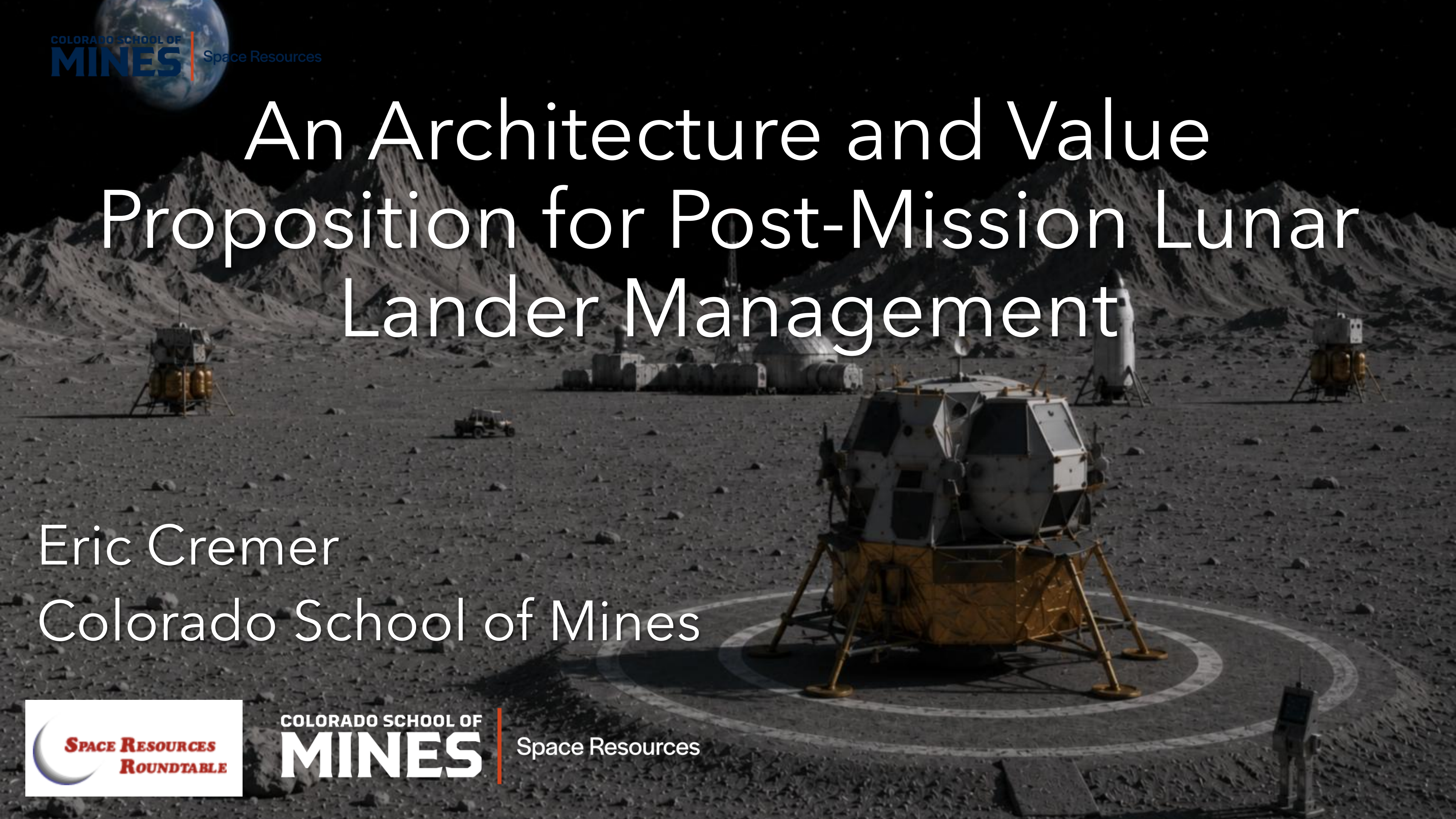


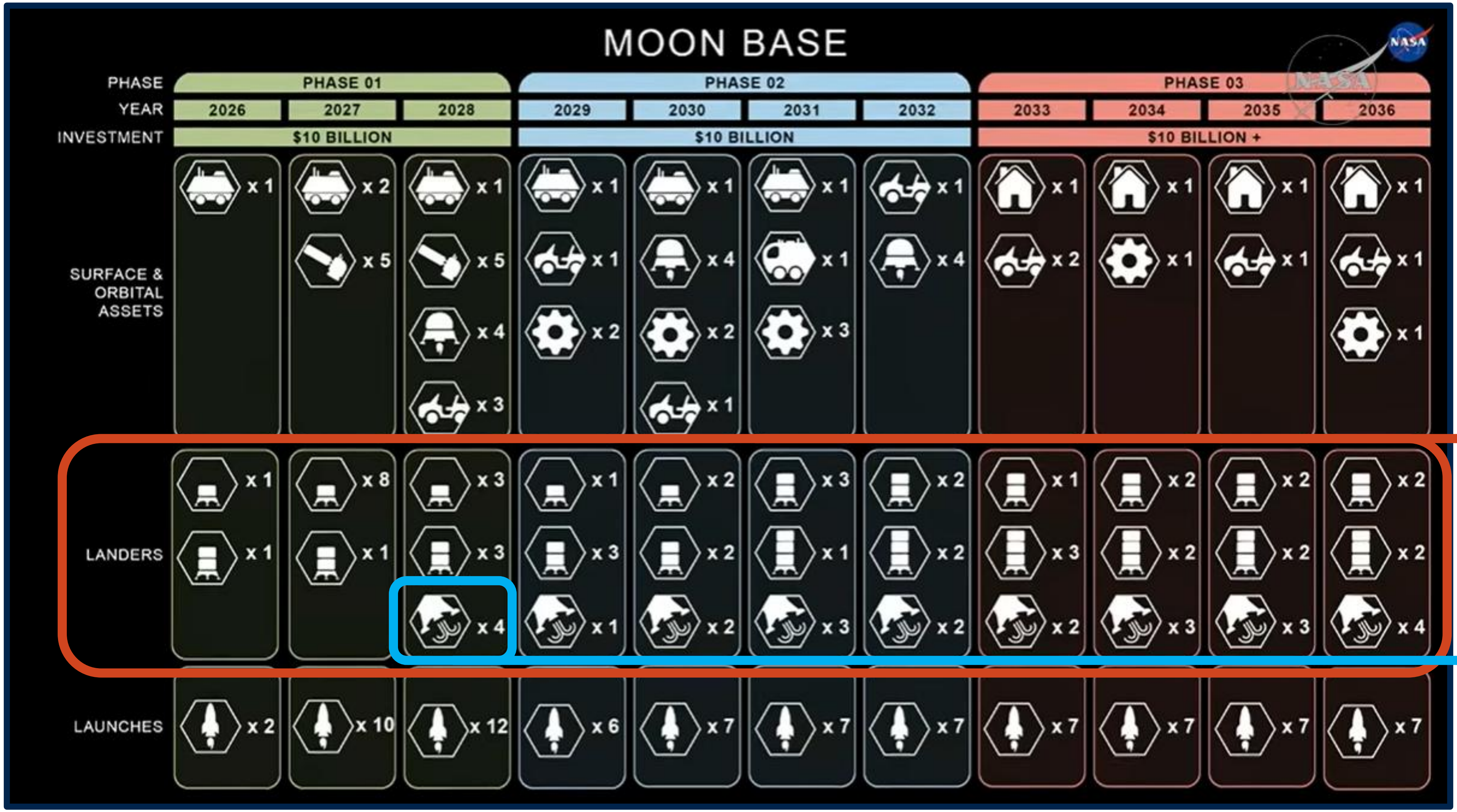
An Architecture and Value Proposition for Post-Mission Lunar Lander Management

