

GLEX-2012.02.P.17.x12620

NASA Human Spaceflight Architecture Team: Lunar Surface Exploration Strategies

Rob P. Mueller

NASA Kennedy Space Center, KSC, FL, USA, rob.mueller@nasa.gov

John C. Connolly* and Ryan J. Whitley†

Abstract

NASA's agency wide Human Spaceflight Architecture Team (HAT) has been developing Design Reference Missions (DRMs) to support the ongoing effort to characterize NASA's future human exploration strategy. The DRM design effort includes specific articulations of transportation and surface elements, technologies and operations required to enable future human exploration of various destinations including the moon, Near Earth Asteroids (NEAs) and Mars as well as interim cis-lunar targets. In prior architecture studies, transportation concerns have dominated the analysis. As a result, an effort was made to study the human utilization strategy at each specific destination and the resultant impacts on the overall architecture design. In particular, this paper considers various lunar surface strategies as representative scenarios that could occur in a human lunar return, and demonstrates their alignment with the internationally developed Global Exploration Roadmap (GER).

INTRODUCTION

OVER the last 40 years, NASA has conducted numerous internal and external studies to assess the overall future human space flight strategy, exploration concepts and technologies. Following the cancellation of NASA's Constellation program in 2010, a broad trade space of program strategies and technical approaches were examined in an effort to meet priorities from the White House, Congress, and other stakeholders [1]. Out of this work, it was concluded that the NASA Human Space Flight (HSF) architecture must provide the flexibility to accommodate technical, programmatic, economic and political dynamics while enabling a safe, affordable and sustainable human space exploration program.

Extending from this desire to maintain an increased level of flexibility, NASA's Human Exploration Framework Team (HEFT) adopted a Capability Driven Framework (CDF) that emphasized the devel-

opment of resources that would enable stepwise missions to ever more-difficult destinations. The CDF builds capabilities that could incrementally enable many potential paths to GEO, L1/L2, the lunar surface, Near-Earth Asteroids (NEAs), Martian moons, and the surface of Mars, not unlike the dual path possibilities of Moon-Next and Asteroid-Next in the Global Exploration Roadmap (GER) [2].

When the HEFT finished its work, the Human Spaceflight Architecture Team (HAT) was formed to carry on strategic guidance for human space exploration planning. The HAT is a NASA wide support team with responsibility for integrated and cross-cutting strategic analysis of human space exploration for NASA's decision makers. HAT's scope includes integrated development and assessment of architectures, systems, mission scenarios, and concepts of operation across the human and robotic space exploration spectrum. The team began to refine Design Reference Missions (DRMs) to generate an integrated capability-driven approach for systems planning within a multi-destination framework. The HAT has also identified and assessed technology and capa-

*NASA Johnson Space Center, Houston, TX, USA, john.connolly@nasa.gov

†NASA Johnson Space Center, Houston, TX, USA, ryan.j.whitley@nasa.gov

bilities needs and priorities consistent with the evolution of the architecture and performed robust cost analyses to assess overall affordability, viability, and sustainability.

DESTINATION FOCUS

While trajectory design is useful in outlining the constraints within a given DRM, the HAT recognized a need to balance transportation studies with specifically articulated deep space destination activities. As a result, Cis-lunar, Lunar, Near-Earth Asteroid and Mars destination teams were chartered to focus on what to do at the destinations and to work closely with the DRM teams to flesh out a complete mission design. In addition to organizing and coordinating the studies regarding human activities occurring at each destination, the destination teams maintained cognizance of all past studies and missions as well as all current events relative to each destination. The HAT destination team also became the primary interface with destination-affiliated agency and external groups such as the Lunar Exploration Analysis Group (LEAG), Mars Exploration Program Analysis Group (MEPAG) and Small Bodies Assessment Group (SBAG).

Each destination sub-team examined the critical decisions that defined destination operations and illustrated these decisions in the form of a decision or trade tree. Down selecting candidate destination missions from this tree, the destination teams expanded the transportation DRM mission descriptions (known as bat charts) to now include surface operations and elements. Each team created a series of what has been termed *Street View* charts that detail the destination operations for each transportation DRM and matches them with detailed operations timelines. In the process of defining the surface mission in greater detail, the teams also gave further definition to destination payloads, defined required new elements, and identified impacts to transportation DRMs.

LUNAR TRADE TREE

Within the HAT Destination Team construct, the Lunar Destination sub-team analyzed many different surface mission configurations, specifically articulated connectivity to the HAT DRMs, and noted where similarities existed with the GER. In order to do a comprehensive assessment of all DRM options regardless of feasibility, the Lunar Destination sub-team pursued

a six-dimensional functional based breakdown of lunar surface mission possibilities. Through a process of logical analysis the trade tree was trimmed down by eliminating branches with obvious inconsistencies. A reduced trade space then becomes the basis by which a comparison could be made to missions already flown or a platform for developing future DRM studies and further drilled down detailed analyses. In the same way, elements of the trade tree were then compared to missions outlined in the current instantiation of the GER.

Constructing the Trade Tree

The lunar trade tree was developed from a brainstorming exercise based on what could drive the need for a given functional capability for a crewed mission to the moon. The focus was on driving out all possible configurations, regardless of heritage. After the trade tree was formulated, previously flown mission architectures (Apollo) and designed project plans (Constellation) were then aligned with the appropriate branches in addition to existing elements of the GER.

The trade tree was constructed by assembling relevant categories for a general capability human mission to the lunar surface. The complete lunar trade tree is displayed in Figure 1. While the specific alternatives are dependent on technological capability, the individual categories come from a function-driven framework. Regardless of the specific exploration goals for a given mission, the basic lunar human mission need is to sustain the crew for the duration of the mission and provide an acceptable amount of mobility for the crew to perform a to be defined set of exploration activities. The first two categories can then be derived from each half of this overall need as *Surface Duration* and *Mobility Range*.

In order for a human based exploration system to provide surface stay capability it will, due to established physical and technological limitations, have certain quantities of mass, volume and power. While mass, volume, and power may be the most basic building blocks, functions that tie these mission driving parameters to physical elements are more helpful as categories. As such, mass and volume needs are translated into habitability and reusability needs, which in turn can be given as two more categories for the lunar trade tree: *Infrastructure Capability* and *Use of Local Resources* respectively. Power can be more directly tied to the fifth category, *Primary Energy*. All of these categories have mass, volume, and power implications. The final category is primarily related to mis-

