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NASA Engineering and Safety Center Lunar Rover Design Concepts Assessments

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Nomenclature

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ATCO	ambient temperature catalytic oxidizer
BFO	Blood-Forming Organ
CO_2	Carbon Dioxide
ConOps	Concept of Operations
DCS	Decompression Sickness
ECLSS	Environmental Control and Life Support Systems
EVA	Extravehicular Activity
FHS	Food Hydration Station
FT	Fault Tolerance
g	Gravity
GFE	Government Furnished Equipment
GNC	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
H_2O	Water
HLS	Human Landing System
HMP	Human Mobility Platform
HSF	Human Spaceflight
IVA	Intravehicular Activity
JPL	Jet Propulsion Laboratory
kg	Kilogram
kg/CM-day	Kilograms per Crew Member-Day
km/h	Kilometers per Hour
LaRC	Langley Research Center
LiOH	Lithium Hydroxide
LRV	Lunar Rover Vehicle
LTV	lunar transfer vehicle
M&P	Materials and Processes
m^3	Cubic Meters
MEL	Master Equipment List
MGA	Mass Growth Allowance
mGy-Eq	Milli-Gray-Equivalent
mm	Millimeter
mt	Metric Ton
N_2	Nitrogen
NESC	NASA Engineering and Safety Center
NTE	Not to Exceed
O_2	oxygen
PDR	Preliminary Design Review
PPR	Passively Propagation Resistant
PR	Pressurized Rover
psia	Pounds per Square Inch Absolute
RCA	Rapid Cycle Amine
RFC	Regenerative Fuel Cell

SAWE	Society of Allied Weight Engineers
SME	Subject Matter Expert
SPE	Solar Particle Event
TBD	To Be Determined
TBR	To Be Resolved
TCS	Thermal Control System
TRL	Technology Readiness Level
VR	Virtual Reality
Wh/kg	Watt-hours Per Kilogram

1.0 Introduction

Mass is a significant risk to programs and projects as they transition from formulation to implementation, especially in larger human space systems where delivery mass or volume can be a constrained commodity.

- Concepts developed without an adequate systems-engineering basis, including design and operations experience, may miss significant functionality and subsequent mass required for integration or operations.
- Further uncertainty can be associated with not fully understanding design best practices and standards that drive mass, such as design for minimum risk or fault tolerance.[1]
- Finally, the appropriate systems engineering mass properties management rigor and technical discipline insight are required to set the mass baseline, including appropriate mass growth allowance (MGA) to ensure program success.

Mass is a key quantity that should be constantly monitored by the systems engineer and the program/project management stakeholder to ensure mission compatibility throughout the project life cycle. In addition, mass is a key programmatic performance metric monitored by the NASA Chief Financial Officer for current and future program cost estimating.

NASA Exploration Systems sought an assessment of reasonableness with respect to different potential rover concepts that balances mass needs and human-class cargo lander capabilities. Appropriate systems engineering mass properties management rigor and technical discipline insight were used, and are required to set the mass baseline, including appropriate MGA to ensure program success.

Two independent Lunar rover concepts were evaluated, with a goal to understand concept credibility and the Lunar rover designs potential extensibility for Mars surface operations. A notional generic rover concept is shown in Figure 1.

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[1] The intent of NASA requirements for failure tolerance and Design for Minimum Risk (DFMR) is that DFMR is used only if an identified hazard cannot be eliminated by fault tolerant design; DFMR is not an alternate to FT, it is a fall back where FT is not possible, such as for Primary Structure.

Figure 1. Notional Pressurized Lunar Rover [ref. 1]

Early indications showed significant (40%) mass variations in the concept designs warranting an independent evaluation, and validation of the design assumptions and subsequent mass estimates. Validation of the concept masses is critical to mitigate risks including exceeding mass delivery capabilities of the launch vehicle, or the lander, and subsequent perturbation of manifest planning which could require additional delivery flights and assets. This assessment was also used to inform the acquisition strategy of a critical lunar architectural component, including adequate functionality as it pertains to the Statement of Work, requirements, design and construction standards, and associated mass growth allowance and management approaches.

To evaluate each rover concept's current level(s) of design maturity, and provide a high-level assessment of mass management, particularly mass growth allowance, the team referenced the "AIAA Standard S-120A, Mass Properties Control for Space Systems". [ref. 2] The reference information was limited to documentation provided by the two independent design organizations. The NASA Engineering and Safety Center (NESC) assessment team (NASA Technical Fellows, subject matter experts (SMEs), and systems engineers) evaluated the information with the following Phase I goals:

1. Are available concepts of operations and requirements reasonable and adequate?
2. Does the concept appropriately respond to the available functional requirements?
3. Are the coinciding ground rules and assumptions technically sound?

