Lunar Exploration and Access to Polar Regions (LEAPR)

RASC-AL 2019 Technical Report
Theme 3: Gateway-based Human Lunar Surface Access

University of Puerto Rico-Mayagüez
Undergraduate Team
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1. Introduction

NASA recently announced that it aims to return humans to the surface of the Moon by the ambitious year of 2024. This has started a major discussion in regards to the feasibility and the current state of the technologies that will enable this feat. The Revolutionary Aerospace Systems Concepts - Academic Linkage 2019 competition sought concepts that could achieve this goal by the original deadline of the year 2028. As part of the Theme #3: Gateway-based Human Lunar Surface Access, the Lunar Exploration and Access to Polar Regions (LEAPR) project provides an architecture that meets and resolves the technical requirements and challenges of an extensive lunar operations campaign. The Karaya Transport Vehicle (KVT) is a single stage reusable lunar lander that has been designed to sustain one annual crewed mission to the Moon beginning in 2028 and lasting for a minimum of 15 years. The design of the vehicle and the overall mission architecture leverages current and future technologies that optimize the efficiency of the mission operations. The human aspect of this mission has driven the team to design ergonomic and redundant interfaces that might otherwise be overlooked in the rush for reaching a particular deadline. The features that have been implemented in this project are essential for extendable lunar surface missions and other deep space endeavors.

2. Concept of Operations

Phase 1: KTV Delivery and Mission Staging

The LEAPR project incorporates a concept of operations (CONOPS) that leverages the operational capability of both NASA and commercial launch services, namely SpaceX. As shown in Figure 1, the first
mission is the most complex as it involves 2 SLS launches and 2 Falcon Heavy (FH) launches. The first SLS launch will transport a partially fueled KTV to the Gateway where the vehicle will remain docked until the start of LEAPR Mission 1 (LM-1). It is noted that this particular SLS vehicle, the Block 1B Cargo version, should be ready by 2028 according to the most recent NASA plans for the Artemis missions. Subsequently the first FH will deliver the Refuelling Utilization Mechanism (RUM) and the Cargo and Resupply (CAR) module to the Gateway. The RUM will implement the technology that is currently being tested in the Robotic Refuelling Missions (RRM) to refuel the KTV fuel tanks. In addition, the RUM-CAR will transport a small cargo compartment that will be transferred onto the Gateway. This transfer will happen by teleoperating the robotic arm of the Gateway. Once the refuelling is completed, the CAR will be disposed via heliocentric escape trajectory. The RUM will remain attached to the Gateway. The second FH launch will subsequently deliver the other CAR to the Gateway, where the RUM will be attached to the tanks and start the refuelling process. When the refuelling is completed, the CAR will be disposed by the same method as the first one. The crew will then be launched and delivered via the SLS and Orion spacecraft. When the crew arrives at the station, they will perform an overall system checkup of the Gateway and the KTV as part of the preparation for the lunar mission. Any repairs or maintenance should be performed at this point in the mission. After completing the aforementioned processes, the crew can transfer to the KTV and commence its descent to the lunar surface. A detailed explication of the flight maneuvers is found in table 4. When the KTV descends, the RUM will detach and the robotic arm will relocate it to some area of the Gateway. The RUM will stay in that location until the next refuelling is made. The landing zones and surface operations depend entirely on the mission objectives. As discussed below in table 6, the lander possesses the capability of landing in both poles as well as some other parts of the equator. At the end of the first lunar surface mission, the crew will return to the gateway where they will perform another systems checkup, maintenance, and any possible repairs. These inspections will assess the need for additional cargo or material that the following missions should deliver to the Gateway. After inspections, the crew will board the Orion once again and commence its trajectory back to earth.

**Phase 2: LEAPR Exploration Missions**

The concept of operation of the remaining missions will be similar to the first one, but they will use a simpler, more cost-effective process. In this phase the crew will still be delivered by the SLS and Orion per competition specifications and the two CAR module will be delivered by the FH. There is only one necessary SLS launch per mission during this phase, which saves $500M from the annual cost of the LEAPR project. Figure 2. Surface Operations Sequence

This guarantees an approximate annual operations cost of $800 million. It is assumed that throughout the extent of the LEAPR project, several current technologies such as ISRU and a lunar roving vehicle will
become available. The eventual additions of these components will significantly extend the capabilities of the lunar surface operations architecture.

3. Design Overview

![KTV Design Overview](image)

1. Solar Panel
2. RCS
3. Main Engines
4. Landing Legs
5. Radiator
6. Docking System
7. Optical Module for Laser Communications
8. Airlock
9. Retractable Egress Ladder
10. Cargo
11. Refuelling Port
12. Auxiliary Thruster

The KTV is designed to be a fully reusable single-stage lunar lander that can transport crews of 2 and 4 astronauts from the Gateway to the lunar surface and vice-versa. The design is inspired by past concepts, but it mainly relies on current and future technology that enables it to comply with certain requirements while also facilitating different types of missions and add-ons. As shown in Figure 3, the lander has a major diameter of 6.25 m and a height of 11.87 m with the landing gear deployed. The vehicle is divided into two sections. The first is the Crew Quarters (CQ) that is the pressurized section where the crew will live and perform some of their duties during their lunar mission. The second is the propulsion stage which holds the fuel tanks, RCS, solar panels, and the landing gear. The vehicle was significantly optimized in terms of mass, dimensions, and component integration to upgrade the efficiency of the propulsion system and of the orbital maneuvers. The two-floor design, which included a separate flight cabin section, was removed as it was found that there was sufficient space in the CQ to accommodate the flight controls and the ECLSS components. The fuel tank diameter decreased as updated calculations proved that the lander required less propellant than originally established. Therefore, the propulsion stage was reduced to 6.25 m in diameter. All of these changes resulted in a slight decrease in mass which ultimately yielded a total of 53.08 - 61.58 mT of wet mass dependent of the landing scenario. Other components such as the landing systems, cargo hold, and airlock were updated.