Eric Cremer
Colorado School of Mines

Space Resources Roundtable

Colorado School of Mines Space Resources

A Lunar Lander Population Explosion



73 landers by 2036!

70 landers if we suspect an HLS typo in 2028

Image source: NASA

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A Lunar Lander Population Explosion

Lander Mass Estimates

Small CLPS: 500kg

Medium CLPS: 2mt

Large CLPS: 50mt

HLS: 100mt

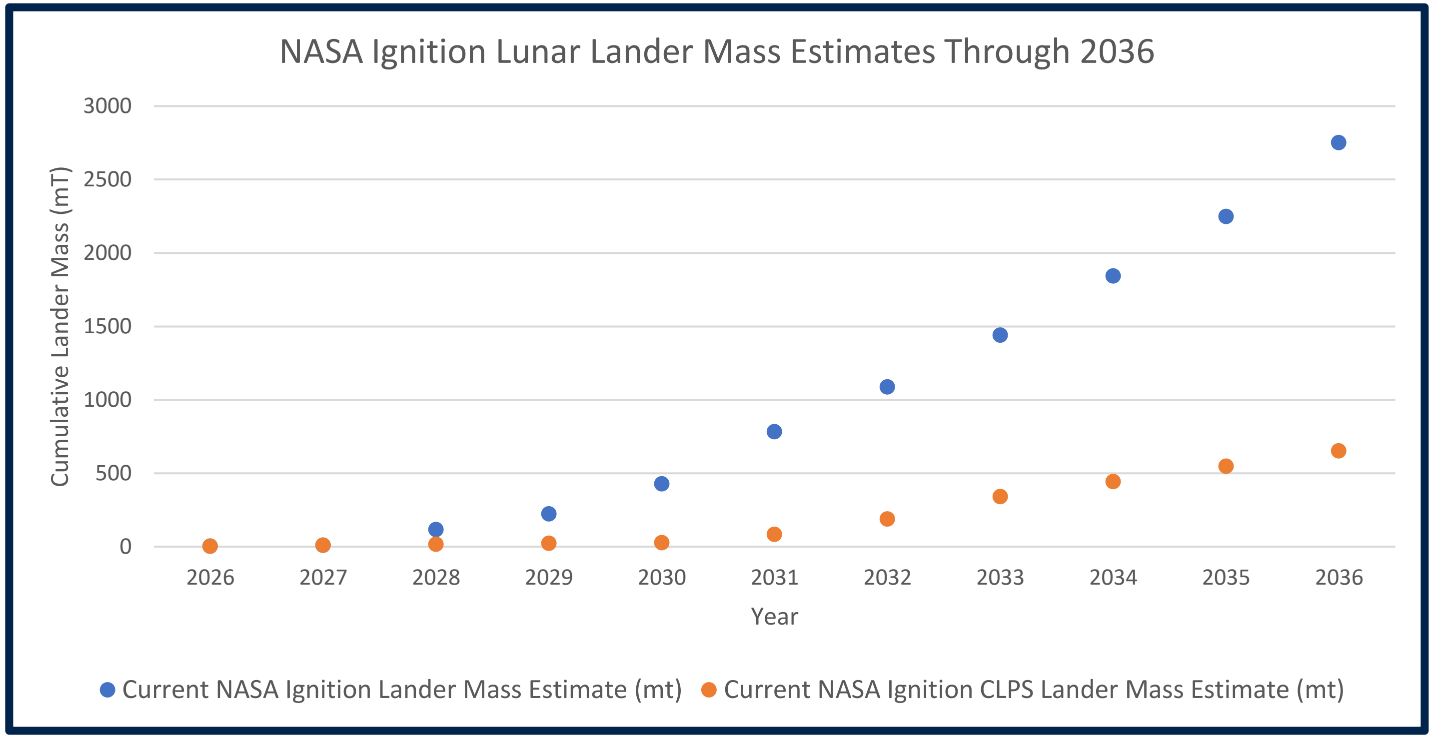


Image source: Cremer et. al.

