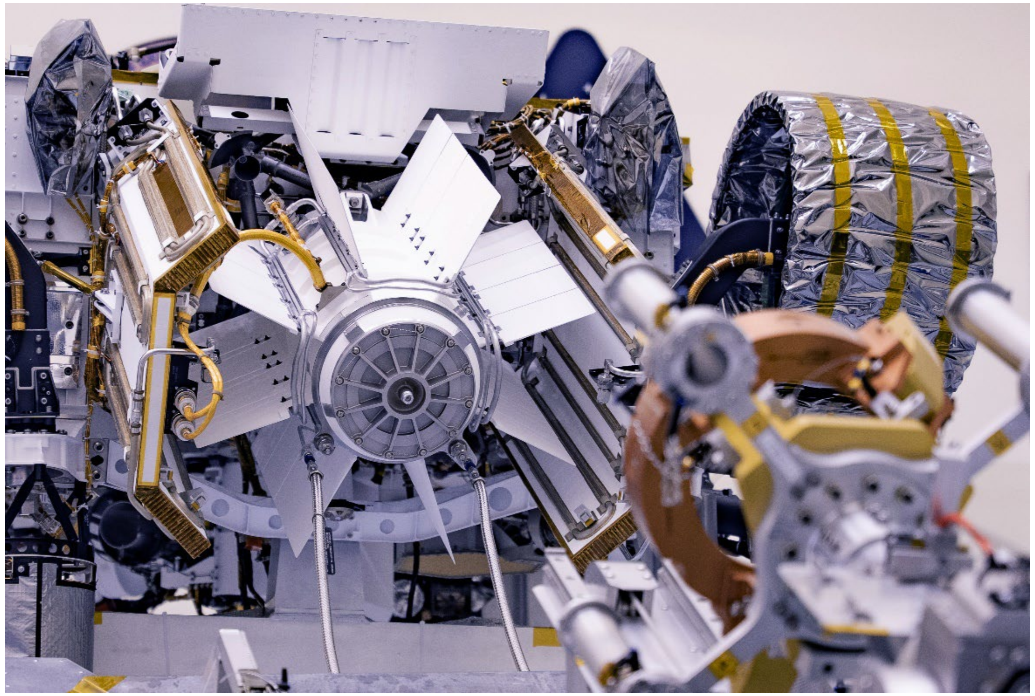
Parameter	GPHS-RTG	MMRTG	Next Gen RTG	DRPS
P_{BOL} (W_e)	291	118	245	300 to 400
Mass (kg)	58	44	56	100 to 200
Length (kg)	1.14	.69	1.14	TBD
Q_{BOL} (W_{th})	4410	2000	4000	1500
P_{EODL}, $P=P_0*e^{-rt}$ (W_e)	N/A	62	177	241 to 321
Maximum Average Annual Power Degradation, r (%/yr)	1.54	3.8	1.9	1.3
# GPHS modules	18	8	16	4-6
Fueled Storage Life, t (yrs)	2	3	3	3
Flight Design Life, t (yrs)	16	14	14	14
Design Life, t (yrs)	18	17	17	17
Allowable Flight Voltage Envelope (V)	22-34	22-34	22-36	22 to 36
Planetary Atmospheres (Y/N)	N	Y	N	Y
Estimated Launch Date Availability	N/A	Now	2029	2030

GPHS RTG: Cassini, Galileo, Ulysses, New Horizons

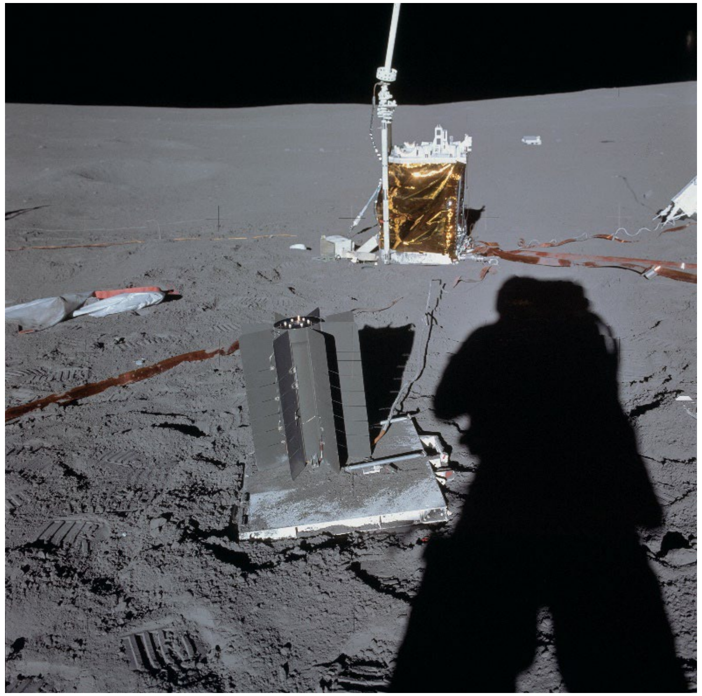
MMRTG: Curiosity, M2020, Dragonfly

Power Generation

Radioisotope Power Systems



Mars 2020 MMRTG Fit Check

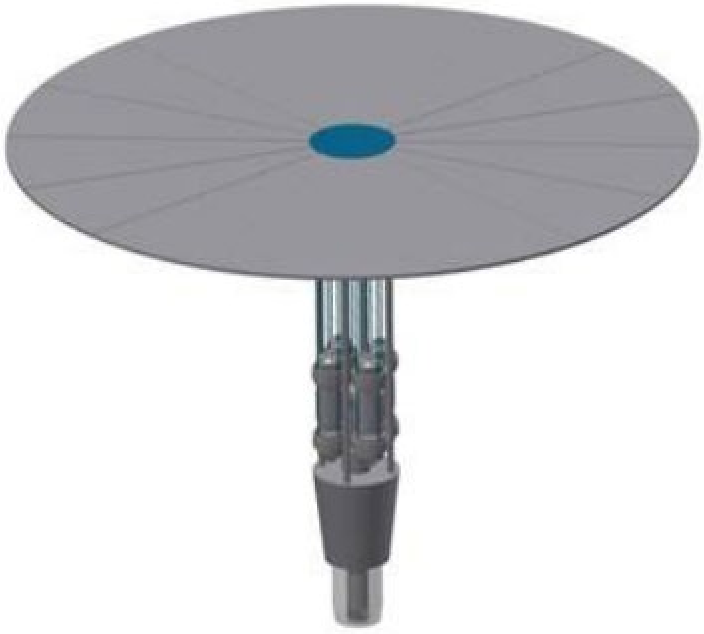


ALSEP SNAP-27 RTG on the Lunar Surface
Apollo 14

Power Generation

Fission Power Systems

- Utilizes Uranium reactor to supply heat to the power conversion system
  - Current designs use Low Enriched Uranium
  - Power Conversion system uses Stirling Engines
    - Brayton also considered
- High temperature radiators reduce impact of Lunar Surface temperature extremes
- Requires shielding and/or distance to reduce radiation to users



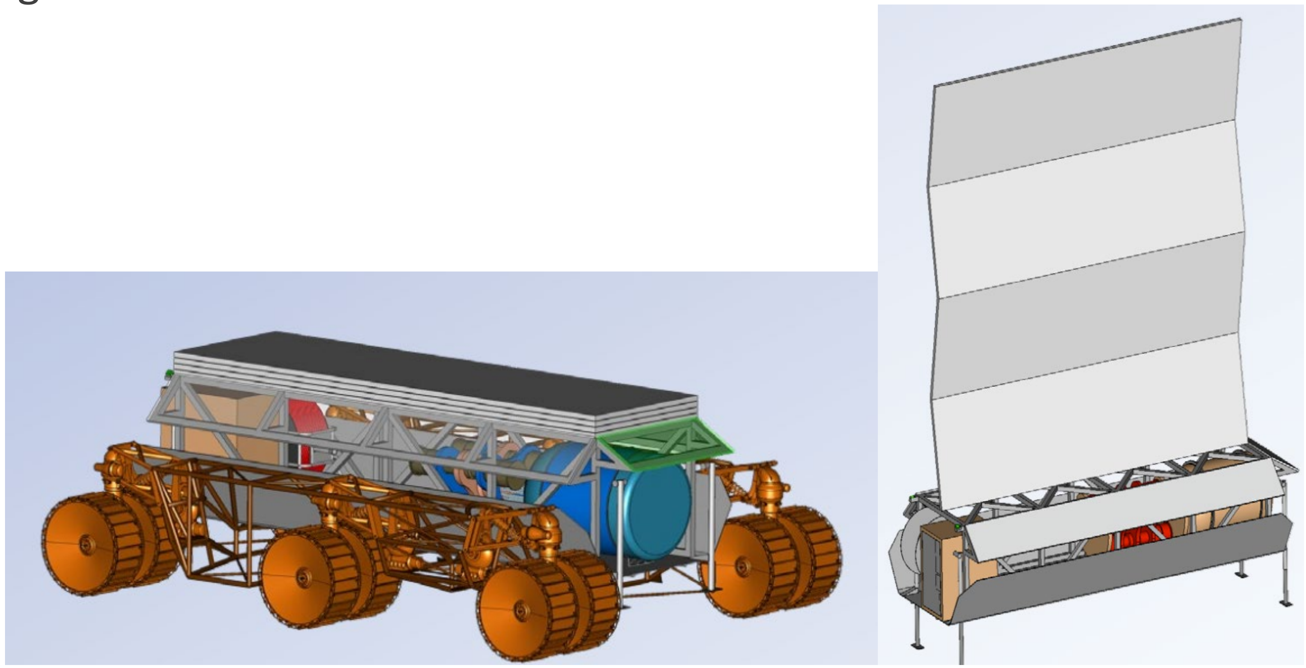
1-10kWe Fission Power System Concept

Power Generation

Fission Power Systems

Recent Design Assessments

- 10 kWe Transportable FPS
  - Power system and rover are integrated together
  - Six 1.7kWe Stirlings
  - LEU Moderated Reactor
  - $40m^2$ Deployable Radiator



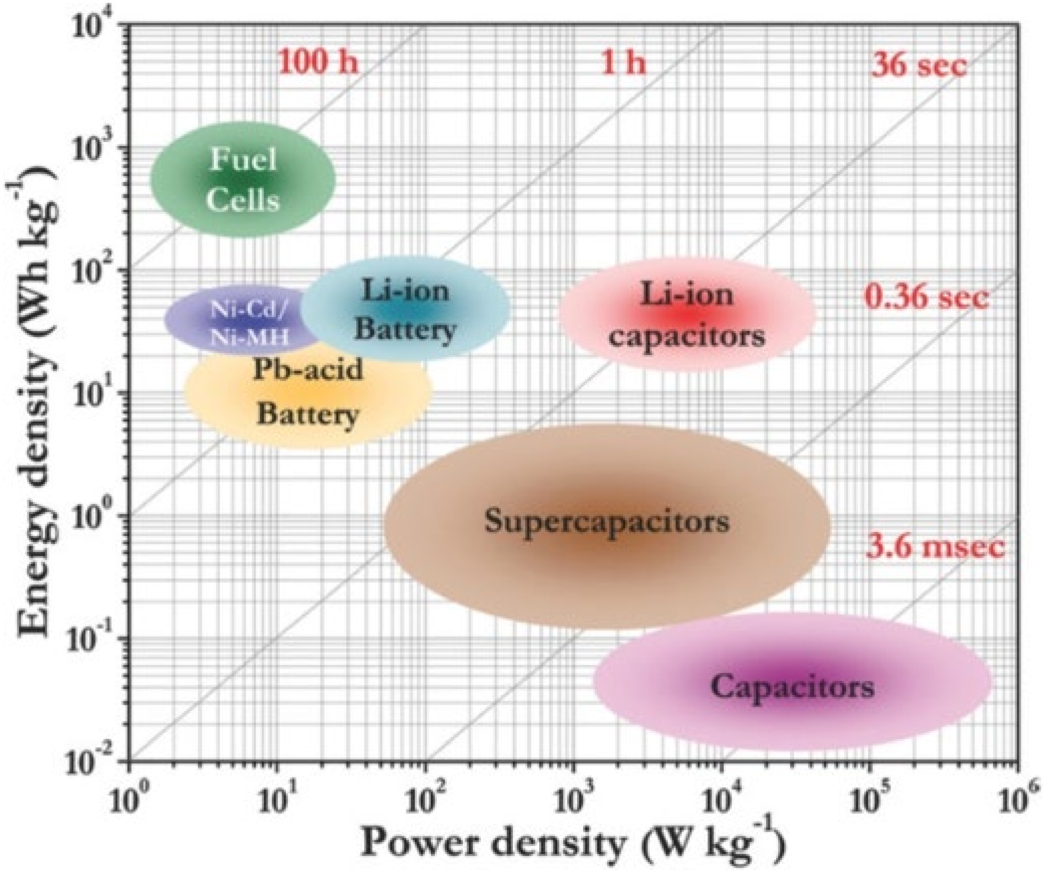
10 kWe Transportable FSP stowed on Lander and Deployed on Surface

Energy Storage

Energy Storage

Batteries

- Long Lunar Nights pose a challenge to missions
- Minimal supplied power is typically required to maintain systems within operational temperature limits
  - RPS and Fission systems may supply waste heat to keep components warm
- SOA Lithium Batteries can supply up to 260 Wh/kg
- Thermal management systems are required to maintain batteries within temperature limits for safety as well as degradation and voltage stability



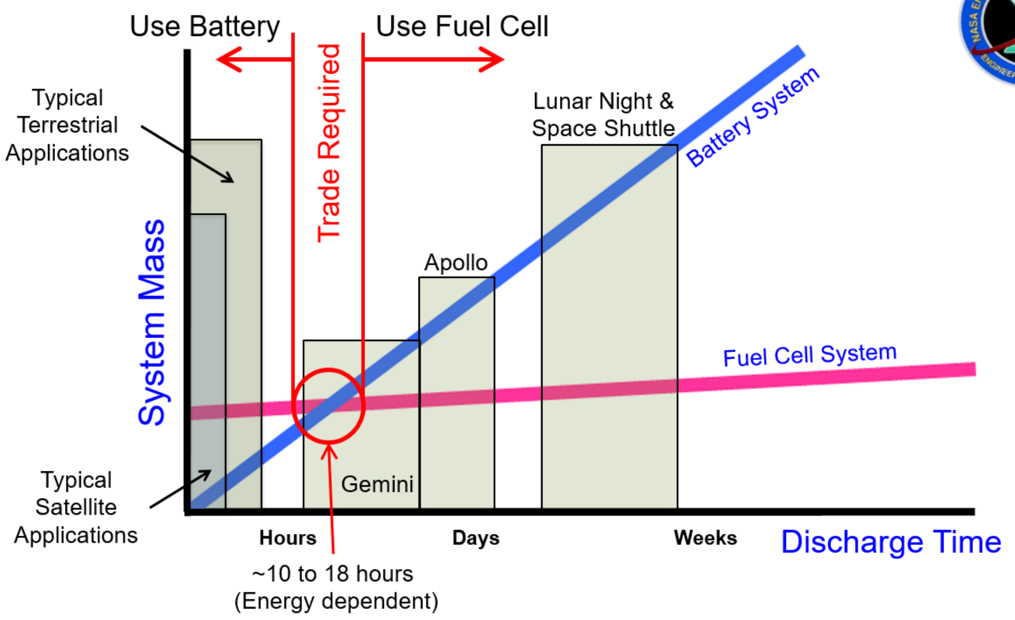
Aravindan et al. (2014) American Chemical Society

Energy Storage

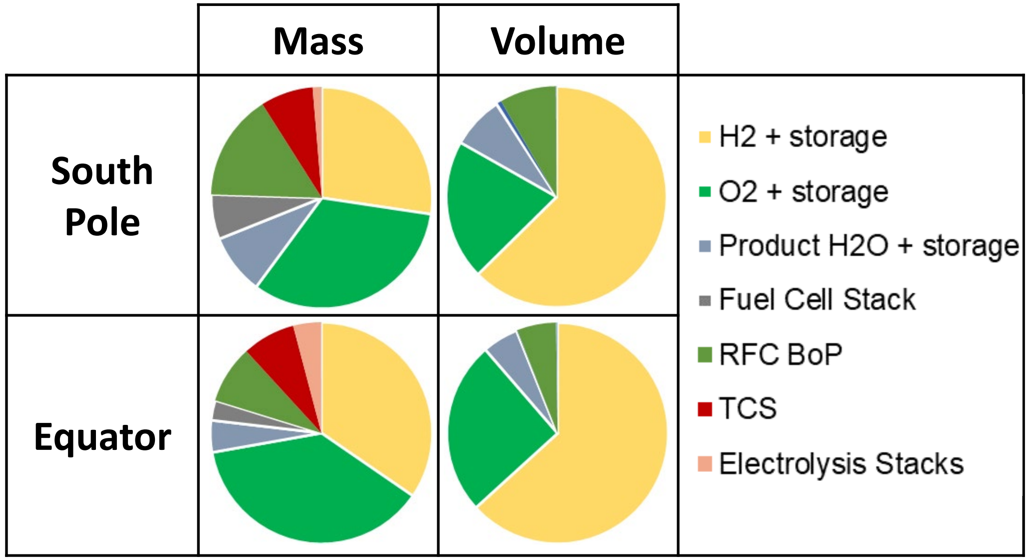
Regenerative Fuel Cells (RFC)

➢ Battery and RFC Technologies are *Complementary* not *Competitive*

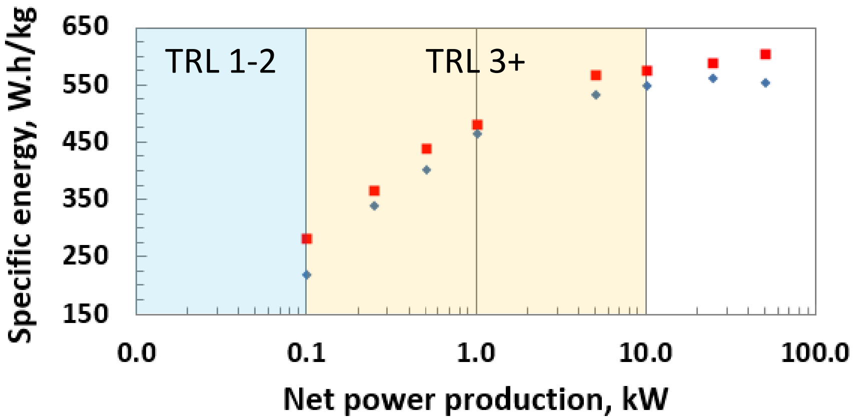
- No power or energy storage technology meets all requirements for all applications
- Each technology has a place within the overall exploration space
- TRL very sensitive to mission
- Energy Storage Metric = Specific Energy (W·hr/kg)
  - ❖ Packaged Li-ion Battery Systems ~ 160 W·hr/kg
  - ❖ Regenerative Fuel Cell Systems < 100 to > 600 W·hr/kg and are sensitive to energy storage requirement and discharge power level