The resultant review inputs were characterized in five themes:

1. Unclear technology readiness levels (TRLs) that create risk and uncertainty when estimating MGA and margin.

2. Preliminary assumptions are unavailable and/or unclear from the presented material or differ from NASA design experience.
3. Apparent disconnect or discrepancy between rover design teams on requirements and/or requirements unavailable in reference material.
4. Apparent disconnect between best practices, lessons learned, NASA and U.S. industry requirements, and the two concepts, based on review of material provided.
5. Conflicting and/or missing information in presented material.

Theme 4 from the above list is of particular interest and details with respect to each concept are further discussed below in Section 3.0 and became an important deliverable of this assessment.

In addition to the above five themes and a deeper dive into Theme 4 specifically, the assessment team evaluated uncertainties and risks with respect to mass information, design maturity, and TRLs and color-coded the results for display in the S-120A [ref. 2] MGA table format (Section 4).

Drawing from the team's extensive experience with crewed space vehicles and Mars rovers, several issues and opportunities were identified, leading to the following suggestions:

1. Cross-check thermal assumptions with the Human Landing System (HLS) Thermal Analysis Guidebook [ref. 3].
2. Assist in the development of a general set of lunar environment trafficability requirements (e.g., soil characteristics, rocks, and boulders to navigate or clear, travel distance desired, speeds) for a pressurized lunar rover (PR).
3. Devise mobility system architecture with the goal of simplification and design for flight, responding only to lunar use cases and more limited Earth test cases of trafficability requirements and lessons learned from Mars surface systems.
4. Reassess window and external lighting configurations.
5. Suggest moving away from the spur-gearbox and recirculating fluid lubrication concepts.

The AIAA S-120A standard [ref. 2] was used as a baseline framework for hardware categories and percent MGA values for threats to the estimated and predicted mass of the proposed approaches. The team:

1. Developed a tailored mass growth allowance table.
2. Developed an initial master equipment list (MEL), or leveraged MEL provided, based on information provided.
3. Assessed uncertainties and risks to mass information and color-coded the results.
4. Categorized the inputs based on the Phase I goal they addressed.
5. Grouped the inputs into the above-mentioned themes.

The S-120A [ref. 2] MGA table is provided as Figure 2 for reference.[2]

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[2] Trafficability is the suitability of the ground and/or vehicle to support travel across terrain to meet transport objectives.

