AN ARCHITECTURE AND VALUE PROPOSITION FOR POST-MISSION LUNAR LANDER MANAGEMENT. E. Cremer[1], G. Sowers[1], I. Casasbuenas Cabezas[1], B. Hopkins[1], M. Nguyen[1], [1] Colorado School of Mines Space Resources Program, 1500 Illinois St, Golden, CO 80401.

Introduction:
In recent years, and coinciding with NASA's Artemis Program, international government and commercial actors have re-prioritized lunar surface exploration and operations. NASA has a legacy of successful lunar landing and return operations, however as NASA has predominantly become a customer of private sector development a competitive marketplace of novel lunar lander manufacturers and operators has matured. This has ushered in substantial new participation in proposed lunar exploration and development activity; NASA alone has contracted 13 US companies to develop and fly landers as a part of its Commercial Lunar Payload Services (CLPS) initiative, and this is in addition to parallel efforts of national space programs from the likes of China, Russia, Japan, and others developing lunar surface landing craft [1].

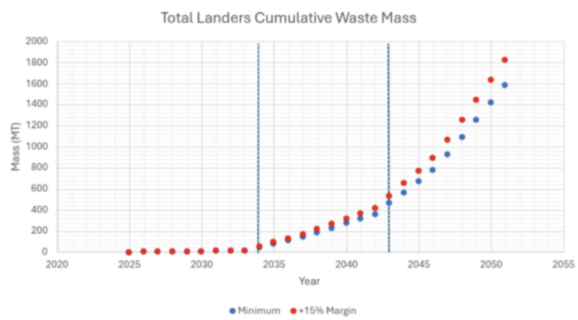

Figure 1: Estimated Lunar Lander Mass Accumulation by Year [5]

Further compounding this increase in lunar surface activity is the high concentration of shared interest in indicated deposits of water ice in permanently shadowed regions (PSRs) near the lunar South pole. The lunar South pole is a heavily cratered area with limited flat, easily-traversable terrain and widely varying illumination. As a result, suitable areas for landing and other surface logistics operations are few, suggesting that competition for and activity at suitable landing sites near lunar South pole water ice deposits will be particularly high. Increasing the value of these sites still is the potential for landing site preparation; NASA has funded development of landing site preparation modalities and methods through SBIR and other research grants, implying the intended reusability of optimal lunar landing sites [2]. Numerous requirements for lander performance have also been proposed as a part of NASAs Moon to Mars Architecture, such as precision landing tolerances and blast ejecta constraints [3][4]. However, these requirements stop short of addressing how to manage landers *post-mission*. With the projected increase in international lander traffic in areas around the lunar South pole PSRs, and the conceivable value of optimal landing sites therein, a post-mission lunar lander management and logistics strategy is increasingly necessary, enabling the relocation, re-use, and recycle of the largest human-made material assets on the lunar surface.

Lander Removal:
Topographical analysis of proposed Artemis mission sites reveals the limitations imposed by the terrain on suitable landing areas. As such, lunar lander operators will need to develop post-mission removal design implementations for their spacecraft. Cost-benefit analyses of lander relocation reveals an estimated cost of $26MM to future missions per km of optimal landing site displacement, providing a suitable business case for investment in lander surface relocation technologies and reusability design iterations to ensure site availability [5]. Smaller, "CLPS-class" landers under 1 MT should be capable of being lifted and transported by surface equipment or special purpose vehicles to staging areas for disassembly and recycle. Larger "cargo-class" and crewed vehicles exceeding 1-2 MT will need to be able to re-light and self-relocate, either with additional propellant stores brought from Earth or by refueling on the lunar surface. If capable of full reusability, these vehicles may relocate to a "parking lot" to be staged for re-use, otherwise the self-relocation would be to the recycling staging area.

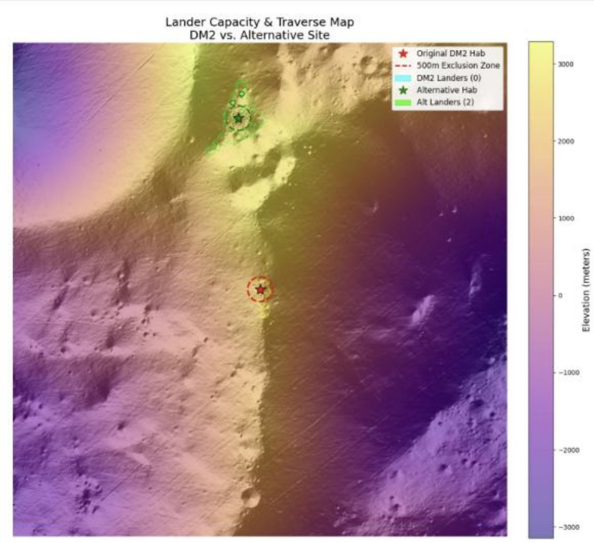

Figure 2: Topographical Analysis of Proposed Artemis Mission Site Nobile Rim 2 [5]