South Pole vs. Equator

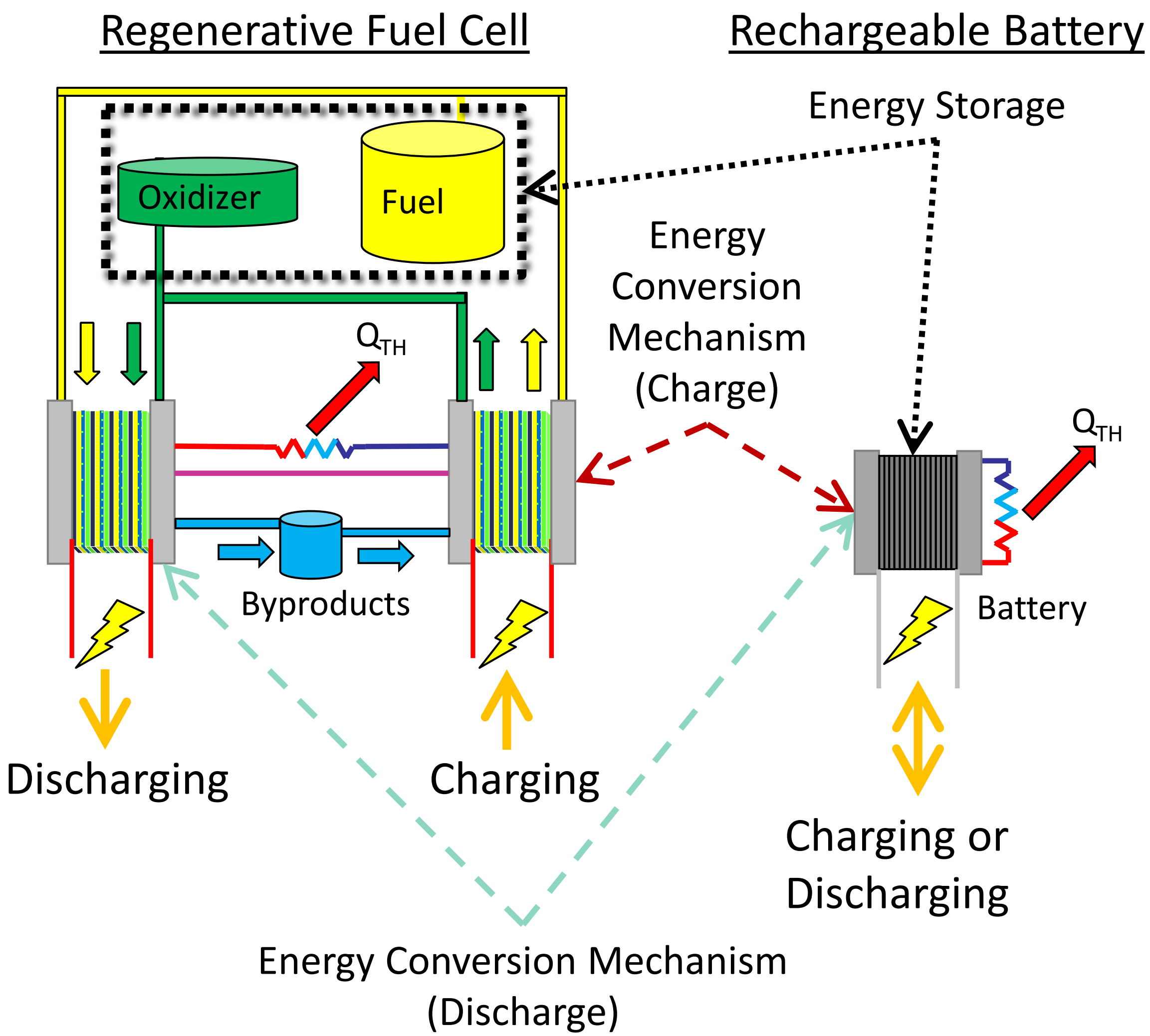


10 kW Class RFC system using 1500 psia reactant storage



Energy Storage

Regenerative Fuel Cells (RFC) vs. Rechargeable Batteries



Primary Metric = Specific Energy (W·hr / kg)

RFC & Rechargeable Batteries Primary Difference: Energy storage Location

- Rechargeable batteries store energy intimately with the energy conversion mechanism
- Regenerative fuel cells (RFCs) store energy remotely from the energy conversion mechanisms

This results in:

- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - RFC have complicated supporting systems
- Different Voltage to State-of-Charge (SoC) relationships
  - Rechargeable battery voltage dependent on charge state
  - RFC discharge voltage independent of charge state
- Different Recharge/Discharge capabilities
  - Battery rates determined by chemistry and SoC
  - RFC “tunable” for mission location and charge/discharge profile
- Different Round-trip Efficiencies
  - Battery round-trip electrical efficiency >90% resulting in limited waste heat
  - RFC round-trip electrical efficiency ~ 50% with thermal energy available to survive the lunar night

Energy Storage

Selection of Potential Electrochemical System Chemistry Options

	Low Temperature		Moderate Temperature		High Temperature	
Electrolyte	Proton Exchange Membrane (PEM)	Alkaline Polymer Membrane (AEM)	Alkaline	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte State	Ionic Polymer Membrane (Solid)	Anionic Polymer Membrane (Solid)	Alkaline Solution in matrix (Liquid)	Phosphoric Acid in matrix (Liquid)	Carbonate in matrix (Liquid)	Conducting Ceramic (Solid)
Maturity (Terrestrial / Aerospace)	TRL 9 / TRL 5* (* = Application-specific)	TRL 6 / TRL 3	TRL 9 / TRL 3 (N/A)	TRL 9 / TRL 3	TRL 9 / TRL 3	TRL 9 (4) / TRL 5* (* = Application-specific)
Power Applications	Base-load, Transient	Base-load, some Transient	Base-load, many Transient	Base-load, some Transient	Base-load only	Base-load only
Aerospace Viability (Development Challenges)	**Very high** (Need μg demonstration, Flight Balance of Plant)	**TBR** (Low TRL, Short life)	**Moderate** (Liquid electrolyte, Ion migration, ***Heritage tech not available***)	**TBR** (Under Development, Liquid Electrolyte)	**Very, very low** (Material Compatibility, Low Specific Power)	**Very high** (Scale-up, Material Compatibility, Balance of Plant)
Reversibility (Fuel cell & Electrolysis modes in same cell)	Very Limited (Hydrophobic / Hydrophilic Surfaces)	Very Limited (Hydrophobic / Hydrophilic Surfaces)	Configuration Limited	Configuration Limited	High (Pressure-limited)	High (Pressure-limited)
Operating Temperature	4 – 85 ºC	20 – 95 ºC	70 – 225 ºC	80 – 250 ºC	600 – 850 ºC	600 – 1,000 ºC
Potential Fuels	Very Pure H_2		Pure H_2		H_2, CO, Short Hydrocarbons (CH_4, etc.)	
Charge Carrier / H_2O Cavity	H^+ / O_2	OH^- / H_2	OH^- / H_2	H^+ / O_2	CO_3^{2-} / O_2	O^{2-} / H_2
Product Water State	Liquid Product		Operation defines product water state		Vapor, externally separated	
Contamination Sensitivity	Very High	High (especially CO_2)	High (especially CO_2)	High	Very Low	
Terrestrial Markets C = Commercial, I = Industrial, R = Residential	Transportation, Logistics, Stationary Power (C, I, & R)	Under Development	Stationary Power (C & I)	Stationary Power (C & I)	Stationary Power (C & I)	Stationary Power (C & I, R under development)

Backups

Energy Storage

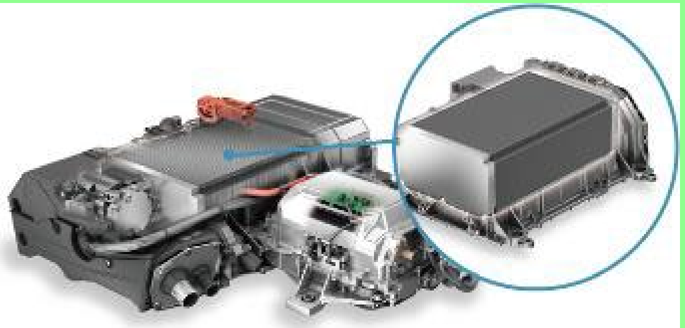
Aerospace vs. Terrestrial Fuel Cells

Aerospace

Space Shuttle Fuel Cell

(1979 - 2012)

Terrestrial



Toyota Mirai Fuel Cell[1]

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Differentiating Characteristics (Aerospace)

- Pure Oxygen (stored, stoichiometric)
- Water Separation in μg

Differentiating Characteristics (Terrestrial)

- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

Fluid management issues and environmental conditions make aerospace and terrestrial electrochemical systems functionally dissimilar

Notes: [1] = http://www.toyota-global.com/innovation/environmental_technology/technology_file/fuel_cell_hybrid/fcstack.html

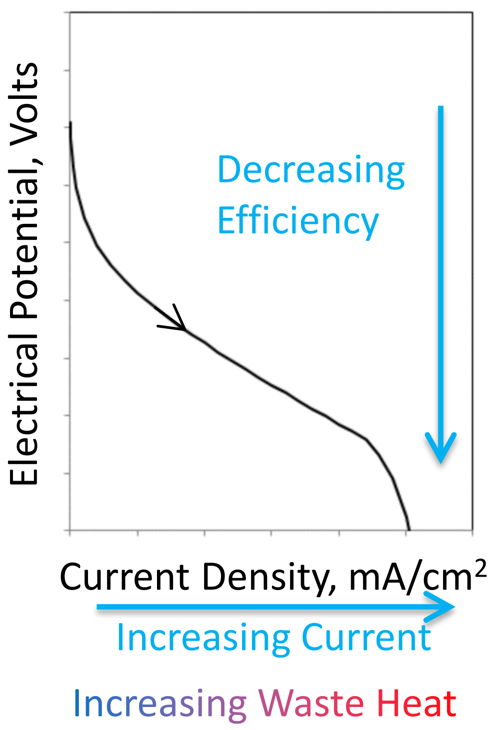
Energy Storage

Regenerative Fuel Cells (RFC) Basics

Fuel Cell Applications

- Primary power
- RFC Discharge power
- Operational duration based on reactant storage

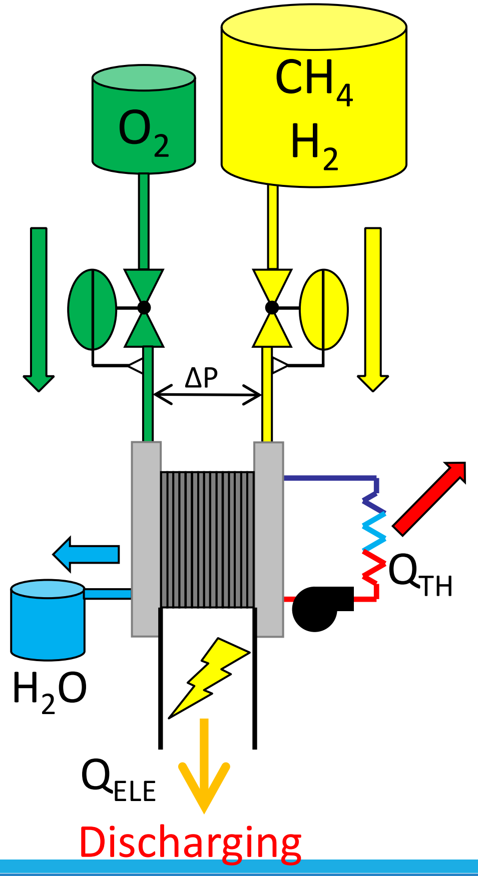
Fuel Cell Performance



Primary Fuel Cell

Discharge Power Only

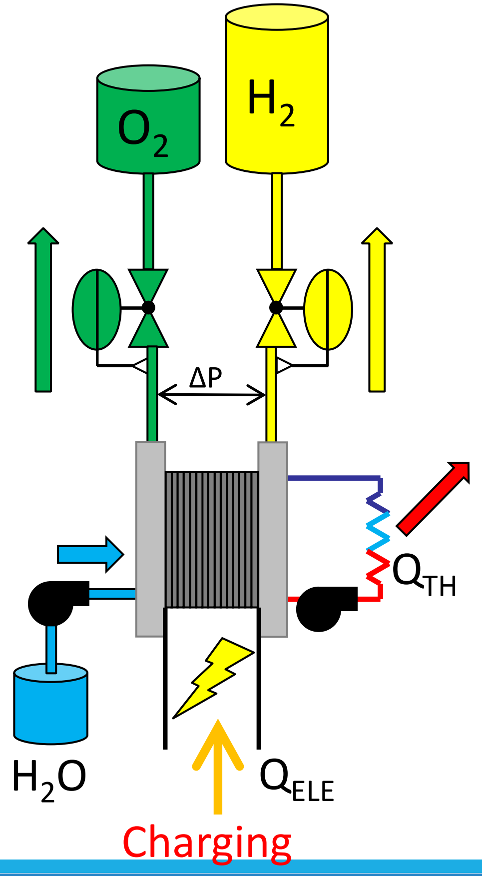
$$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + Heat$$



Electrolysis

Chemical Conversion

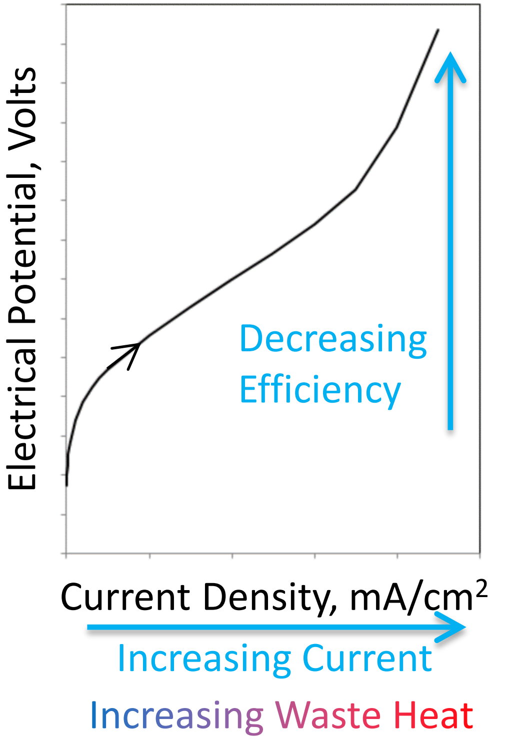
$$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + Heat$$



Electrolysis Applications

- Life Support (O_2 Generation)
- Generate H_2 and O_2 for Propellants, RFC Charging
- ISRU Material Processing