Asset Category	Through 2036
Total Asset Mass	2889.5 mt
Lander Mass	2751.5 mt
% Lander of Total	93.88%
# Landers	70

NASA Acknowledges Terrain Challenges

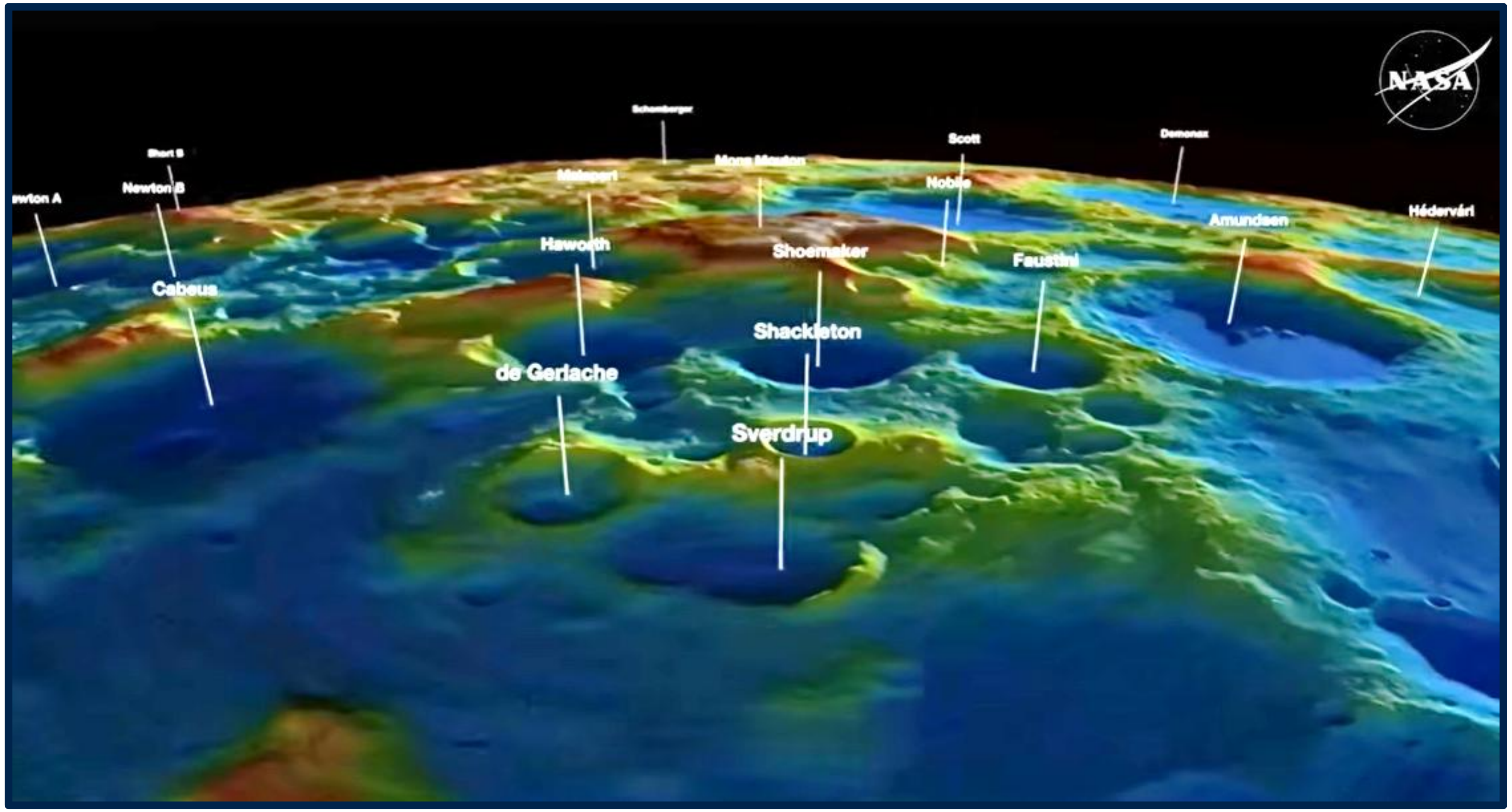


Image source: NASA

"This false-color image that you see is the dramatic terrain that's [found] in the lunar South pole. The Shackleton crater, for example, is one of the areas where we're interested in going. That is double the depth of the Grand Canyon."

NASA acknowledgement of the difficulties presented by the lunar South pole terrain as it pertains to landing, surface traverse, illumination, and access.

Example South Pole Target Landing Site Analysis

Study objective:

Establish a process to estimate the number of landers that can suitably land in an accessible area around a proposed exploration site. In this case, Nobile Rim 2.

Data Foundation:

- Topography: Lunar Orbiter Laser Altimeter
- Illumination: PSR Maps
  - Data from DPS Geosciences Note / MIT Imbrium
- Algorithm: "Flood-Fill" Cost Analysis
- Engineering Constraints Applied
  - Habitation/Landing Sites: ≤ 5˚ (sunlit)
  - Traversability: Path slope ≤ 10˚
  - Safety Buffer: 500m separation between Hab and Landing Zone
  - Resource Access: Hab must be <8 km traverse from a Volatile/PSR zone.

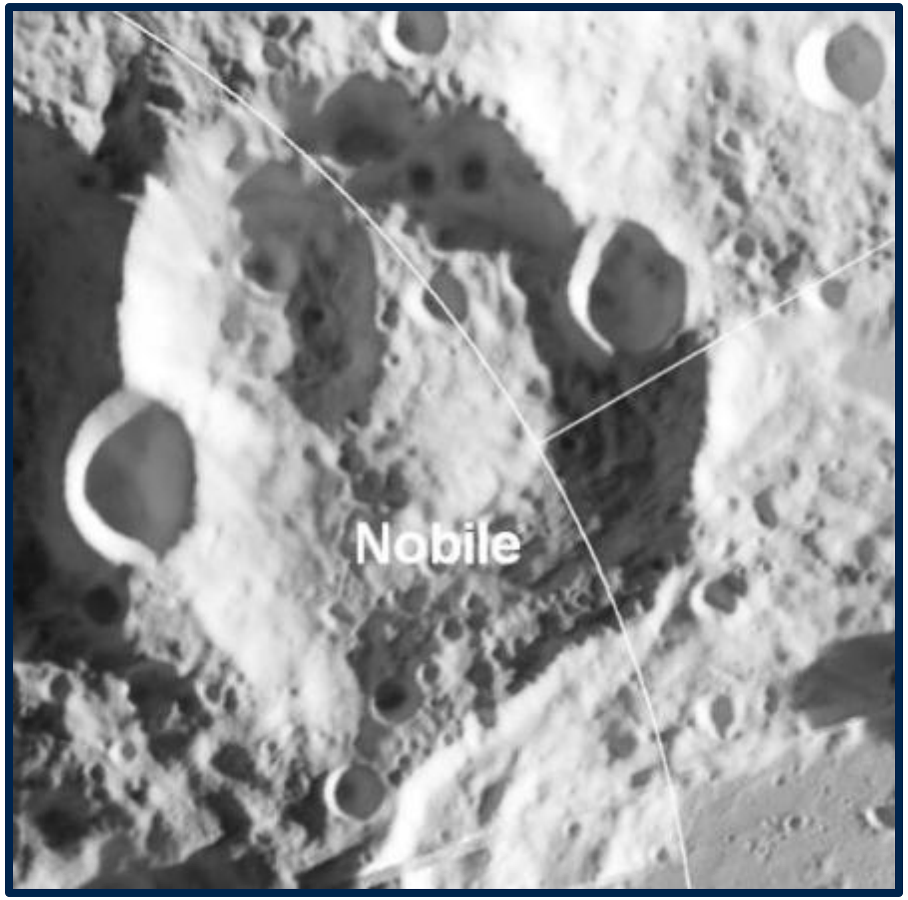


Image source: NASA

Nobile crater

Example South Pole Target Landing Site Analysis

Topography of Nobile Rim 2

Surface Slope (Blue Shades ≤ 5˚ Limit)

