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GLOBAL EXPLORATION ROADMAP DERIVED CONCEPT FOR HUMAN EXPLORATION OF THE MOON

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Abstract

Taking advantage of the development of Mars-forward assets in cislunar space, a human lunar surface concept is proposed to maximize value for both lunar exploration and future deep space missions. The human lunar surface missions will be designed to build upon the cislunar activities that precede them, providing experience in planetary surface operations that cannot be obtained in cislunar space. To enable a five-mission limited campaign to the surface of the Moon, two new elements are required: a human lunar lander and a mobile surface habitat. The human lunar lander will have been developed throughout the cislunar phase from a sub-scale demonstrator and will consist of a descent module alongside a reusable ascent module. The reusable ascent module will be used for all five human lunar surface missions. Surface habitation, in the form of two small pressurized rovers, will enable 4 crew to spend up to 42 days on the lunar surface.

1. Introduction

The Global Exploration Roadmap (GER)¹ is a document published by a group of international space agencies, formally known as the International Space Exploration Coordination Group (ISECG), which identifies opportunities to unite national plans into a multi-faceted collaborative framework. The roadmap endeavors to maximize the contributions of each international agency to simultaneously meet well-defined global exploration goals, a truly win-win proposition for the participants. With exploration destinations ranging from low Earth orbit and International Space Station (ISS) to the Moon and Mars, the GER has the potential to engender collaboration in all aspects of future human space exploration.

In this paper, opportunities for collaboration that lead to human return to the lunar surface are postulated. Most recently, NASA has proposed the development of a Deep Space Gateway (DSG) around the Moon that will provide the ability to support multiple U.S. and international partner objectives.² The DSG concept, described as the Evolvable Deep Space Habitat in the GER, is emerging as the consensus next step

that meets multiple exploration paths including the Moon, Mars and beyond. The DSG will be built up over a series of launches, both as crew co-manifested payloads and independent smaller launches, and will contain functions that permit habitation, EVAs, assembly, science experiments, and technology demonstrations while serving as a docking station for visiting vehicles. Contributions from all nations are currently being welcomed that will directly lead to future deep space exploration missions.

To that end, a cislunar orbit for the DSG has been selected that represents a bold step beyond Low Earth Orbit, is reasonably accessible from Earth-based spacecraft currently available or in development, all while maximizing the ability for all nations to conduct missions from a common location to multiple deep space destinations. Known as the Near Rectilinear Halo Orbit or NRHO, it is a 3-body halo orbit around the Earth-Moon Libration Point 2 that exists sufficiently out of the lunar gravity well to be readily accessible from Earth-based spacecraft, but with properties favorable for relatively fast and cheap transits to the lunar surface compared to other comparable cislunar orbits.³

Table 1: Mapping Lunar Surface Principles

GER Principle	Surface Campaign Principle
Affordability	Limit lunar surface infrastructure to what is necessary to achieve priority lunar exploration goals
Exploration Value	Use unique value of astronauts on the lunar surface and in lunar orbit for advancing goals and objectives of lunar, fundamental, and applied science
International Partnerships	Define a modular surface architecture, which maximizes opportunities for international partnership
Capability Evolution	Prepare for Mars surface exploration and maximize synergies between lunar and Mars surface campaigns
Human-Robotic Partnership	Identify opportunities for robotic elements to augment achievement of goals and ensure safety of the astronauts
Robustness	Provide dissimilar redundancy for critical functions on the lunar surface and define contingency/abort modes

The return journey to the lunar surface will begin from the Deep Space Gateway. How would the DSG be used to support human lunar surface missions? Some options include: storage and refueling of a reusable ascent module, safe haven for crew aborting from the surface, communications relay to Earth from the lunar far side, teleoperations of robotic systems (on the far side) as well as access to medical and exercise equipment for reconditioning when returning from a lunar surface mission. Probably the largest benefit to staging from the DSG is the potential to enable partial lander reusability. The DSG could become a hub for refueling both crew and spacecraft consumables which in turn could help open new commercial markets. The transportation trade space is examined fully in the next section where it is demonstrated that the DSG staging location fits favorably within a lunar surface architecture.

2. Mission Architecture

Knowing that the number of possible lunar surface architecture perturbations are endless, the consensus GER lunar surface mission concept was narrowed by considering three primary inputs: 1. GER derived strategic principles, 2. GER derived goals and objectives and 3. Capability based constraints as framed by potential international contributions.

2.1 Architecture Drivers

In the case of the first guideline, the ISECG community crafted a set of lunar strategic principles by mapping them directly from previously published GER principles¹ as shown in Table 1.

Of these principles the two that were most critical in determining the mission architecture were the desire to promote “Affordability” and “International Partnerships”. The combined principles could be summarized as an endeavor to maximize partnership opportunities by prioritizing modular systems while at the same time

minimizing cost and complexity, ultimately favoring minimum mass solutions.

The second input to the study was a list of clearly stated goals and objectives, articulating that the human lunar return should be both focused and fresh. The primary architecture drivers were specified simply: the lunar surface campaign should feature 5 missions of 28+ days each and enable crews of 4 to reach the lunar surface at any one time. A more detailed breakdown of individual objectives, based on the GER goals and objectives were identified to drive technology development programs and address priority scientific opportunities.

Finally, the various architectures must align with the capabilities currently available or in development by the international partners engaged in the human lunar return activity. At this point, the architecture features involvement from the Canadian Space Agency (CSA), the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA) and the United States National Aeronautics and Space Administration (NASA). As such, the envisaged architecture features expertise and capabilities available from these communities, including the active launch vehicles from ESA (Ariane V) and JAXA (H-II) as well as the crew transportation system currently being developed by NASA (Space Launch System (SLS) and Orion).