Electrolysis Cell Performance



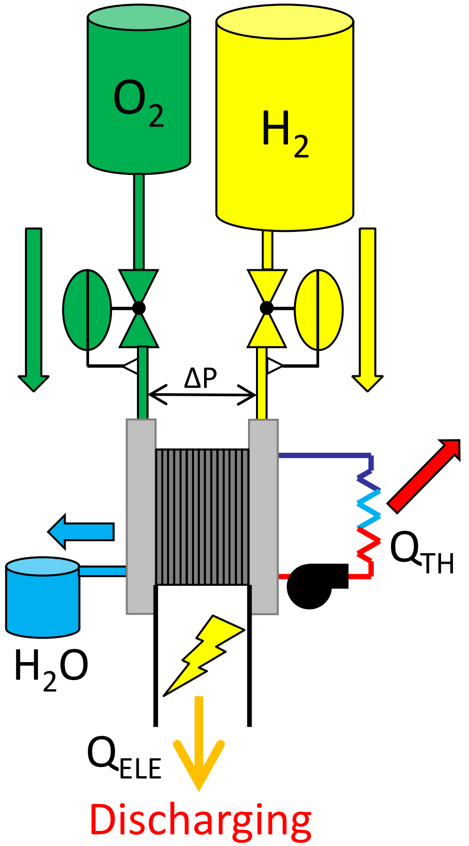
Energy Storage

Regenerative Fuel Cells (RFC) Basics

Primary Fuel Cell

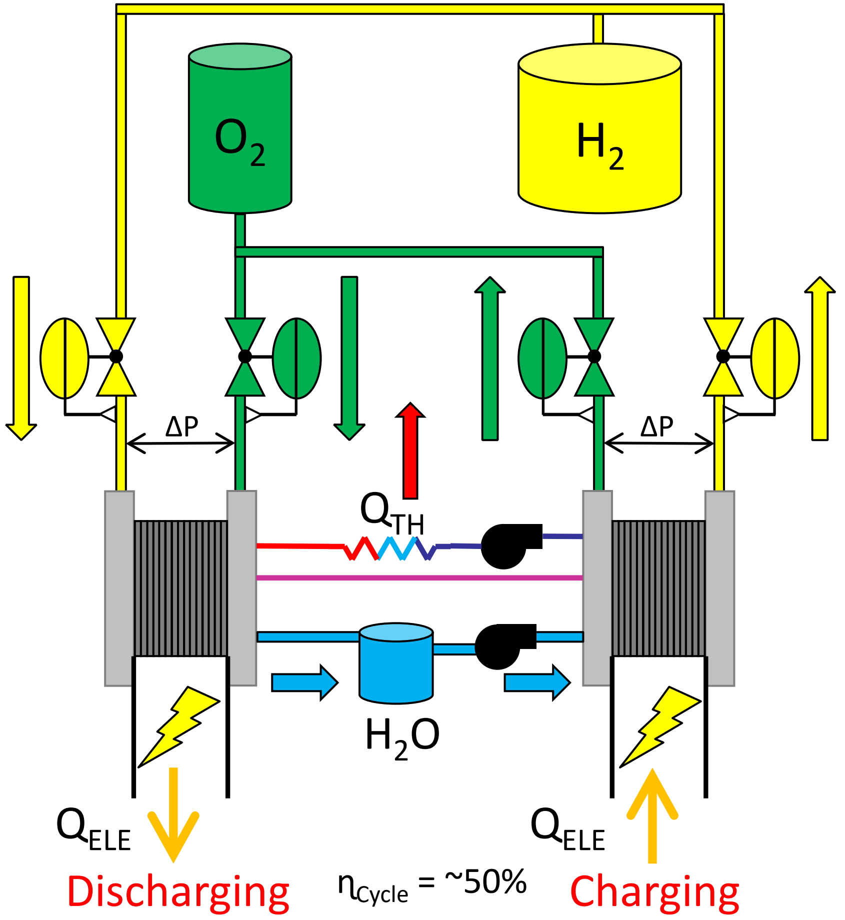
Discharge Power

$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + Heat$



Regenerative Fuel Cell

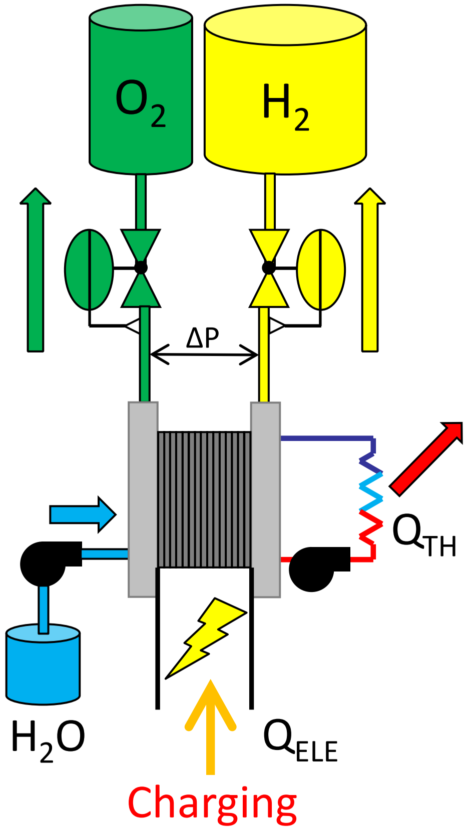
Energy Storage



Electrolysis

Product Generation

$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + Heat$



Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

Energy Storage

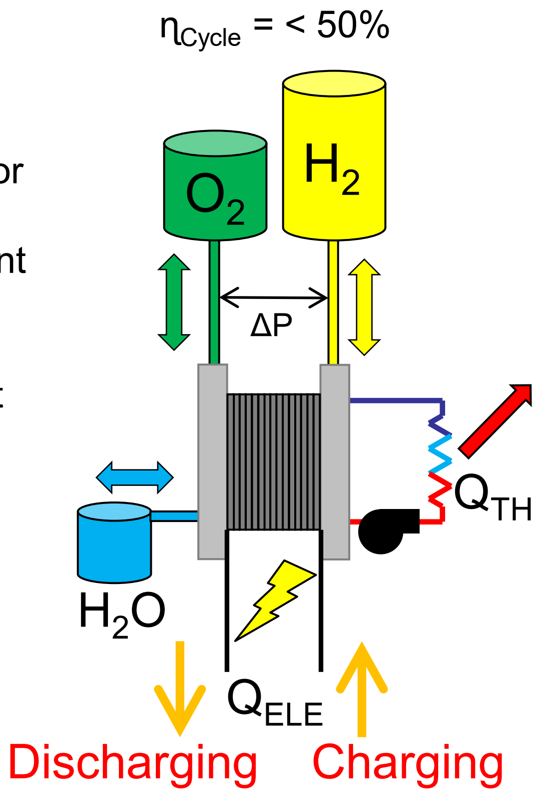
Regenerative Fuel Cells (RFC) Basics

Unitized RFC

Energy Storage System

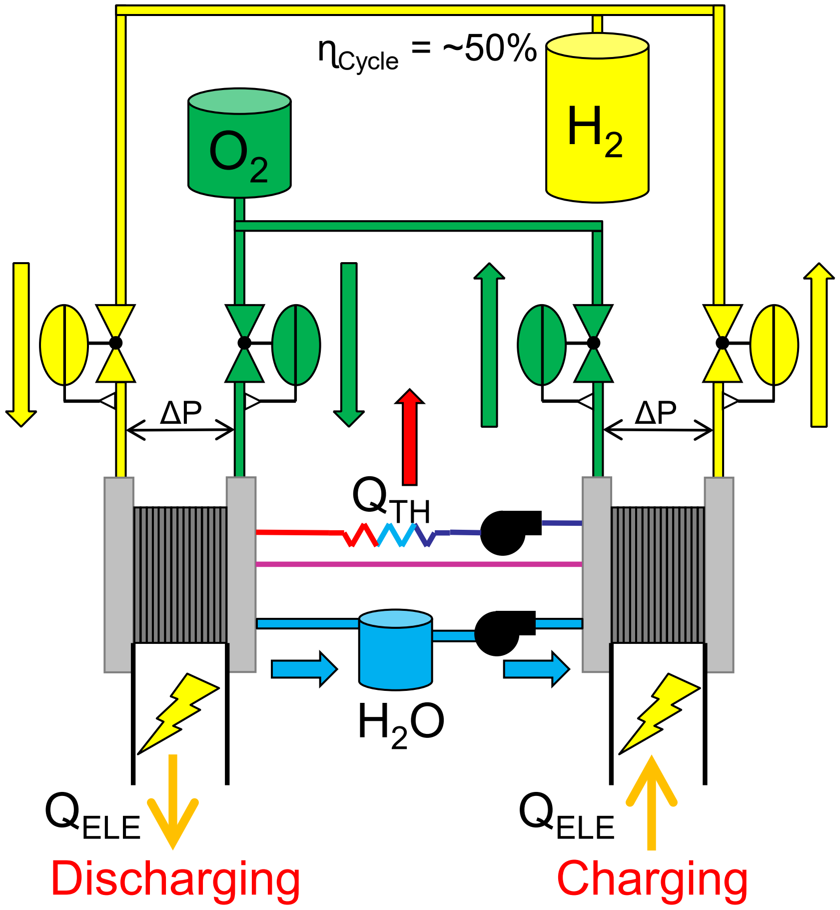
Notes

- Very low TRL for space applications
- Operational pressure limited resulting in very large tanks or independent compression
- Limited by water management issues in low temperature chemistries
- Significant recent investment indicating some promise



Discrete RFC

Energy Storage System



Notes

- Potentially complicated water management
- Proof-of-concept demonstrations
    - Multiple chemistries
    - Aeronautic systems in flight configurations
    - Space systems in laboratory configurations
- Commercial H_2/air systems available
    - Uninterruptable Power Supply (kW·hr to GW·hr)
    - On-time performance primary requirement
    - No roundtrip or specific energy requirements

Energy Storage

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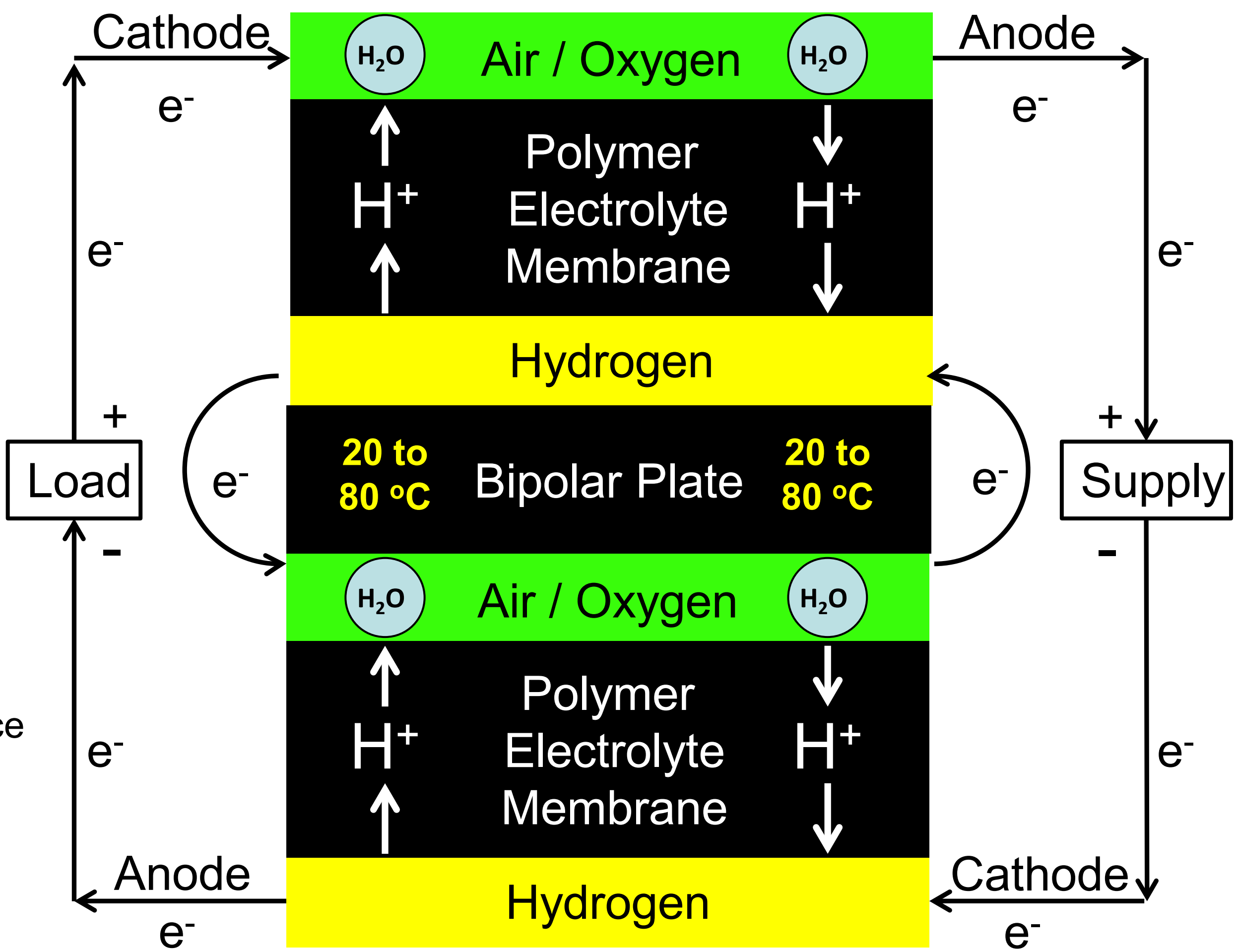
Energy Storage

Proton Exchange Membrane (PEM) Fuel Cell and Electrolysis Basics

Key Notes:
- Common for mobile terrestrial applications
- Terrestrial systems vent Oxygen to remove product water from stack
- Mature for terrestrial applications; Needs development for Aerospace

Development Areas:
- Expanded Temperature Range (Currently 4ºC to 85ºC)
- Improved life / Reduced Performance Degradation Rates
- Improved Contamination Tolerance
- Reversibility (Amphiphilic surface treatments)
- Cost Reductions
- Balance of Plant (supporting components) life, maintainability

Fuel Cell Reaction / **Electrolysis Reaction**



Advantages:
- Rapid reaction kinetics enable transient load response capability
- Minimal start times (typ.< 1 min)
- Demonstrated high pressure operation (400 psig fuel cell, 12 ksi electrolysis)
- Solid polymer electrolyte eliminates migration of acidic electrolyte

Disadvantages:
- Very sensitive to CO or Sulfur contaminants
- Water-based electrolyte limits temperature regimes
- Limited list of acceptable wetted materials (especially at high pressures)

Energy Storage

Solid Oxide Fuel Cell and Electrolysis Basics (Anionic)

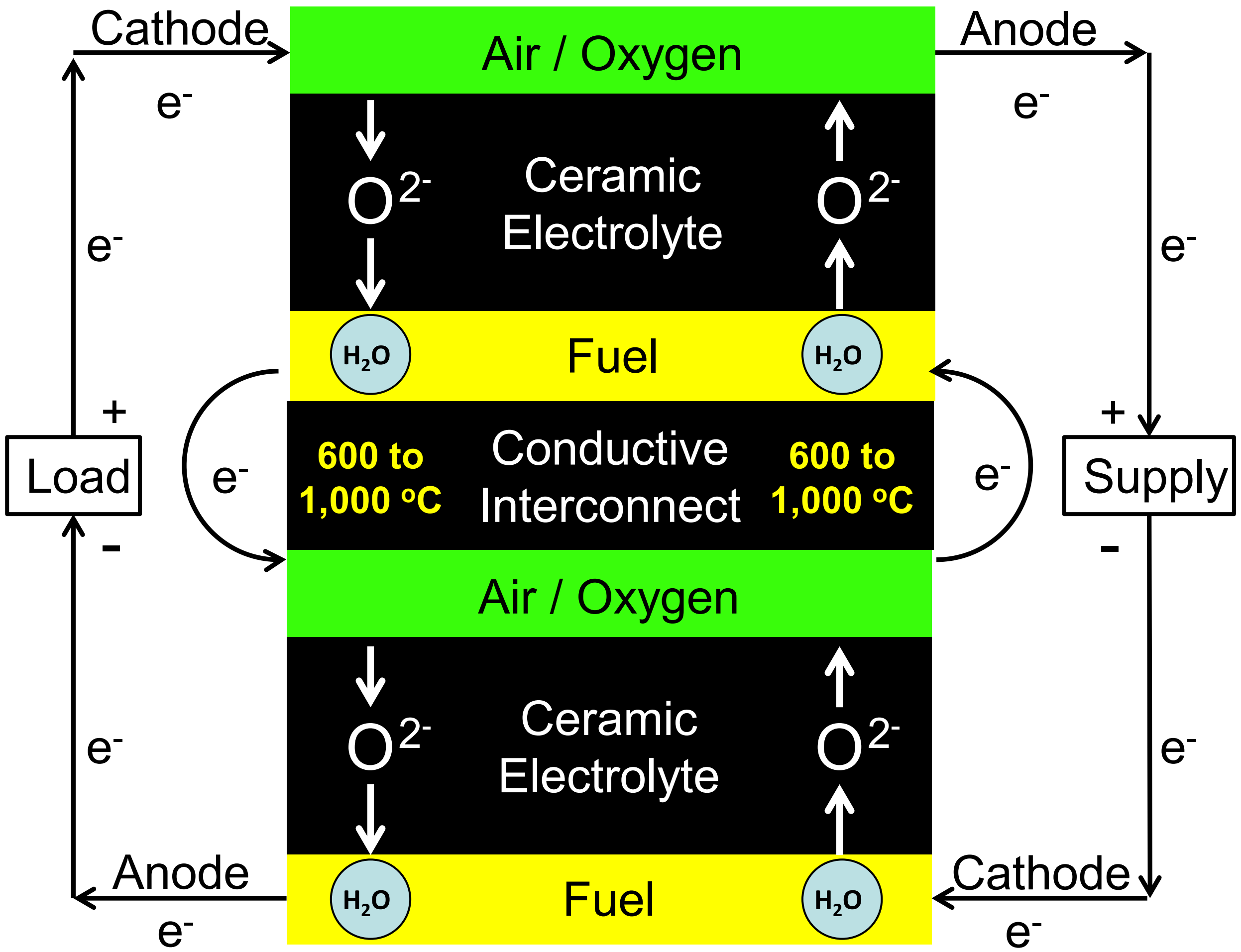
Key Notes:

- Common for stationary terrestrial applications
- Terrestrial systems vent hydrogen to remove product water from stack
- Mature for terrestrial applications; Needs development for Aerospace

Development Areas:

- Expanded Temperature Range (Currently 650ºC to 1050ºC)
- Thermal Cycling Capability
- Improved life / Reduced Performance Degradation Rates
- Seals (currently pressure-limited)
- Cost Reductions
- Balance of Plant (supporting components) life, maintainability

Fuel Cell Reaction **Electrolysis Reaction**



Advantages:

- Wide range of fuels (H_2, CH_4, CO, etc.)
- Can be configured to internally reform hydrocarbons
- High tolerance to contaminants (CO is a fuel)
- Resistant to freezing when stored
- Select designs have demonstrated reversible operation

Disadvantages:

- Ceramic electrolyte prevents transient load response capability
- Ceramic electrolyte limits start-up times from 10's of minutes to hours based on cell area
- Seals need development for Aerospace applications
- Limited to low-pressure applications

Energy Storage

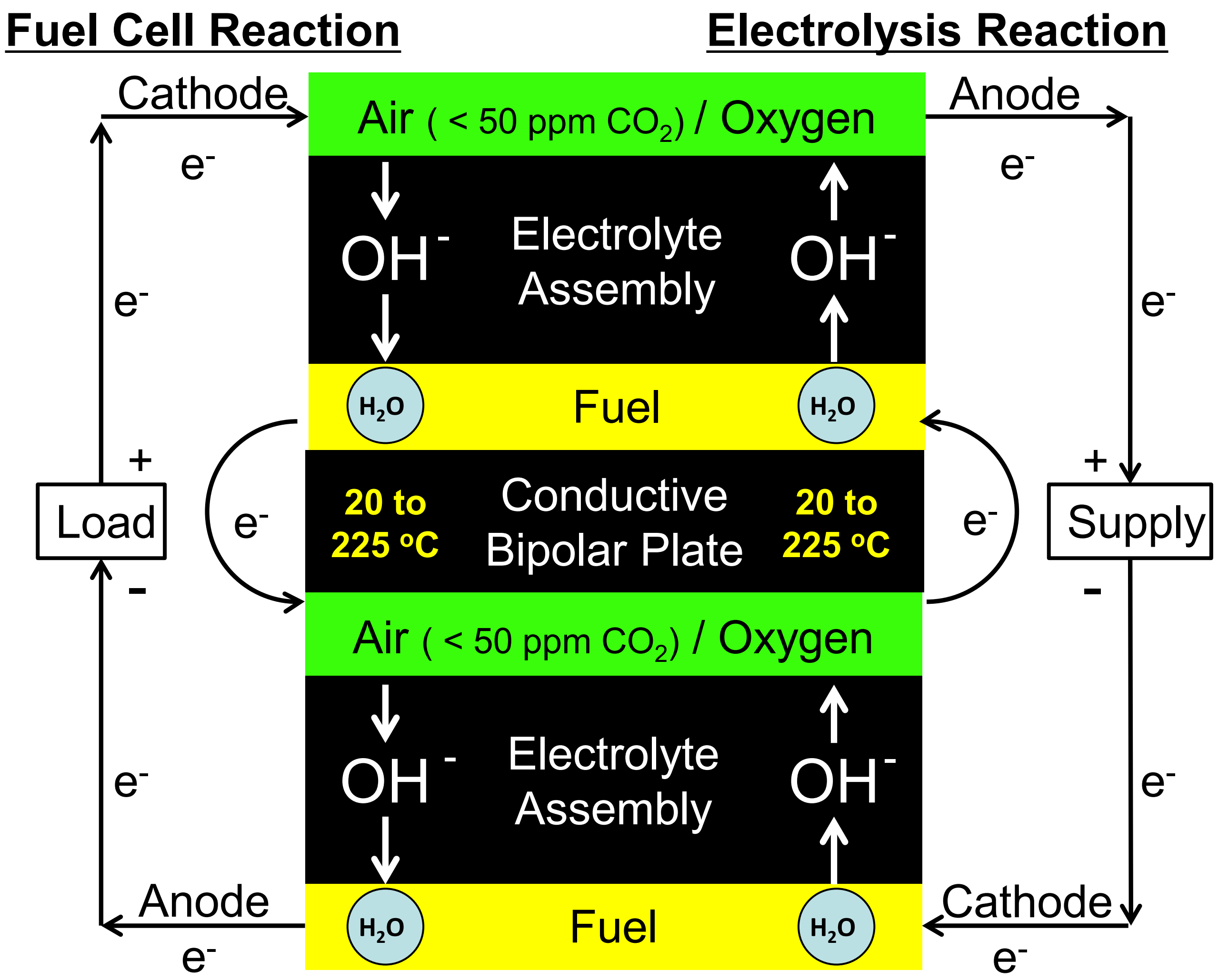
Alkaline Fuel Cell and Electrolysis Basics

Key Notes:

- Very established terrestrial industrial electrolysis technology (e.g. chlor-alkali, H_2 production)
- Heritage Flight design no longer manufactured in US

Development Areas:

- Improved life / Reduced Performance Degradation Rates
- Reversible system operation
- Elevated Pressures
- Balance of Plant (supporting components) life, maintainability



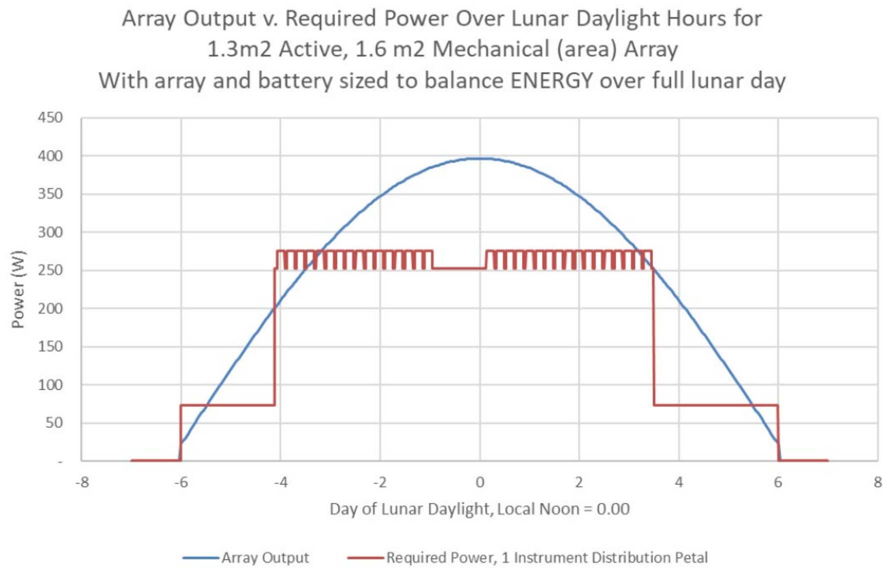
Advantages:

- Reaction kinetics enable transient load response capability in many applications
- Wide range of acceptable wetted materials
- Demonstrated operation for industrial applications
- Select designs have demonstrated reversible operation

Disadvantages:

- Very, very sensitive to CO2 contamination
- Electrolyte seeping/weeping a significant issue
- Performance sensitive to solution concentration
- Typically have very small differential pressures
- Water-based electrolyte limits temperature regimes

Reference Missions
FARSIDE



- Landing Site - Between 60° NS Lat
- Rover – Shuts down at night
  - One 30 Ah Lithium Ion Battery
  - Solar Powered – 1.3 m^2 cell area
  - RHUs to Survive Night
- Base Station
  - Two 30 Ah Li-Ion Batteries for 311W Peak loads for science at night
  - Two eMMRTG* (271W EOM)

*eMMRTG is not currently in development, alternative is Next-Gen RTG shown in later slides

Reference Missions

FarView

- Landing Site - 20°- 60° S Lat
- Rover – Commercial
- In-Situ manufacturing of Solar Arrays, Power Transmission Lines, and Batteries
  - Solar Concentrators for VDM

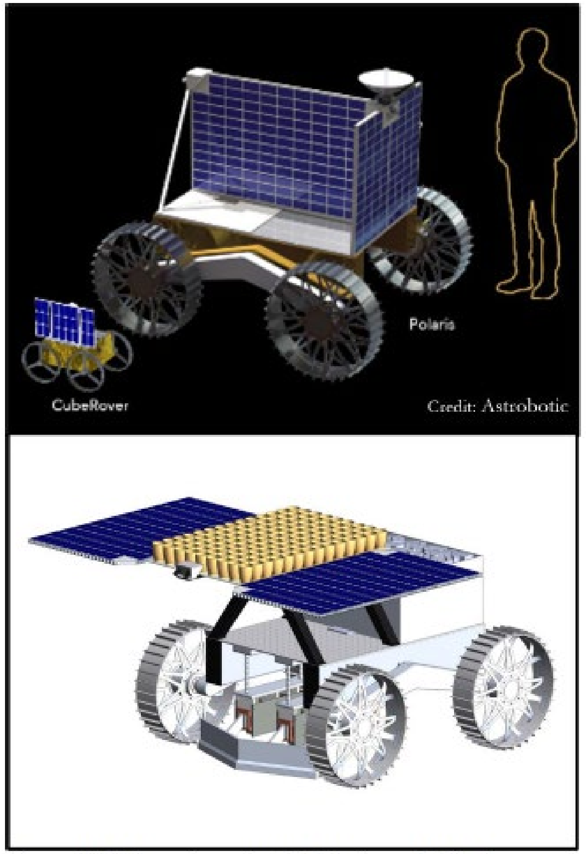


Figure 17. *Upper:* Astrobotic Polaris and CubeRover. *Lower:* Polaris reconfigured for *FarView* with VDM payload and solar concentrators.