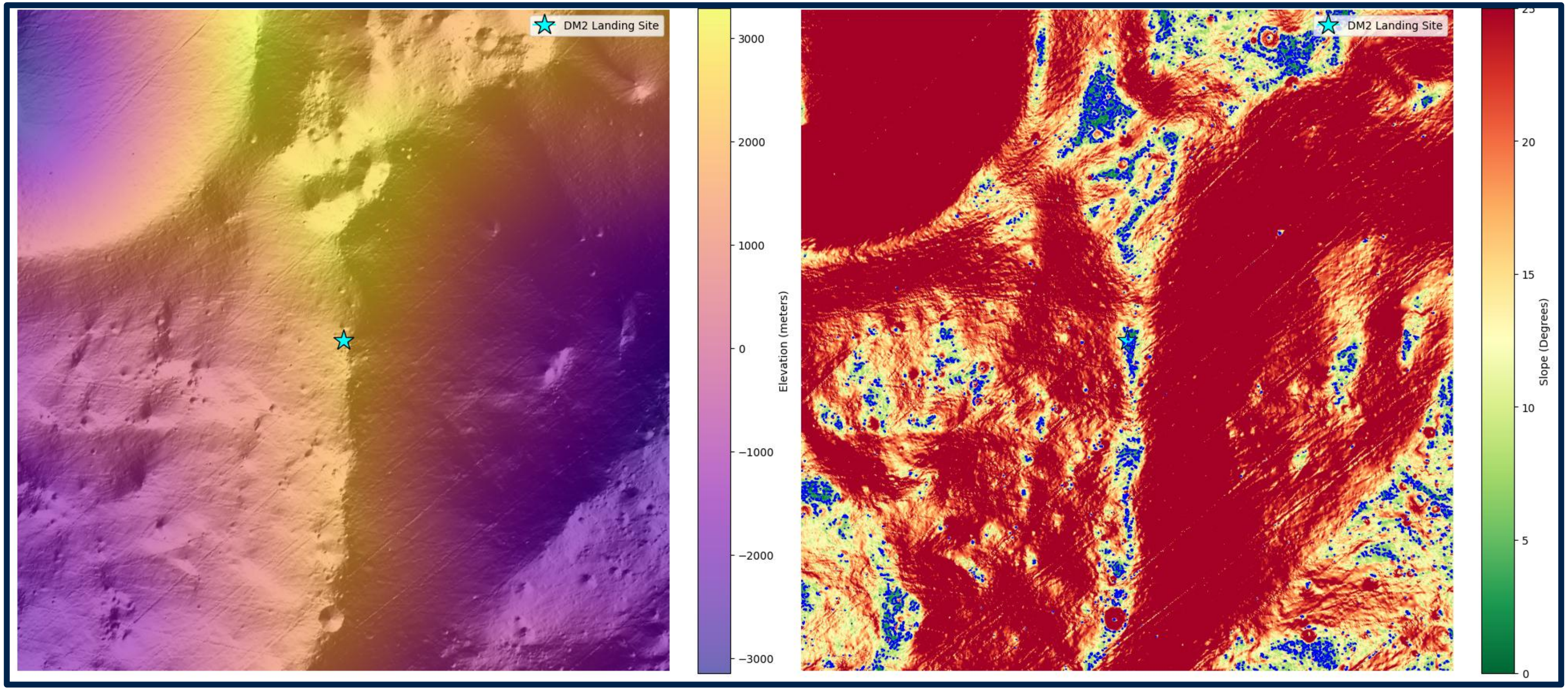


Image source: Cremer et. al.

Example South Pole Target Landing Site Analysis

Analysis Outcomes:

- Capacity at proposed Nobile Rim 2 exploration coordinates extremely limited
- Alternative coordinates (in green) marginally improve landing and traverse capacity
- Total traversable area (Slope ≤ 10˚):
  - Proposed Nobile Rim 2 exploration coordinates: 0.54 km²
  - Alternative coordinates: 2.64 km²