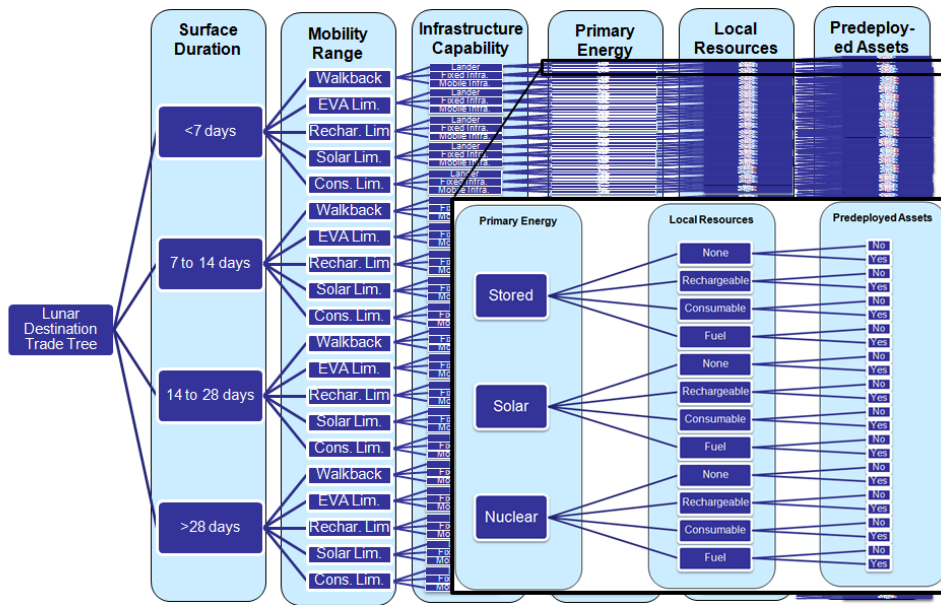


Figure 1: Overall Lunar Trade Tree.

sion planning rather than a level of lunar surface mission need. Some mission architectures logistically require large mass and volume payloads that require pre-deployment due to launch service restrictions. Thus, the sixth and final category is *Pre-deployed Assets*.

Once the categories were determined, the fields were populated based on established and available technological solutions, as shown in Figure 2, which each category having a different number of fields. While future innovation is vital to space exploration, only those technologies that were reasonably available in the near-term were considered. To get the total

number of possible branches, each field count can be multiplied together; this operation results in a grand total of 1440 possible cases.

Eliminating Logical Disconnects

While the categorization process created 1440 possible branches, not every branch 1.) *can* or 2.) *should* be a real mission. Thus, a trade trimming process was implemented. In order to remain unbiased, only those cases that are truly illogical (in both the *cannot be* or *should not be* sense) were removed. The

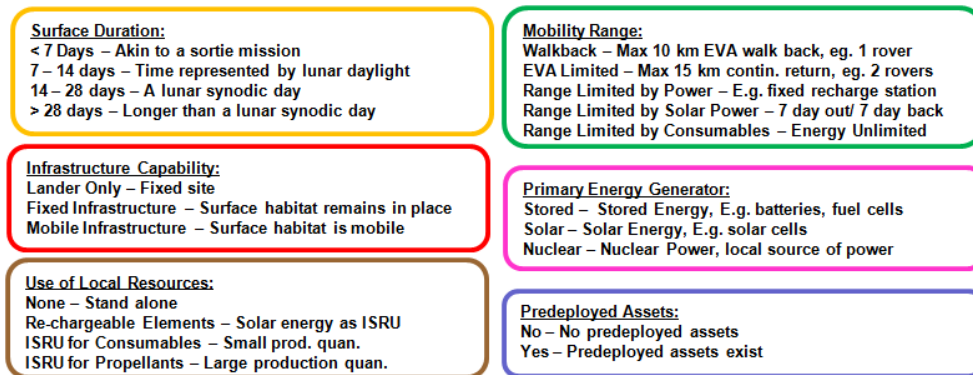


Figure 2: Field breakdown of lunar trade tree categories.

so-called logical disconnects stem from inconsistencies between specific fields from one category to the next. To simplify the elimination process, a 2-D trade tree matrix was constructed, where every field from a given category was weighed against every field from every other category. This matrix is shown in Figure 3. It is not surprising that inconsistencies exist. While the categories were based on specific functional capability, the fields are largely interdependent, especially since the individual fields were designed broadly to include both low and high capability levels to flush out all possible combinations.

An individual logical disconnect in the 2-D matrix has the ability to eliminate a large swath of branches, as illustrated in Figure 3. Each category versus category sub-matrix is bordered by a red box containing cross-field matrix elements that include the possible combinations of fields between any two categories. The grayed out region represents redundant branches of the trade space (order does not matter). The diagonal of the matrix is also grayed out since a category cannot be evaluated against itself. If every

possibility within one of the 15 individual red boxes is eliminated, then all 1440 branches are eliminated. For example, in the upper left hand corner of Figure 3 there is red box representing the *Surface Duration* vs. *Mobility Range* fields. Logical disconnects numbered 3, 4, 8 and 12 indicate specific cross-field cases that should be removed from the tree. Assuming no other branches from any other categories were eliminated (all the other boxes were blank throughout the matrix), 9 blacked out boxes out of a possible 20 boxes means that 648 cases are removed from the lunar trade tree. When other logical disconnects from other red boxes are added, the interdependencies must be accounted for. Thus, as more logical disconnects are found, fewer cases are removed. In the end, for all 28 logical disconnects listed, the total number of viable branches reduces from 1440 to 51.

Evaluating the Remaining Cases

With more than 96% of the trade tree eliminated, the final 51 cases can be scrutinized in more detail. Many

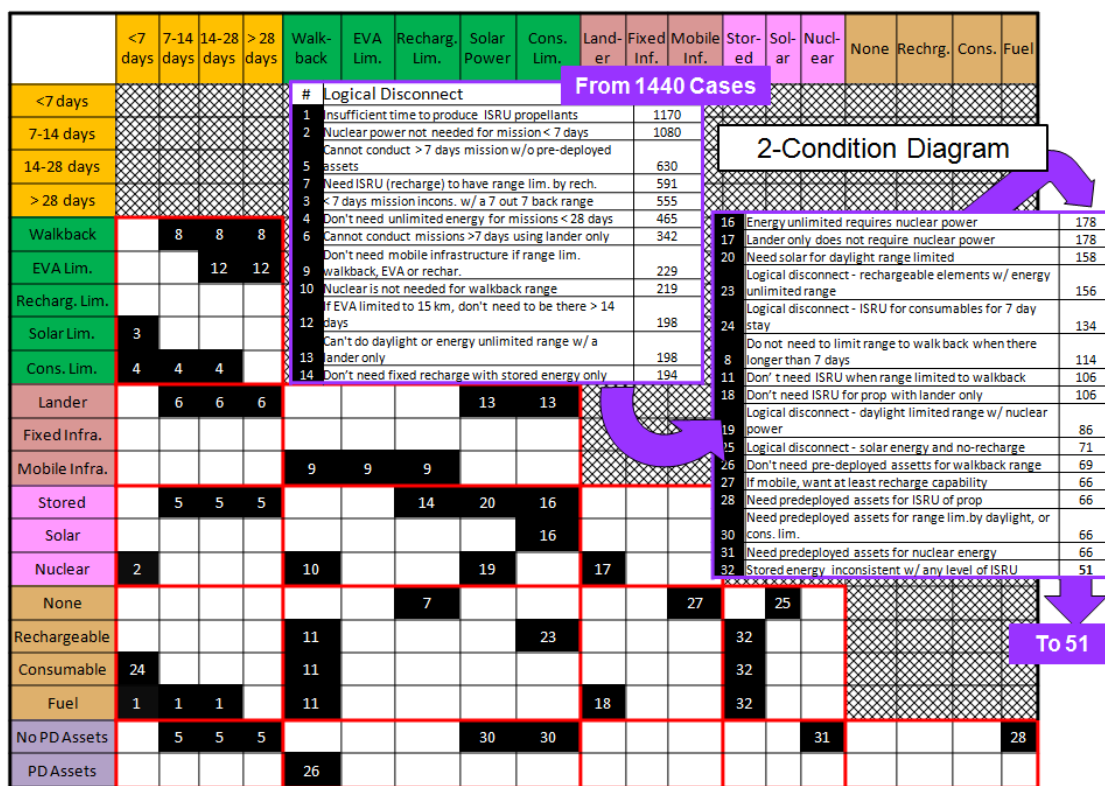


Figure 3: Elimination of branches from lunar trade tree.