2.2 Trade Space Options

There are two primary aspects of a lunar surface architecture: the lunar lander design and the number and type of surface elements. The ISECG community accomplished the first aspect of the architecture by building a trade matrix featuring potential staging locations, launch vehicles, and the number and type of propulsive elements. All architectures must necessarily adhere to the dynamics governing the mechanics of spaceflight. Thus, trading the staging locations is

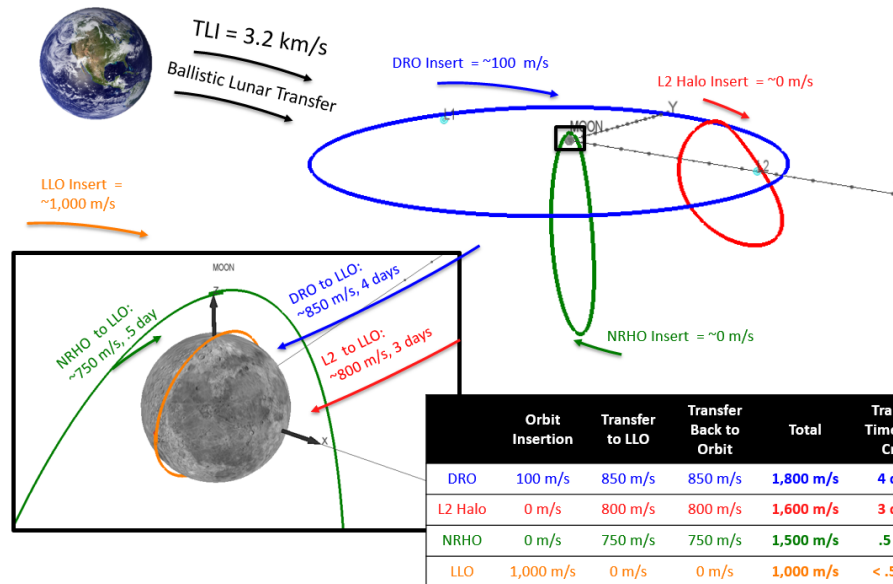


Fig. 1: Staging orbit options and costs

especially important for determining the total propellant cost (ΔV) required, identifying which element will perform each burn and understanding the active lifetime of the crewed module. Each aspect is critical in determining design feasibility.

To that end, Figure 1 provides a breakdown of propulsive costs and transfer times associated with a representative set of staging orbits: Distant Retrograde Orbit (DRO), Earth-Moon L2 Halo, Near Rectilinear Halo Orbit (NRHO) and Low Lunar Orbit (LLO). While other orbits exist in between the four shown in Figure 1, the examples cover a large swath of orbits both close to the moon such as LLO or the DRO which is far from the moon. Thus, the representative orbits are useful proxies for determining propulsive requirements and crew systems / consumables to be levied on a lander design.

The preferred orbit from a lander standpoint would be LLO. However, previous studies³ have demonstrated that LLO (as well as other low lunar energy orbits similar to LLO) require propellant loads that exceed NASA's Orion vehicle capabilities. One option would be to add an in-space propulsion stage to the SLS/Orion architecture to enable LLO and then design a lander to operate out of LLO. For this study the assumption was made to limit the number of new elements to the lander and surface based systems which constrains the staging orbit to an orbit larger than LLO.

Comparing the three remaining orbits reveals a big difference between NRHO and the other orbits, not in terms of total ΔV , but in terms of vehicle lifetime and crew consumables required. A lunar lander has

what is called a very large gear ratio in terms of mass of propellant required per unit of dry mass. This is due to the fact that a lander must only use thrusters to descend to the lunar surface without atmospheric drag to use as a decelerator. The total cost is about 2,000 m/s each way or 4,000 m/s total. Depending on the design a two stage lander could require up to 10 kg of propellant for every 1 kg of additional payload. Thus, it is critical to minimize the systems dry mass, especially systems necessary for the crew such as consumables. As Figure 1 demonstrates, the DRO and L2 Halo orbits have round trip time of 8 days and 6 days respectively. This is true for most higher energy cislunar orbits. The NRHO on the other hand is unique due its once per revolution close perilune passage and thus can do the round trip within 1 day (1/2 day each way) one time every orbit period. That is equivalent to a 85% to 90% reduction in crew time on the lander which is directly correlated to decrease in the mass of supplies, air and associated systems that result in a multiplied increase in propellant mass. Thus, with the ΔV costs relatively comparable, the NRHO is the preferred staging orbit of the 3 cislunar orbits examined.

The remaining trade matrix items for the lander design include propellant type and staging strategy along with launch vehicle specifications. The biggest mass driver for the lander trade study is the propellant type of the descent module. While the propellant efficiency of the ascent module is important, it was much less of a factor than the propellant type of the descent module which must transport the ascent module as payload. As a result, a high Technical Readiness Level (TRL) storable bi-propellant combination (MON/MMH) was

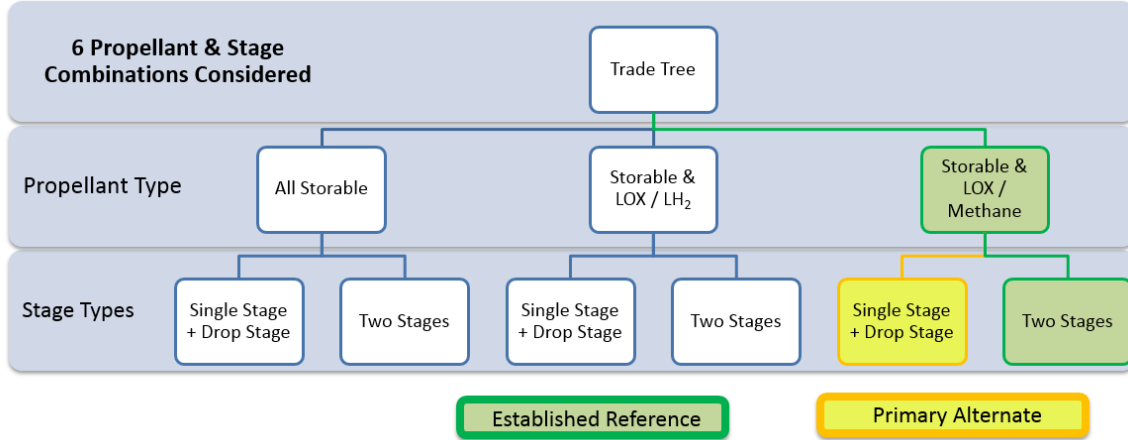


Fig. 2: Potential combinations of propellant type and staging strategy

selected for the ascent module. The transportation trade tree then reduces to two items, 1) the propellant type of the descent module and 2) the staging strategy. If the launch vehicle is considered as a constraint rather than a trade variable, the remaining trade decisions can be broken down as shown in Figure 2.

To that end, the feasibility of various human lunar lander propellant types in the transfer scenario were assessed considering three primary thruster types: LO_2/LH_2 , LO_2/CH_4 , and MON/MMH . Performance assumptions of each main engine are given in Table 2 below. The primary concern of the LO_2/LH_2 and LO_2/CH_4 propellant options is boil-off. Liquid hydrogen is also problematic from a volumetric standpoint. While technology projects are in work to mitigate the propellant loss due to boil-off, technology solutions are low TRL. Thus, in this analysis conservative figures associated with boil-off were applied.