3.1 Materials and Structure

The layers of the lander structure were updated to add the Multi-Layer Insulation (MLI) assembly to function as a heat insulator as part of the thermal control and protection systems updates, as seen in Figure 4. This thin layer just adds an approximate of 2.2 kg to the mass of the lander. The inner construction was also redesigned to further optimize the mass of the structure. This now consists of a frame of six vertical tubes of titanium of ~ 60 x 60 mm that covers the perimeter of the lander in stages and sections. Two horizontal ring-shaped frames of 6 m in diameter were added to the bottom and top of the propulsion stage to hold the tanks in place, and another smaller ring-shaped frame of 3.7 m was placed at the top of the lander to secure the docking platform. Mass savings reduced this Titanium inner structure to near 1,775 kg, as described in Table 2. The tanks were designed with a thick Korex honeycomb structure compacted between two sections of a Carbon Fiber Reinforced Polymer (Figure 5). With a TRL of 6, this configuration is favored by the industry due to mass savings. In this case, the fuel tanks have a mass just below 800 kg.
These mass changes were incorporated to the dry mass of the lander, which resulted in 14,853.12 kg. This final dry mass accounts for the structure, cargo, legs, batteries, and other important components.

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<tr>
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<th>Table 2. Material Layers</th>
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<tr>
<td>Titanium (structure)</td>
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<tr>
<td><strong>Total</strong></td>
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3.2 Crew Cabin

The pressurized section of the KTV was designed to be human-rated while additionally providing increased capabilities to the overall surface mission logistics. From the CAD models of this section, it was determined that the crew cabin contains an approximate habitable volume of 21.5 m³. When compared to the habitable volumes of the Apollo and Orion, 4.53 m³ and 8.95 m³ respectively, the habitable volume of the KTV is significantly larger. For a mission with a crew of two astronauts, there is a habitable volume of 10.75 m³ per person. In contrast, in a mission with a crew of four astronauts, there is a habitable volume of 5.38 m³ per person. According to Celentano et al [23], these values are tolerable and acceptable for performance. The crew cabin is equipped with reclining chairs that have been designed based on the seating considerations presented by Gohmert (2011) [41]. LED lights have been added to help the crew maintain the circadian cycle (more information is found in the Life Support section). The seats allow three configurations: (1) flight (2) bed, and (3) workbench. This versatility optimizes the space inside the lander while maintaining a sense of comfort which is beneficial to the health of the crew. The positioning of these seats is shown in Figure 6. The ECLSS components, the electrical systems, and the waste and food box units have been organized in accessible compartments inside the cabin, as shown in Figure 6 and 13.

3.3 Landing System

The KTV landing system underwent a significant evolution throughout the entire project. The final version of the landing system design was based on a dynamic system that can adjust to the impact forces that the vehicle will be subjected to upon landing. The KTV propulsion system will propel the lander directly to the surface of the Moon; however, a system for impact absorption was designed in case the propulsion system fails to start up in time. The proposed system is a redeployable triple tube system where a V-shaped hollow tube will allow upward movement while the main center tube will dissipate and distribute the energy caused by the impact load. The main tube will have a system of three metal bellows in series providing stiffness while a visco-elastic material will be located at the end of the rod to distribute the energy across the lander. The inside of the bellows will be filled with compressed air that will increase.
or decrease its pressure depending on the readings of a motion sensor located on each end of the legs. The motion sensor will utilize the data to determine the force of impact and then the system will send a signal to a pressure gauge to release the required air to counteract the force that was expected. The interior of the footpad will also encase the same visco-elastic material used for the bellows to further enhance energy absorption, thus providing redundancy. In addition to the bowl shape of the footpad, a 0.25 m diameter titanium ball will connect the footpad to the rods to allow the pad to rotate with ~ 10 degrees of freedom and accommodate on the ground. This makes the system very dynamic and able of absorbing impact from a high altitude while absorbing and distributing the energy of the lander in a balanced and effective way. The visco-elastic material protects the main structure as it prevents the energy wave that is produced when landing to reach the main structure. Preliminary estimates indicate a TRL of 3 due to its highly conceptual design. A detailed view of the landing system and its components can be observed in Figure 7.

3.4 Cargo and Experiment Compartments

To meet the 100 and 500 kg load requirement, the KTV makes an innovative approach to transport the cargo. The lunar lander includes an initial configuration of six containers placed on the sides of the egress ladder and a smaller configuration inside the crew cabin. Each exterior canister has a storage capacity of 0.4174 m³, for a combined capacity of 1.6696 m³. It will also provide protection from micrometeorites and radiation since they have been designed with the same materials as the wall layers of the KTV. Each container is compatible with the latching system of the cargo containers. These containers will be used to transport scientific equipment, hold samples retrieved from the lunar surface, and also carry experimentation equipment or any other unpressurized cargo. Considering the case that 500 kg of lunar regolith are retrieved from the surface, it can be stored in a volume of 0.33 m³. In this case, four containers meet and exceed the cargo requirements. Twelve smaller compartments were implemented in the interior so that the crew can store personal items, instrumentations or any other equipment that is needed inside the crew cabin.

3.5 Structural Analysis

The landing gear system (composed of four legs) was analyzed by means of a finite element software (NASTRAN) applying the static loads from the overall structure to an individual leg when the lander reaches the lunar surface. The analysis aimed to make sure that the landing gear was not compromised with plastic deformation and over design. The legs were initially designed with parameters previously obtained from handmade computations. These helped state initial measurements to create a finite element method. The computed structural analysis proved useful to identify deformation and maximum stresses in the structural component. After some dimension adjustments, the team was able to reach the optimal design for the landing gear. This design is able to stay within the elastic deformation margin with a safety factor that falls within the recommended range for untested spacecraft structures (2-2.6).