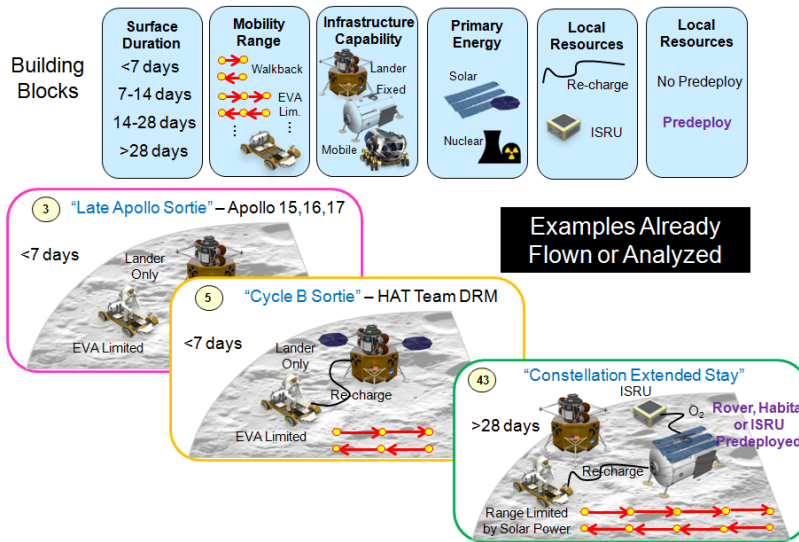


Figure 4: Example street view diagrams of heritage missions.

of the branches have heritage in Apollo or Constellation or other studies. The cases already flown (Apollo) are on the shortest duration and limited capability extreme while many of the future mission designs are at the long duration and high capability extreme. This leaves room for new cases in-between these extremes for future study.

In order to better understand the remaining cases, each branch was assigned physical components and laid out individually in mini street view diagrams, smaller versions of the full detailed graphical synopsis diagrams shown in Figures 8 and 11. These individual diagrams were then placed into groups to identify cases worth further study. Figure 4 provides a leg-

end for the building blocks used in each category and some example mini street view diagrams for heritage missions. Many of the categories have cross-physical hardware implications, so the individual components were designed to be modular. Also, the diagrams are at the stick-figure level and should be treated as models to be populated with additional design analysis, as needed.

Figure 5 articulates a few new branches that are available for further study. Most of the remaining branches are in the >28 day category since this surface duration offers the most flexibility in capability. However, there are many intermediate 7-14 day and 14-28 day missions worth diving deeper into.

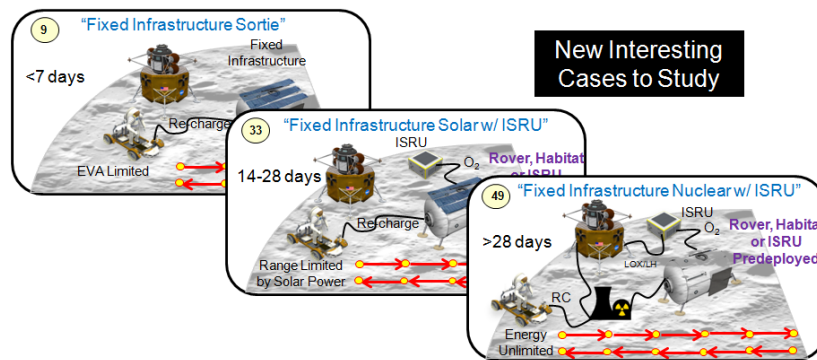


Figure 5: Example street view diagrams of new lunar surface mission possibilities.

HUMAN LUNAR SORTIE DRM

Of the two lunar surface DRMs currently being carried by the HAT, the Lunar Sortie DRM exists on one extreme of the continuum of possible lunar surface missions. Sortie missions, by definition, do not use any significant quantities of pre-placed elements or logistics, and are conducted with the crew living out of the lander throughout the surface stay. To further examine the minimum hardware and energy extreme, a Lunar Orbit Rendezvous (LOR) to either a polar or equatorial landing site from a Low Lunar Orbit (LLO) staging orbit was chosen to minimize the combined Lunar Orbit Insertion (LOI), descent and ascent maneuver sequence ΔV energy. In contrast, crew size and Extra Vehicular Activity (EVA) activity is maximized in this surface DRM. The 4 member crew conducts simultaneous EVAs on all 7 days on the lunar surface, including landing and departure days bookending the stay. While the crew descends to the surface, the un-crewed MPCV is left in a low lunar orbit that “node walks” over the landing site, enabling a minimum energy planar descent and ascent. The crew conducts the descent and ascent in Launch/Entry Suit (LES)-type suits, and performs surface exploration in separate surface EVA suits that are pre-docked to suit

locks. To further minimize mission complexity, the 7-day mission is conducted entirely during lunar day, and is therefore capable of being powered by solar arrays on the surface. The lander delivers 500 kg of cargo to the surface and returns 250 kg of samples on ascent.

Sortie missions emphasize the use of EVA for exploration science and technology demonstrations for short durations. This surface DRM simultaneously deploys all 4 crew members on the lunar surface to maximize the scientific and exploration return for the mission. When not conducting EVAs, the crew resides in the lander habitation module, which provides all the routine functions of eating, sleeping, housekeeping, exercise, and personal hygiene. Intra Vehicular Activity (IVA) functions also include preparing and maintaining pressure suits, planning for subsequent operations on the lunar surface, and all activities associated with post-landing and pre-ascent operations.

