LUNAR RECYCLER: REUSABLE ROBOTIC LUNAR SAMPLE RETURN VEHICLE ARCHITECTURES.

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Introduction: Lunar sample return is stated within the Planetary Science Decadal survey as being amongst the highest-priority future activities for solar system science. The development of a reusable lunar sample return vehicle would be of significant science interest to the lunar community as it would allow for samples to be gathered from a wide range of landing sites without needing to construct and launch a new vehicle each time. NASA is currently undergoing studies on developing a cislunar habitat as a staging point for exploration of the Moon. This could be an ideal platform to support a reusable robotic lunar sample return mission architecture.

Mission Concept of Operations: The Lunar Recycler concept is for a reusable robotic sample return vehicle that would utilize existing human exploration architecture to deposit samples for eventual return to Earth. After delivering the samples the lander would then be prepared for another cycle of sample returns. The refurbishment of the lander could be accomplished through refueling the spent propellant tanks or by completely replacing the descent stage.

The first mission would launch the lander on a trans-lunar injection (TLI) to be parked in a low-lunar orbit (LLO). It would then de-orbit and descend to the first landing site. After landing, the solar arrays would deploy and nominal science operations would begin. Samples would be identified through on-board cameras, collected by a robotic arm, and stored in the sample storage capsule. The solar panels would be stowed and the vehicle would then perform the ascent burn to return to LLO. After reaching LLO, it would perform the necessary burns to rendezvous with the cislunar habitat.

The samples would then be transferred to the cislunar habitat and the refurbishing process would begin. This process is discussed in more detail below. Following successful refurbishment, the mission cycle would repeat. The lander would de-couple from the habitat and perform the necessary burns to land at the next sampling location. It would then return to the habitat to deposit the samples and be refurbished for yet another sample return mission. The samples would be returned to Earth on a separate spacecraft such as a payload in a crew return vehicle from the cislunar habitat.

Single-stage, Dual-stage, or Hybrid: The driving design consideration for a re-usable lunar lander is the propulsion system. The traditional method is to have a two-stage lander that leaves the descent stage on the surface such as was done with the Apollo Lunar Module (LM) or the Luna 24 mission [4]. This architecture increases the payload fraction by significantly reducing the ascent mass of the return vehicle, but increases refurbishment requirements.

A single-stage approach is another potential architecture for the Lunar Recycler. Single-stage lunar landers are highly desirable for both human missions and sample return missions but have yet to be developed and flown. The payload fraction for a single-stage sample return spacecraft is the lowest of the three discussed architectures.

An alternative to the single-stage and dual-stage designs is a hybrid lander approach. A potential hybrid-stage lander would have a similar design to a single-stage lander but would have the ability to discard the empty propellant tanks used for the descent burns. This would allow for reduced inert mass for the ascent burn while leaving in place the support structure for the replacement descent tanks. The discarded tanks would be replaced in orbit. The payload fraction for the hybrid-stage approach is between the dual-stage and single-stage.

Refurbishment Process: Each architecture requires significant on-orbit capabilities to refuel and refurbish the lander. Common amongst all three concepts is the capability to refuel the ascent propellant tanks. In-space refueling depots have been proposed since the mid-1960s when the Space Transportation System was in early concept studies. Refueling has been successfully demonstrated multiple times by the Russian spacecraft Progress and through experiments performed by the Robotic Refueling Mission on the ISS [3]. There are engineering design issues with refueling in-space that must be addressed, specifically concerns with propellant transfer, liquid hydrogen boil off, and propellant settling in microgravity [1]. Just-in-time delivery of propellant for refueling could reduce loiter time which drives the hydrogen burn off. Another issue is how to determine the fuel level in a tank. This fuel level issue can be eliminated by venting the tank to vacuum before refueling so as to assure the tank is empty.

The dual-stage and hybrid-stage approaches require more complex refurbishment capabilities. A dual-stage lander would need to be able to accommodate the replacement of the descent stage while in orbit. This process could be accomplished in a similar way as an on-orbit rendezvous, proximity operations and docking which is a well-understood maneuver. Development of reusable latching and separation mechanisms, as well as remotely actuated fluid connectors, would be needed but this is possible within our current technologies. The hybrid-stage lander would require the ability to replace tanks within the descent stage which leads to further complexity within the architecture.