To establish optimal structural integrity in the aforementioned scenario, some assumptions were made: (1) The whole leg structure is built utilizing Ti-10V-2Fe-3Al. (2) The lander falls from a distance of 2 m above the surface. (3) The lander has a falling velocity of 2.54 m/s. (4) Utilizing the mass of the lander at the time it reaches lunar surface (See appendix Eq. 4.1) along with these assumptions, sufficed the formulas to provide the impact force computation. For the structure analysis scenario, the probability of failure if the total load will be only carried by one leg was studied. The behaviors in the finite element analysis were studied considering that the impact force resulted in 173,341.06 N (Eq. 2.2 Appendix). The
impact load was applied where the landing legs attach to the lander, and this force simulated the effect of the load of the whole lander over one leg in touchdown (worst case scenario). A fixed constraint was added to the bottom part of the footpad to simulate the effect of the leg touching down the lunar surface. After running the simulation and making some adjustments to the thickness of the landing leg tubes, the maximum nodal stress reached a maximum of 442.40 MPa. This value was reached considering that the outside leg diameter (for the middle tube and the “V” section) \( D \) was 0.180 m and utilizing a thickness of 5 mm for the middle tube and 15 mm for the “V” section. The factor of safety was then computed using the maximum stress given from the analysis as compared to the Ti-10V-2Fe-3Al yield point, to make sure that the deformation stays within the elastic region. Given that the Yield strength for the titanium alloy is 1145 MPa the factor of safety resulted in 2.59 falling within the range for untested spacecraft structures.

3.6 Thermal Control Systems

The lander will consist of two integrated thermal loop systems that will keep the fuel tanks and interior habitat at their proper temperature. As seen on Figure 9 below, the 1st and 2nd loop will circle Helium to maintain the tanks at their cryogenic temperatures. Loop 1 is a reverse turbo Brayton cycle, and thus, it has a turbine and a compressor to increase energy transfer. Excess heat will be given off to the Helium of Loop 2 in the heat exchanger, from where it will ultimately be liberated to outer space through the radiators. The ECLSS water loop system will circulate through Loop 3 to keep interior cabin temperatures in the ambient range. This will be a closed loop, only accessible by the Helium of Loop 2 by valves through the phase change material (PCM) heat exchanger. The PCM will be paraffin wax, since it has greater energy absorption due to its latent heat of fusion. Heat in the cabin will be generated by batteries, computers, and humans, and, when interior temperatures are too high, valves will open for a minimal amount of time to take excess heat out through the radiators.

3.7 Future Add-ons

The KTV will feature a customizable design. This design allows for the implementation of different assets throughout the course of its lifetime, increasing its capabilities. This constant evolution of the design means that the KTV will gain new and improved functionalities. This will broaden the types of missions the crew will be able to carry out. The planned add-ons include:

- Movable Platform: With a mass of up to 35.29 kg, this platform will be mounted at the side of the KTV’s propulsion stage, making it possible to transport cargo and materials to and from the lunar surface.
- Robotic Arm: Weighing up to 1,094.96 kg and capable of lifting an additional 547.48 kg, this add-on will feature rotary joints, as well as an extendable, telescopic design capable of reaching up to 8.8 m. It will allow a level of precision and mobility not found in the moving platform and will be able to transport cargo and crew alike. The robotic arm can also add the capability to transport injured astronauts.
4. LEAPR-Gateway Impact
The KTV will have a fairly simple yet important impact on the Gateway. The functions of Orion, the Gateway, and the KTV will be treated as separate systems to reduce the complexity of working on simultaneous modular systems and provide versatility for other missions while also increasing safety. It is assumed that the Gateway will have three docking ports available by 2028 so that the lander remains docked during the eleven months that the station will remain uncrewed. The Gateway’s primary role in its interaction with the KTV will be to provide the refuelling of the main tanks for lunar reentry as well as servicing to the whole vehicle, including maintenance and restocking necessary supplies. As for the interaction of the primary systems of the KTV and the Gateway, the lander is capable of full independent reliance with power being generated from the solar panels, thermal impact being managed by the thermal control systems, and the structure being capable of being operated manually. This was decided to benefit both systems, as minimal interaction between them generates less risk. Taking into consideration the effect of docked vehicles in the ISS, it can be assumed that the same type of behavior will apply when docking the KTV. Once the prepared mission is completed, the KTV will remain docked to the station until the next mission.

5. Life Support
The objective of the LEAPR Life Support System implemented to the KTV is to attend to basic human needs and countermeasure possible life-threatening situations by providing systems that assure the safety of the crew members at any moment during the mission.

5.1 ECLSS
The ECLSS system provides the necessary conditions to maintain habitable environmental circumstances, sustain life, and promote workability until mission completion. A non-regenerative-open-loop ECLSS configuration was originally chosen. The ECLSS is a simple configuration that will supply the mission with resources linearly dependent on the flight time. Because of this configuration, it is the most cost-effective in comparison with other subsystems. This default system for spacecraft has a TRL value of 9.

5.2 Airlock System
A new and more detailed design for the airlock system was developed. The airlock system aboard the KTV is composed of three different subsystems: two of these subsystems focus on the removal of lunar dust from the spacesuits, while the other provides the revitalization of the atmosphere and pressure inside the airlock. One of the systems will remove lunar dust by 95% using the technology of electrodynamic dust shield (EDS), which utilizes an induced dipole by applying a non-uniform electric field, generating a dielectrophoretic force that induces the movement of particles with electric charges. The electric field is
generated by the alternating current on a set of electrodes embedded in a high dielectric strength material. The component used for this magnetic field is indium tin oxide and copper on polyimide coated with fluorinated ethylene propylene, laminated to provide a top layer with high dielectric strength. The airlock contains four magnetic fields, each field with a dimension of 353 mm of width and 665.14 mm of length. The other system that removes the remaining 5% of the lunar dust is the nylon ring. The soft nylon with adhesive properties can trap the lunar dust particles with neutral charges when the astronaut passes through the ring. The nylon ring covers an area of 17.06 m². The third and final system on the airlock is the Atmosphere Revitalization and Pressure Control System (ARPCS). This system controls the pressurization and depressurization of the airlock when the astronaut is exiting or entering the lander. This highly innovative yet recently developed system has a TRL rating of 3. The effectiveness of each system provided by Calle, C.I. et al. [21] might include some minor errors as it is possible that some lunar dust particles are unable to be removed from the spacesuit. This is due to the lunar dust being micrometers in size and some samples being diamagnetic particles. This problem is exacerbated by the spacesuits having areas that are out of range for the moon dust removing systems, for example: armpits, boots, etc. Boots and gloves will be stored on each side of the airlock. For this reason, it is better to conclude that the lunar dust removing systems will be effective the majority of the time when being used.