Reference Missions

LCRT

- Projectile Approach
- Rover Approach

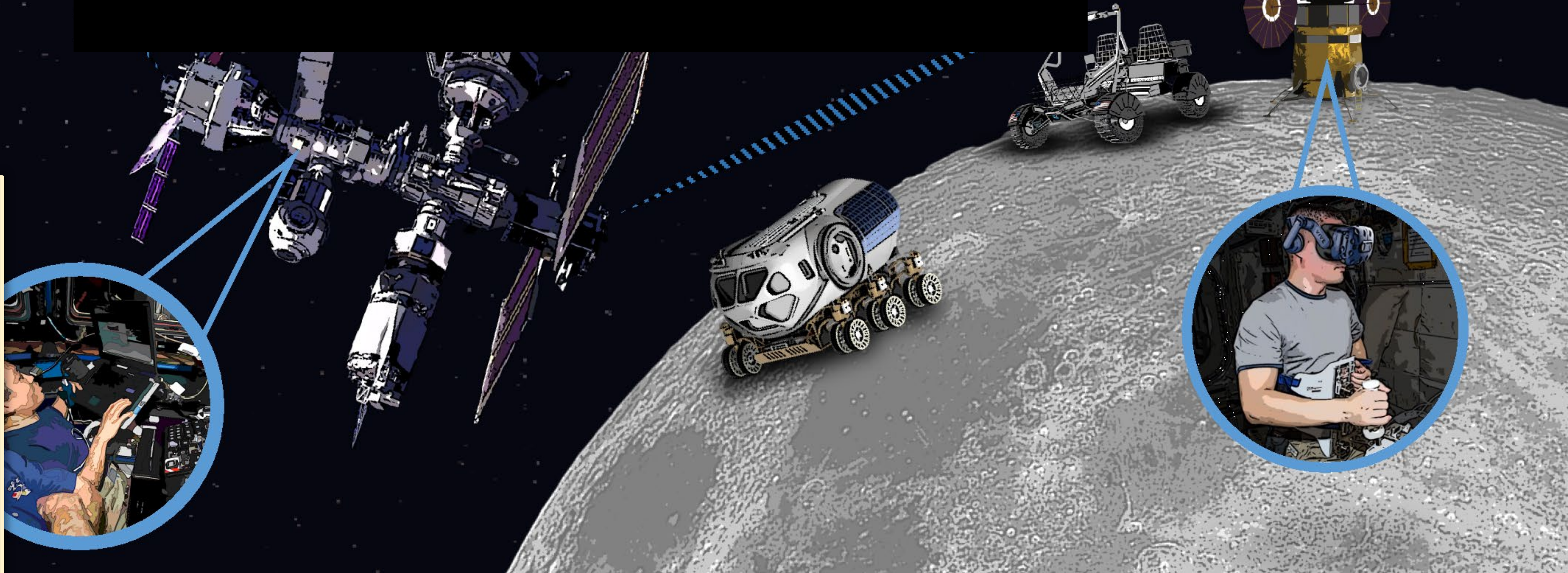
Space Flight Infrastructure and Science Facility Deployment

Carey McCleskey

NASA KSC

Day 2 / June 8, 2022

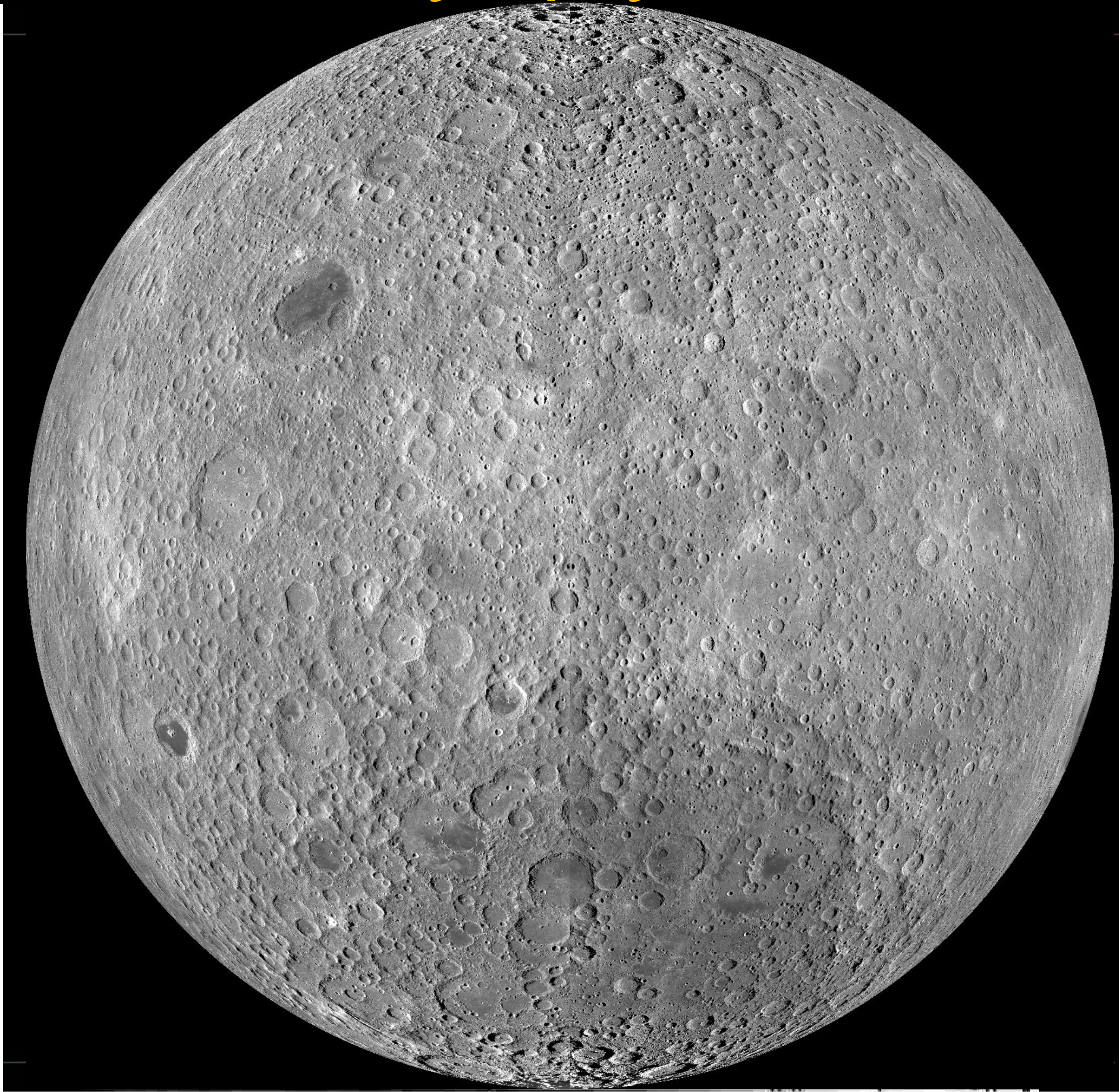
National Aeronautics and Space Administration



UNIQUE SCIENCE FROM THE MOON

Topics—Space Flight Infrastructure and Science Facility Deployment

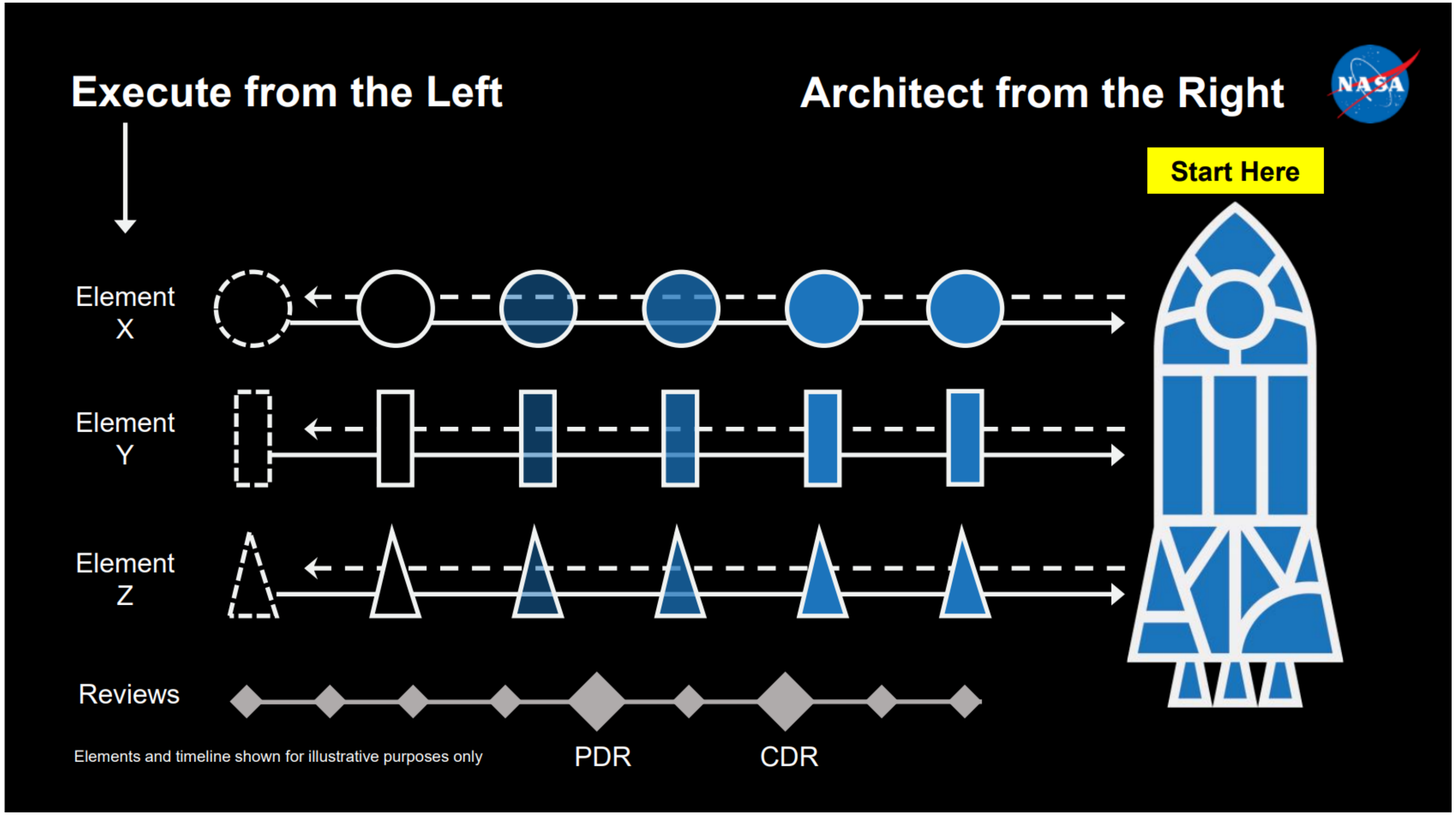
- ❑ Architectural Approach/Context
- ❑ Surface Architecture Functions
- ❑ Surface Site Planning
- ❑ Overview Human/Robotic Use Cases and Support Tasks
- ❑ Surface Science Facility Deployment (Far-side Astronomy)
- ❑ Takeaways



Architectural Approach/Context

Architecting Science from the Lunar Surface

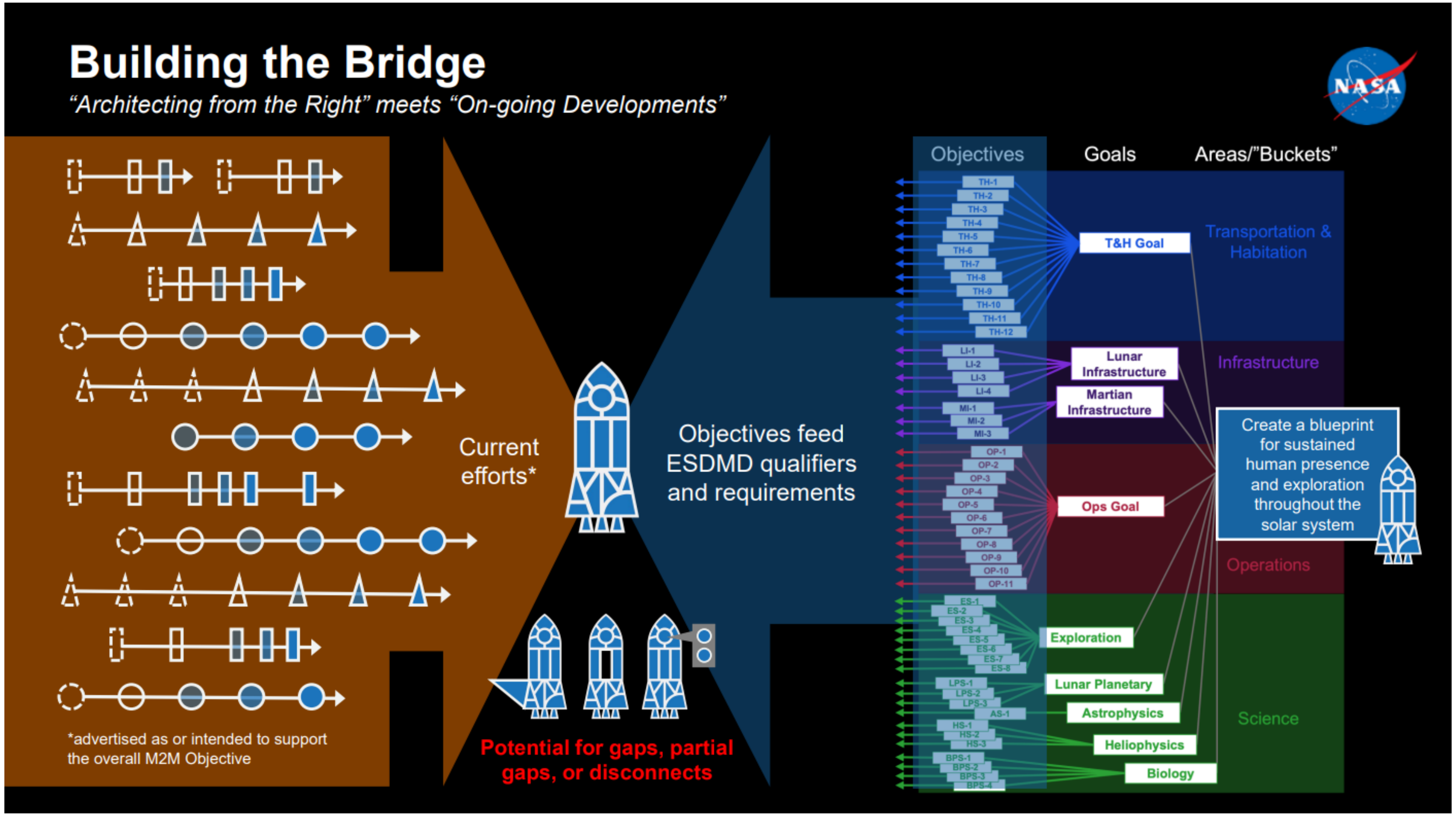
- **Architect surface science *from the right***
  - Envision sustainable science
- **Execute lunar surface science *from the left***
  - Understand initial capabilities



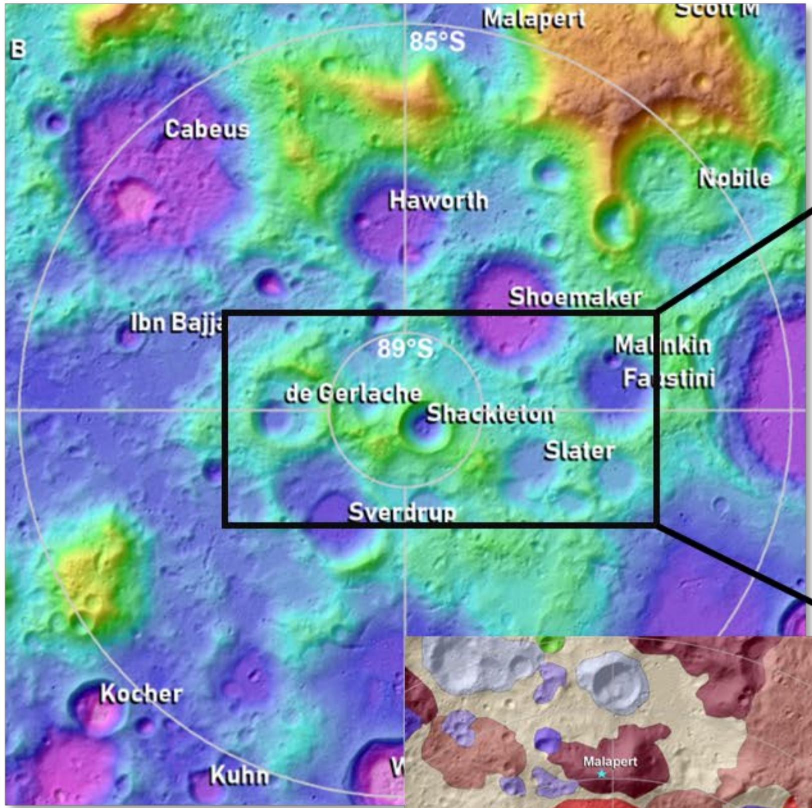
Architectural Approach/Context

Architecting Science from the Lunar Surface

- **Analyze the gaps in science and necessary infrastructure**



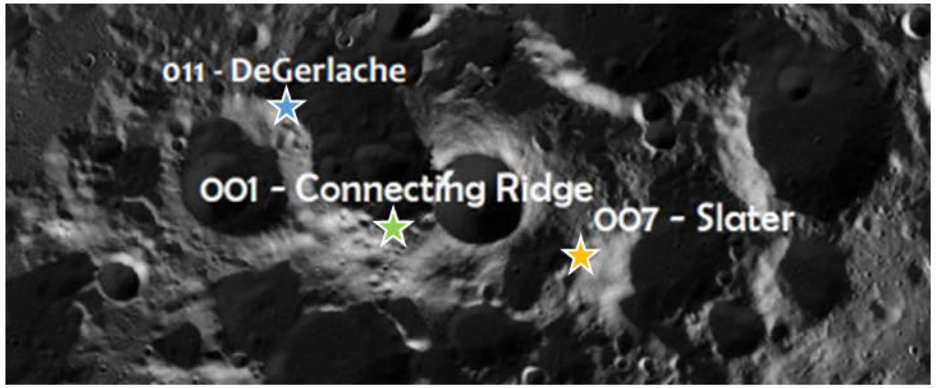
Potential Artemis Base Camp Locations about the South Pole