Transportation Architecture

The transportation DRM associated with the lunar surface sortie mission is shown in Figure 6. Two Space Launch System (SLS) launches place the Orion Multi Purpose Crew Vehicle (MPCV) and lunar lander into

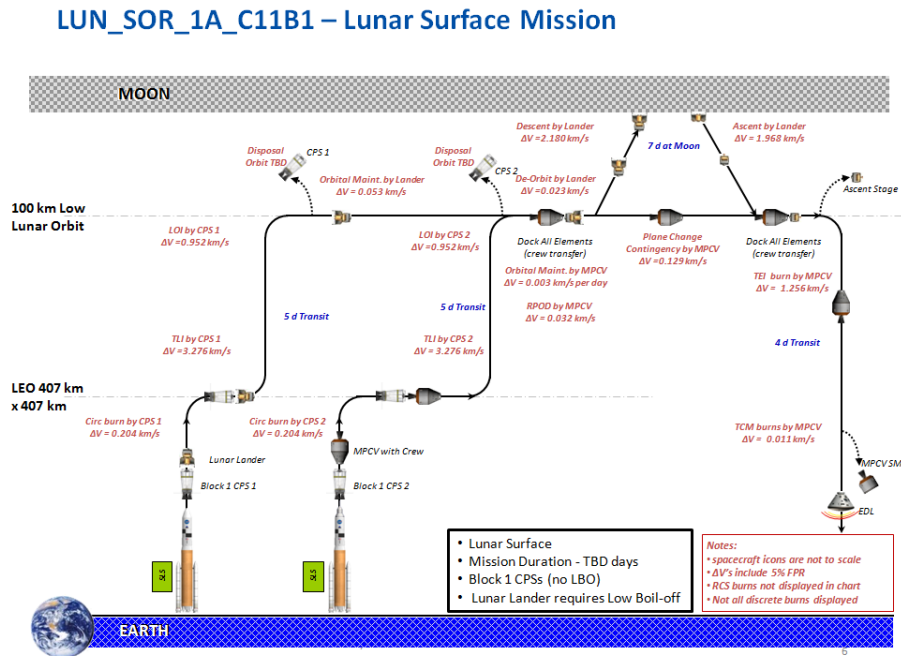


Figure 6: Lunar sortie mission transportation DRM.

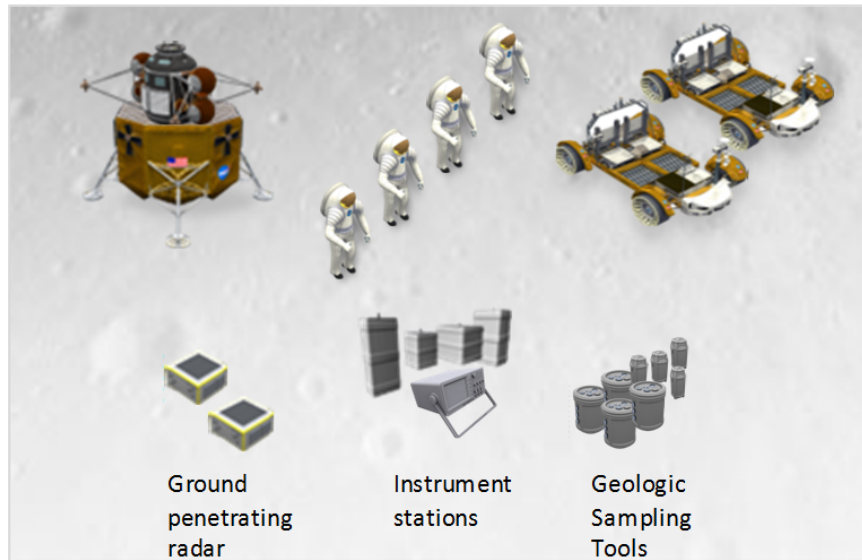


Figure 7: Lunar sortie mission surface hardware elements.

an inclined LLO that allows for a minimum energy descent and ascent at the bookends of the 7-day surface mission. Each SLS launch has a cryogenic upper stage to execute the trans-lunar injection (TLI) maneuver, and then again to perform the lunar orbit insertion (LOI) burn to reach LLO. With crew on-board, Orion arrives into lunar orbit after a 5 day coast and performs the rendezvous and docking maneuver sequence with the pre-positioned lander, already in LLO. The crew proceeds to check out and then transfer from Orion to the lander which is then followed by a descent to the lunar surface to perform the primary mission. While on the surface, the crew lives out of the lander's habitation module. Along with the descent stage, the habitation module is left on the surface at the end of the mission. When the 7 day mission is complete, the crew returns to lunar orbit in the lander's ascent module and docks again with the Orion vehicle. Crew and samples transfer to Orion and the service module performs the trans-Earth injection (TEI) burn. The lander ascent stage is expended prior to TEI. The return to Earth also last 5 days, and then the Orion capsule performs a direct Earth entry and lands in the Pacific ocean to the west of California.

Surface Hardware

An example architecture was developed specifically for a mission to Tsiolkovsky Crater. This lunar sortie

mission emphasizes geology and substantial rover traverses in order to investigate multiple geological units near the central peak of Tsiolkovsky Crater. This sortie mission also highlights a minimalist approach to science equipment, expressing the importance of diverse, substantial geologic sample return. The surface hardware is graphically illustrated in Figure 7. To accomplish this sortie mission, two unpressurized rovers are deployed to give each pair of crewmembers the capability to rove up to 32 km roundtrip. Rovers are recharged between EVAs from the lander. Each rover carries a ground penetrating radar to map the subsurface structure and determine mare thickness during traverses. Rovers also carry 4 instrument stations to be deployed during selected traverses designed to operate subsequent to departure. The instrument stations contain geophones, seismic sources, and surface magnetometers for detailed sub-surface mapping. Each rover is also equipped with an array of geological sampling tools including core drills, sample rakes, bulk sample tools, sample bags, and cameras for documentation.

Concept of Operations

Corresponding to the specific articulation of surface hardware, a day-by-day concept of operations was developed for the Tsiolkovsky crater sortie mission describing all IVA and EVA crew activities. Each surface day involves an EVA by all 4 crewmembers, including

rover traverses between 15 and 32 km to the 4 unique geological units. The geology emphasis of this surface mission requires the crew to stop approximately every kilometer and sample regolith and collect selected rake samples. Along the way the ground penetrating radar maps subsurface structure and determines mare thickness while the crew deploys a network of four instrument stations. An overview of the surface mission is shown in Figure 8.

A typical traverse is shown in Figure 9. The primary objective of this traverse is to characterize the troctolite spur at the east end of the Tsiolkovsky central peak to assess lateral variations of central peak compositions, determine age relationships, and determine the relationships of a peak complex and mare. During the 18 km traverse, the crew will sample anorthosites, troctolites, and norites, observe mineralogic, age and textural relationships, and collect bulk regolith surface and rake samples during traverses. In detail, the crew day Concept of Operations is as follows:

Step 1: The crew conducts post-sleep activities and pre-

pares the morning meal.

Step 2: The crew reviews the day's EVA plans with mission controllers and checks out EVA suits.

Step 3: The crew don their surface EVA suits via the 4 suit ports located on the Habitation Module.

Step 4: All 4 crewmembers egress the Habitation Module and begin the EVA.

Step 5: The crew descends the ladder and detaches the charged rovers from the lander power supply.

Step 6: The crew loads sample collection equipment required for the EVA onto the rovers.

Step 7: All 4 crew depart together on two unpressurized rovers for the pre-planned traverse.

Step 8: The crew traverses to the troctolite spur northeast of the Tsiolkovsky central peak to assess the lateral variation in the peak complex.