5.3 Habitat
The initial KTV design lacked key ergonomic features, such as a waste disposal area with privacy for the crew and a comfortable resting area. Therefore, a small compartment was added to allow privacy for biological waste disposal. The Maximum Reach Analysis presented in Figure 14 illustrates the ergonomic considerations that were taken into account when designing the crew cabin.

5.4 Crew Psychological Health
The mental health of crewmembers is vital for mission success. A system of light-emitting diode (LED) lights was implemented to regulate the circadian rhythm of the crew. If a severe case is presented, there is an aid kit which contains sleeping pills that can be administered to the affected crewmember. If an emergency occurs due to the feelings of isolation, confinement, or distance from Earth, the crew will initially try to resolve the issue themselves but, if needed, they will be able to communicate with a mental health specialist back on Earth using the KTV communication systems.

5.5 Waste Management and Food Supply
The initial design for the KTV did not count with a waste management system of low-energy consumption. This system was added in the form of a 30x30x30cm box with a 10.00 kg capability and a leak-resistant double lid. Biological waste, trash, and food residue must be placed in small bags that will later be deposited inside the container. The same box design was implemented for food storage.

5.6 Maintenance
Maintenance will take place once the KL is docked to the Gateway and after completing each lunar surface mission, and will be addressed with a complete general inspection. The departing crew will inspect the internal and external components and structure of the lander to determine if it is properly enabled assuming that the Gateway provides an airlock capability; this will be revised too, as well as the electrical and propulsion systems. The exterior of the vehicle shall be inspected via an EVA that the crew performs. For
instance, the KTV batteries must be replaced every five years since that is their average lifetime. Despite
the fact that the lander will be protected with a layer of lotus coating, inspections must be made every year
to make sure that the lunar dust does not affect its efficiency. The interior components of the lander shall
be inspected as well with different tests addressed for each component. At the end of the mission, before
returning to Earth, another complete inspection will be made, such as reviewing and ensuring the cleanliness
of the equipment and structure. If the crew finds any equipment that needs to be replaced and cannot be
fixed at the time, information will be taken from it and it will be added to a list of revision with the status
of each component. This data will then be collected and shared with ground control and the next crew so
that these are responsible for carrying the necessary materials to fix and replace the components that require
deeper inspection.

6. Orbital Dynamics and Fuel Usage

6.1 From Earth to the Moon Stationed at the Southern NRHO 9:2

The KTV will be launched on the SLS Block 1B Cargo version that should be ready by 2028. The
following parameters for the trajectories calculated by Zimovan et al [155] were used for the analysis. After
the KTV is launched, it will need to be stationed at LEO with an altitude of 200 km and a 28-degree angle.
From there, SLS Block 1B second stage engine will perform a TLI with a $\Delta V$ of 3,124 m/s. Before it arrives
at the cislunar space, it will detach from the SLS 1B second stage. When it reaches the vicinity of the Moon,
it will perform another injection towards the Southern NRHO with an approximate $\Delta V$ of 835 m/s [155]
using 3,145.76 kg of fuel reaching an apolune of 70,000 km. The travel time to reach NRHO from LEO
using these maneuvers is ~5.33 days. This trajectory is cost-effective for various reasons: it is easier to enter
at apolune for the reduced sensitivity required for navigational purposes, and it is a direct trajectory with
low duration and low fuel cost [155]. The KTV vehicle fuel consumption for this trajectory is calculated to
be 3,337.25 kg of fuel.

6.2 Launch Date and Arrival time for Gateway Rendezvous

To get to the Gateway, some assumptions were made to find a launch date and arrival date to
rendezvous. It was assumed that by 2028 the Gateway would be in orbit and, furthermore, that it would be
at an apolune of 70,000 km on January 1st at 12 a.m. The time at which the Gateway will be at apolune was
calculated using the 6.56-day period of the Southern 9:2 orbit. This helped determine the dates in which
each revolution occurs and, by utilizing the time of 5.33 days to arrive at NRHO, the launch and arrival
dates were estimated. The time at which the Moon will be closest to the Earth in 2028 was also considered
when choosing the launch date. The ideal arrival date resulted to be around February 10th, 2028. These
constitute the reasons for which the following dates were chosen: February 4th as an ideal day for launch