Table 2: Assumptions for Propellant Trade Study

Item	Value		
ΔV to Surface	2,800 m/s		
LEO to DSG	Weak Stability Boundary Trans.		
Transfer Time	100 days		
Payload Mass	10,000 kg		
	LO_2/LH_2	LO_2/CH_4	MON/MMH
Boil-Off Rate	1.0%	0.1%	0.0%
I_{sp}	450 s	370 s	320 s
Struct. Ratio	25%	20%	15%

Trade-off results are given in Table 3 assuming a 10 t payload to the surface (which is a few tons lighter than the current ascent module design, see Section 3). Due to the high boil-off mass the total human lunar lander mass with an LO_2/LH_2 descent module is over 55 t at the launch time. This mass significantly ex-

Table 3: Descent Module Propellant Trade-off Results

Item	Value		
	LO_2/LH_2	LO_2/CH_4	MON/MMH
Fuel Mass	34.0 t	18.1 t	19.3 t
(boil-off mass)	21.4 t	1.7 t	0.0 t
Dry Mass	21.3 t	14.5 t	13.4 t
Total Mass	55.3 t	32.6 t	32.7 t
Lunar ISRU	All Prop	O_2 Only	None
Mars ISRU	All Prop	All Prop	None

ceeds the Trans-Lunar Injection (TLI) capability of the SLS Block 1B Cargo vehicle. A main engine that uses LO_2/CH_4 fuel has a significantly lower boil-off rate compared to a LO_2/LH_2 engine, a decrease of about 90%. Thus, the total lander mass for a LO_2/CH_4 stage descent module decreases to about 32.6 t. It is the minimum mass result of these three options, and is feasible for a SLS Block 1B Cargo launch, even when scaled up to the actual ascent module size closer to 14 t. In addition, this engine can take advantage of In-Situ Resource Utilization (ISRU) scenarios for future exploration at both the moon and Mars. A main engine featuring storable MON/MMH fuels have no boil-off gas and has the highest TRL. The mass of storable descent module is very close to the LO_2/CH_4 engine case as the I_{sp} difference, boil-off mass and dry mass differences tend to cancel each other out. However, a storable engine does not lend itself to ISRU options, and there is an opportunity for further LO_2/CH_4 mass decreases if the TRL of boil-off mitigations advance further. Thus, LO_2/CH_4 was selected as the reference descent module propellant. In addition, the more traditional staging strategy was selected as the reference, recognizing that a drop stage has advantages of increasing some level of reusability and minimizing hard-

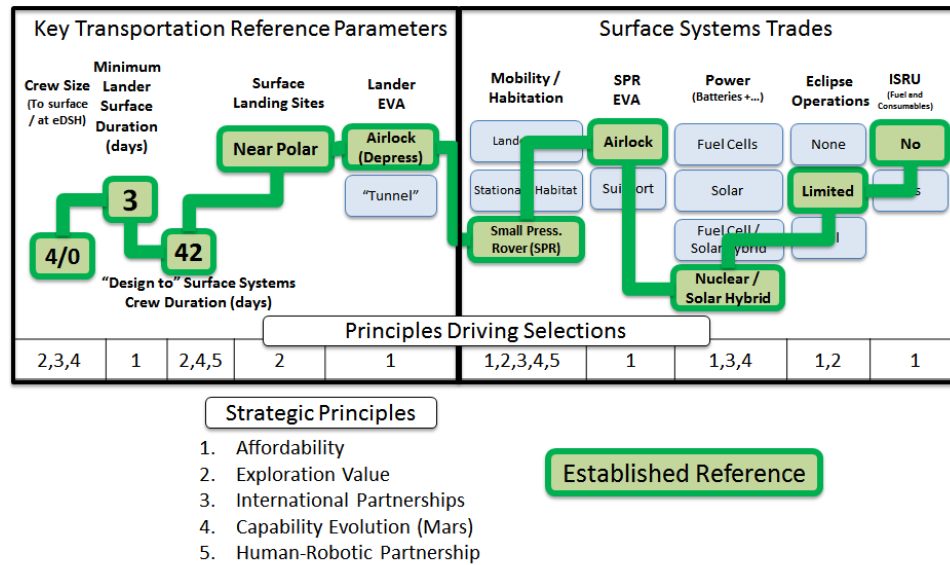


Fig. 3: Final Trade Space

ware on the lunar surface. However a drop stage makes cargo delivery more difficult as a descent module would require significant modification or a new element altogether.

With the reference transportation elements set, a matrix of surface system options were identified. The final version of the trade space, both options and reference selections, is shown in Figure 3. The primary design choices were the Extra Vehicular Activity (EVA) method, surface habitation strategy, ISRU approach, and power system. The level of exploration activities to be conducted during the lunar night played a large role in design choices and overall mass. Three potential levels of exploration activity were identified: no lunar night operations, limited lunar night operations, and full exploration lunar night operations. These levels were then juxtaposed with the GER principles and guidelines to seek a diverse set of landing sites in a single region so that all 5 missions were successful in achieving unique scientific value. As a result, a mobile habitat with greater than 30 day stay capability was selected as the preferred implementation for the crewed stays. The other option, a stationary habitat, would require deploying a new habitat at each potential new exploration zone. In contrast, a mobile and reusable habitat would require only one new element (or two copies of the same element but delivered on the same cargo lander).

The most interesting trade relates to the strategy for lunar night operations. If a 14 Earth day lunar night cycle is to be achieved, the power system must not rely extensively on solar-panels and batteries. Surviving the lunar night using only batteries requires bat-

teries that are so big that they exceed the allocated mass/size budget. The only other way to conduct a 28+ day mission without 14 days of darkness is to park on a permanently lit region at one of the poles. However, this conflicts with the goals and objectives of the mission to explore diverse regions. So the trade is reduced to two options: full night time vs limited night time operations. In the end, the design focused on limited operations as a full night time the power system, either nuclear or fuel cell or a combination of both was too heavy to meet the mass constraints of the lunar lander cargo design. A nuclear-based (radio-isotope) system supplemented by solar panels and batteries was selected for the reference design (described in more detail in Section 3). In addition ISRU requirements were eliminated due to the risk of both quantifying available resources (part of the reason for returning to the moon) and the methods of extraction required.