Step 9: The crew visits approximately 10 individual stations on the 18 km traverse stopping to collect bulk,

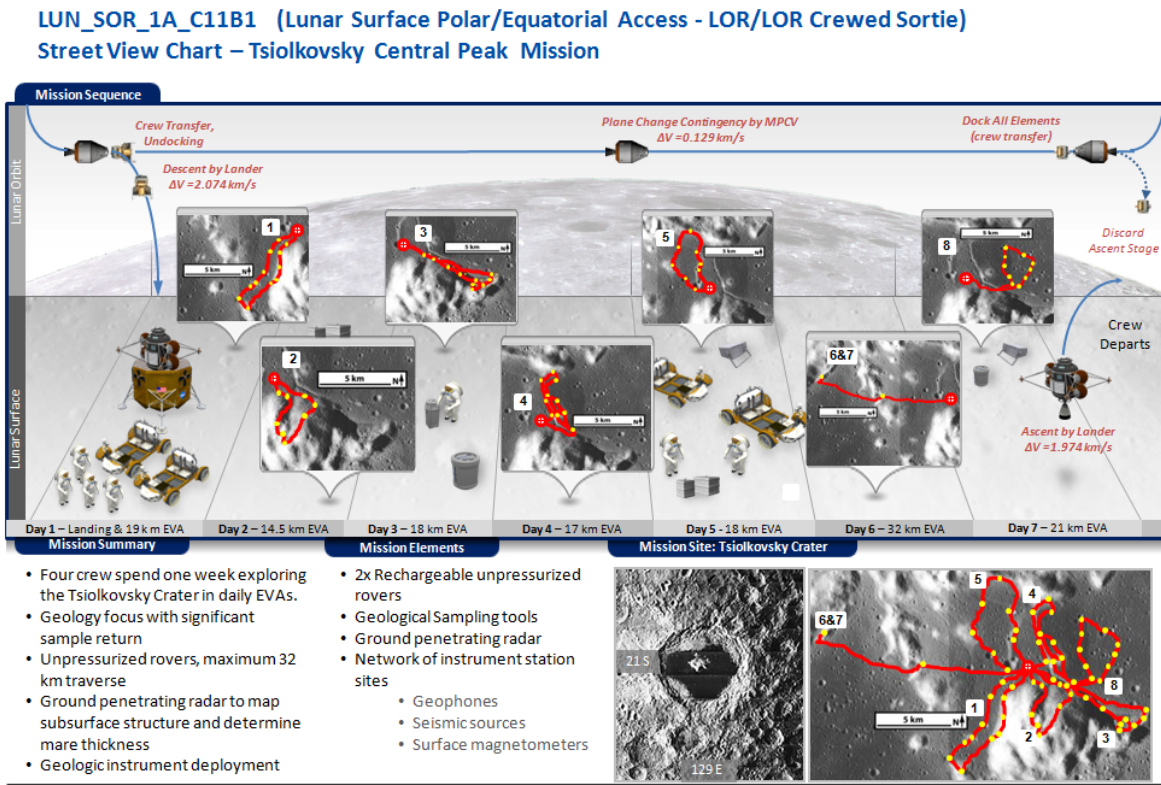


Figure 8: Lunar sortie mission surface operations street view.

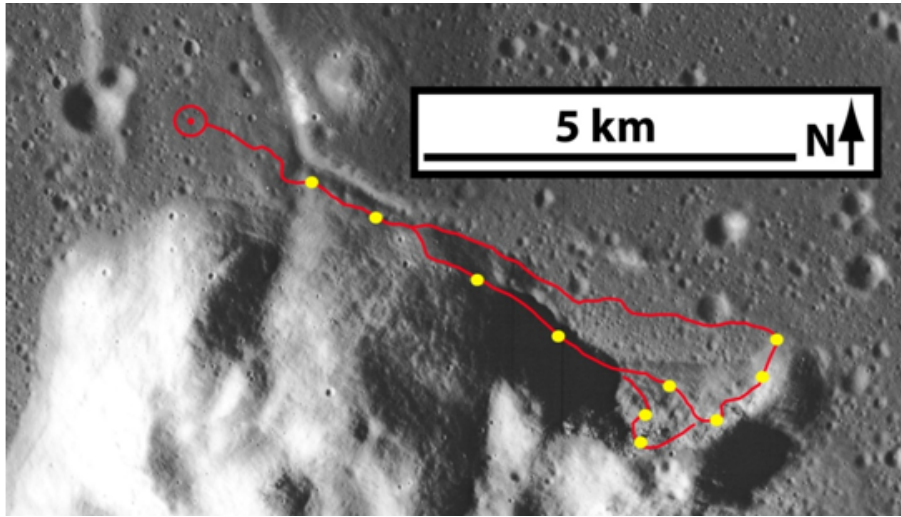


Figure 9: Typical sortie mission traverse path with scientific stations shown.

rake, and targeted geologic samples, and to record geologic observations. The crew performs photo documentation of each sample collected and panoramic photography of each station along the traverse.

- Step 10: During the EVA, one pair of crewmembers may traverse different paths from the other EVA pair in order to maximize the number of stations visited. The distance separating EVA pairs will not be more than 1 (TBR) kilometer.
- Step 11: At each station, the crew establishes high data-rate communications with Earth for video and system status monitoring.
- Step 12: While traversing between stations, the crew has low data-rate communications with Earth.
- Step 13: Upon return to the lander, the crew attach the rovers to the lander power system for recharge.
- Step 14: The crew ascends the ladder to the lander's Habitation Module with the samples and imagery collected during the traverse.
- Step 15: The crew ingress the Habitation Module via 4 suit ports to conclude the EVA.
- Step 16: The crew transfers the collected samples to the Habitation Module.
- Step 17: The crew recharge PLSS batteries and consumables.
- Step 18: The crew prepares and consumes the evening meal, and transmits the day's traverse imagery to Earth.

Step 19: The crew configures the Habitation Module for sleep and begins an 8-hour sleep period.

Lunar Sortie Conclusions

Working the details of each surface reference mission is an opportunity to identify areas for improvement and inconsistencies with the matching transportation DRMs. The example lunar geological sortie presented may be a simple mission but a number of issues were identified. The primary example is the need for additional delivered payload mass as the 500 kg delivered down-mass is 200 kg short of being able to deliver the 2 unpressurized rovers and science instruments required for an aggressive 7-day geological sortie. The lengthy traverses also require both unpressurized rovers (and all 4 crewmembers) to remain together, since a single unpressurized rover will limit traverse radius to walk back distances (~10 km). Certain traverses also split the crew midway to maximize science sites visited, but limit the separation distances to less than 1 km.

Other important challenges worthy of future study can be ascertained by reviewing the crew timeline. Seven consecutive 4-crew EVAs will challenge the crew's physical limits, especially on landing and departure days, where EVAs and significant mission flight events will occur back-to-back. This may exceed a reasonable crew day timeline on those days. The 8 hour EVAs will also challenge the crews meal schedule, necessitating a 2 meals per day schedule:

post sleep/prior to EVA, and pre-sleep/post-EVA. Finally, transferring the daily collected samples into the pressurized volume will produce a challenge to control dust and sample environment integrity.

known as Space Exploration Vehicles (SEVs). With this capability in mind, the ground rules and assumptions have been delineated in Table 1.

HUMAN LUNAR EXTENDED STAY Transportation Architecture

While the Sortie mission is on one end of the continuum, the Extended Stay enables a much broader set of missions from the trade tree and can include missions at the longest duration extreme. In general, an Extended Stay mission makes use of pre-deployed surface assets to literally extend the crewed surface stay time beyond the current single mission sortie limit of seven days. Twenty-eight days is currently the max stay time, as the most recently articulated polar only excursion phases do not have large enough habitats to enable stays longer than 28 days.