<table>
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<th>Scenarios with Robotic Arm</th>
<th>NRHO to LLO</th>
<th>LLO to Moon</th>
<th>Moon to LLO</th>
<th>LLO to NRHO</th>
<th>Rendezvous</th>
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<td>1,900</td>
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<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>PR ($\Delta V$ in m/s, 6 days mission)</td>
<td>707</td>
<td>1,900</td>
<td>2,100</td>
<td>717</td>
<td>56.3</td>
<td>5,480.30</td>
</tr>
<tr>
<td>Fuel Usage (kg)</td>
<td>8,396.84</td>
<td>16,918.72</td>
<td>11,919.23</td>
<td>2,935.58</td>
<td>210.99</td>
<td>40,381.37</td>
</tr>
<tr>
<td>ER ($\Delta V$ in m/s, 6 days mission)</td>
<td>795</td>
<td>1,900</td>
<td>2,100</td>
<td>798</td>
<td>56.3</td>
<td>5,649.30</td>
</tr>
<tr>
<td>Fuel Usage (kg)</td>
<td>9,697.60</td>
<td>17,199.94</td>
<td>12,117.36</td>
<td>3,292.12</td>
<td>216.0</td>
<td>42,517.63</td>
</tr>
<tr>
<td>PR ($\Delta V$ in m/s, 2 days mission)</td>
<td>707</td>
<td>1,900</td>
<td>2,100</td>
<td>800</td>
<td>56.3</td>
<td>5,480.30</td>
</tr>
<tr>
<td>Fuel Usage (kg)</td>
<td>8,686.72</td>
<td>17,502.80</td>
<td>12,330.72</td>
<td>3,557.76</td>
<td>214.22</td>
<td>42,092.20</td>
</tr>
<tr>
<td>ER ($\Delta V$ in m/s, 2 days mission)</td>
<td>795</td>
<td>1,900</td>
<td>2,100</td>
<td>810</td>
<td>56.3</td>
<td>5,661.30</td>
</tr>
<tr>
<td>Fuel Usage (kg)</td>
<td>9,890.69</td>
<td>17,542.40</td>
<td>12,358.62</td>
<td>3,403.68</td>
<td>214.22</td>
<td>43,409.61</td>
</tr>
</tbody>
</table>
while the estimated date of arrival would be around late February 8th to February 9th. The dates are estimated since the orbit changes periods throughout the year. Using the mentioned assumptions, when arriving near lunar vicinity and the vehicle makes an NRHOI, a small burn was considered for rendezvous at the Gateway due to errors in the trajectory that may occur [30]. This is assumed to be the minimal fuel usage, since getting to NRHO from LEO is already calculated, but this is covering for errors around the burns and it may be unneeded. The reason behind the rendezvous occurring at apolune is because at perilune the orbit is sensitive to change and it would alter the orbital path of the Gateway, thus the Gateway would need to make a correction maneuver [30].

6.3 Fuel Usage for Orbital Changes and Landing

The KTV needs sufficient fuel to execute all the necessary maneuvers for the missions. Some of the parameters, calculated by Whitley et al. [151], were used for the ideal orbital trajectories and velocity changes to obtain an approximate estimate of the fuel mass. The fuel mass was calculated with the velocity changes from NRHO to LLO, from LLO to the Moon Polar Regions (PR) and Equatorial Regions (ER), and vice versa for different scenarios. As it appears on Table [4], this is the required fuel mass with its corresponding velocity changes with its corresponding scenario. The same scenarios were applied if the KTV had the robotic arm add-on, which requires more fuel. As it is mentioned by Ryan Whitley [151], the landing and launching \( \Delta V \) remain for all descends and ascends at the Moon. The time that it takes to produce the maneuvers from NRHO to LLO and vice versa is about 0.5 days for PR, and around a day for ER [151]. To land on the Moon, it takes around 4-6 minutes depending on the desired landing site and the velocities from entry [143]. The times calculated by Trofimov et al [143] assumed a specific acceleration for its analysis but it won't be same acceleration for the KTV. Meaning that the time for entry of the KTV would be around 5-8 minutes and back to LLO. Table [5] shows the time it will take to rendezvous with the Gateway for 6-day missions and 2-day missions. An approximate assumption was made that the crew would need to wait ~0.25 - 0.5 days loitering in LLO for a rendezvous window. The 2-day mission requires more time to return, given that the Gateway hasn’t given a full revolution since the detachment of KTV. This implies higher velocity changes assumed to be about ~740 m/s - 810 m/s, following the argument of the anytime abort mentioned by Whitley et al. [151], having a flight time of 3.6 days for the PR and 3.3 days for the ER. There are also direct landing trajectories that can be used from various points of the orbit by making \( \Delta V \) of 50 m/s - 500 m/s to go to the Near Polar Orbits [143] around the Moon at different angles that depend on the selenocentric distance. The vehicle can perform a direct landing to some places, mostly at PR and ER, with \( \Delta V \) of 2,400 m/s to ~3,000 m/s [143]. The Table [6] shows the distribution of velocities that the KTV can do. Utilizing this for the 2-day missions presents a better solution for a minimal time of return to the Gateway, considering the departure point in NRHO. This would happen in around 0.5 day - 1 day using the exact same velocity changes from the 6-day mission; from this and its fuel usage, it would be about 44.22-45.09 mT.

6.4 Landing at the Poles and Equator

From the aforementioned estimated fuel usage calculations, there is a variety of landing zones on the Moon that the vehicle can land on with sufficient fuel. Some require more fuel and time for the mission, while other orbits require less, depending on how the mission will run.

<table>
<thead>
<tr>
<th>Mission Elapsed Time</th>
<th>PR</th>
<th>ER</th>
<th>PR</th>
<th>ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRHO-LLO</td>
<td>0.5 days</td>
<td>1 day</td>
<td>0.5 days</td>
<td>1 day</td>
</tr>
<tr>
<td>LLO-Moon</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
</tr>
<tr>
<td>Moon-LLO</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
<td>5-8 minutes</td>
</tr>
<tr>
<td>LLO-NRHO</td>
<td>0.5 days</td>
<td>1 day</td>
<td>~3.6 days</td>
<td>~3.3 days</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>6 days</td>
<td>6 days</td>
<td>2 days</td>
<td>2 days</td>
</tr>
<tr>
<td>Loiter</td>
<td>~0.5 days</td>
<td>~0.5 days</td>
<td>~0.46 days</td>
<td>~0.26 days</td>
</tr>
<tr>
<td>Total Time</td>
<td>~7.51 days</td>
<td>~8.51 days</td>
<td>~6.67 days</td>
<td>~6.57 days</td>
</tr>
</tbody>
</table>

Table 5. Mission Time from NRHO to the Moon and Back
A significant constraint is radio communication with the Gateway and the lander. Looking at the communication coverage map from [68], there’s more coverage at the South Pole and the equator at the Far Side, and little to no coverage at the North Pole and above the equator on the Near Side. With this knowledge, it had been determined it would be better to land on the South Pole. But, in the lander, a laser communication system and a backup S-band radio frequency antenna were implemented for communication with Earth. Thus, it becomes viable to land on the North Pole. Some locations where the KTV could land can be found in the Table [7]. The sites identified comply with landings and direct landing calculations for the KTV, in which they were selected for their significance regarding water, geology, topography, and mining.