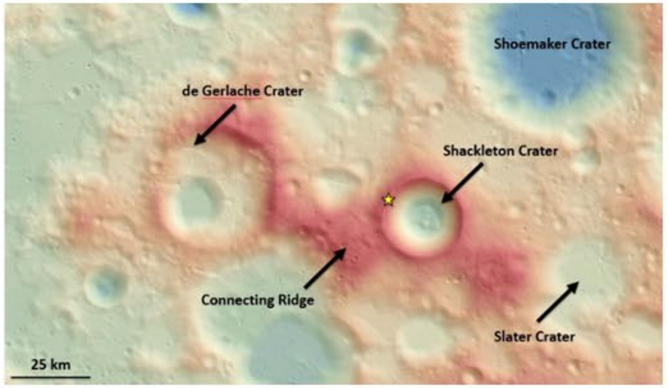


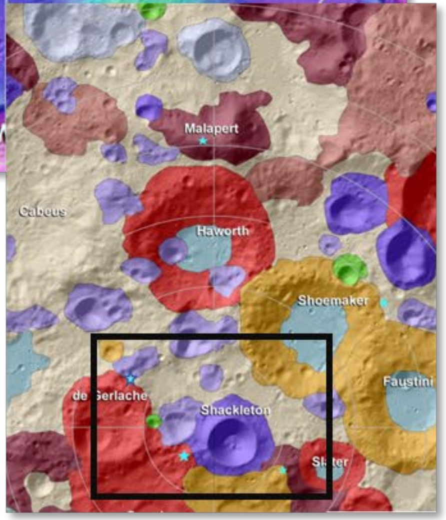
South Pole Region

Candidate Base Camp Sites

Connectivity





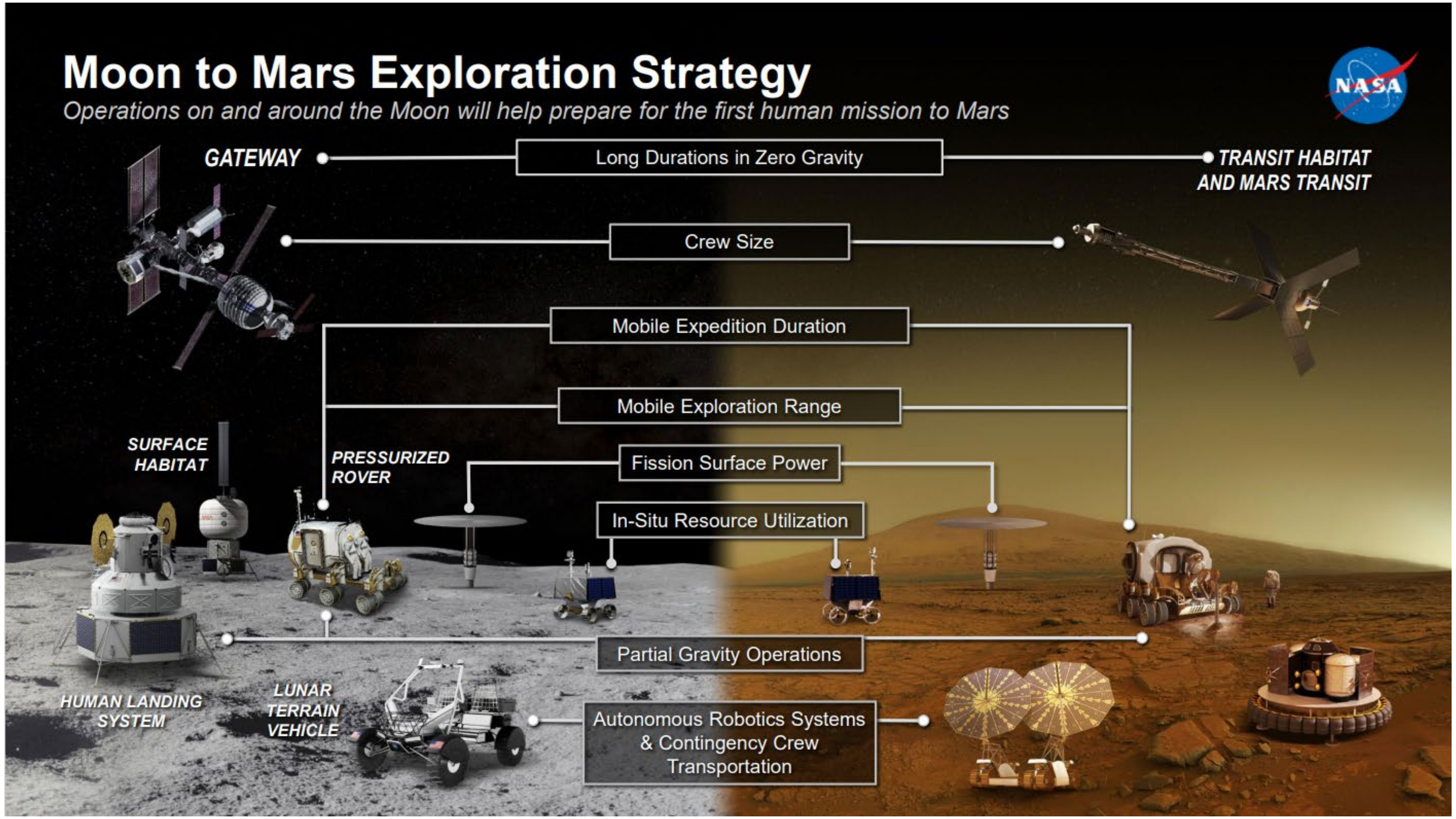


Geologic Unit Variation

Architectural Approach/Context

Where are we now? What's Already Planned to be Available?

- **Current M2M Strategy**
- **Emplaces many of the types of capabilities that will be needed**

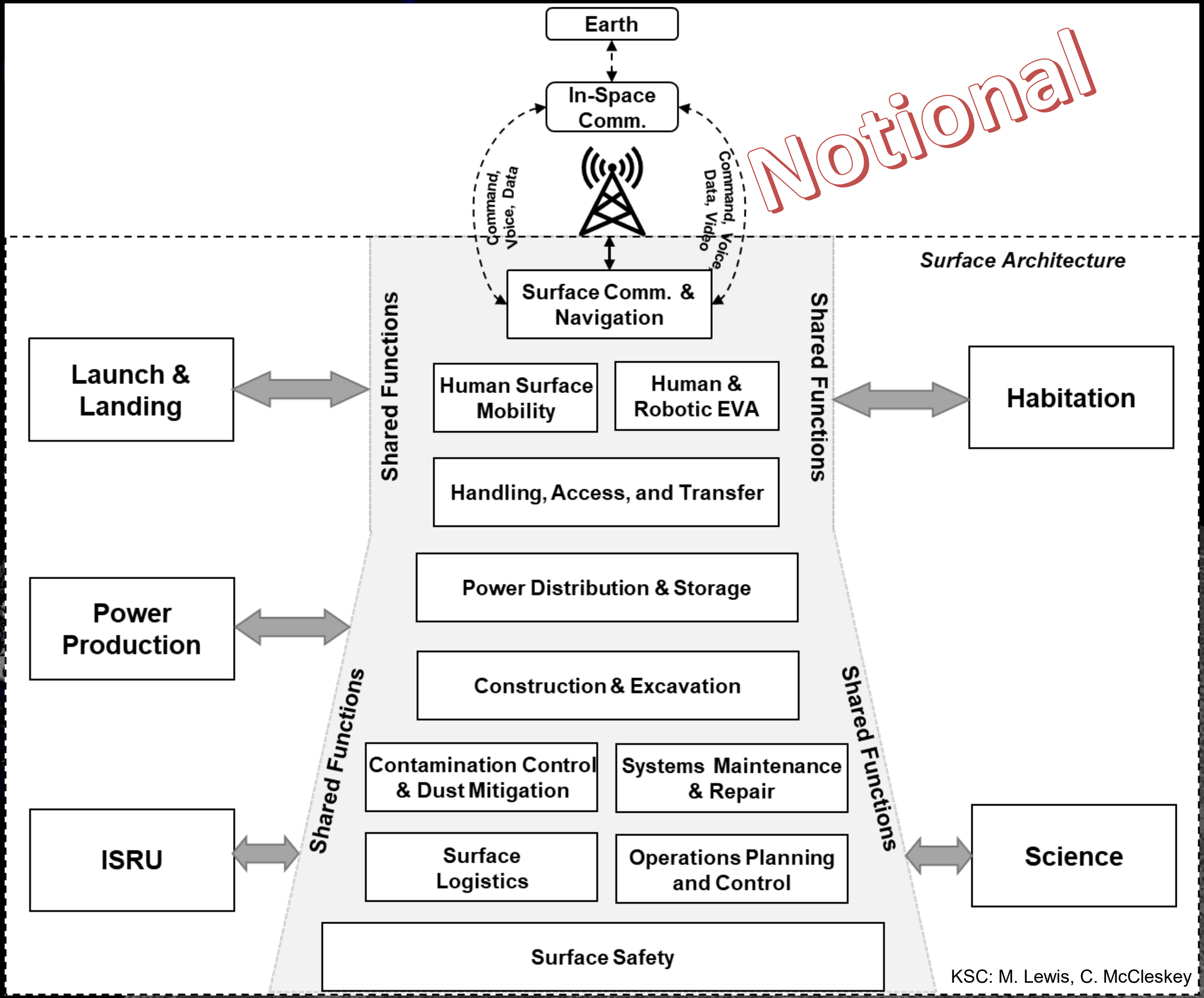


What more is needed to build the "bridge" that enables, for example, radio astronomy from the lunar surface?

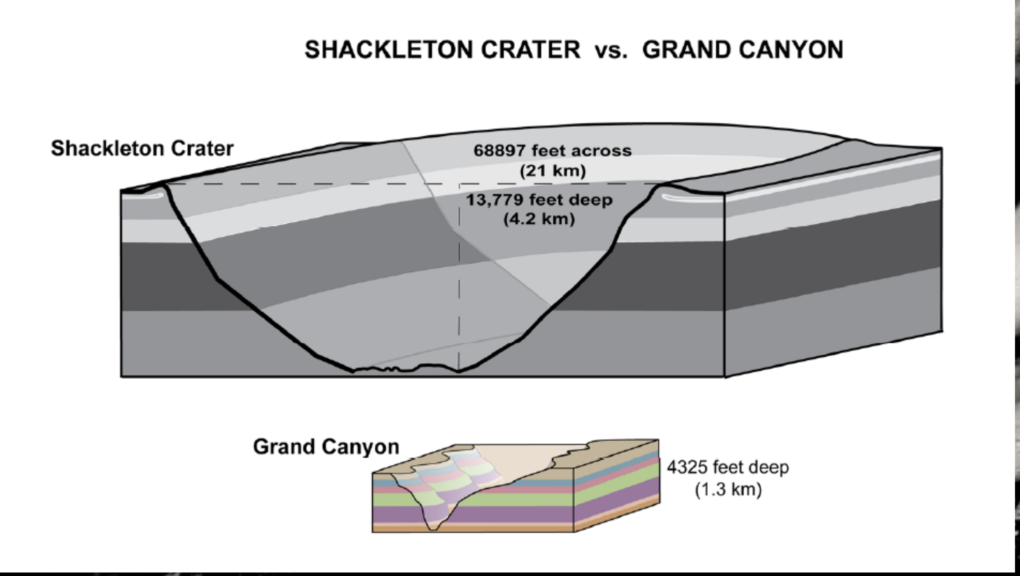
Surface Architecture Functions

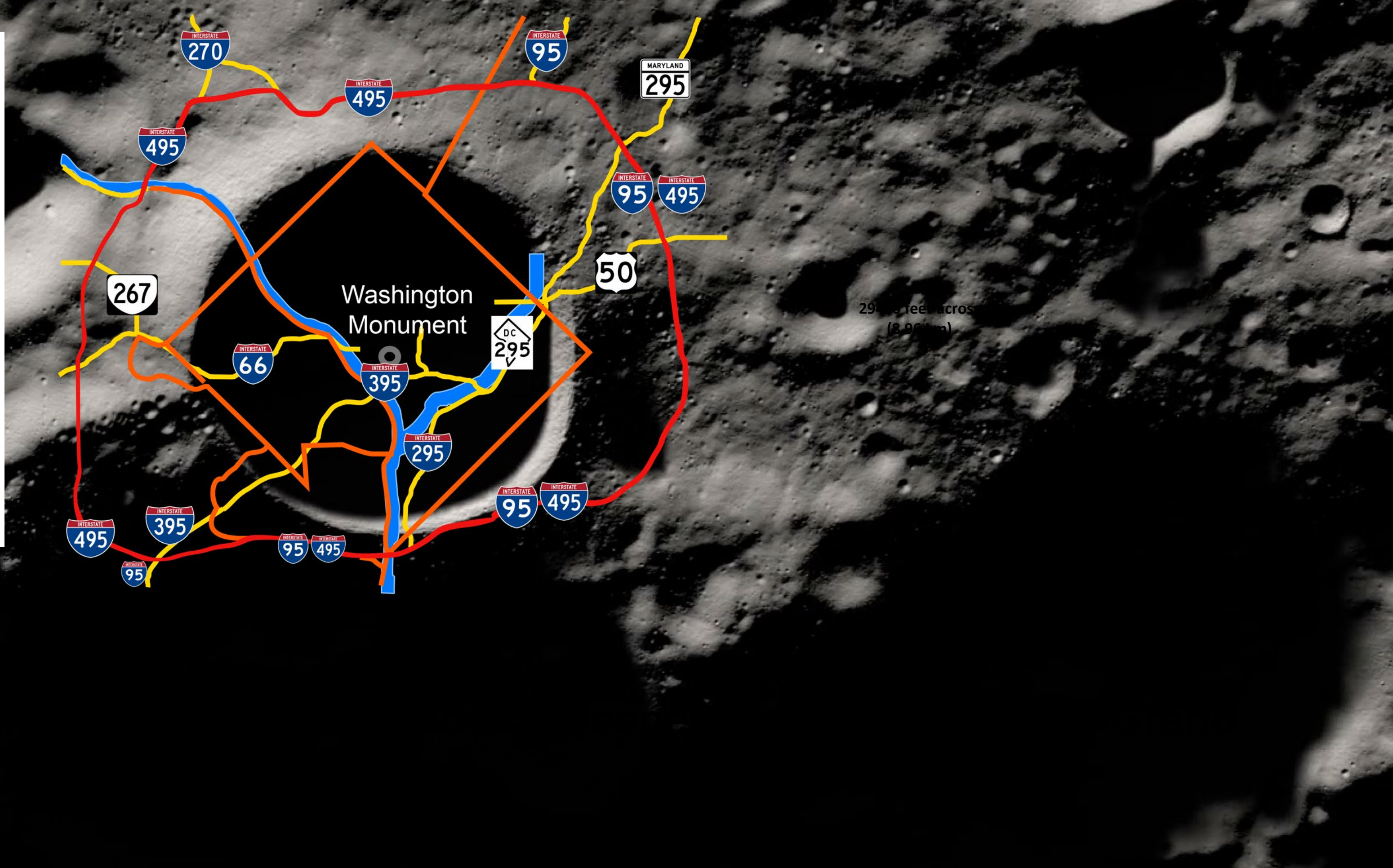
With Focus on Longer Term Infrastructure and Shared Functions

- **Notional *functional* view of surface architectures when "architecting from the right"**
- **Some functions tend to be *sited***
- **Important in *master planning* and layouts**
  - Launch and Landing zones
  - Habitation Zones (*down & out* scenarios)
  - Fixed power production
  - Resource extraction & production zones
  - Science sites (i.e., fixed in location)
- **Many shared infrastructure functions**
  - Some highly visible—EVA and Human Surface Mobility (suits and rovers)
  - Many other ops & support functions required for building and constructing a sustainable presence



The Lunar South Pole





Example Operational Conditions on Surface of South Pole

Operations & Support Simulation Tool Prototypes under Development

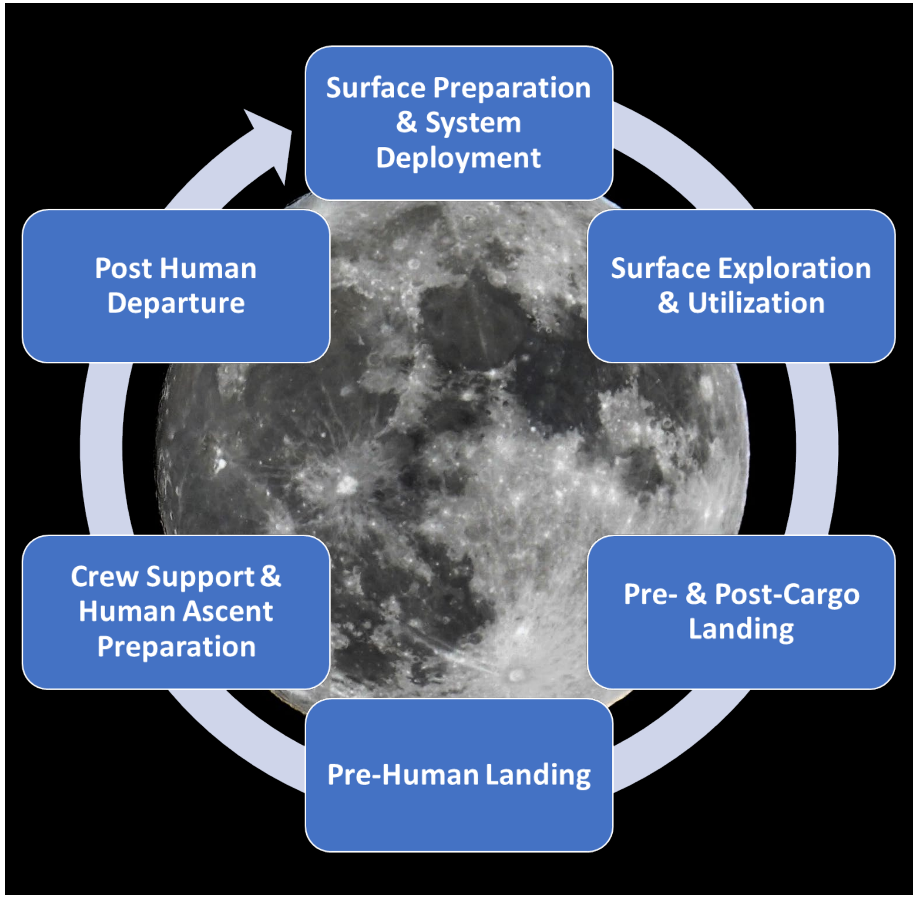
KSC: M. Lewis & D. Gershman

Overview Human/Robotic Use Cases and Support Tasks

Cycle of Surface Science Activity

Types of Surface Science Operations

- Crew Preps for Surface Science IVAs/EVAs
- Checkout Science Payloads Brought to Surface
- Access, Handle and Transfer Science Payloads
- Activate/Operate Science Payloads
- Utilize Surface Resources to Support Lunar Science
- CONDUCT SCIENCE INVESTIGATIONS (See chart)
- Perform Contingency Science Crew Operations
- Perform Contingency Uncrewed Science Ops
- Prepare to Return Lunar Scientists & Science Cargo from the Surface
- SUPPORT SCIENCE ON THE SURFACE (See chart)



Overview Human/Robotic Use Cases and Support Tasks

Cycle of Surface Science Activity

Types of Surface Science Operations (Examples)