To stress the bounds of an Extended Stay capable mission, a 28 day duration Extended Stay Human Lunar Mission that could be conducted at either lunar pole has been analyzed. One of the primary means by which the concept of continuous excursion has been enabled is with the use of small pressurized rovers

The Extended Stay mission transportation architecture is very similar to the Sortie mission, including the same heavy lift launch vehicle that has the capability to deliver cargo or crew. As in the Sortie mission, represented by the third and fourth notional SLS launchers in Figure 10, the Orion crew capsule and the pre-positioned lunar lander dock in LLO prior to crew transfer and descent. However, unlike the Sortie Mission, some cargo and robotic precursor missions are pre-deployed, represented by the first and second launches in Figure 10. To aid in these pre-cursor missions, international partner launchers may be available. After the surface mission the crew departs in an ascent stage and performs its second LOR with Orion which has remained parked in LLO. After a crew and sample transfer, the journey home is completed solely in Orion, ending with a direct entry and water landing.

Table 1: 28 Day Extended Stay Ground Rules and Assumptions

Category	Description
Mission Capability	<ul style="list-style-type: none"> Multiple (5) extended stay (up to 28 day) missions beginning with: <ol style="list-style-type: none"> 1. Robotic precursors 2. Initial cargo landers Lunar surface emphasis is preparation for Mars missions: <ol style="list-style-type: none"> 1. Test the capabilities 2. Learn self-sufficiency Long distance mobility (100's km)
Mission Content	<ul style="list-style-type: none"> 4 crew Polar Site Small cargo landers (1mt) Large cargo landers (8mt) Automated pre-deployment Rover chassis No airlock for lander Portable Utility Pallets (PUP) will provide all power Crew egress and ingress will be done with suitports Pressurized Rover (SEV) will provide Mobile Habitation
Technologies	<ul style="list-style-type: none"> Dust Control Habitation Autonomous landing and hazard avoidance Advanced surface power (if available)

Lunar Surface Activities

The Extended Stay lunar mission requires a number of phases over a period of several years to culminate in the anticipated full 28 day surface stay as outlined in Figure 10. The mission campaign can be best articulated as a series of 3 phases. First, as a robotic precursor only to the surface phase with a crewed lunar flyby (likely free return), followed secondly by a crew to LLO with tele-operated assets phase, culminating in a the third and final phase which starts with exploration infrastructure deployment, builds to the first human mission to the surface, or Human Lunar return (HLR), and concludes with a full 28 day surface mission.

The first robotic pre-cursor phase begins with a small 1 ton class lander delivering several small robots to one of the lunar poles. These robots work together to identify a suitable landing site for an upcoming 8 ton human class lander. In addition to local reconnaissance, the small rovers gather science data, validate technologies and refine concurrent operations. The robots will practice servicing operations, scout the region for future crew/cargo landing areas, and deploy landing guides. All robots will send back to Earth a

steady stream of engaging and informative data package including video of the descent and touchdown of future crewed/cargo landers.

During this first phase, a crewed lunar flyby is performed, utilizing for the first time the cryogenic propulsion stage to escape Earth's gravity well. A year later, an un-crewed human scale 8 ton lander touches down at the site identified by the small robots. It is carrying a version of the mobility chassis used by the small crewed pressurized rover. It could also optionally carry small communications relay satellites that are deployed in lunar orbit to enable better coverage of the poles before descending. The mobility chassis will operate in autonomous and ground supervised modes at speeds and ranges far exceeding any previous planetary surface rover, and is outfitted with enough energy storage to survive up to 14 day eclipse periods. It will also be furnished with hundreds of kilograms of science instruments and manipulators. The vast science payload, substantially increased speed and range, along with the capability to survive lunar eclipse will allow it to traverse long distances away from the polar landing site to achieve regional exploration. In addition to its own science payloads, it will also be capable of transporting one or more of the previously deliv-

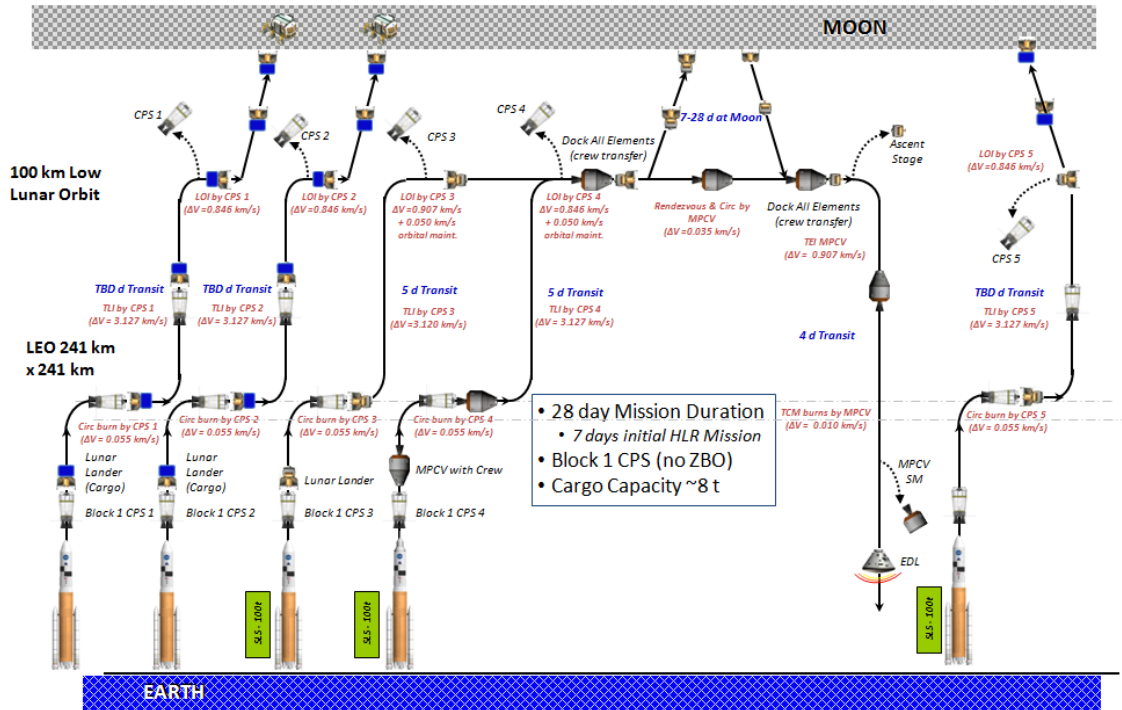


Figure 10: Lunar Transportation Architecture (U.S. Launcher Only).