3. Lunar Exploration Elements

As discussed in the Section 2, the concept of the human lunar lander is driven by the goals and objectives of lunar exploration in the frame of the global exploration roadmap and informed by the associated strategic principles given in this paper. Guided by that framework, the human lunar lander has been conceptualized to be a two-stage, partially reusable vehicle for four crew providing mainly transportation between DSG and the surface, and only short-term habitation. The surface habitation function is to be provided by the pressurized rover. The lander mission is designed to protect for global access to the surface, however, not

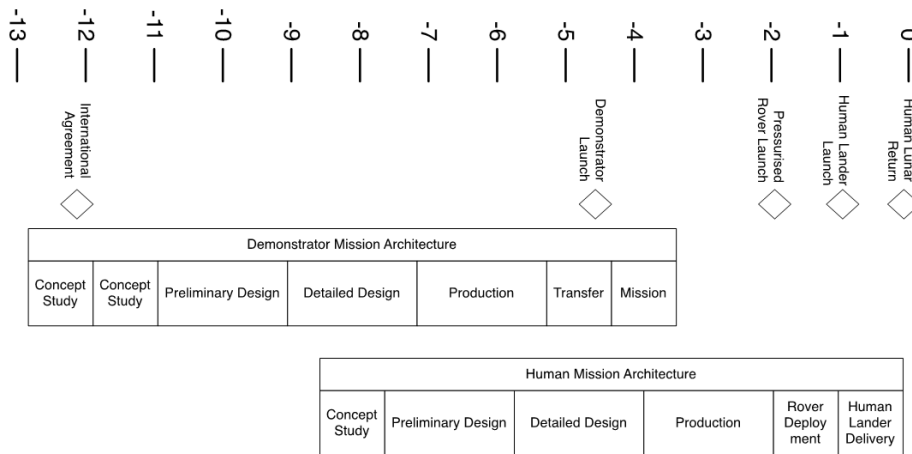


Fig. 4: Envisioned co-development approach. The time scale on the top of the figure indicates years to Human Lunar Return.

allowing this requirement to impact the affordability of the design. Further, the descent stage of the human lander must double as a large cargo lander.

The human lunar lander is sized for a single SLS Block 1B Cargo launch but remains compatible with a dual launch or as a co-manifested payload (CMP) partially fueled. The lander arrives and rendezvouses with the Deep Space Gateway (DSG) and loiters until the crew arrives on a separate launch. After docking, the crew transfers via the DSG to the lander. The lander carries crew to the lunar surface and returns crew and samples to the DSG after surface operations.

The reference configuration features a two-stage lander comprised of a descent module (DM) and ascent module (AM). The DM completes all descent maneuvers from the DSG until touchdown. The DM is left on the surface of the moon while the AM returns to the DSG for reuse. The cargo variant of the lander does not carry an AM. There is also an optional configuration with a drop stage. The design figure of the two-stage lander is shown in Figure 6.

3.1 Element Co-Development Plan

A programmatic analysis was performed of how such an architecture could be realized. The study findings indicate that the approach to develop a sub-scale robotic demonstrator lander allowing the implementation of system components (see Figure 4) corresponding to the partnership roles in the human architecture is the most affordable solution for the international co-ordination.

The timing of the programmatic realization is constrained by the assumed decision making process, the duration of the development of key technologies, the typical time scales of space vehicle design and integration, and the relative timing of the demonstrator

mission implementation with respect to the human architecture. The programmatic analysis has found that: (a) the time between the launch of the demonstrator mission should be between 4 and 6 years before human lunar return, and that (b) the introduction of a demonstrator mission does not significantly increase the duration of the end-to-end time from decision to human lunar return.

Regarding finding (a) it should be noted that times shorter than 4 years would not allow sufficient impact of findings of the demonstrator mission to influence the design and production of the human mission, and that times longer than 6 years risk the demonstrator technologies becoming obsolete for the human architecture. Finding (b) is based on the assumption that key technologies and components (e.g. descent propulsion) drive the development of the human architecture and that identical components are used on the demonstrator and the human vehicles. Without a demonstrator, the human architecture would still require flight-demonstration in order to achieve human rating. It should be noted that with different programmatic assumptions, the results can be different.

The conceptual designs for the elements of the robotic demonstrator and the human lunar lander and the demonstrator mission are described in more detail below (see Figure 5).

3.2 Reusable Human-Rated Lunar Ascent Module

Industrial concept studies performed earlier this decade have yielded the basic configuration and system characteristics of a reusable ascent module hosting a crew of four for three to four days of transportation. The main function of the ascent module is to deliver the crew and samples safely to the DSG after the end of the surface mission. Its habitation function is re-

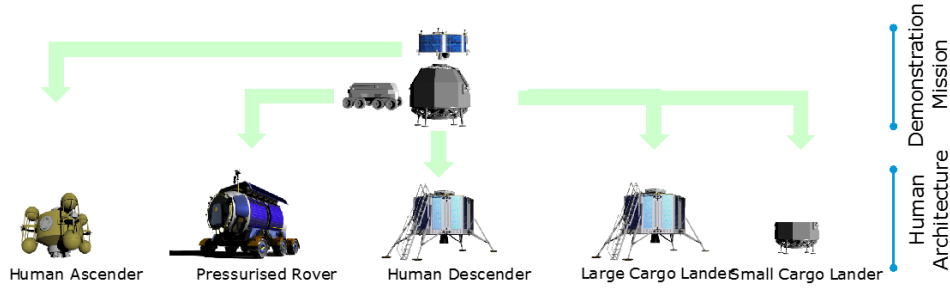


Fig. 5: Relationship between demonstrator and human elements

quired also for the descent and in a short contingency case, in which the crew cannot reach the pressurized rovers. Further, the ascent module has to support the various contingency and abort modes that allow safe return of the crew to the DSG at any point along the mission (this includes, for example, the return from the lunar surface during night).

On-going concept studies of the ascent module have the objective to further reduce the overall mass performance of the ascent module taking into account the significant mass leverage of the system dry mass with respect to the vehicle overall wet mass (as applicable to its mission initial state at the DSG) of 1:7.3. The basic idea is to tailor the concept for the mobility-based mission scenario with relatively short time the crew spends inside the ascent module (assumed two times 12 hours for transfer plus EVA preparation). The concept relies thus on a minimization of the structural mass of the vehicle through reduction of the pressurized volume that is available to the crew from a previously set 20 m^3 to 10 m^3 . Besides improving the mass performance of the concept, the volume reduction also enables consideration of alternative split-launch concepts with a wider variety of launch vehicles.

In order to achieve a good mass performance, the atmospheric pressure inside the ascent module will be below standard atmosphere. This is in principle compatible with the standard atmosphere inside the DSG assuming the presence of an airlock with docking ports for the human lunar lander. Besides the reduction in structural mass the lower pressure inside the ascent module allows reducing the mass of the life support system.