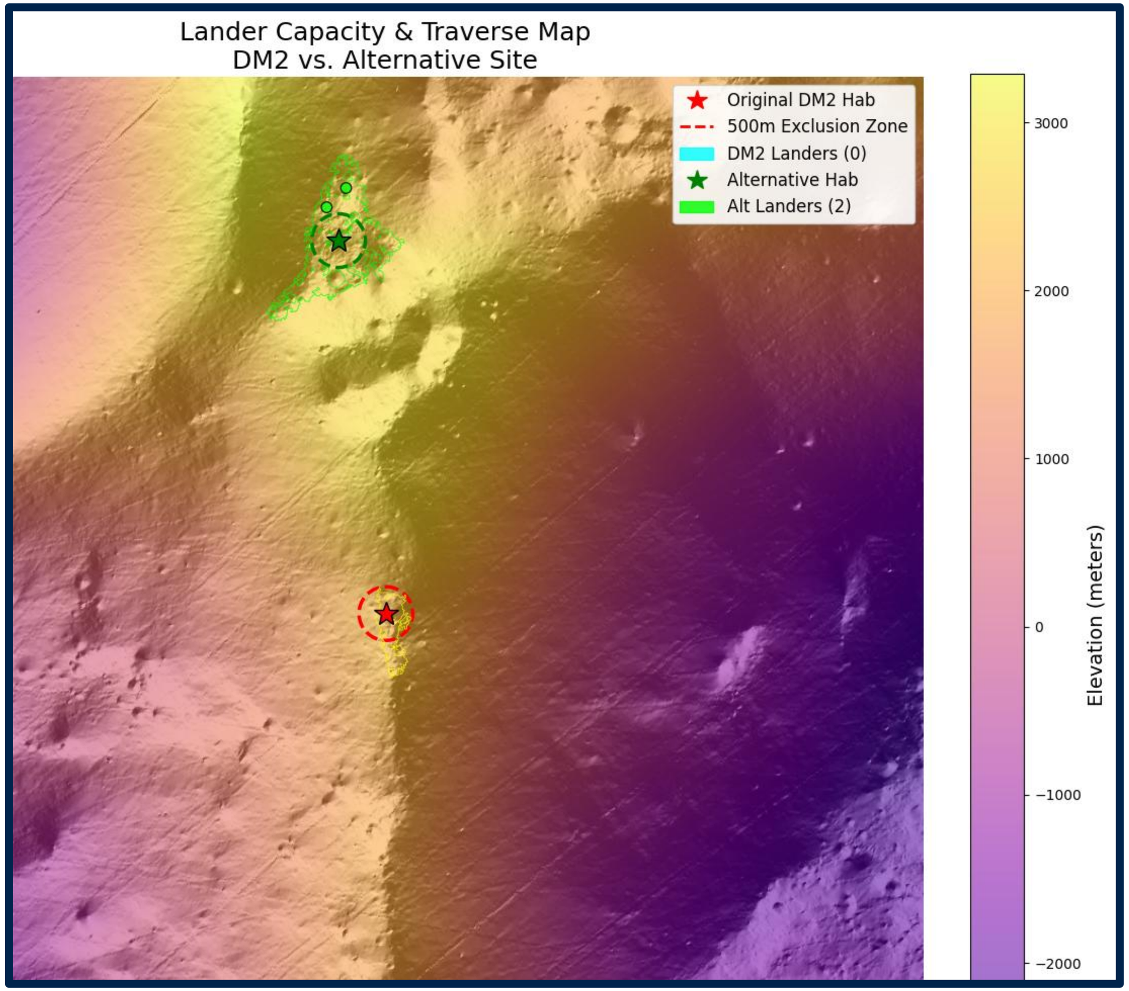


Image source: Cremer et. al.

Example South Pole Target Landing Site Analysis

Takeaways

There is value in performing this type of analysis when considering South Pole mission CONOPS and exploration destinations.

Can we land multiple assets at the location over time?

Can we perform surface traverse operations at reasonable cost and efficiency?

Lunar South Pole exploration sites will often be terrain and illumination constrained.

Do performance requirements for landers and rovers sufficiently reflect this?

Do proposed CONOPS accurately price cost and risk associated with terrain constraints?