Table 2: Lunar Surface Elements for a 28 day Extended Stay DRM

Element	Quantity	Description
Crew	4	International Astronaut Crew
PUP (Portable Utility Pallet)	3	100 kW-hr battery storage each 2 kW solar array each Transported by SEVs
PCT (Portable Comm. Terminal)	1	Provides high bandwidth communications Transported by PUP
Robotic Precursor 1 (R1)	1	Small International Science Rover
Robotic Precursor 3 (R3)	1	Small International Science Rover
UPR (Unpressurized Rover)	1	Provides excursion capability before second SEV
Off-loader (LSMS or Cradle)	1	Can tele-robotically offload cargo landers or be used off the back of an SEV
Science Package	1	Pre-deployed in second mission
Logistics	9	Multiple logistics payloads required
STM (Suit port Transfer Module)	1	Allows transfer of material through a Suit-port
SEV (Space Exploration Vehicle)	2	200 kW-hr battery storage each Average speed toward destination = 5 km/hr
Robotic Precursor 2 (R2)	1	Small NASA Robotic Assistant and Science Rover
ALC (Airlock Logistics Carrier)	7	Pressurized Logistics

ered small robots as it explores which could be used for servicing and remote observation. This mobility platform will provide multiple partnering opportunities while substantially reducing risk for future exploration missions.

The second phase begins with crewed missions to LLO which are designed to augment the lunar surface roving capability for a few years. The crewed missions test the transportations system as well as refine techniques for tele-operating the surface assets from LLO. This activity is analogous to operating rovers on the surface of Mars from Mars orbit, as would likely occur during a Mars orbital mission. The second phase introduces an opportunity for practicing lunar orbit rendezvous techniques with crew rated systems (such as an ISS technology module, alternate transportation systems, and SEV/Ascent module prototypes). Extended tele-operations supported by the communication relays can be achieved by docking to these crew rated systems for periods beyond nominal crew capsule lifetimes (typically about 7-9 days in LLO). Docking to systems with additional habitable volume will allow for longer duration stays in LLO.

The third and final segment of the extended stay lunar exploration phase begins a few years later with infrastructure deployment and HLR with human capable missions increasing from 7 to 28 days. The robotic

precursor work has incrementally built up confidence in operations and systems design in preparation for the more aggressive lunar exploration with humans. HLR occurs at one of the lunar poles due to the favorable solar and thermal conditions, preventing exposure of the systems to the harshest operational environment of a full, approximately 15 day, lunar night.

Before HLR can occur and after the site on the moon that will host HLR has been sufficiently investigated by the robots, the deployment of the exploration infrastructure begins. The deployment of the pressurized rover and the crewed ascent module occur within a year of each other, thus increasing the potential to share systems development like Environmental Control and Life Support Systems (ECLSS), thermal and power. In addition, a small pressurized rover with supporting power infrastructure lands in the polar region and self-deploys. The small pressurized rover is initially tested, then sent on excursions (in a ground supervised mode) progressively further away from the landing location, beyond the range of the small robots, to identify opportunities and optimal paths that can be used by the humans on the first crewed mission.

The predeployment assets are now poised for HLR which will be a test mission with a shorter Sortie-equivalent 7 to 14 day stay duration. The humans along with any critical spares arrive to use the fully checked

out rovers (original mobility chassis and the new small pressurized rover) that are already waiting for them. The crew then performs the up to 7 to 14 day mission, exploring the near polar region and practicing operations and contingency scenarios for upcoming traverses. Having two human scale rovers (one pressurized, one unpressurized) offers redundancy and rescue capabilities in the event one rover becomes non-operational. The crew leaves the surface at the end of their mission while the robots continue exploring before the next crew arrives, enhanced by PUPs and cargo delivered by small international landers. Six months later another small pressurized rover is delivered, autonomously deployed and tested, so that it can join the previously delivered mobility chassis and pressurized rover at the next crewed landing location.

The third and final phase eventually builds from this initial 7 to 14 day mission to a 28 day mission. First, the original HLR mission is repeated with a similar 14 day mission six months later using the extended range and duration resulting from coupling the small pressurized rovers to the PUPs. A crew does not return to this location for a year as the small pressurized rovers, the servicing robots and the PUPs perform extensive ground supervised exploration. One year after HLR, a third crewed mission arrives at the pole and the mission duration is lengthened to the full 28 days. This cycle repeats for two more years, with each mission

lasting 28 days, enabled by the mobile infrastructure meeting the crew at new polar region landing sites and delivery of logistics and science instruments by small 1 ton landers. By the time the mobile infrastructure is near the end of its design life, humans have spent 105 days on the lunar surface exploring and tested key planetary surface capabilities and operations. The required elements for this final 28 day extended stay are articulated in Table 2.

Manifest of Missions

The sequence of missions and elements or manifest can be graphically shown for a general Lunar Extended Stay Mission in a street view layout as demonstrated in Figure 11. Four large cargo landers, six small cargo landers, result in the five crewed missions for the extended stay DRM manifest. A notional location of landing at the South Pole Shackleton crater rim is shown but there are a number of other candidate locations that are likewise interesting from a science and exploration point of view.

Extended Stay Conclusions

The Lunar Extended Stay DRM is a preliminary architecture that features a feasible set of elements, concept of operations and deployment manifest. How-

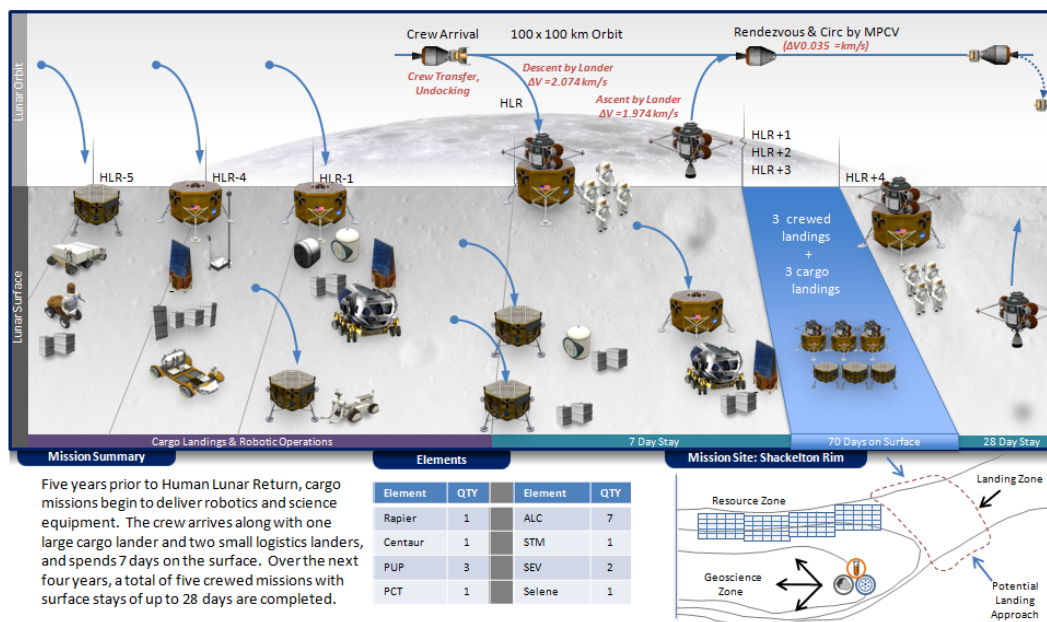


Figure 11: Street view of a 28 day lunar extended stay mission.

ever, there are many details regarding logistics and habitation that have not been addressed which warrant further study. New strategies will likely be required to enable four crew members to live productively in only two SEVs for 28 days. One solution might be to position accessible supply caches on the lunar surface for periodic replenishment. In addition, suit ports are assumed viable although they have a very low Technology Readiness Level (TRL). Also, advanced energy storage will be required or the SEV will have to remain in the sunlit regions and rely solely on photovoltaic power. Finally, risk reduction through the use of robotic precursors is highly desirable but would require significant international coordination for transportation, deployment and operation with uncertainty regarding the availability of newly developed U.S. launchers. Thus, this study is a valuable starting point but it should be used as a point of departure for discussion as well as for spurring further analysis to address the implementation challenges.

illustrates the international effort within ISECG to begin defining long range strategies for human exploration beyond low Earth orbit and looks for opportunities to coordinate and cooperate in near-term activities which prepare for these challenging missions.