- **CONDUCT SCIENCE INVESTIGATIONS (On-site/Remote)**
  - Scout Areas of Scientific Interest
  - Load & Transport Instruments
  - Offload & Emplace Instruments
  - Test/Verify Instruments
  - Perform Closeout Inspections
  - Monitor Instruments
  - Conduct Experiments
  - Drill/Collect Samples
  - Package & Transport Samples
  - Perform Analysis
  - Store Samples
- **In Pressurized Habitat Volumes (IVA) – Lockers/Racks**
- **In Dedicated Pressurized Laboratory Facilities (IVA)**
- **EVA-oriented Science (EVA) – Traverses, Excursions, Science Station Visits**
- **Remote Lunar Science (Uncrewed)**

Apollo 17 Geology

NASA

ISS Food Production

NASA

Overview Human/Robotic Use Cases and Support Tasks

Cycle of Surface Science Activity

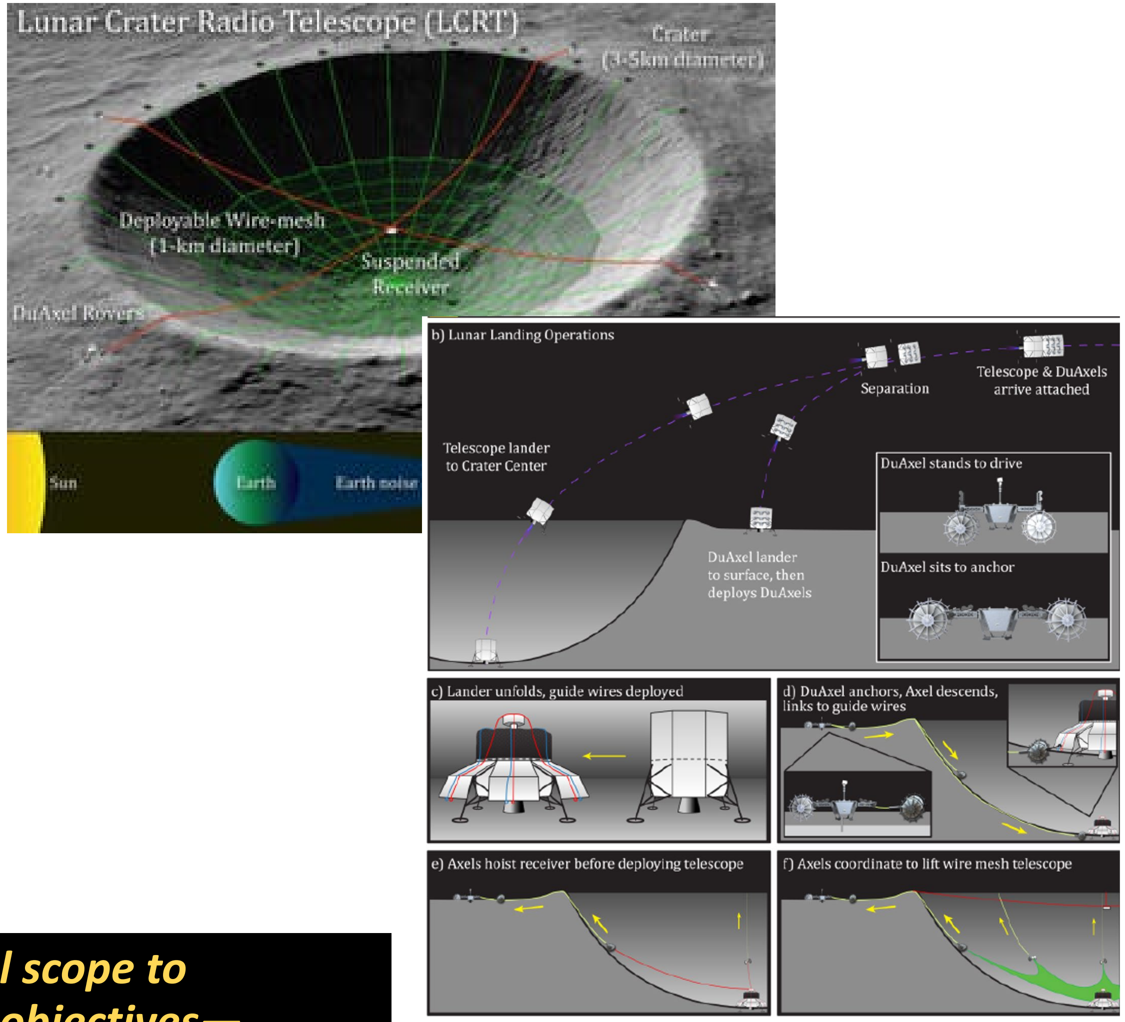
Types of Surface Science Support

- **Power Supply to Surface Science Assets**
- **Human Support to Surface Science Crews**
  - IVA, EVA, EVR, Gateway, Earth-based
- **Surface Mobility of Human Science Crews**
- **Science Information Support on the Surface**
- **Science Comm, Navigation, Pointing, Tracking**
- **Surface Science Imagery**
- **Contamination Control Support-Dust Mitigation**
- **Surface Safety Support for Science**
- **Engineering Support for Science Activity**
- **Science Logistics Support (spares, supply/disposal)**
- **Science Planning, Scheduling, Deconfliction**
- **Access Support to Science Subjects, Equipment, Sensors and Electronics**
- **Heavy Equipment Transfer Support Across Surface of Large Scientific Equipment, Assemblies and Materials/Commodities**
- **Construction Support of Science Stations**
  - Excavation Services
  - Human/Robotic Assembly Services
- **Other Support Services**
  - Fabrication
  - Cleaning
  - Maintenance, Repair and Malfunction Analysis
  - Metrology / Calibration
  - Storage

Lunar Surface Science Facility Deployment Objectives
Far Side Radio Telescope Science Objectives

- **Foregoing surface operations and support functions all likely needed for this application in some fashion—*Excellent capability integration exercise!***
- **Basic concepts of deployment need further architectural exploration (e.g., concept of power, concept of delivery and logistics, etc.)**
- **Human vs robotic, as well as robotically-augmented human activity needs further examination**
  - Pre-arrival robotic set-ups/pre-fab deployments
  - Complex operations better done by on-site crews
  - Follow-up robotic tasks, as well return crew sustainment activities
- **Far-side Radio Telescope Architecture Life Cycle Analysis and Trades: Methods and techniques for:**
  - Site Master Planning / Governance
  - Delivery, emplacement, construction, assembly, activation, test, operations, and sustainment
  - Cost & Economics

[Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon | NASA]



Credits: JPL, Saptarshi Bandyopadhyay

Architectural trades needed with comprehensive functional scope to determine best means to meet science facility deployment objectives—human, robotic, hybrid –across the science facility life cycle

UNIQUE SCIENCE FROM THE MOON

Trends and Takeaways - Surface Infrastructure & Science Facilities

Let's Think BIG

TRENDS

↑ Payload volumes
↑ Payload mass
↑ Number of landers
↑ Reusability
↑ Availability of lander services
↑ Landing/departure frequencies
↑ Mass flux to/from surface (MT/yr)

↓ Unit $$'s
↓ Downtime
↓ Cost-per-ton delivered/returned
↓ Cost-per-seat
↓ Acquisition cycle time

↑ Available pressurized volumes
↑ Crew sizes
↑ Crew stay time/duty cycles

What if it was OK to Tinker & Create in Space!

IMPLICATIONS

Forward-based continuous improvement of capabilities *on the surfaces of other worlds*

- More robotics, greater autonomy
- Diverse mobility
- Increases in Information Capacity/Flow
- Increases in Energy Storage/Power
- More brains – in situ human resources!
- More brawn available (heavy equip)
- More resources: 3D printers, on-site fabrication and even production lines
- On-site shop / laboratory support

Game-changing efficiencies/affordability?

GAPS

- Facilities, equipment, software/AI?
- Services needed?
- Supplies needed?
- Sites encompassed?
- Observatory personnel needed? Surface-based? In-space? Ground?

EVA Operations Design Considerations

NESC Workshop
Unique Science from the Moon in the Artemis Era

June 7-9, 2022

NASA EVA Officer

Jaclyn Kagey

Purpose

Open a dialogue regarding incorporation of EVA requirements in future vehicles, payloads, and other lunar surface hardware.

- Astronaut Requirements for Assembly and Servicing
  - EVA Basics
  - EVA Gaps & Requirements
  - Human Space Flight infrastructure
  - Robotics interaction
- Lessons Learned
  - Historical Testing
  - Shuttle & Station era construction
- Going Forward

EVA Basics

An EVA or Spacewalk is anytime when a crewmember is no longer protected by their home vehicle and are exposed to the external vacuum environments (Micro-gravity, Lunar, or other).

- An EVA is one of the top 3 highest risk events in Human Spaceflight

EVAs have a limited duration based on both crew and suit system consumable resources.

EVA task operations vary in both time and technique between crew members.

- Crew members interact and manipulate a suit differently due to human variations. Tasks cannot be as structured as a robotic operation.
- Interfaces with the suited crew require intentional thought and planning with EVA experts

A spacesuit is a single person spacecraft which protects the crewmember from the external elements and provides life sustaining needs in a mobile workable volume

- Human-shaped and sized space vehicle
- Requires same key systems as other spacecraft however, it needs to be carried by a person
- Habitable pressure, breathable atmosphere, thermal control, mobility, visibility, communication, and protection from environmental concerns

The benefit of an EVA crewmember is the human ability to react to unexpected failures in real-time.

- Robotics and automation is continually growing but has not surpassed a crewmember in this aspect.

EVAs are performed in buddy pairs

- Pairing crewmembers is to help with contingency responses. This is modeled after scuba diving and other high-risk activities.

EVA operations are planned to be as efficient as possible as time is limited and EVA is a higher risk activity.

- Goal is to reduce overall required EVA time
- Time to effect of potentially catastrophic events can be small therefore, risk increases the further the EVA crew is from a habitable space system asset

EVA Limitations

Although EVA space suits provide a crewmember with protection from the space environment, they also limit their abilities beyond a shirt sleeve environment.

Limited mobility / flexibility

- Pressurized gloves make it difficult to do hand intensive or intricate tasks. Specialized hardware is needed due to space suit dexterity.

Greater mass

- A space suit adds mass to the crewmember’s nominal mass which the crewmember needs to account for during operations.

Greater volume

- The volume that the spacesuit takes utilizes more space than a shirt sleeve environment. Tight spaces that restrict movement and body positioning can adversely affect crew health and mission priorities.

Center of gravity differences

- The additional mass and its location on the spacesuit changes the crewmembers typical center of gravity such that many tasks like walking, kneeling, turning, climbing can throw off their balance. Although NASA uses a variety ways to train these differences, they can only simulate part of the equation such that lunar EVAs may still have some learning and real-time adjustments.

Suit Limitations directly affecting payload and science

EVA suits have restrictions with what it can interact with (sharp edges, materials, etc.)

- Hardware hazards near EVA worksites often have KOZs or need inhibits to accommodate EVA suit and crew safety

EVA suits 'off-gas and/or transfer contaminates’ to the space around them such that the environment is no longer pure

Additional Lunar Considerations

Extreme Lighting conditions

- Lunar South Pole will have oblique lighting angles casting extreme shadows
- Lunar regolith can be highly reflective
- Permanently Shaded Regions (PSRs) are extremely dark and very cold

Navigation

- Return to vehicle (crew safety)
- Pinpointing scientific locations accurately (EVA efficiency and Science utilization)

Communication and Autonomy

- Task intricacy = additional communication with MCC
- Hardware/software concepts could increase crew autonomy

EVA Gaps

- What technology development is needed for Artemis and beyond?
  - There are more than 100 gaps across the NASA exploration architecture that affect EVA.
- References:
  - Beyond Artemis EVA Gap Overview
    - October 2021 Exploration EVA Technology Workshop (NASA/Chris Nelson)
    - https://www.nasa.gov/sites/default/files/atoms/files/8.0_-_beyond_artemis_iii_eva_gap_update_overview_final_updates-1_-_chris_nelson.pdf
  - https://www.nasa.gov/suitup/reference

- Notable Gaps:
  - Dust Tolerance and Mitigation
  - Lighting
  - Communication
  - Autonomy
  - Navigation
  - Mass reduction

EVA Operations Thinking

Using this Mars Architecture rendering, what do you see?

- What works operationally for EV Crew?
- What does not make for good operations?

- Winch system √
- Fall protection X
- Pressurized Rover √
- Incline ramp with no rails or aids X
- No Handholds or large labels on crates X

EVA Hardware Requirements

The concept for EVA assembly and repair is to keep it simple

- Plan Orbital Replacement Units vs intricate repairs
- Big elements by robotics and intricate or detailed work by EV crew
- Standardization of bolts, connectors across vehicles and payloads

There are a multitude of EVA documents that describe con ops and requirements

- Public info at https://www.nasa.gov/suitup/reference and additional documentation available within NASA
- We are working to make a primer to get hardware developers started
- Early integration with EVA Operations is essential

Exceptions to requirements will be analyzed and tested by NASA EVA

- Potentially granted on a case-by-case basis but not guaranteed

Operations Influencing Design

- All designs start out with a concept to build the best 'x'.
- Requirements may not design hardware that optimizes the operation of the hardware.
- Thus, it becomes very important for the operations teams to play an influential part in the design process.

Injury and Risk Prevention	• Can this design injure or pose significant risk to crew?
Reliable	• Where does this design need to be more robust or redundant to keep crew safe and to prevent design failures?
Efficient	• Does this design increase crew efficiency in operations?
Reduced Workload	• Does this design add to the cognitive or physical workload?
Upgradeable	• If we must live with this design for the next 10, 20, 30, 40 years, can we make easy upgrades?
Maintainable	• Does this design significantly reduce or eliminate the need for corrective maintenance requirements?
Flexible	• Does this design lock in only one ops concept or does it allow for operation flexibility?
Testable	• Does this design have a plan to test and evaluate prelim concepts? How early can the ops community get hands-on?
Compatible	• Is this design compatible with the current and future ops concepts and other existing hardware?
Trainable	• Does this design require new or modified training infrastructure? Is there a plan for early training hardware?

EVA Operations Integration into the Design Process
Flight Operations Directorate (FOD)

During the design phase, FOD EVA is involved in early design reviews to evaluate the crew – hardware interactions.

- FOD EVA will provide the hardware team with assessments of the compatibility of the design to EVA operations. There may be required changes (safety) and desired changes (EVA efficiency and ops ease).

After a tool, payload, or hardware has a preliminary design, FOD EVA and the crew office will test the EVA Operations with it.

- Hardware will be rated: Acceptable, Unacceptable (design changes required), or Inconclusive

EVA is a unique skill and does not always align to defined actions

- The crew office and FOD (Flight Operations Directorate) EVA assess hardware and develop procedures and will incorporate workarounds if required.

Infrastructure Essential for Optimal EVAs

HLS vehicle

Base Camp (Hab)

Home Base
- Crew living area
- Consumables recharge
- Communication relays
- Earth Return

Communication & Navigation Resources

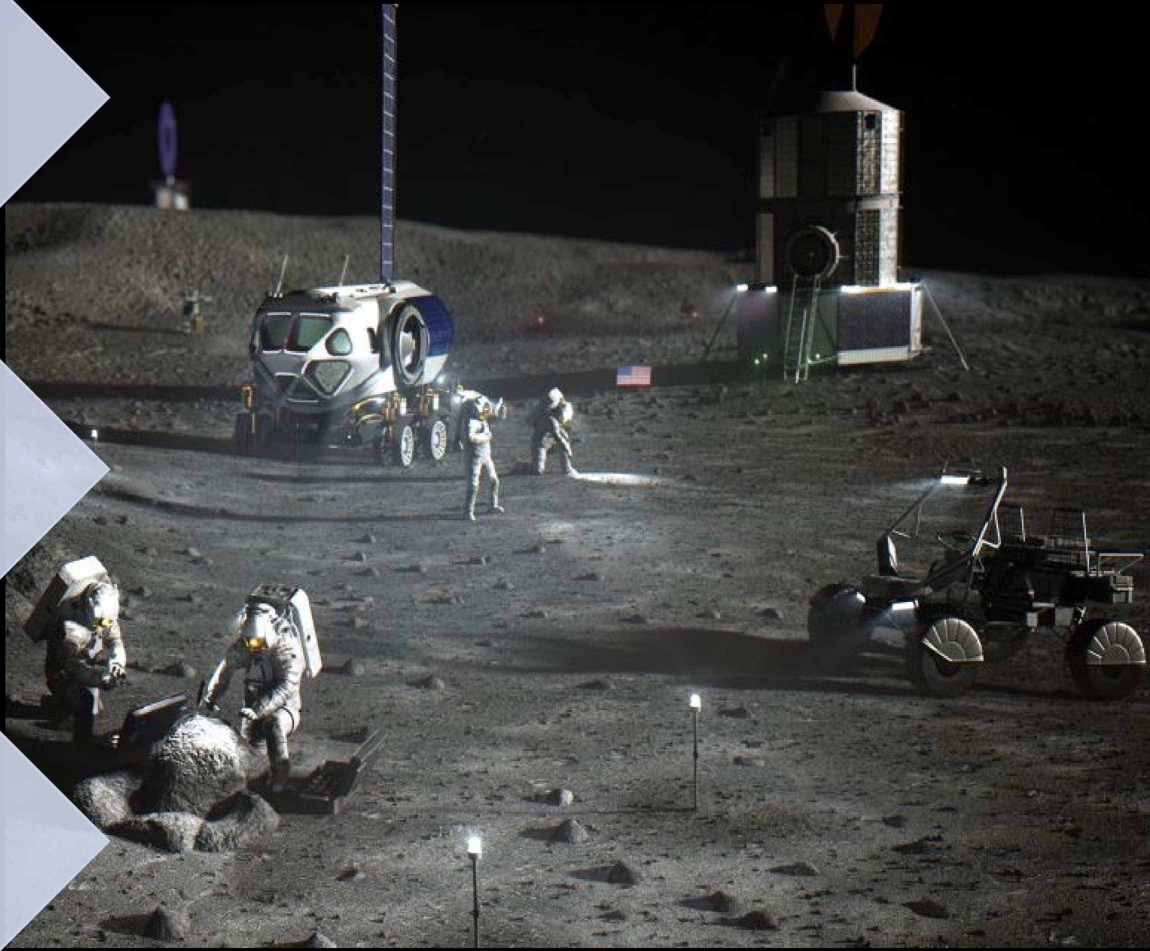
- EVA crew needs constant communication with each other
  - Easy comm with MCC for guidance as needed
- Precise navigation
  - Science & Safety

Expanded mobility

- LTV
  - Reduces workload on crew
- Pressurized Rover
  - Take your “safe haven” with you
  - Allows for farthest exploration

Ease of EVA

- Going EVA needs to become easier, less overhead
- “Safe Haven” readily accessible