Landing Site Preparation

An Additional Sunk Cost

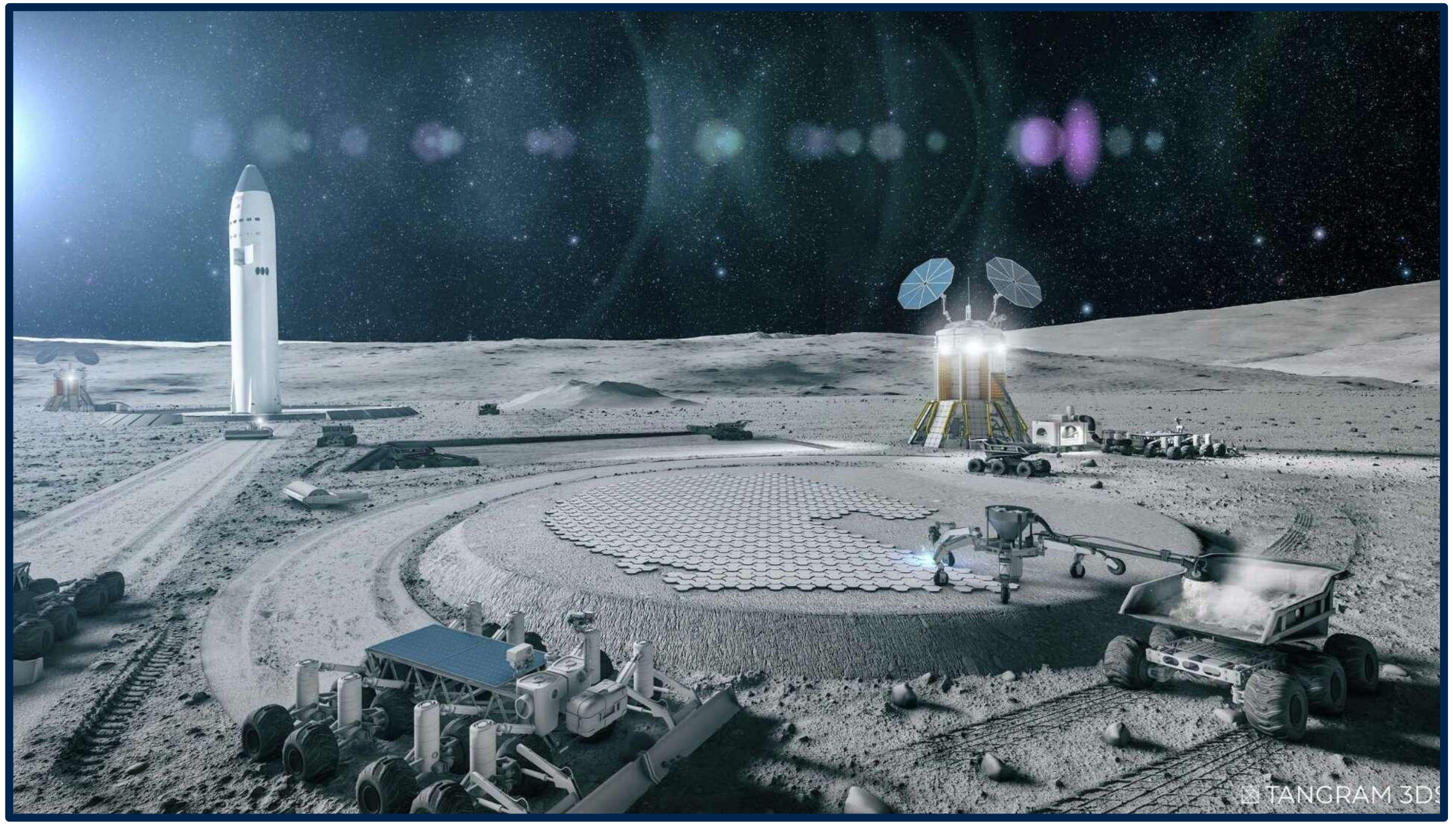


Image source: Astroport Space Technologies

Concept lunar landing pad construction

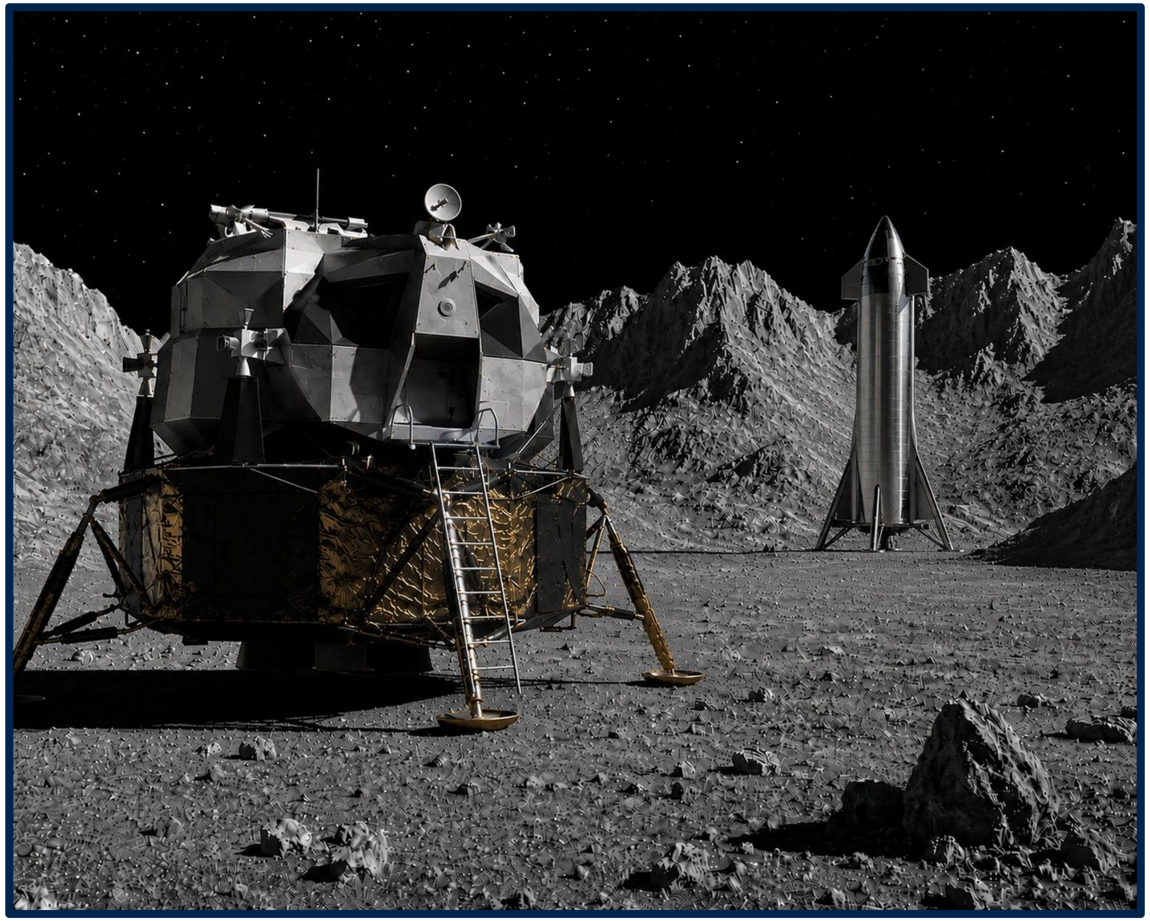
- Heavy investment in developing lunar landing pads and prepared landing site concepts
- Landing site preparation will come at a cost
- Reusability is a must

Post-Mission Lander Handling Options

Trade Study using example CONOPS

Three lander handling options were examined:

1. Leave in place
2. Relocate on surface using surface equipment
3. Relocate on surface using lander propulsion system



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Leaving Spent Landers In Place

Trade Study using example CONOPS

Lander Site Use CONOPS and LTV Assumptions	Value	Units
LTV estimated average traverse speed fully autonomous (no remote command latency, fully loaded)	8	km/hr
LTV estimated cargo carrying capacity	500	kg
LTV estimated power consumption varied mission profile and temp control	0.3	kWh/km
Estimated distance Hab from optimal landing site	1	km
Estimated distance from next closest landing site	5	km
Estimated lander payload mass	5000	kg
Estimated number of traverses to move cargo	10	trips
Total traverse distance from optimal site (considering each is a round trip)	20	km
Total traverse distance from alternate site (considering each is a round trip)	100	km

Cargo Transfer Parameters for Optimal Lander Site Use	Value	Units
Estimated distance to Hab from optimal landing site	1	km
Total traverse distance from optimal site (considering each is a round trip)	20	km
Time to load and unload LTV per trip	2	hr
Traverse time per round trip to optimal site (Hab site to lander site and back + 2 hr loading/unloading)	2.25	hr
Estimated recharge time (considering 2 hr charging while being loaded at lander)	6	hr
Number of recharges per lander cargo transfer from optimal site	0	recharges
Total cargo transfer time from optimal landing site to Hab site	22.5	hr

Cargo Transfer Parameters for Alternate Lander Site Use	Value	Units
Estimated distance from next closest landing site	5	km
Total traverse distance from alternate site (considering each is a round trip)	100	km
Time to load and unload LTV per trip	2	hr
Traverse time per round trip to alternate site (Hab site to lander site and back + 2 hr loading/unloading)	3.25	hr
Estimated recharge time (considering 2 hr charging while being loaded at lander)	6	hr
Number of recharges per lander cargo transfer from alternate site	5	recharges
Total cargo transfer time from alternate landing site to Hab site	62.5	hr