6.5 Abort Risk Fuel Consumption and Time Intervals

According to Whitley et al. [151], there are some estimates of emergency abort trajectories from the Moon to NRHO. The fuel needed to perform this maneuver was calculated using the maximum abort velocity changes for any time abort of 739 m/s for the poles and 789 m/s for the equator. These abort maneuvers take about 2.5 days with a total of 3.6 days to get back from the poles and a total of 3.3 days to get back from the equator. From this analysis, some viable options were determined to successfully land the KTV with and without the robotic arm and a crew of two to four astronauts, while also maintaining the abort capability. This occurs at polar and equatorial landings as well as in some other parts of the Moon. The maximum fuel usage was considered by taking into account the abort fuel requirements from Table [8], and normal scenarios from Table [4] to identify which scenario consumed the most by mission. It was concluded that, with the maximum fuel usage per mission needed to cover a normal mission and an abort trajectory, the KTV can perform the missions without any risk of consuming all of the fuel.

7. Propulsion System

The propulsion system of the KTV will operate with chemical propellant to perform effectively as required and comply with its main objectives. After further analysis, the chemical engines will work with LOX/LH2 as their propellant, with a 5.5:1 mix ratio since the specific impulse of 451 s, cost, and total mass proved to be beneficial for this type of application. Taking into consideration the Tsiolkovsky rocket equation, this equation resulted in a minimum total wet mass of 57,139.98 kg and a maximum total wet mass of 60,136.72 kg. Therefore, the propellant mass resulted in 40,664.86 kg and 43,409.61 kg.
respectively. The RL-10A-4-2 engine proves to be efficient for this application since it is capable of producing the thrust required with two (2) engines which are ~202.12 kN; this is totally reached with the auxiliary thrusters. Eight (8) R-4D-11 auxiliary engine thrusters with an equivalent force of 490 N each, designed by Aerojet Rocketdyne, including twelve (12) R-4D around the body and cockpit with about a force of 220 N each, will be added along with the Main Propulsion System to ensure better mobility for the lander, and as a redundancy for the main thruster.

8. Fuel Storage and Transfer

The tanks that will carry LH2 and LOX will be built with several features to maintain the cryogenic fluids in their liquid phase throughout the voyage to the Gateway. Some of these features are: fuel level sensors, complete insulation/thermal control system, a transfer liquid method, and a pressurization system. To perform the transfer of the cryogenic fluids in low gravity, a Liquid Acquisition Device (LAD) will be used to manage fueling. The LAD includes a screen channel capillary that will retain the liquid of the tank but not the gases, and a guide in the fluid transfer. To avoid the change from liquid to gas, the cryogenic temperature of each propellant should be maintained at -252.7°C for liquid hydrogen and -182.7°C for liquid oxygen. The temperature inside the tanks depends on the pressure in which they are stored. Both tanks have a pressure under three bars. A comprehensive and appropriate Active Thermal Control (ATC) System should include insulation and a refrigeration cycle cryocooler. The tanks should have Self-Supporting Multilayers Insulation (SS-MLI), Spray-On Foam Insulations (SOFI), and Broad Area Cooling (BAC) shield. The insulation helps avoid the heat transfer of the radiation coming from outside and maintains the low temperatures inside the tanks. The BAC is used in the tubes where the fluids will flow from one tank to the other. The tubes need to be chilled down to avoid the change of phase and possible cavitation during the fluid transfer. To maintain the right temperature in the tanks, the reverse turbo Brayton cycle cryocooler should be implemented. The ATC system will provide the liquid oxygen a zero boil-off (ZBO) and will reduce boil-off (RBO) at 60% of the liquid hydrogen. In addition, the pressure in the tanks and the tubes should be controlled with pressurization using helium for the LOX and autogenous pressurization for the LH2 with a diffuser placed on the top (or bottom) of the tank. The LAD provides a pressure difference in the tubes that induces the fluid flow through it. Both tanks should have pressure sensors and vent valves for safety reasons.

8.1 Cargo and Resupply (CAR) Modules and Refueling Utility Mechanism (RUM)

Launching the entire fuel resupply on a single vehicle proved to be expensive after taking into consideration the capabilities and cost of current launch vehicles. While it is expected that heavy-lift launch vehicles will be available at a lower cost by 2028, the capabilities and cost of the SLS and the FH were compared. The SLS Block 1B, with a maximum payload of 40 T, costs $500 million, while the FH has an estimated TLI payload range of 18 T to 22 T and costs $150 million. Therefore, the FH will be used for the TLI due to its ability to perform the same task as the SLS Block 1B while staying within a reasonable budget. The fuel mass was divided into four tanks. A basket-like module called CAR will be used to carry two tanks that will each contain half the mass of LH2 and half the mass of LOX, and will have a small compartment for light cargo. To have a successful fuel transfer, a robotic system, like the Robotic Refueling Mission 3 (RRM3), is going to be implemented into the CAR. It will make the necessary maneuvers to dock the CAR and transfer the fluid without boil off. The robotic mechanism reduces the use of a robotic arm in the KTV for the docking maneuvers to make the refueling process. This robotic system was called the Refueling Utility Mechanism (RUM) and will serve as the refueling mechanism of the lander for every mission. The fuel transfer time for each type of fuel would take approximately 2 hrs to be completed since both fuels will be transferred simultaneously. Accordingly, the entire refuelling of the KTV will take 4 hours. The LOX will be transferred with a mass flow rate of 10 tons/hrs while the LH2 will be transferred at a rate of 1.7374 tons/hrs.

The arrival of the RUM and CAR can be seen on the CONOPS, Section 2. The CAR will be similar to the RRM3 system that can maintain ZBO in the tanks for six months. The two Falcon Heavy vehicles are going to be launched on specific dates that match with the period of the Gateway when they arrive to rendezvous.
When the CAR completes the refuelling process, it detaches from the KTV and it is disposed as described in Section 8.2. The KTV waits for the other tanks to be delivered by the next FH to complete the fuel transfer. When the refuelling process is finished, RUM will remain stationed at the Gateway for the following missions. For the first missions, the RUM will be tele-operated from the Earth to make the docking and the transfer. The RUM can be controlled by several stations on Earth, such as NASA Goddard Space Flight Center in Greenbelt, Maryland.