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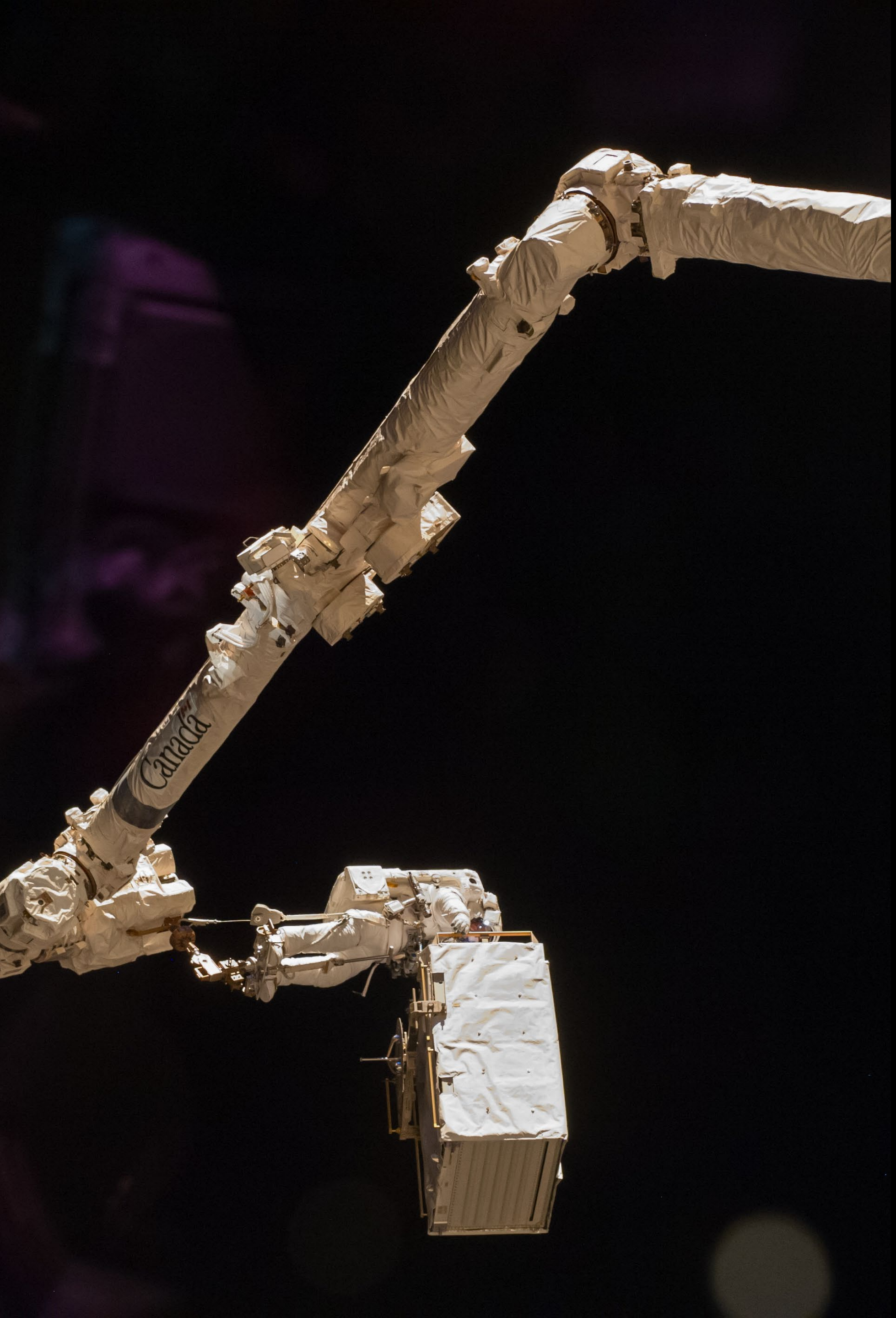


Robotics Integration

Robotics is typically utilized for EVA in 2 distinct methods

- During EVA
  - Direct interaction between robotic entity and EV crew
    - Current operations are predominately controlled by a local IVA or internal crewmember
    - Very limited work analyzed for remotely controlled (MCC)
    - No experience base with autonomous robotics
  - Typical interactions
    - Utilize robotics as a mobile platform (move crew to worksite in microgravity)
    - Robotics move large hardware and hold in position for EVA crew
- Pre EVA-Setup and Post EVA Cleanup
  - Robotic resource may setup worksites (tools, restraints, hardware) before the EVA to make EVA time more efficient
  - Similar post EVA cleanup and “housekeeping”

Robotics Requirement Considerations for EVA

Planned operation of lunar transport vehicles while crew on or in vicinity is crew operated

Future work to identify "follow along" or "summon" features

Remote operation should be possible while crew is not EVA or a defined safe distance

Ability to have inhibited motion when crew is near

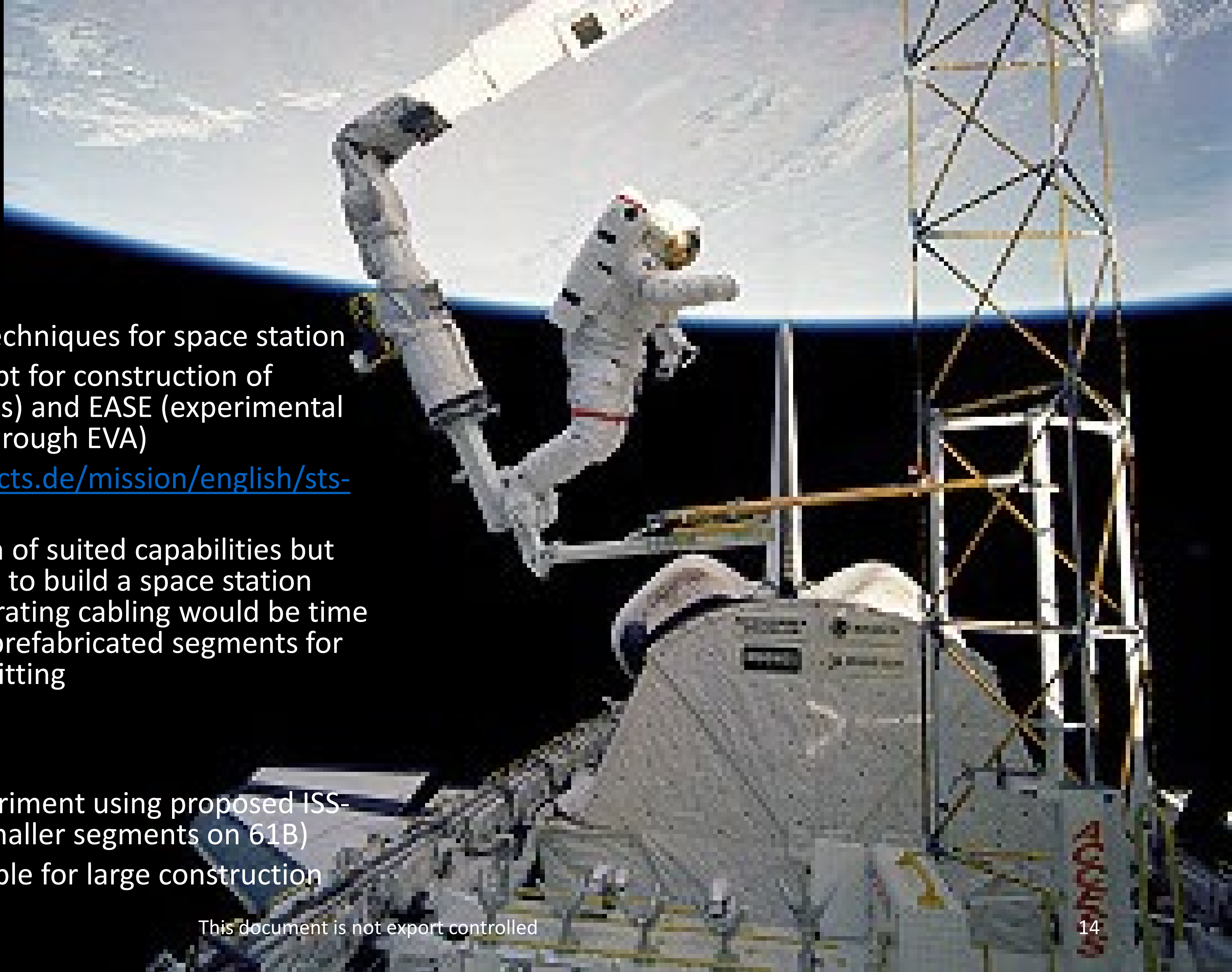
Especially during ingress & egress of a vehicle like the Pressurized Rover

Large uncontrolled robotic maneuvers could cause harm to crewmembers and EVA suits

To enable non-local crew controlled robotic operations, remote sensing to stop robotic operation prior to impact of crew needs to be explored

This is not specific to space exploration. Integrate research on human robotic interactions and apply to spaceflight.

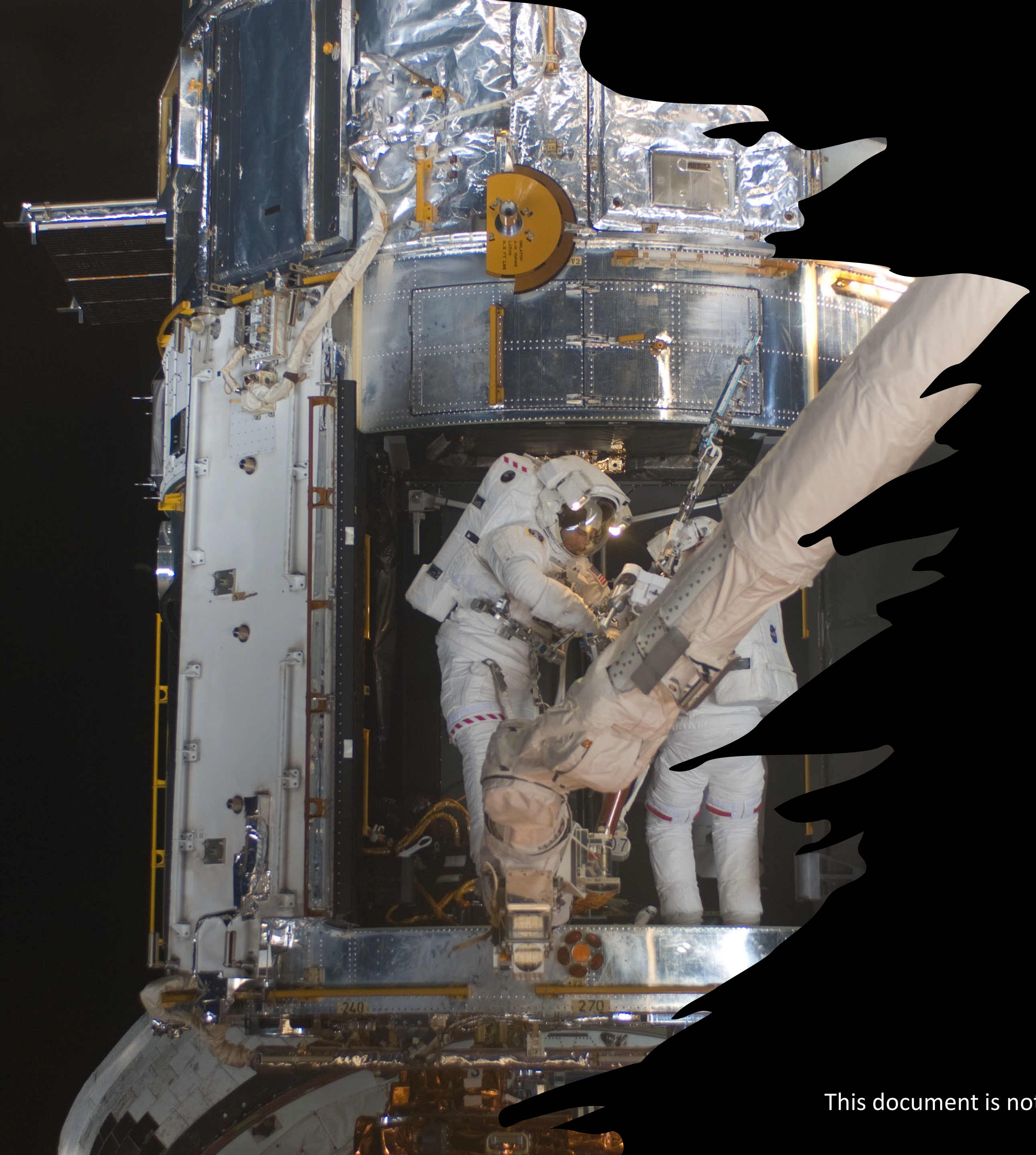
Shuttle Era Concept Testing



- STS-61 B EVA 1 & EVA 2
  - Demonstrate assembly techniques for space station
  - ACCESS (Assembly concept for construction of erectable space structures) and EASE (experimental assembly of Structures through EVA)
    - http://www.spacefacts.de/mission/english/sts-61b.htm
  - Successful demonstration of suited capabilities but did show that attempting to build a space station beam by beam and integrating cabling would be time consuming vs launching prefabricated segments for EVA attachment and outfitting
- STS-49 EVA 4
  - Second EASE / ACCESS
  - Updated truss build experiment using proposed ISS-like truss segments (vs smaller segments on 61B)
  - Proved concept not feasible for large construction project (ISS assembly)

Planned Assembly & Servicing

- The International Space Station was designed to be assembled and serviced by EV crew
  - Common parts, captive bolts, hardware that meets the EVA requirements documents
- ISS construction – mating of truss segments and deploy of radiators and solar arrays
- ORUs (Orbital Replacement Units) are best – replace an entire box
  - No splicing wires, non-captive bolts, etc.
- IROSA (ISS Roll Out Solar Array)
  - More intensive EVA construction than mate/bolt but designed specifically for EVA



Unplanned Servicing and Repair

Successful examples of unplanned servicing of hardware not designed for EVA crewmembers. Additional tools or hardware had to be built and operational constraints waived to accommodate new tasks.

- Skylab
  - Heat shield and “parasol” EVA
- Hubble
  - Unique that is had planned and unplanned servicing over its life
- LEE (Latching End Effector) Lubing
  - ISS arm grappling mechanism wear
- AMS (Alpha Magnetic Spectrometer)
  - Cooling pump failures on a scientific experiment with no EVA aids or even sharp edge verification

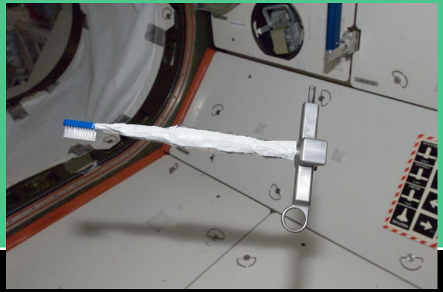
Contingency Workarounds

Spaceflight is not a stranger to needing to address Off Nominal situations real-time during a Mission or EVA.

Apollo 17 Lunar Rover fender fix

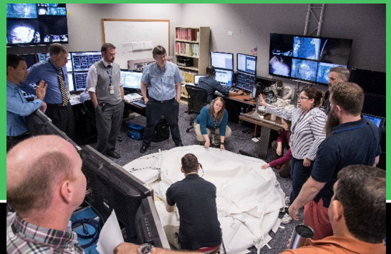
STS-120/10A Solar Array Repair

US EVA 19 MBSU bolt lubing



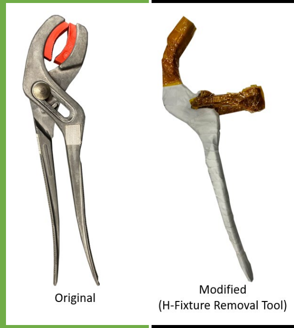
US EVA 41

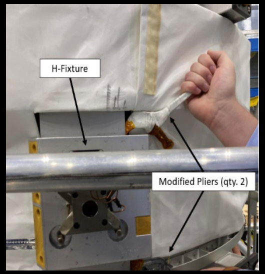
- Axial shield lost overboard and real-time workaround



US EVAs 66/68

- Inability to remove fixture
- IVA channel locks disassembled and modified for EVA





Lessons Learned Summary

- Keep It Simple
    - Standardization
- Design with EVA Requirements from the beginning
    - Although we often can make it work later; it costs significant more money and EVA time thus more risk (to both crew and mission success)
- Integrate EVA experts from the beginning

Going Forward

- Steer future designs to include EVA requirements
  - Don't focus only on the desired plan of your hardware concept but also on the "what if"
  - Other projects have not included basic EVA requirements which led to significant issues when EVA assistance was needed
- Use EVA expertise to bring EVA capability actualities into concepts

- Questions?
- Additional Resources:
  - https://www.nasa.gov/suitup/reference
    - Links to published EVA documents including gaps
  - https://www.nasa.gov/jsc/procurement/xevas
    - xEVAS RFP, waiting on vendor selection

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Cost Challenges and Opportunities

Nick White, Jay Bookbinder, Carol Grunsfeld

Challenges of Human and Science Partnership

- Many in the space and Earth science community have concerns hitching their wagon to the human program
  - Fear of cancellation
  - Fear of human rating
  - Fear of delay
  - Fear of extra cost
- Result has been a NASA space and Earth science program that is currently largely decoupled from the human program
- However, there have been examples of successful collaboration
  - The key is building trust and having overlapping goals

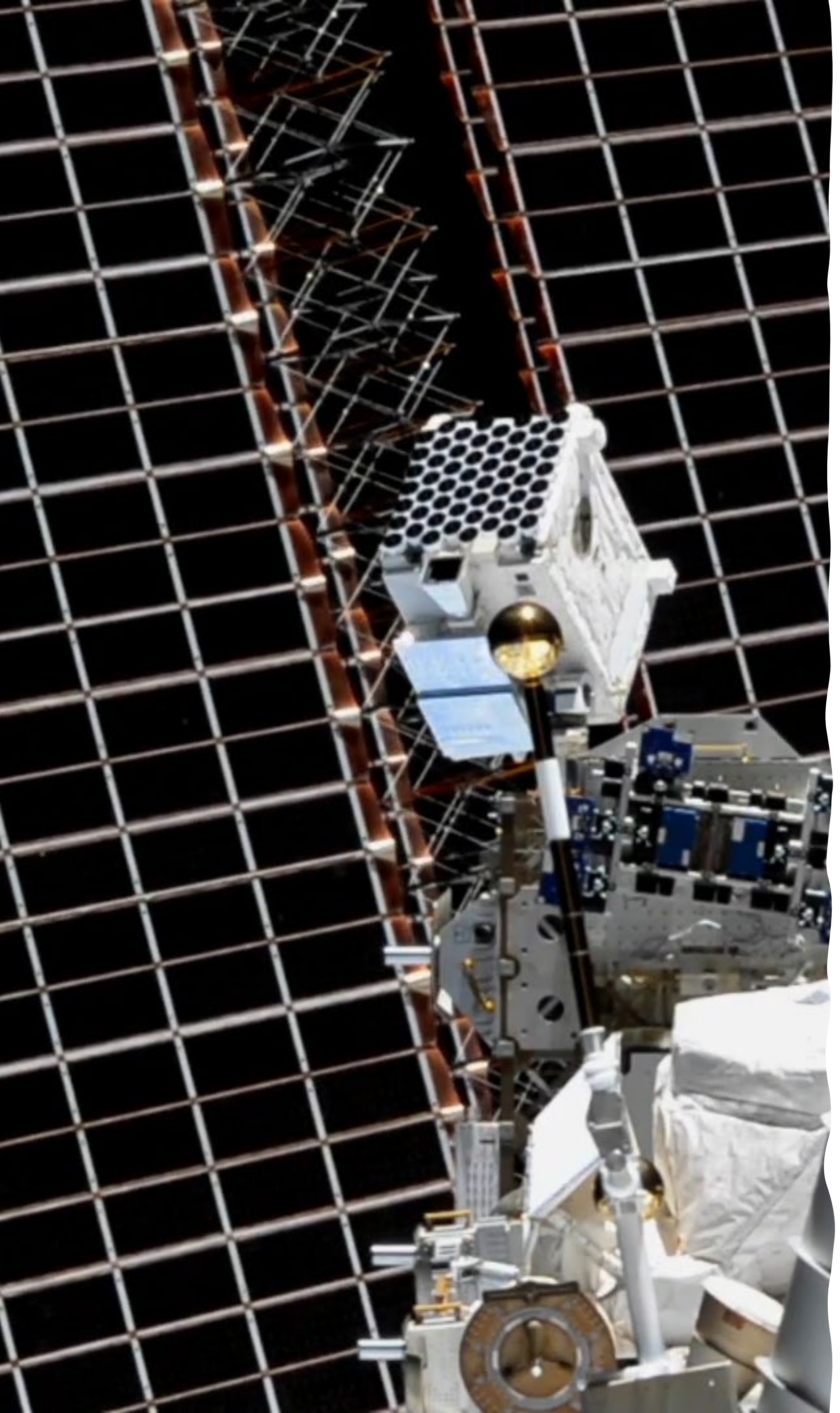
Partnership Model

Nick White

Hubble Space Telescope

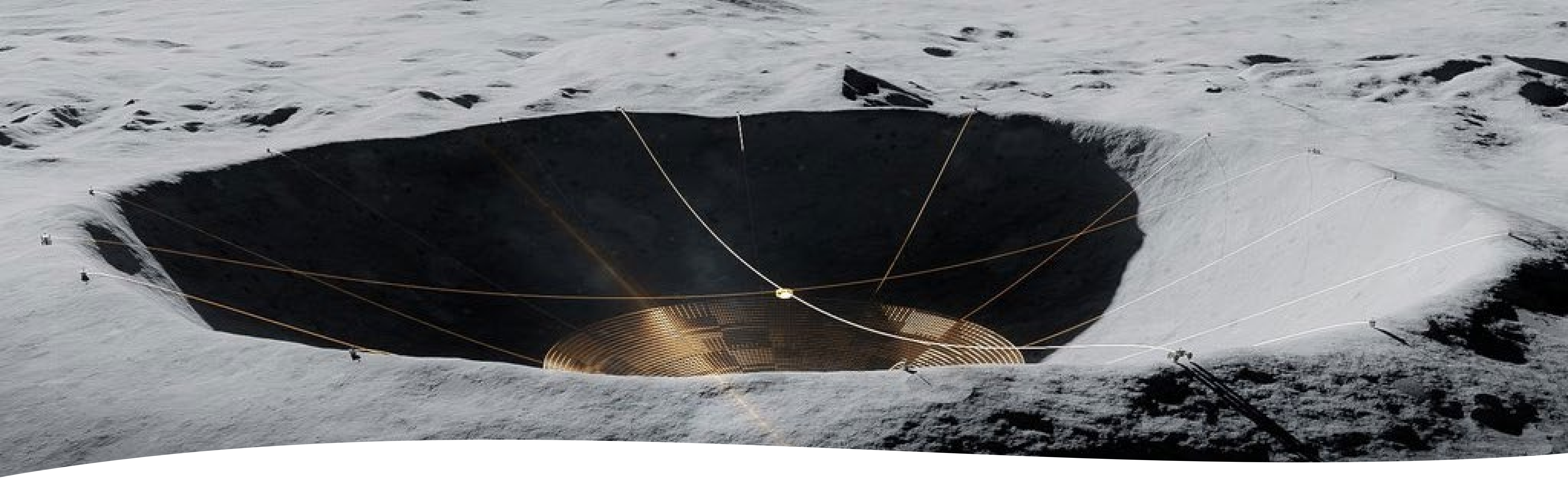
- Outstanding successful partnership between NASA human spaceflight and science programs
- Science funded observatory and instruments ($14B)
- Human space flight funded launch and servicing missions ($6B)
- Servicing capability provided ability to recover from unexpected challenges and perform complex repair tasks