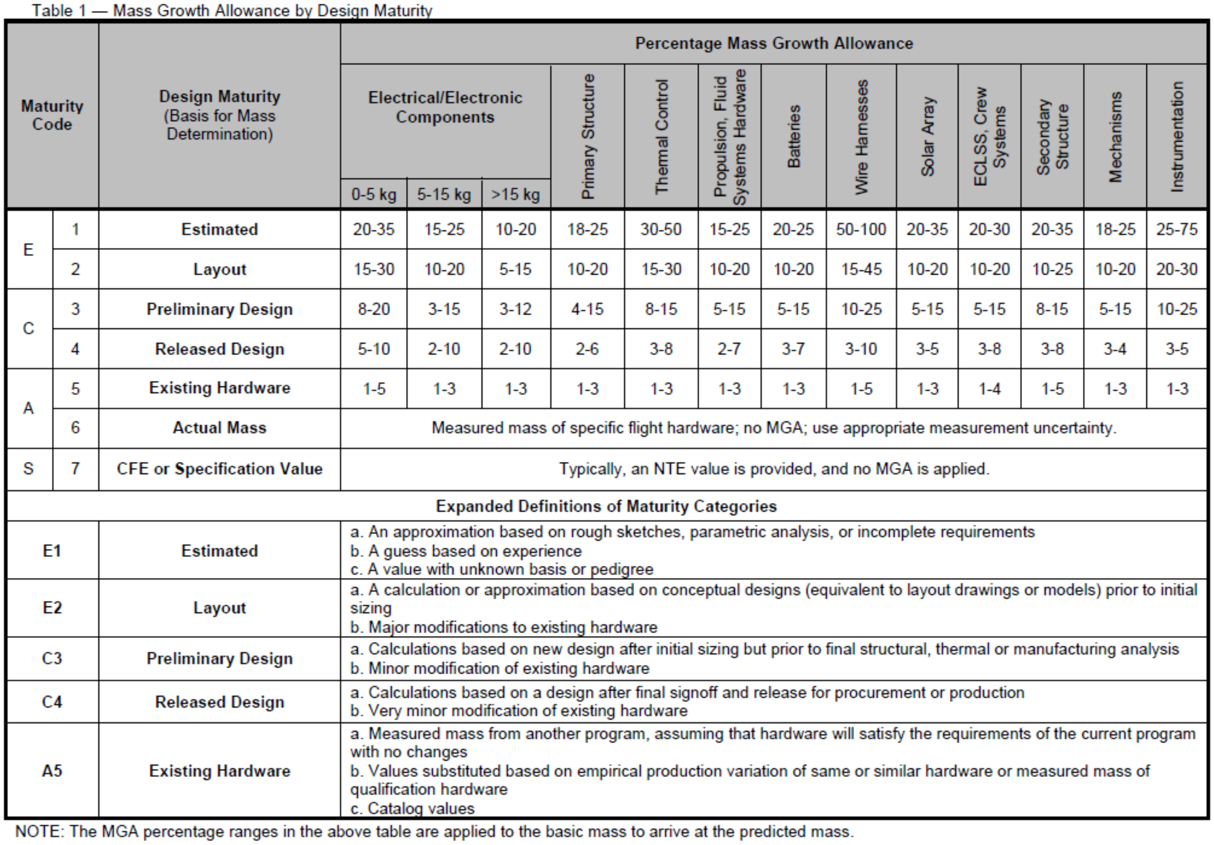


Table 1 — Mass Growth Allowance by Design Maturity

Maturity Code		Design Maturity (Basis for Mass Determination)	Percentage Mass Growth Allowance												
			Electrical/Electronic Components			Primary Structure	Thermal Control	Propulsion, Fluid Systems Hardware	Batteries	Wire Harnesses	Solar Array	ECLSS, Crew Systems	Secondary Structure	Mechanisms	Instrumentation
			0-5 kg	5-15 kg	>15 kg										
E	1	**Estimated**	20-35	15-25	10-20	18-25	30-50	15-25	20-25	50-100	20-35	20-30	20-35	18-25	25-75
	2	**Layout**	15-30	10-20	5-15	10-20	15-30	10-20	10-20	15-45	10-20	10-20	10-25	10-20	20-30
C	3	**Preliminary Design**	8-20	3-15	3-12	4-15	8-15	5-15	5-15	10-25	5-15	5-15	8-15	5-15	10-25
	4	**Released Design**	5-10	2-10	2-10	2-6	3-8	2-7	3-7	3-10	3-5	3-8	3-8	3-4	3-5
A	5	**Existing Hardware**	1-5	1-3	1-3	1-3	1-3	1-3	1-3	1-5	1-3	1-4	1-5	1-3	1-3
	6	**Actual Mass**	Measured mass of specific flight hardware; no MGA; use appropriate measurement uncertainty.												
S	7	**CFE or Specification Value**	Typically, an NTE value is provided, and no MGA is applied.												
Expanded Definitions of Maturity Categories															
E1		**Estimated**	a. An approximation based on rough sketches, parametric analysis, or incomplete requirements b. A guess based on experience c. A value with unknown basis or pedigree												
E2		**Layout**	a. A calculation or approximation based on conceptual designs (equivalent to layout drawings or models) prior to initial sizing b. Major modifications to existing hardware												
C3		**Preliminary Design**	a. Calculations based on new design after initial sizing but prior to final structural, thermal or manufacturing analysis b. Minor modification of existing hardware												
C4		**Released Design**	a. Calculations based on a design after final signoff and release for procurement or production b. Very minor modification of existing hardware												
A5		**Existing Hardware**	a. Measured mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes b. Values substituted based on empirical production variation of same or similar hardware or measured mass of qualification hardware c. Catalog values												

NOTE: The MGA percentage ranges in the above table are applied to the basic mass to arrive at the predicted mass.

Figure 2. AIAA S-120A Mass Growth Allowance by Design Maturity with Highlights [ref. 2]

The "bucketing" of inputs into themes motivated the stakeholder to request a summary of theme "4" in the form of a separate document that was provided to the design team representatives. For completeness, the NESC team performed the same "bucketing" of theme "4" inputs and both are presented here. The NESC team took three key steps: first, group inputs into themes highlighting disconnects between design concepts and best practices, particularly from Mars and Apollo lunar rover experiences; second, perform a detailed assessment of requirements revealed critical differences in design approaches and how requirements were applied, leading to the creation of a comparative table; and third, a 'quick look' review was conducted with the stakeholders to further refine the evaluation process.