8.2 CAR Disposal Trajectory

Once the refuelling process finishes, the CAR will detach itself from the Gateway and it will be sent to a disposal trajectory for a heliocentric escape [152]. This particular trajectory was chosen because it is a common disposal trajectory since it accounts for one third of all propagated disposals. Furthermore, it was not chosen for a direct impact on the Moon or the Earth because it would require additional safety and logistics considerations such orbital tracking. This will be achieved by doing a propulsion impulse using the 400N Chemical Monopropellant thruster attached to the CAR [10]. This monopropellant component has a TRL of 9. For this to work, the following assumptions were done using similar parameters like the ones Williams et al. [152] used: it would need an approximate $\Delta V$ of $\sim 5$ m/s and $\sim 120$ days to achieve escape after the initial impulse. The impulse to escape can occur any point in the orbit since it has significant redundancy in the disposal window [152]. It should be noted that the maneuver has to be executed near apolune to avoid any changes to the orbit of the Gateway.

9. Power Generation and Storage

Power generation relies on the photovoltaic cells Triple-junction GaAs Solar Cell 3GA-2-32% by Shanghai YIM of Space Power-Sources; they have an efficiency of 32% and TRL of 8. These cells will be arranged in two Ultraflex solar panels. This solar panel design has a TRL of 9. in addition, each one has eight divisions where each division has an area of 5.46 m². With this new design, they can be adjusted to different angles to provide maximum efficiency. At certain times, the panels must be facing perpendicular to the Sun for peak energy recollection. To achieve this, the beta angles formed with the Moon’s orbit will be used as the reference point. To assure the panels are facing the Sun while in orbit, a torque is needed to allow the LEAPR to rotate, which will be monitored by the KTV telemetry system. These solar cells are able to generate an estimated of 85k W/hr of power in this arrangement. To store this energy, 22 arrangements of 16 lithium-ion batteries by EaglePicher Technologies will be implemented; the specific model is SLC-16050 which has a TRL value of 9. As backup energy storage, 4 extra arrangements of these batteries will be designated to the KTV to provide power to the essential systems of life support if a worst-case scenario would occur.

10. Electrical Systems

The computer chosen that has been implemented for the final design of the KTV is the Honeywell Vehicle Management Computer (VMC) for aerospace applications. This specific model has a TRL of 9 and has enough processing power for Autonomous Fault Detection, flight control systems, avionics systems, amongst other computer analytical software. Additionally, the lander will collect its data via a Magnetoresistive Random Access Memory device (MRAM) like the 1Gb STT-MRAM by Everspin Technologies. The sensors to be used have a TRL of 9, and these include: the GG1320AN Digital Laser Gyroscope, the QA3000 Accelerometer, and the Precision Barometer and Altimeter (HPB/HPA); all developed by Honeywell. Additionally, two HP ZBook 15 laptops will also be on-board; this specific model retains a TRL value of 9. The laptops occupy an essential role in the overall functioning and monitoring of the KTV which include: examining, collecting, and analyzing data, keeping track of the astronauts’ medical history, upgrading and/or repairing interfaces, personal tasks, amongst other functions.

11. Redundancy System

The Vehicle Management Computer (VMC) was chosen as the main computer of the KTV due to its capability and reliability of operating and withstanding the space environment on the Orion spacecraft. The VMC is highly capable and responsible for managing all software commands that control the spacecraft’s flight communications and navigation systems. It also works as the redundant system via redundant Ethernet connections using TTEthernet Network Interface Controllers and network switches in one physical enclosure as it offers internal redundancy and has enough processing resources for the
functions of the spacecraft consisting of four independent modules that deliver the processing capabilities for the lunar module.

12. Communications

The communication systems for the KTV were detailed to adequately comply with the requisites for communication in its mission environment. For communication back to Earth from lunar orbit and the Moon, the lander will use laser communication systems based on the Lunar Laser Communications Demonstration (LLCD) mission [18]. This technology has a current TRL of 8. The space terminal consists of an optical module on the exterior of the lander, and a modem module and controller electronics module in its interior. Meanwhile, on Earth, there will be three ground terminals in dispersed locations which could include New Mexico, California, and Spain. This technology possesses the capability of transmitting data back to Earth from the lander at source rates up to 20 Mbps while communicating data to the lander from Earth at sources rates up to 622 Mbps. Evolution of this technology is expected for subsequent LEAPR missions, and further testing of laser communications could be viable on the KTV. The EnduroSat CubeSat RF Antenna for UHF communication, which has a TRL value of 9, will be implemented for communication between the Moon and the Gateway. The EnduroSat CubeSat RF Antenna for S-Band communication, which also has a TRL value of 9, will serve as a backup mode of communication back to Earth as a mitigation to the risk of laser communication failure. The optical module and the antennae on the KTV exterior can be seen in Figure 19.

13. Budget

For the budget estimates, the LEAPR team implemented the guidelines presented in “Rapid Cost Estimation for Space Exploration Systems” [11] to produce a higher fidelity estimate. The equations found in the Life Cycle Cost (LCC) document were used to produce a Cost Estimating Relationship (CER) which provides the actual value. The LCC estimates two major factors for cost estimation which are: Design, Development, Testing, and Evaluation Cost (DDT&E), which represents the cost of promoting the mission from the concept phase to the design phase, and the Flight Unit Cost, which is the cost of constructing the vehicle itself. The Equation 3.1, which represents the CER, employs the surface habitat table [9] from data gathered from The NASA/Air Force Cost Model (NAFCOM) to determine the parameters of k, a, and b, which are complexity factors and constants defined by the regression for the analogous system, in order to then determine cost. The Surface Habit was selected because it most closely represented the LEAPR project. The following table illustrates the values of the parameters used and the estimated cost of DDT&E and the Flight Unit Cost.