2017 dollars



International Space Station

- Science enabled by exterior payload attach points viewing up (astrophysics) and down (Earth science)
- Human spaceflight provides launch and enabling infrastructure
- NASA Science Directorate funds instrument typically via competed opportunities e.g. Explorers
- Other agencies e.g.,
  - DOE funded AMS instrument
  - JAXA MAXI experiment
- Slow start, but now very successful



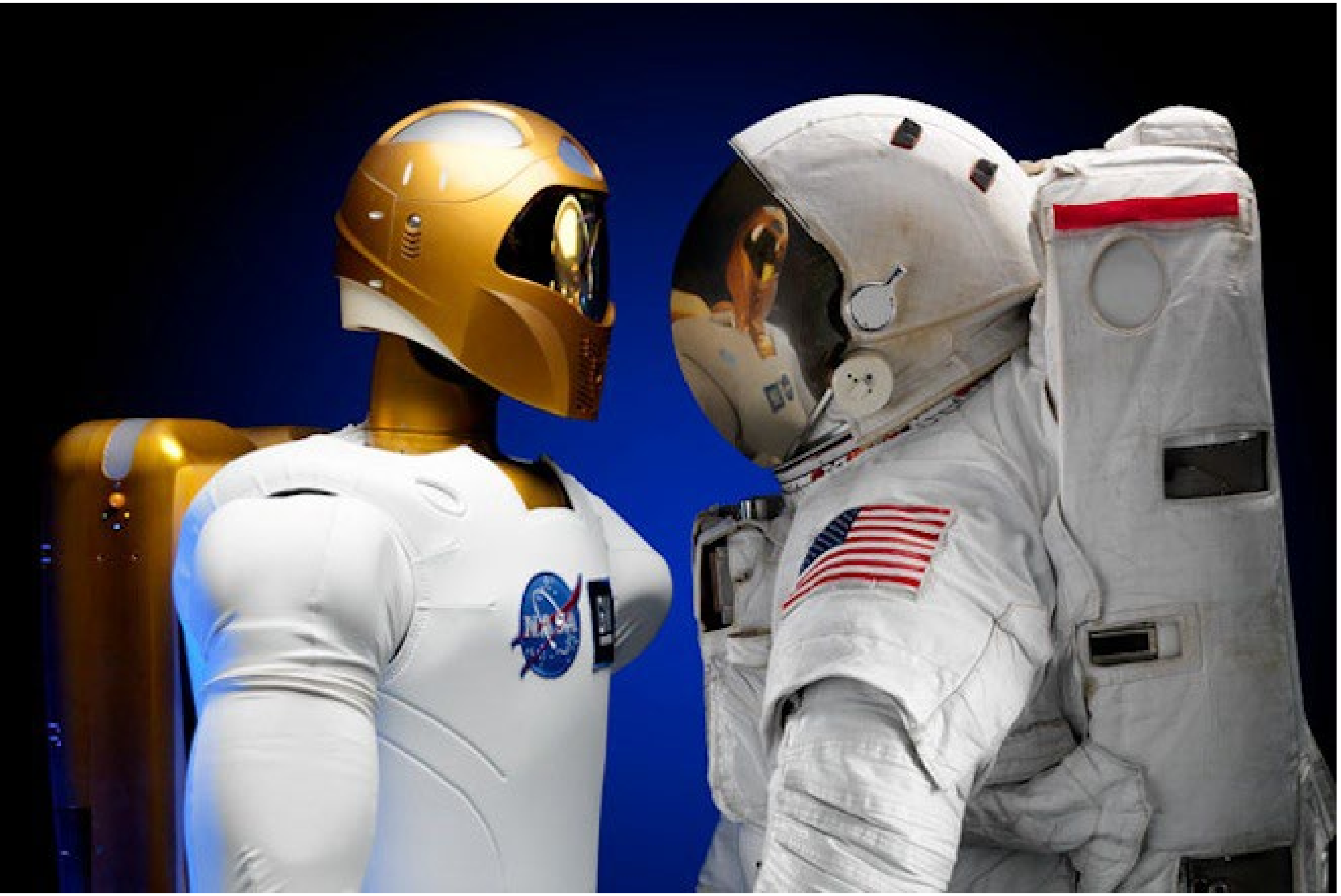
Artemis Science Opportunities?

- Future Lunar radio telescope and other observatories/instruments are only likely to happen if it is a partnership between Human and Science programs
- Follow the successful Hubble and ISS model i.e.
  - human space flight program funds launch, any human assisted construction, comms and servicing,
  - science funds the observatory and instruments
- Agreements and plans in place for next Decadal survey in 2030

Human vs. Robotics

Jay Bookbinder

Human vs. Robotic



Generalizations:

Assign Risk Posture

Minimize costs at a given risk

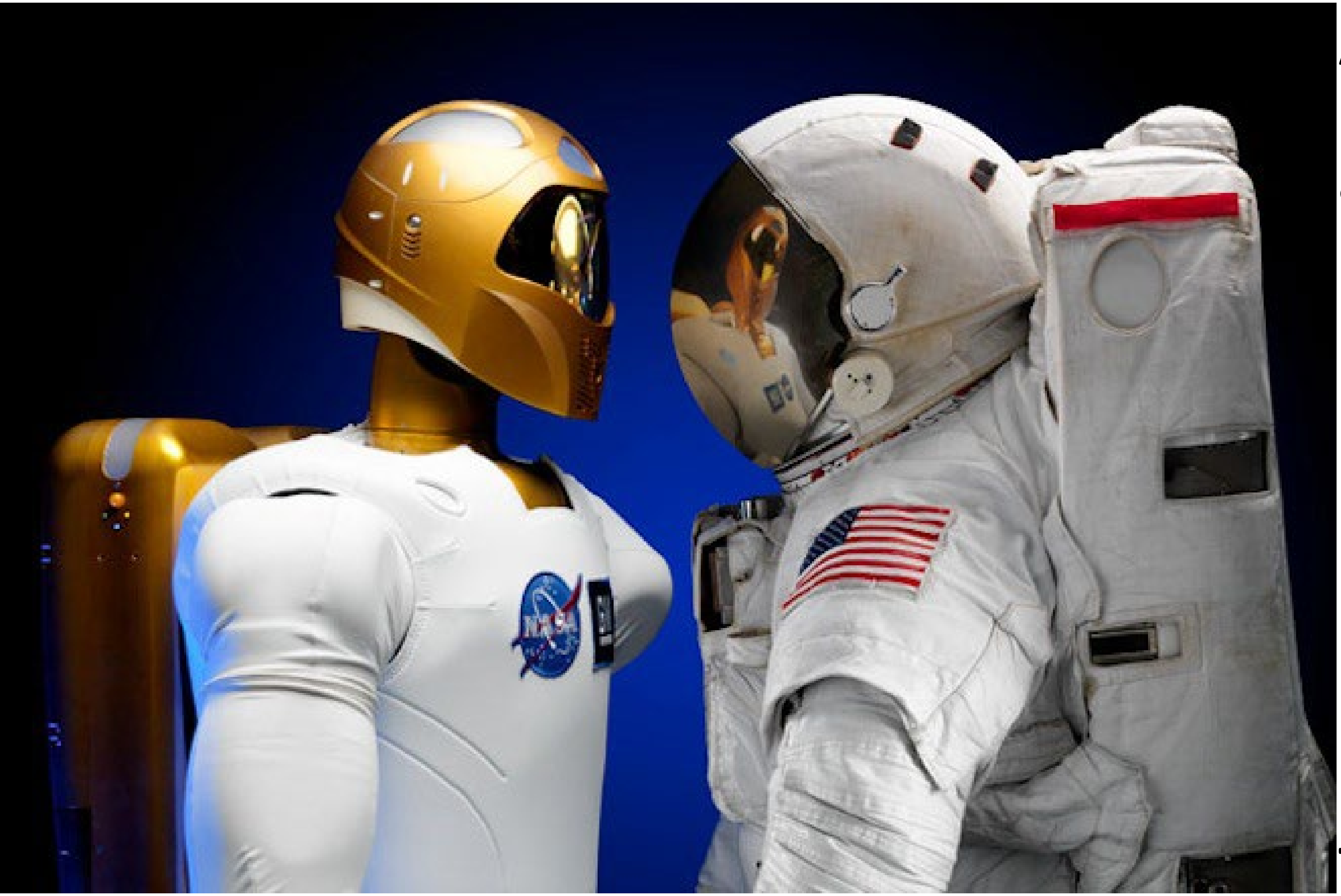
But:

Not even conceptual cost models exist

Concern:

Cost credibility won’t be high

Human vs. Robotic

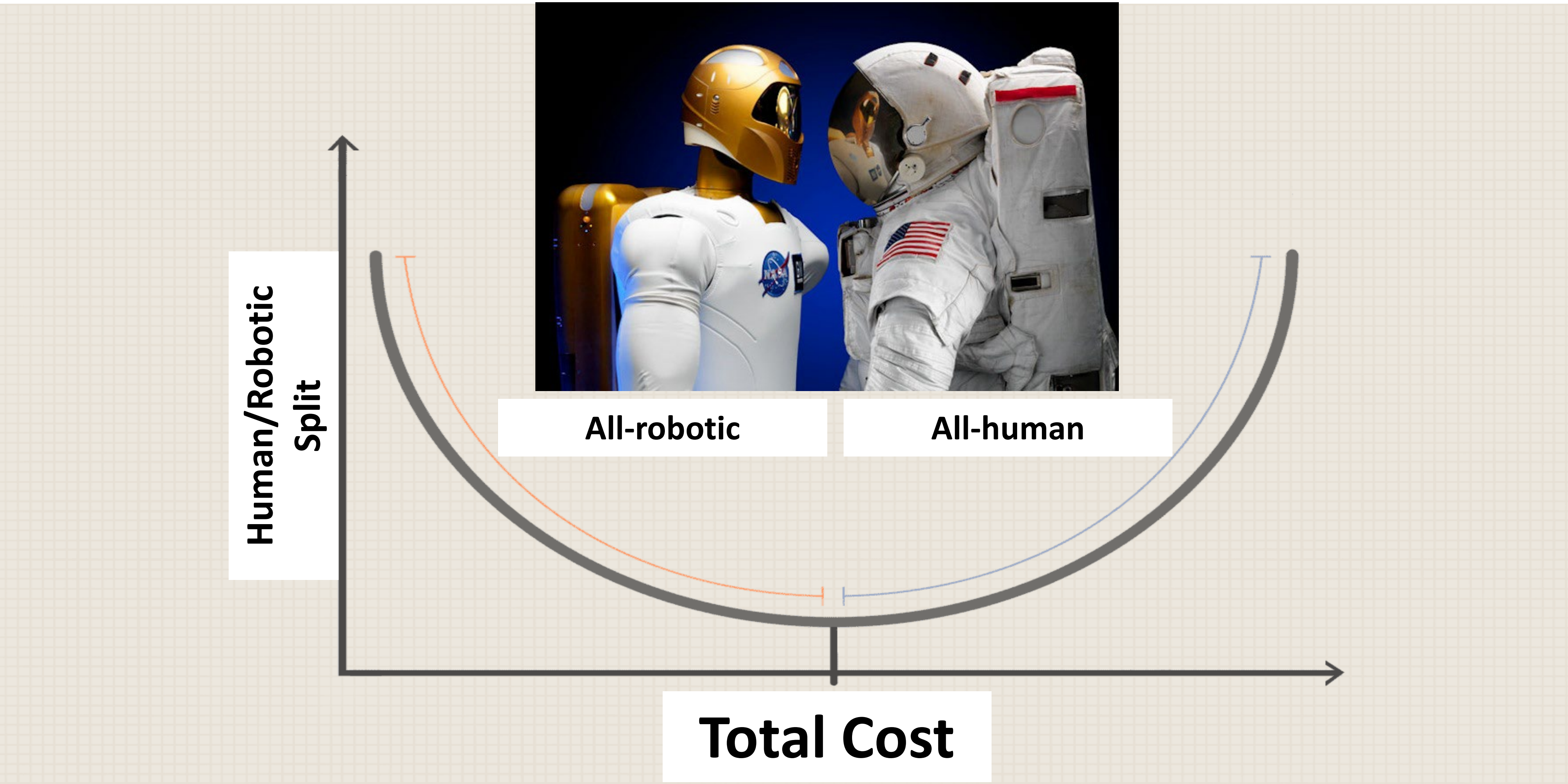


A safe assumption: Cost minima are likely to be a combination of robotic and human at the task level. E.g.

Initial assembly:	**robotic**
(some) final integrations:	**human**
Routine maintenance:	**robotic**
One-off repairs:	**human**

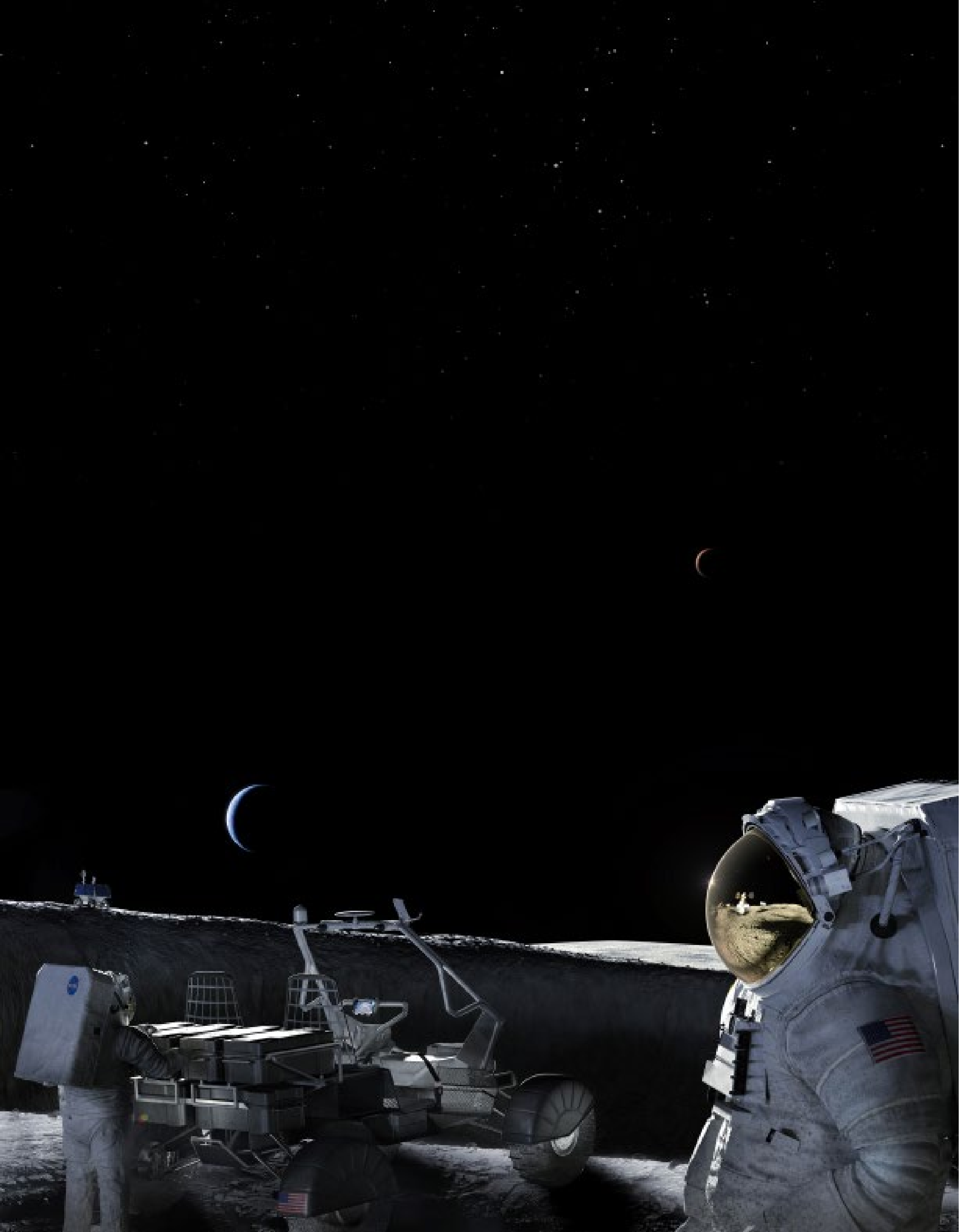
True minimization will require careful parsing => "Local" teleoperation??

Human Ingenuity vs. Robotic efficiency



Infrastructure & Capabilities Strategic Investments

Carol Grunsfeld



Infrastructure & Capabilities are Strategic Investments

- Enable Future Exploration and Unique Science
- Engage and Inspire Next Generation
- Maximize Investments from Government, Private Industry, and International Partners
- Utilize Geo-strategic, Geo-political and Economic Sphere
- Reduce Risk for Mars Missions, Prove Capabilities, Provide Lessons Learned
- Drive Effective and Efficient Delivery of Services

Infrastructure & Capabilities: Science Goal Challenges

- Identify Science Unique Requirements
- Vette with NASA Future Systems Formulation/Moon & Mars Architecture Communities
- Get Requirements into the Baseline Program

Artist's rendering of astronauts conducting science and exploration activities on the lunar surface.