For propulsion of the ascent module two separate systems have been conceptualized. The main ΔV will be provided by either a single large or a cluster of smaller, pump fed engines operating at a mixture ratio chosen for maximum performance in specific impulse. A pump fed engine has a higher chamber pressure, which allows for a more compact and lower mass engine, while at the same time achieving a higher spe-

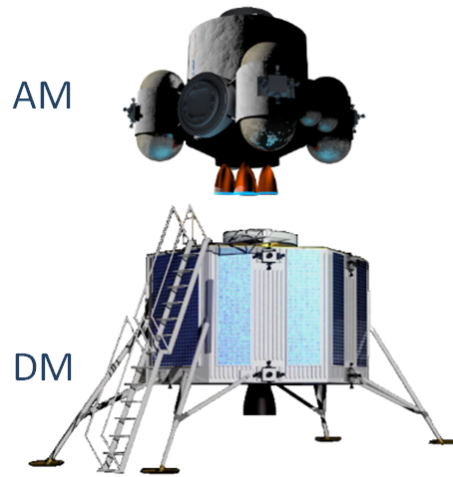


Fig. 6: Human Lunar Lander Schematic

cific impulse than a pressure fed engine. At the same time lower subsystem masses can be achieved through lower tank pressures. The engine cluster option comes with the added advantage of offering a flight demonstration of an identical single engine in the frame of the sub-scale demonstrator.

Other aspects of the ascent module that is currently under study are the opportunities for a common human-machine interface shared between the ascent module (crew control of landing and ascent) and the robotic control terminal in the DSG (monitoring of visiting vehicles and robotic capture and berthing, and tele-operations of surface assets such as the demonstrator rover).

3.3 Human-Rated LOX/CH₄ Descent Module

As described in Section 2, LO₂/CH₄ was selected as the propulsion system for the descent module. For the majority of the mission, the ascent module is the primary source of avionics and vehicle control, while the descent module has avionics necessary for independent operation as well as in the cargo variant. The

AM is reusable, while the DM is not. Both AM and DM elements provide power to the human lander as a whole. In addition, while waiting for the crew, the DSG provides power for the system while the lander remains attached. After separation, lander uses power from AM and DM. Key features of descent module are described in Table 4.

Table 4: Key Features of Descent Module

Item	Descent Module (DM)
Main Engine Propellants	LO_2/CH_4
# Main Engine Casters	3
Main Engine Thrust	>80 kN
Main Engine I_{sp}	370 s
RCS Thrusters	40 x 220 N
Power	Body Mounted Solar Panels

3.4 Reusable Surface Rovers

Following the surface access trades conducted, the international team iterated on a conceptual design of the Small Pressurized Rover (SPR) for crew habitation and mobile exploration of the lunar surface. Amongst the different constraints, a reduced number were driving significantly the pressurized rover concept. Given a surface mission of 42 days for a team of 2 up to 4 crew members per rover in a contingency situation, the habitable volume had to be sufficient to fulfill crew needs. This added to the constraint of launching the two rovers on the same SLS flight and having the rover configured with an airlock and most likely radioisotopes sources for power and thermal resulted in some very interesting challenges. After some iterations and trade studies, the concept evolved and matured into a notional representation based on a vertical launch configuration of the two rovers as illustrated in Figure 7. This configuration option would be to launch both rovers back to back resting on a vertical attachment structure that could also serve as the deployment system as illustrated in Figure 8.

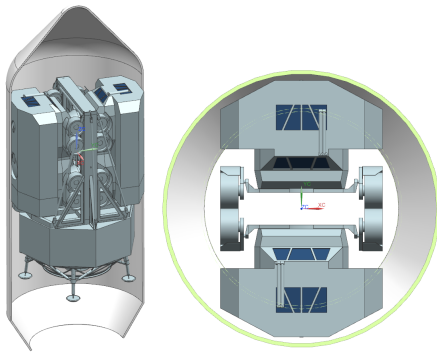


Fig. 7: Notional launch configuration of rovers

The rover itself can be broken down into four main systems, opening the door to partnership and sharing of the pressurized rover development:

- Mobility and cross-cutting sub-systems, essentially the rover platform
- The radioisotope power/thermal source
- The airlock, and
- The pressurized module

At this point in the rover design process, mass estimates for the airlock and the pressurized portions of the element can be calculated by simply scaling existing hardware elements and/or other mature design plans. The module that needs further design consideration due to its uniqueness is the design of the second main system listed: the radioisotope power/thermal source.

The envisaged hybrid power system includes partially deployable solar panels, multiple radioisotope power systems and an electrochemical energy storage system of either rechargeable batteries or regenerative fuel cells. The design and sizing of such a system is a complex multivariable problem, with the optimum architecture being dependent upon the operational concept, the power requirements of the various electrical systems required to deliver those operations, the lunar surface environmental and lighting conditions, and the performance characteristics of the various power system technologies.

A complex parametric model of a lunar rover power system was created in order to investigate the various trade-offs, determine the optimum configuration and estimate the power system mass. A meaningful power system architecture for the rover could be determined only by considering, in parallel, some key aspects of the thermal management system. The cooling requirements of the rover during the lunar day demand that much of the available body area is dedicated to radiators, and is therefore unavailable for solar power generation. During the night, heating power may form a large proportion of the electrical load requirement.

An adequate autonomous power system was found, dependent on the availability of radioisotope power units that enable the lunar-night survival. The utilisation of compact radioisotope systems also alleviates the difficulty balancing the daylight energy budget given the constrained solar panel area. A well-insulated rover with a switchable fluid loop cooling system should keep the crew warm in the lunar night with little heating power above that provided by the electrical systems and human metabolism. Any additional thermal support would be most effectively provided by large radioisotope heater units.

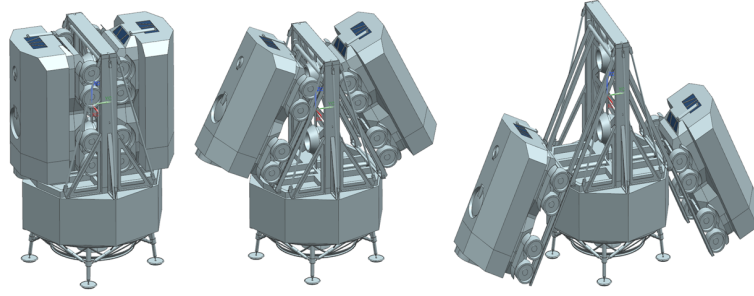


Fig. 8: Notional deployment concept for rovers

4. Surface Operations Concept

Armed with a reusable pressurized rover design, a robust surface operations concept is devised. With an exploration blueprint consisting of five consecutive missions and a plan to reuse the pressurized rovers from mission to mission, an operations concept must both examine how to conduct a 42 day crewed surface stay with lengthy light and night cycles as well as find scientifically interesting landing sites that are close enough to each other to enable telerobotic relocation of the rovers between missions.