Leaving Spent Landers In Place

Trade Study using example CONOPS

Cost Calculation for Optimal Lander Site Use	Value	Units
LTV estimated power consumption varied mission profile and temp control	0.3	kWh/km
Total traverse distance from optimal site (considering each is a round trip)	20	km
LTV energy consumption optimal site	6	kWh
Cost per kWh	100	$
Crew time (x 2 crew) from optimal site	45	hr
Estimated crew time cost (ISS cost x 10)	1300000	$/hr
Total cost of lander cargo transfer from optimal landing site	58,500,600.00	$

Cost Calculation for Alternate Lander Site Use	Value	Units
LTV estimated power consumption varied mission profile and temp control	0.3	kWh/km
Total traverse distance from alternate site (considering each is a round trip)	100	km
LTV energy consumption alternate site	30	kWh
Cost per kWh	100	$
Crew time (x 2 crew) from alternate site	125	hr
Estimated crew time cost (ISS cost x 10)	1300000	$/hr
Total cost of lander cargo transfer from alternate landing site	162,503,000.00	$

Average cost *per additional km* of cargo traverse from landing site to hab:

$5.2M/mt cargo

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Relocating Landers with Surface Equipment

Trade Study using example CONOPS

Item	Value	Units
Special purpose vehicle (SPV) estimated mass (assuming delivery via CLPS)	500	kg
SPV development cost factor	50	$/kg
SPV production cost factor	20	$/kg
SPV estimated power consumption (assuming more load bearing capability than LTV)	0.7	kWh/km
SPV estimated average traverse speed during transport	1	km/hr
Transport cost to lunar surface	100,000	$/kg
Total cost of 1 SPV on lunar surface	50,035,000	$
Estimated required transfer distance to safe storage site	1	km
Estimated distance from storage site to base	1	km
Total traverse distance for lander relocation	3	km
Traverse time for both vehicles per transfer given landing site and storage site locations	3	hr
LTV energy consumption per transfer	1.5	kWh
SPV energy consumption per transfer	2.1	kWh
Cost per kWh	100	$
Estimated crew time (in the event transfer is not fully autonomous)	3	hr
Estimated crew time cost (ISS cost x 10)	1,300,000	$/hr
Total lander relocation cost for 1st transfer with special purpose autonomous transport vehicle	**50,035,210**	**$**
Total lander relocation cost per transfer assuming 10 transfers with SPV	**5,003,710**	**$**
Total lander relocation cost per transfer assuming 37 transfers with SPV (100% CLPS < 2mt)	**1,352,666.22**	**$**

If we amortize the development of an SPV to relocate the 37 CLPS landers ≤ 2mt in dry mass projected through 2036:

$1.35M/relocation

Lander Self-Relocation

Trade Study using example CONOPS

Item	Value	Units
Estimated cost of lunar-sourced LOX/LH2 propellant	$1,630	$/kg
Total lander payload capacity (using Blue Ghost example)	150	kg
Total lander propellant capacity (using Blue Ghost example)	1000	kg
Propellant mass flow rate during lunar relocation flight (using Blue Ghost LEROS 4-ET engine example, assuming full lunar gravity the whole time)	2.52	kg/s
Lunar relocation flight duration	100	s
Lunar relocation flight propellant consumption	251.91	kg
Cost to relocate lander with lunar-sourced LOX/LH2 propellant	**410,619**	**$**
Cost to relocate lander with propellant brought from Earth (assuming payload capacity could be sacrificed for propellant capacity)	**$/kg propellant + $100k/kg payload opportunity cost**	

If a lander can refuel with lunar-sourced propellant and re-launch for a 100s relocation burn:

$279.52/kg wet mass

If a lander sacrifices payload to carry relocation propellant:

addt'l prop cost + lost payload opportunity cost

Post-Mission Lander Handling Options

In terrain-limited operating environments it pays to be able to relocate landers post-mission.

Image generated with ChatGPT

Re-use and Recycle

An ISRU Opportunity

Landers at end-of-life aren’t just waste. They present a resource that can be utilized in a variety of ways:

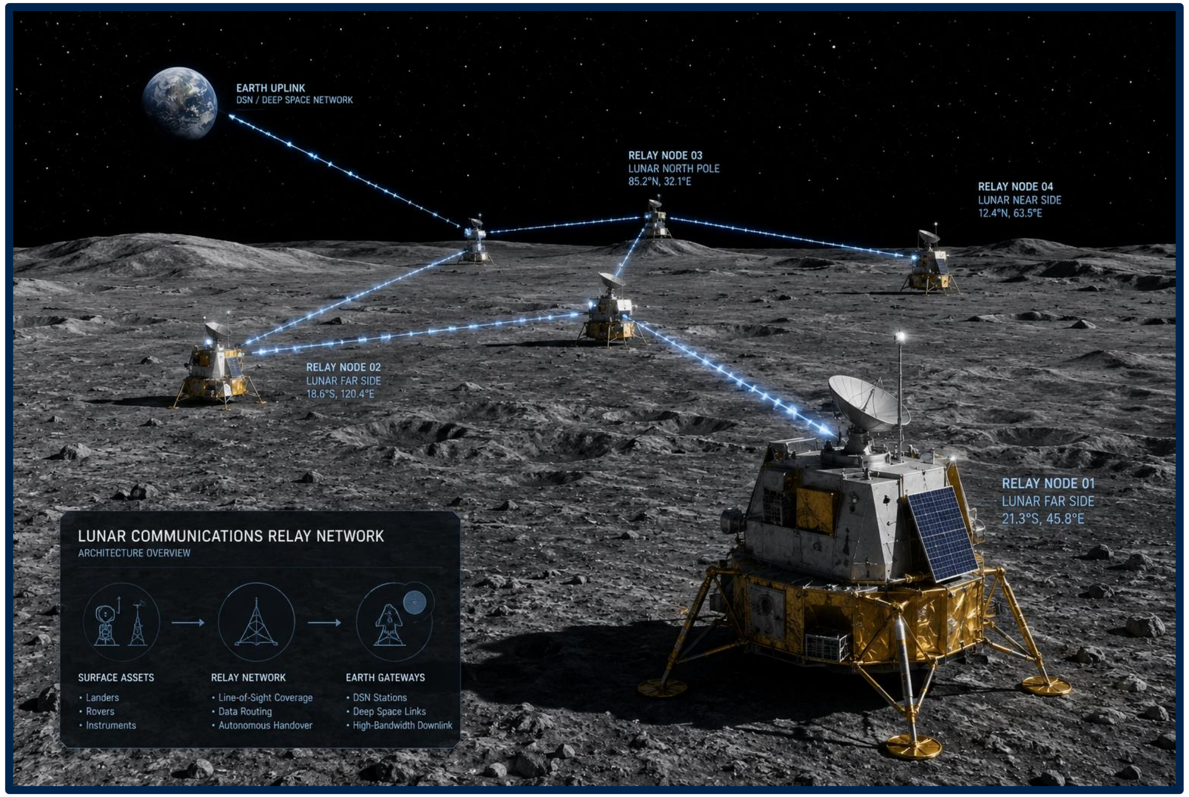

Image generated with ChatGPT

- Re-positioning for use as comms relay or surface GPS
- Re-use as stationary habitat, data/compute resource, power generation node
- Disassembly for valuable components and recycling of metals