Lander Disassembly and Recycling:
At an estimated 30-70 wt% metal lunar landers present a compelling value proposition for material recycling. Cost-benefit analyses of the application of various terrestrial metals recycling processes, such as electric arc furnace melting, to the presumed lander population reveal a substantial margin, quickly outpacing NRE and any sunk costs related to the development and implementation of space-rated recycling systems [4]. This value proposition further underscores the importance of the ability to move and handle landers post-mission.

FE Phase			SLE Phase		
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

- **Assumptions**
  - Single arc furnace deployed once and used throughout FE and SLE
  - Non-recurring includes development , production, launch, & landing
  - Annual operating cost includes operation, maintenance, & power

Figure 3: Lander Recycling Cost-Benefit Analysis Across Moon to Mars Architecture FE and SLE Phases [5]

In order to feed spent landers into a recycling furnace it is necessary to develop the ability to disassemble them into parts. In the lunar operating environment robotic disassembly is highly preferrable for the development of a sustainable, highly repeatable process. While some low TRL options for robotic disassembly exist, such as GITAI's Inchworm, it is apparent that the value proposition estimated by this study and associated with the removal and recycle of spent lunar landers has not been fully constituted in support of technological development in this area [6]. A substantial opportunity exists for industrial-scale solutions for the robotic disassembly of spent landers in anticipation of metallic recycling.

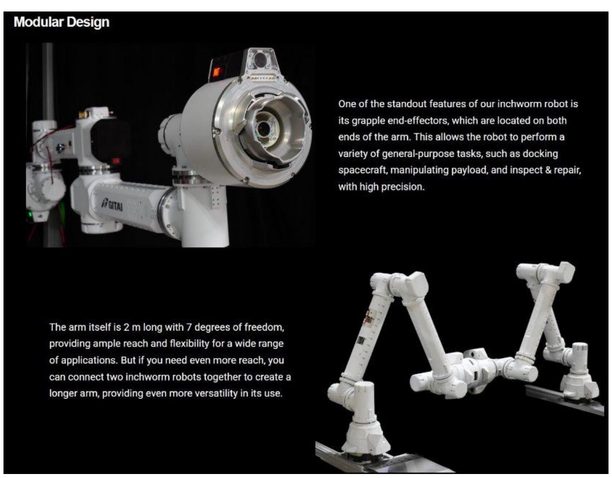

Figure 4: GITAI Inchworm Robotic Arm Capable of Hosting Disassembly End-Affector [6]

Conclusion:
As lunar operations increase, perspectives on the post-mission management of lunar assets must evolve in kind. Nowhere is the value proposition for this more true than with lunar landers, the largest near-term material assets on the lunar surface. Landing sites at areas of scientific interest are limited, placing a high value on the preparation and reusability of these optimal sites. To enable landing site reusability, landers must be able to relocate post-mission, whether under their own power or via surface vehicle transport. After relocation, a substantial and compelling value proposition for lander metal recycling exists, made possible at scale via robotic disassembly of spent landers. This proposed relocation, re-use, and recycling post-mission lander management architecture not only ensures long-term access to high-value lunar sites, but also creates a viable business case for material management and ISRU value chains that may support further development of lunar surface activities.

References:
[1] A. Bowman (2026) *Commercial Lunar Payload Services Overview*.

[2] E. Bell et. al. (2023) *Lunar Surface Site Preparation for Landing/Launch Pad and Blast Shield Construction.*

[3]T. George et. al. (2024) *Safe and Precise Landing at Lunar Sites whitepaper- NASA Moon to Mars Architecture* 1-3.

[4] C. Stromgren et. al. (2024) *Lunar Mobility Drivers and Needs whitepaper- NASA Moon to Mars Architecture* 1-5.

[5] Original research by the author(s) as part of *NASA's NextSTEP 2 BAA* in conjunction with SAS (2025-26).

[6] GITAI (2026) *GITAI Inchworm Robot Product Brochure.*