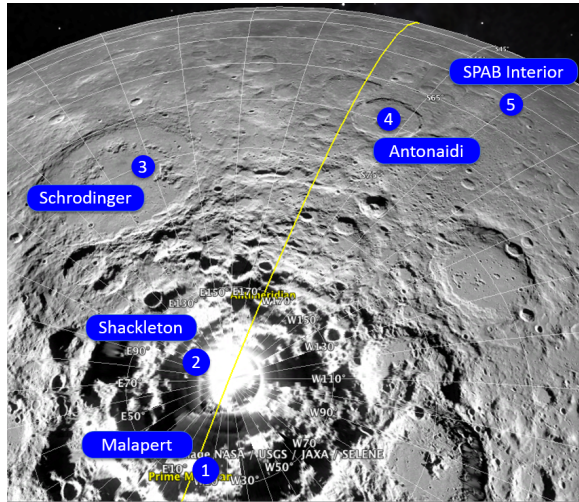


Fig. 9: Notional Landing Sites

4.1 Landing Sites to Connect 5 Missions

There are multiple regions on the Moon where such a set of five missions enables significant regional exploration campaign to be undertaken. Examples include both the North and South Poles, multiple impact craters, and volcanic features such as lava flows. Based on the consolidated, globally recognized rationale for human exploration of the Moon^{4,5} a sequence leading from the South Pole Region to the interior of the South Polar Aitken Basin (SPAB) has been identi-

fied as a good reference. The South Pole Aitken basin is the largest impact structure on the Moon, indeed one of the largest in the Solar System. With a diameter of approximately 2500 km, it dominates the lunar farside, extending from the South Pole at one point on its rim to the 135 km Aitken crater at the opposite point on the basin rim. This exploration region is compatible with an orbiting staging location (visibility for communication relay and transfer ΔV) of the DSG on an NRHO, and it allows addressing the top-priority science and exploration goals.

Table 5: Coordinates of notional landing sites

#	Site	Lon.	Lat.
1	Malapert Massif	0	-85
2	Shackleton Plateau	126	-89
3	Schrödinger Basin	139	-75
4	Antoniadi	172	-70
5	SPAB Interior	160	-60

Even just considering the South Pole Aitken basin as a place for humans to explore, there are many more than five interesting potential landing sites. For this study five notional sites have been chosen that extend from the rim of the basin to the far interior of the basin as shown in Figure 9. The first two are both on the rim of the basin, Mallapert Massif, and the South Pole (located on the rim of the 20 km Shackleton crater). Then moving into SPAB there is Schrödinger basin, the Antoniadi crater (which contains the lowest elevation on the Moon), and finally arriving at a point close to the center of the SPAB. Coordinates for all five are given in Table 5. The five sites represent a good design case for the architecture concept driving power, thermal, and communication subsystem designs, as well as the assumptions on the terrain environment for surface landing and mobility. For each potential site, there are many opportunities for science and future exploration. Some of the major science and future exploration themes at SPAB are described in Table 6. A detailed breakdown of notional SPAB landing sites is

Table 6: Science and exploration themes at the SPAB

Theme	Objective
Geological Features	Geological Exploration as wide area of SPAB
Water or Ice	Lunar Water/Ice or Volatile component exploration for future in-situ resource utilization.
Observation	Moonquake observation. Astronomical Observatory on lunar surface.

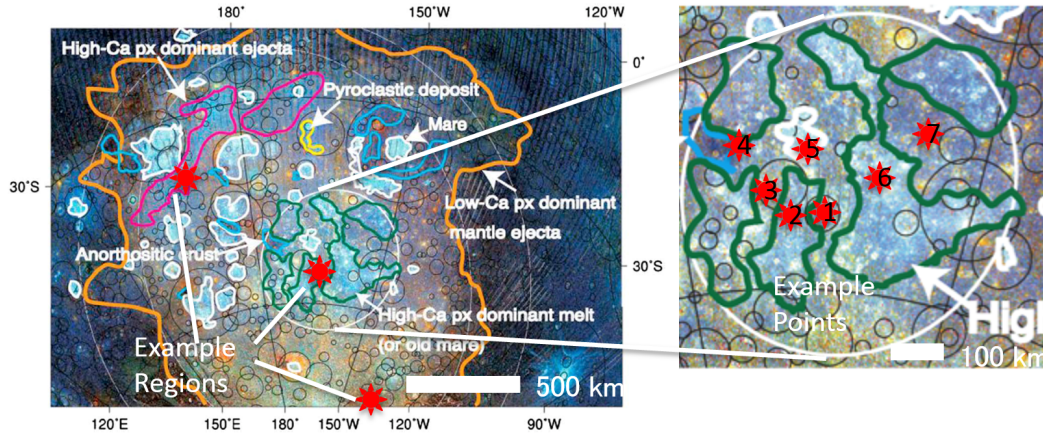


Fig. 10: Example landing sites within the SPAB

given in Figure 10.

4.2 Crew Concept of Operations

The surface operations of the human architecture rely entirely on the capabilities of the two pressurized rovers, each of which provide habitation for two crewmembers in the nominal case. In order to address the envisioned science goals and to gather the required operational experience for future planetary surface exploration (e.g. Mars), the surface mission duration cannot be limited in general to a single lunar day. While the earlier missions in the program might be shorter, in general the mission duration is envisioned to be constrained by a day-night-day cycle equal to 42 days, requiring night survival for the crew and equipment. The operational modes for lunar day and lunar night will be significantly different. While during daytime the crew drives to multiple scientifically interesting sites for investigation and sampling, they return to the vicinity of the lander for the night and spend the night inside the rover with analysis of previous EVAs and incremental training preparing for the next lunar day. This approach will not only enable a feasible power and thermal design for the pressurized rover, but also enable a safe abort scenario during lunar night. Another key operational concept is to exploit the split of the crew between rovers “Crew A” and “Crew B”) with an approach of alternating schedule of rover-based EVA every second day for each crew. This

would facilitate the coordination with mission control and science backroom on the ground.

Contingency operations are driven by the goal of keeping the crew safe. At any point in time the crew will be able to return to the DSG within 36 (TBC) hours, out of which 24 (TBC) hours are allocated to the return from the crew’s location to the lander. For this reason, the maximum distance of the rovers from the landing site must be lower than 100 km and the rover average speed in the reference terrain approximately 5 km/hr. During lunar night, the rovers will be parked sufficiently close to the lander, so the crew can reach it on foot in EVA suits within 4 hours.