Re-use and Recycle

An ISRU Opportunity

There will exist a substantial mass of waste metal on the lunar surface as activity increases.

Waste category	%Metal	Ignition Phase 1 (kg/yr)	Ignition Phase 2 (kg/yr)	Ignition Phase 3 (kg/yr)
Human waste (biological)	0	0	0	0
Human Waste (non-biological)	0	0	0	0
Packaging Materials	0	0	0	0
Spent/Failed hardware	50	450	2,300	23,000
Vehicles	50	2250	5,900	60,000
Total		**2,700**	**8,200**	**83,000**

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Re-use and Recycle

Trade Study and Example CONOPS

Terrestrial metal recycling technologies are high TRL, with some well-suited for lunar applications.

Recycling Method (System)	System Volume (m3)	System Mass (kg)	System Power (kWh)	Processing Rate (kg/day)	Inputs	Recovery (%)	Value/Usability of Recycled Output	Power (kWh/day)	Power (kWh/kg)
Natural Gas Reverberatory Furnace	42	NA	1760^	5900 (10h-shift)	Building scrap, transport scrap, foil scrap, beverage cans	91.5	609 kt/yr Dry Salt, 110 kt/yr Aluminum granulate, 604 kt/year non-metallic residue.	17,600	2.98
Vacuum Electric Arc Furnace (VAF)	35	27,215	400*	163,293	Direct reduce iron (DRI), Scrap steel, aluminum?	90-95	Molten steel, slag, dust, and vapors	65,317	0.40
Vacuum Electromagnetic Induction Furnace	44	20,000	520*	460,560	aluminum, Scrap iron steel, copper	95%	Molten metal (steel, aluminum, copper). Slag, heat, and electrical energy	239,491	0.52

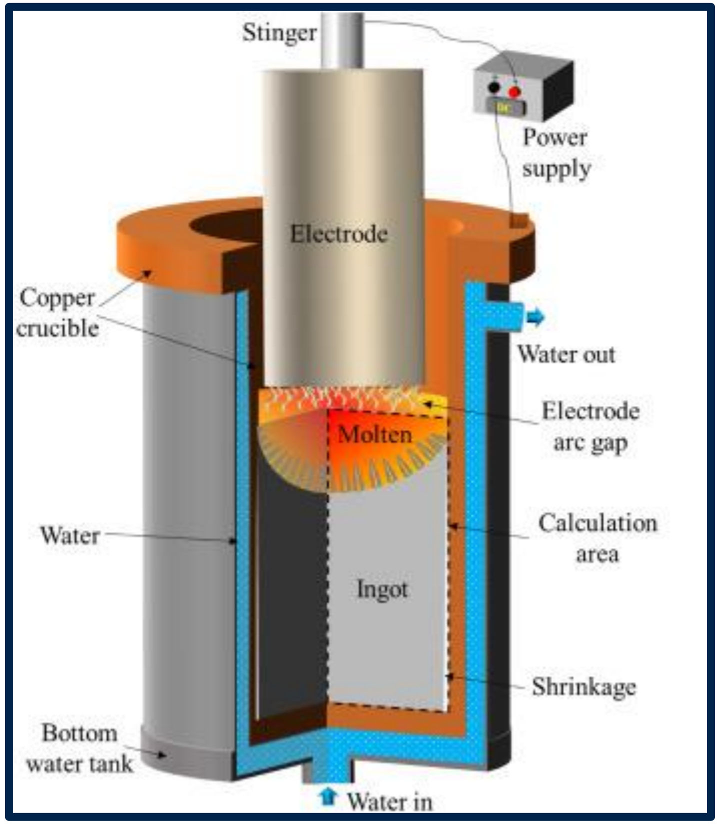
Electric Arc Furnace selected for example CONOPS due to vacuum operations, lower power consumption, and smaller system volume

Re-use and Recycle

Vacuum Arc Furnace Value Proposition

Assumptions

- Single arc furnace deployed once and used throughout phased 2 and 3
- Non-recurring includes development , production, launch, & landing
- Annual operating cost includes operation, maintenance, & power
  - Size to be capable of recycling all available metal in phase 3
    - 83,000kg/yr = 455 kg/day
  - Assume linear scaling with scaling adjustment factor of 2
  - System availability = 50%
  - 90% recovery rate
- Scaled system mass = 152 kg
- System power consumption = 33,200 kWh/yr



Cutaway of vacuum arc furnace

Image source: Yang et. al.

Ignition Phase 2			Ignition Phase 3		
Non-recurring Cost ($k)	Annual Operating Cost ($k)	Annual Benefit ($k)	Non-recurring Cost ($k)	Annual Operating Cost ($k)	Annual Benefit ($k)
26,530	4,000	516,600	0	4,000	5,229,000

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Conclusions on Lunar Lander Management

Lunar South Pole landing sites are limited and surface traverse may be difficult. We need to land close to areas of interest and do so repeatably.

There is a positive value proposition for the relocation of spent landers vs. being displaced from optimal landing sites. Even more so in the case of a landing pad or surface preparation.

There is a substantial positive value proposition for the recycling of spent landers.

Proposed Lunar Lander Requirements

CLPS-class landers less than 2 mt dry mass must be picked up and re-located via surface equipment. CLPS 2.0 landers to accommodate lift and fitment with surface equipment and/or special purpose vehicles.

Large cargo and HLS-class landers must self-relocate. Large landers must carry sufficient propellant for self-relocation until lunar-sourced propellant refueling supply chains mature.

Thank You!

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