The ultimate agreed to goal for all international partners involved is the human exploration of Mars. The GER roadmap has currently identified two strategies for consideration to achieve this goal: Moon-Next and Asteroid-Next, which both culminate in a human mission to Mars. Both take advantage of ISS as the first step as an Exploration Test Module element. A version of the 28 day Extended Stay Lunar Mission fits the GER profile in either scenario. Because of the close coordination of the ISECG and the HAT teams there is a significant amount of coherence between HAT DRMs and GER objectives outlining enhanced international collaboration.

GER LUNAR MISSION

The Global Exploration Roadmap (GER) is a tool developed by ISECG participating agencies to facilitate advancement of coordinated and cooperative human space exploration plans and programs, building on the vision in the Global Exploration Strategy. The GER

GER Identified Cases

The Global Exploration Roadmap (GER) provides a detailed architectural reference mission design with a cooperative international focus. Human missions to the lunar surface play central roles in both the Moon-Next and Asteroid-Next exploration paths. In the end, seven different branches of the 51 remaining branches of the lunar trade tree can be tied to the GER framework as described by the ISECG team. Figure 11 out-

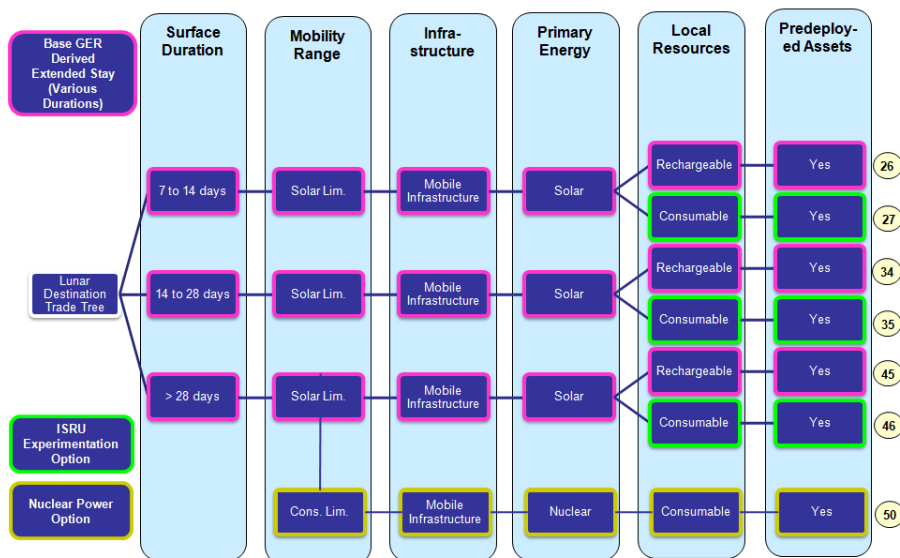


Figure 12: Multi-duration, multi-path GER-derived missions on the lunar trade tree.

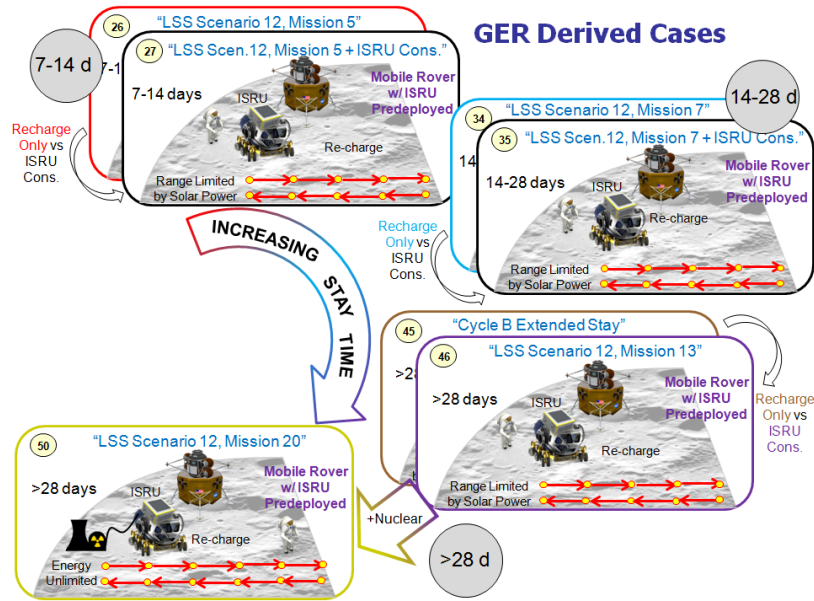


Figure 13: Street view diagrams for GER-derived mission options.

lines the three main branches (26, 34, 45) that align with a base-level GER mission as well as the four potential off-shoot alternatives (27, 35, 46, 50).

The seven branches are built from variations from three of the six trade tree categories. The first relates to the desired incremental increase in stay time that exists over a lunar surface mission campaign, delineated in Figure 11 by the *Surface Duration* category. The second relates to In-Situ Resource Utilization (ISRU) optional instantiation as specified in the *Local Resources* category. A minimal path relies solely on rechargeable elements, while a more ideal approach would be to incorporate ISRU capability to produce fuel and other consumables reducing overall mass. ISRU is identified by the GER as one of the eight key areas for technology development. Finally, the seventh branch is an optional opportunity for taking advantage of advanced energy sources such as nuclear power. Advanced energy power is mentioned as a potential investment in the GER. The mini street view diagrams that illustrate the differentiations for the GER-derived missions are given in Figure 12. Note that 6 out of 7 of the mission scenarios can be tied to the Constellation driven Lunar Surface Study (LSS) at NASA and the seventh ties directly to the final mission in the Extended Stay DRM campaign. This demonstrates close alignment between the international efforts and NASA's on-going in-house work.

CONCLUSIONS

The HAT lunar destination team has defined a continuum of surface reference missions ranging from simple sortie missions to fully capable international extended-stay missions. Each mission represents a logical path in a comprehensive decision tree of lunar surface design options. Representative surface DRMs have been worked in detail to define operations concepts, timelines, hardware elements and issues. The HAT team will continue to explore other paths through its trade space in order to identify destination missions that balance performance and affordability.

References

- [1] Augustine et al. Seeking a human spaceflight program worthy of a great nation. In *Review of US Human Spaceflight Committee Report*. White House Office of Science and Technology Policy, 2009.
- [2] International Space Exploration Coordination Group. The global exploration roadmap. September 2011.