<table>
<thead>
<tr>
<th>Launch + Maintenance Costs Per Year</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Year</td>
<td>Launch Cost</td>
<td>Maintenance Cost</td>
<td>Total Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>1,300,000,000</td>
<td>0</td>
<td>1,300,000,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 2 - 15</td>
<td>800,000,000</td>
<td>295,953</td>
<td>800,296,953</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Launch Costs</td>
<td>2,100,000,000</td>
<td>4,143,342</td>
<td>12,504,147,122</td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction Cost</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DDT&amp;E Cost CER</td>
<td>751.64</td>
<td>32,083 lbs</td>
<td>0.1183</td>
<td>$2.57 B</td>
<td></td>
</tr>
<tr>
<td>Flight Unit Cost CER</td>
<td>124.32</td>
<td>32,083 lbs</td>
<td>0.1402</td>
<td>$534 M</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance Costs</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel x15</td>
<td>4,135,845</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food x15</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airlock x15</td>
<td>4,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4,142,345</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tables 9: Total & Annual Project Costs

With a flight unit cost of $534 million and DDT&E costs being displaced along eight total years with an annual investment of around $312 million, this estimate fits inside the NASA annual budget of $21.3 billion. Maintenance cost estimates give a total of $4 million, while annual maintenance costs amount to $276,223. Total launch costs amount to $12 billion displaced through the 15
years, while annual costs plus maintenance add up to $1.3 billion the first year of launch and $800 million from the second year of launch. Finally, total mission estimates result in $3.17 billion, which includes every cost from designing a concept to the mission itself. To make a comparison, other proposed landers in the industry have a cost range between $3 and $5 billion dollars, making this proposal a much more affordable solution.

14. Risk Analysis

A thorough analysis of numerous potential risks for the mission was completed, as displayed in the Risk Matrix below. These risks were classified by the probability of occurrence and by the severity and/or possible dangers of the situation. Each risk was taken into consideration and analyzed with viable mitigation to prevent or reduce the number of threats that could potentially jeopardize the mission. The same was done with the risks typically associated with the astronaut crew. The risk analysis for the mission was carefully reviewed and optimized from the previous version.

<table>
<thead>
<tr>
<th>Risk List:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Door and hatches failure</td>
</tr>
<tr>
<td>2. Loss of power</td>
</tr>
<tr>
<td>3. Computer hardware failure</td>
</tr>
<tr>
<td>4. Memory storage failure</td>
</tr>
<tr>
<td>5. Electrical component or wiring failure</td>
</tr>
<tr>
<td>6. Landing failure</td>
</tr>
<tr>
<td>7. Pressure leak</td>
</tr>
<tr>
<td>8. Fire accident</td>
</tr>
<tr>
<td>9. Solar panel failure (mechanical and electrical)</td>
</tr>
<tr>
<td>10. Failure to communicate to Earth and Gateway</td>
</tr>
<tr>
<td>11. Micro meteor impact</td>
</tr>
<tr>
<td>12. Engine failure</td>
</tr>
<tr>
<td>13. Docking failure</td>
</tr>
<tr>
<td>14. ECLSS failure</td>
</tr>
<tr>
<td>15. Medical emergencies</td>
</tr>
<tr>
<td>16. Radiation and solar particle events</td>
</tr>
<tr>
<td>17. Pollution due to lunar dust</td>
</tr>
</tbody>
</table>

15. Conclusions

The LEAPR project completely addresses the requirements of Theme #3: Gateway-based Human Lunar Surface Access of the RASC-AL 2019 competition. The team thoughtfully designed a human-oriented architecture that enables a sustainable campaign of human exploration on the Moon. This project is leveraged by NASA and commercial launch services. In addition, it uses existing and future innovative technologies that will extend the capabilities of the Karaya Transport Vehicle. Some of these innovations include: the combination of the metal bellows and the sorbothane in the landing gear, the moon dust cleaning system in the airlock, the ergonomic features of the crew cabin, the reliable and efficient flight maneuvers, and the robotic refuelling of the KTV fuel tanks.
16. Appendix

16.1 Calculations and Formulas

Tsiolkovsky rocket equation:

\[
\Delta V = I_{sp} g \ln \left( \frac{m_0}{m_f} \right)
\]

- \(\Delta V\) = Velocity Change
- \(I_{sp}\) = Specific Impulse = 551s
- \(g\) = Earth’s Acceleration = 9.81 m/s²
- \(m_0\) = Initial mass or wet mass
- \(m_f\) = final mass or dry mass

Equations for Structural Analysis:

\[
(1.1) \quad V = \sqrt{2gxd} = \sqrt{2 \times 1.62 \text{m/s}^2 \times 2 \text{m}} = 2.54 \text{m/s}
\]

\[
(1.2) \quad F = \frac{m}{2a} \left( \frac{V}{x} \right)^2 = \frac{32.703.63(2.54 \text{m/s})^2}{2 \times 0.6086 \text{m}} = 173.341.06 \text{N}
\]

\[
(2.3) \quad \sigma_{\text{max}} \leq \frac{\sigma_{\text{m}}} {S_x F} = \frac{900 \times 10^6 \text{Pa}} {1.75} \sigma_{\text{m}} = 514.286 \times 10^6 \text{Pa}
\]

\[
(2.4) \quad \sigma_{\text{max}} \leq \frac{F}{A} = \frac{173.341.06 \text{N}} {\pi \left( \frac{D_0^2 - D_i^2}{4} \right)}
\]

\[
D_i = \sqrt{-\frac{173.341.06 \text{N} \pi}{514.286 \times 10^6 \text{Pa}} + D_0^2}
\]

\[
D_i = 0.1788 \text{m}
\]

Cost Estimating Relationship Formula

\[
(3.1) \quad C = k \cdot aW^b
\]

- \(k\)=multiplicative factor for technology, system complexity, etc.
- \(b\)=coefficient (slope)
- \(a\)=coefficient (first pound cost)

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