Each of these concepts assumes significant supporting capabilities of the cislunar habitat that are beyond the scope of the designs being discussed presently.

Architecture Capabilities: The long-term mission cycle for the Lunar Recycler concept would be heavily driven by the ability to provide propellant and hardware to LLO. Depending on the chosen lander design, this may also entail delivering propellant tanks or even full descent modules to LLO. The capability to refuel the propellant tanks at the cislunar habitat would also need to be developed. This supporting infrastructure is not trivial and should not be ignored when discussing long-term lunar sampling campaigns. The support infrastructure could be compatible across multiple mission types enabling reusable sample return spacecraft to Near Earth Objects (NEOs), Mars, or even the Asteroids Belt. This would help share developmental and operational costs across multiple programs.

Mass Trades: A basic mass trade study was performed for each of the lander concepts. The spacecraft is assumed to begin and return to a 100 km circular orbit. Payload mass was nominally chosen as 300kg as based on similar lander missions of Luna 24 and Phoenix. Propellant mass was estimated using a form of the Tsiolkovsky rocket equation [2,6]:

$$m_p = m_f \left\{ e^{\left(\Delta V / I_{sp} g \right)} - 1 \right\}$$

where m_f is the final dry mass of the spacecraft, ΔV is the velocity change for each manuevor, I_{SP} is the specific impulse, and g is the gravitational constant. Working backwards through the mission profile, propellant masses were calculated at each burn beginning with the final rendezvous burn. This process was iterated twice to produce a more accurate estimate [2,6].

Two propellant options were considered for the analysis: N_2O_4/MMH and LOX/LH_2. Propellant tanks and supporting structure were estimated as a percent of the propellant mass [2,5,6]. Oxidizer-to-fuel mixture ratios were used to calculate the mass of each and from there a volume was calculated using the densities. The LOX/LH_2 calculations assumed a higher percentage of mass for tanks and structure due the significantly increased volume needed for LH_2 storage and the cryogenic temperatures involved.

Trade Outcomes: The results of the trade analysis is shown in Table 1. The dual-stage lander concept has the lowest mass and volume. While having significantly reduced mass and volume in this configuration, the dual-stage lander would require the replacement of the descent stage for every mission. In contrast, the single-stage lander is the heaviest and largest of the three concepts but would only require on-orbit refueling without needing replacement of components. The hybrid lander falls in-between the single and dual-stage concepts for both mass and volume.

Lander Architecture		
Payload Mass	300 kg	
Propellant	N2O4/MMH	
Specific Impulse	320 s	
Lander Stages	**Mass (kg)**	**Volume (m^3)**
Dual-Stage Lander	5,383.08	4.16
Hybrid Lander	9,803.92	7.23
Single-Stage Lander	12,024.75	9.14
Propellant	LOX/LH2	
Specific Impulse	450 s	
Lander Stages	**Mass (kg)**	**Volume (m^3)**
Dual-Stage Lander	3,018.14	6.19
Hybrid Lander	4,726.44	9.71
Single-Stage Lander	7,059.82	15.37

Table 1: Cross comparison between three lander architectures (Single, Dual, Hybrid stage) and two propellants (N2O4/MMH and LOX/LH2).

One important outcome to note is the mass/volume trade-offs between the two propellants. While propellant mass is reduced for the LOX/ LH_2 system, there is a significant increase in propellant volume [5]. Mass and volume are both important factors when evaluating the launch feasibility for a mission concept as each launch vehicle is limited by the size of the payload fairing and the total payload mass. There is also a significant design concern with hydrogen boil off for the LOX/LH_2 propellant that must be overcome.

Conclusion: A sustained, long-term lunar sample return program utilizing a reusable lander would be highly beneficial for the lunar scientific community. The presence of a cislunar habitat could be leveraged to support the lunar recycler concept. Dual-stage, single-stage, and hybrid-stage landers each have benefits and drawbacks that should be considered when discussing reusable lander architectures.

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