A more detailed chronological overview of the surface crew operations could proceed as follows (“Crew A’s” perspective is illustrated by Figure 11): after the landing at lunar dawn, the crew performs an EVA from the lander to the rover and initiate the commissioning of the rover. Once the safe operation of the pressurized rover is ensured, Crew A drives to the first exploration site during the first Earth day while Crew B stays in the vicinity of the lander. Crew A surveys the geology at the first exploration site and prepares the rover-based EVA in cooperation with the science backroom on the ground. The two crew dons for EVA and leave the rover through the airlock for surface exploration of up to 4 hours. On the next Earth day Crew B repeats the process at a different exploration site while Crew A remains inside the rover. The crew that is active on

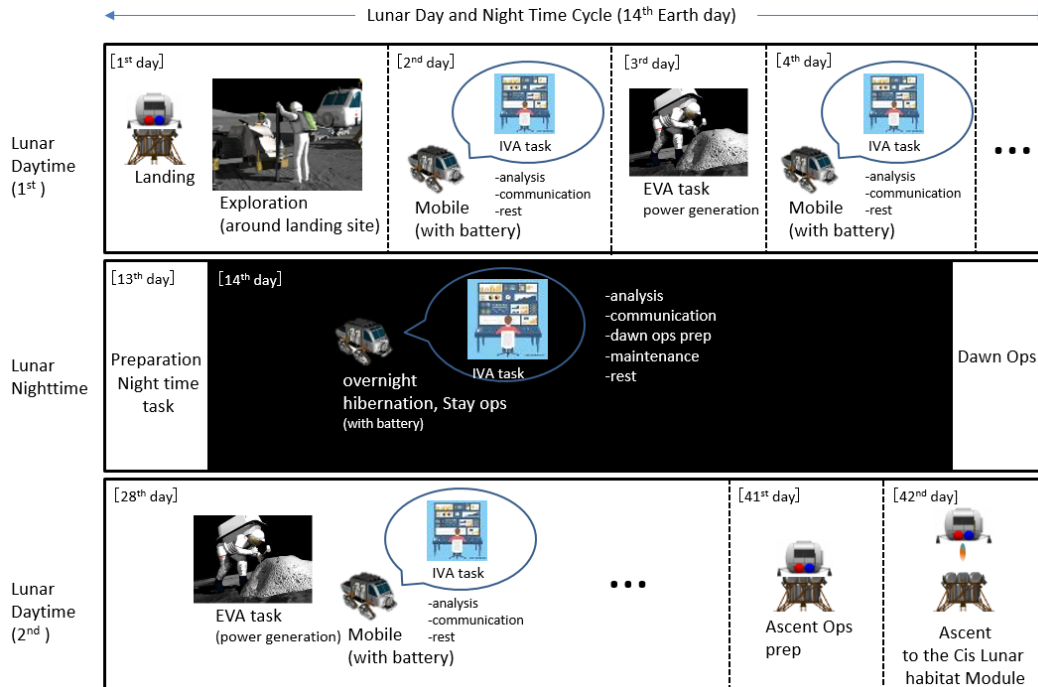


Fig. 11: Concept of Operations for Human Lunar Surface Exploration: "Crew A" Perspective

the surface might complete multiple excursions during a single shift. Each shift ends with 8 hours of crew rest. The total mobility distance during the lunar day is several hundred kilometers.

Both crews drive back to close to the landing site before the Sun sets on the first Moon day. During lunar night, as the solar arrays will no longer be generating energy, the rovers enter a hibernation operation mode. Each Earth day during the night cycle is spent with in-situ analysis and on-board training preparing the next lunar day as well as performing public events transmitted back to earth. The second lunar day is spent similar to the first, with the exception that the return to the landing site occurs earlier to allow for the final EVA to the lander. Once inside the lander, the crew re-pressurize the ascent stage of the lander, doff their suits, clean all items that were in contact with the lunar dust environment, and start the process of commissioning the ascent stage of the lander for safe return. The ascent burn is initiated after full functioning of the ascent stage has been confirmed completing the surface operations.

Another aspect of surface operations is the activities of the rovers when crew is not present. Since the pressurized rovers have to be transferred to the next landing site prior to the next crew arriving, the rovers must be controlled to drive across long stretches of lunar terrain to reach the next landing site in sequence. A team of scientists have investigated potential traverses and have found less than 3000 km traverses into

the SPAB from the South Pole with maximum slopes less than 23.⁶ If the rover could drive at 0.1 m/s on average, the accumulated driving time would be a little less than a year to cover the full distance.

4.3 Aspects of Human-Robotic Integration Operations

During the 42-day human surface mission, the crew has various tasks to accomplish, amongst which are driving the rover and to collect samples from the lunar surface. The pressurized rover is driven by the on-board crew. Sampling can be done via EVA and via a robotic arm on the rover. During an EVA, the crew member can approach the sample while taking into account the safety requirements - and use manual tools to collect the samples. This can be advantageous in areas where the rover cannot easily access due to the surface or the size of the rover, e.g. a smaller rock in between two larger rocks. In these scenarios, the dexterity of the astronaut on the surface can potentially enable a larger variety of samples to be retrieved. In the second option, when the robotic arm of the rover is used, this requires a human-machine interface (HMI) aboard the rover. The crew member inside the rover can control the robotic arm by operating it using the HMI. In case of the demonstrator mission (see separate section below), the same operations can be performed by the crew aboard the DSG using an HMI onboard the station. In this case, a small, yet limited, delay is introduced, and potentially the use of force feedback could to enhance the control operations.

The robotic arm on the pressurized rover is controlled by the crew members aboard the rover, or, alternatively by HMI if crew are not present, such as during the traverse periods. Multiple end-effectors are required on the robotic arm in order to enable the collection of different types of samples. Examples of the functions of the end-effectors are chipping pieces of rock(let), scooping regolith and volatiles, and taking core samples. Another advantage of the robotic arm is its reach, especially for places that cannot be accessed by the crew, e.g. for sampling sites that are too high or high-risk for the crew to reach physically.

The surface operations of the Apollo program have provided valuable insight in efficient approaches to crew surface operations. It has shown that at times the collection of samples or tool handling were challenging for the crew at certain parts of the operations, while at other parts of the operation it was essential. The presence of both humans and robotic elements on the surface in the reference mission scenario described above introduces human-robotic interaction that can be used to enhance the efficiency of surface operations. This can for example be achieved if parts of the operations of the robotic element are automated for efficiency, or if variable automation can be introduced such that the surface crew or the mission control team can make decisions to take over the control from the rover.

4.4 *Preparing for Human Lunar Return with a Sub-Scale Demonstrator*

An integral part of the approach for co-development of the human lunar lander in an international partnership is the preparation of technologies, operations, components, and roles in the frame of a human lunar surface demonstration mission scenario. One finding of an internationally coordinated of Human Lunar Exploration Precursor Programme (HLEPP) study,^{7,8} is that a sub-scale robotic lander can achieve flight qualification and mission preparation in the most efficient way. At the same time, such a development will implement the small cargo lander and provide opportunities for significant scientific investigations of previously unexplored regions of the Moon.

Like the human lander, the robotic lander is comprised of a descent stage, ascent module, and a rover (see Figure 5). The propulsive stages feature identical rocket engines thus enabling their qualification in flight. The higher thrust requirement of the four times heavier human lander is met by combining the engines that are flown as single units on the demonstrator into clusters on the human lander. Another element that is considered identical or at least representative is the guidance, navigation, and control subsystem.

At the center of the operational demonstrations is

the robotic rover that will spend the first (approximately 70 days) part of its mission collecting samples for return to the DSG, where they will be received by a crew for ultimate return to Earth. After the robotic ascent module will have left the surface, the rover will continue to traverse the lunar surface in the 1-year mission to demonstrate long-range durability and reliability of planetary surface mobility. Other operational demonstrations achieved by the demonstrator mission are landing operations, ascent operations, and rendezvous operations with the DSG. Key technologies required for enabling the human architecture are high-efficiency throttle-able propulsion for descent (e.g. liquid O_2/CH_4 bi-propellant), hybrid power systems for night survival, and durable mechanisms for long-range, long-duration mobility in dusty environments.

Based on the objective of flight demonstration described above, a concept for the HLEPP mission scenario has been advanced to phase-0 level by the participating agencies CSA, ESA, and JAXA (see Figure 12). A mid-sized expandable launch system with performance in the order of ten metric tonnes into Geostationary Transfer Orbit (GTO) such as Ariane 5 (or future evolution) is sufficient to put the robotic lander on a transfer to the Moon (either via weak stability boundary, WSB, or minimum-energy depending on the boil-off characteristics of the semi-cryogenic propellant in the descent stage). After landing, the surface mission of the rover is envisioned to use a lunar day-night-day-night-day cycle to cover tens of kilometers to collect up to 15 kg of samples from previously unexplored regions of the Moon. During the surface mission the interface to the DSG comes into play when a crew arrives. The crew tele-operates the rover thus gaining operational experience of controlling a vehicle on the lunar surface. The crew vehicle docked to the DSG plays an essential role after robotic ascent module has launched from the surface and after it has been berthed to the DSG: the precious samples (red oval shown in Figure 12) collected during the surface mission are transferred to the crew vehicle for safe return to Earth. The operations of the elements of the robotic demonstrator mission thus mimic a human mission, thus improving the operational confidence and certification level of key components for the human lander.

Finally, the robotic demonstrator will be a vital part of enabling reusability of the human systems, as only enough supplies for a single 42 day mission will be manifested on the rovers to reach the mass targets. Thus, a copy of the demonstrator lander will be used to resupply the crew and vehicle consumables. At this point, between 1 and 2 small cargo vehicles are required to resupply with a goal to reduce to a single cargo vehicle.

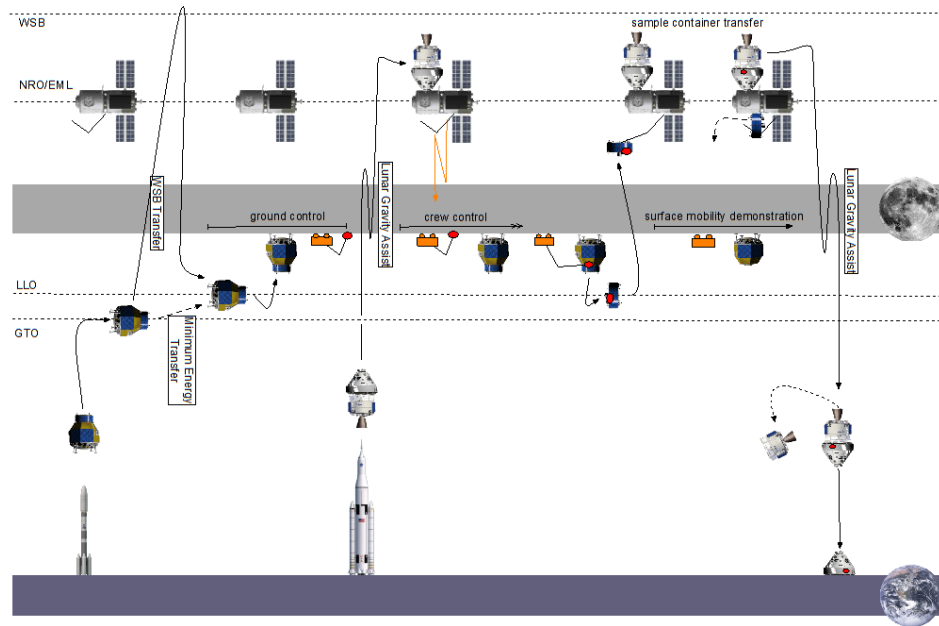


Fig. 12: Scenario of the lunar surface demonstrator mission

5. Conclusion

Work on realizing elements of the Global Exploration Roadmap has started to paint a picture of an affordable, yet valuable scenario for human lunar exploration based on decades of previous work. With some key elements for human spaceflight beyond Earth orbit coming together today - such as the Space Launch System and Orion crew vehicles - as well as more and more international partnerships and private sector initiatives in lunar exploration becoming reality, now is the time for next steps. Already today a partnership of ISECG participating agencies is considering to move ahead in the construction of the Deep Space Gateway, which could be the staging location for, in the first phase, a sub-scale demonstrator mission and, in the second phase, return of humans to the surface of the Moon. The demonstrator mission is moving beyond the conceptual phase and into a focussed and coordinated design study phase with the objective to consider key decisions by participating agencies towards the end of this decade. While the scenario described above is a product of a minimalist approach to conceptualization, affordability remains a major risk for the implementation of such an architecture. Operational and technological risks remain as well, both of which are intended to be "bought down" in the frame of the demonstrator mission. A careful phasing of demonstrator and target architectures remain a key programmatic challenge for the participating agencies in order to propose an attractive program to their respective stakeholders.

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