2.0 Review Discussion

Fundamentally, each rover concept consists of a pressurized and habitable volume with systems and subsystems capable of sustaining life and supporting scientific exploration activities by two or more astronauts for weeks at a time. The pressurized volume sits on a chassis with unique suspension and drive train capabilities as well as suit ports to enable extravehicular activity (EVA).

Significant variations exist in the mass of designs, warranting the validation of design assumptions and associated mass estimates. The NESC assessment team's initial information/discussion on technical aspects, ground rules and assumptions, concept of operations (ConOps), and overarching general requirements included:

1. One of the initial concepts of 20 mt (i.e., 10 mt rover, 10 mt power cart) used a regenerative fuel cell system to provide most of the power needs to survive a 14-day lunar night.
2. NASA provided a target mass of 5 mt for a single-system rover based on the NASA-designed lunar lander; entry, descent, and landing initial landing capabilities; and the desire to explore near the Moon's south pole.
3. A minimal set of initial requirements corresponded to what was called the "May Baseline Design" in stakeholder notes (e.g., carbon fiber shell, four suit ports, minimal windows).
    a. Recently, one concept updated the "May design" to include an aluminum shell, two suit ports (i.e., government furnished equipment (GFE)), a side hatch, and larger windows, consistent with other approaches.
4. Two options that may include potential disconnects with one rover approach:
    a. Suit ports – 4 vs. 2, with a side hatch.
    b. Viewports and virtual reality (VR) vs. larger windows.
5. One concept was approximately 5 mt dry mass, aligned with NASA's Artemis Base Camp ConOps.
6. Early indications from provided information suggested that one rover concept mass was approximately 40% greater than another approach.
7. NASA stakeholders have indicated the conceptual lunar lander total mass target is approximately 12 mt total for the rover, lander adapter, offloading device, logistics, utilization, and program reserves.
8. In every case, NASA plans to provide EVA suits, suit-ports, and other minor support items (e.g., medical, air monitors).

Concepts may differ in how hardware is categorized for the purposes of mass management. For instance, one concept may separate mobility (e.g., chassis) and structure (e.g., cabin). For example, although "avionics" shows up in the cabin and chassis MEL categories, the assessment team evaluated this category in aggregate and provided assessment and input in the MGA table's "Electrical/Electronics" hardware category. Despite an extensive overview and detailed MEL, a lack of information at the subsystem and component levels made detailed assessments difficult across all systems. Members of the NESC assessment team with analysis experience and lessons learned associated with Mars rovers learned on Mars 2020 (Perseverance Rover) that as-built hardware could have MGA more than S-120A [ref. 2] recommendations. One example was associated with the wheels, as small variations in part thickness due to allowable fabrication tolerances resulted in masses of 5% more than expected. The NESC assessment team did not directly compare lunar rover concepts and the Mars rovers but leveraged the experience and expertise of Jet Propulsion Laboratory (JPL) personnel when assessing the lunar rover concepts.

It was unclear from the documentation provided that one rover was designed to perform a 14-day mission after lunar surface touchdown and required resupply or stand-alone, and it was unclear whether another rover was designed for at least, or even more than, 14 days. Designing a rover that enables rigorous 1-g testing may include hardware and subsystems that are overdesigned for lunar gravity and environment. Having a robust 1-g environment does create the ability to identify design issues and performance with similar designs. However, all the capability enabling 1-g operation, and its accompanying mass, could be reduced in a 1/6-g version.

In PR design, avionics will be a small percentage of the total mass (i.e., approximately 5%). Given large uncertainties at the conceptual design phase, this value is within the mass estimation range provided in S-120A [ref. 2] for Electrical/Electronics. The review materials for the rover concepts did not include a comprehensive system architecture description, and the content that was presented lacked detail. Such a system-architecture level view of a PR could describe the system, how it behaves, the elements it comprises, and how they interact with each other and is considered a best-practice in space craft design.

Lighting systems, specifically external vehicle lighting for visibility of the rover and the paths it will travel, were not clearly defined in the information provided for review. The NASA Langley Research Center (LaRC) Visualization and VR Team has generated a preliminary south pole visualization (Figure 3). The Earthshine is considered overly generous, but the figures make clear the visibility issues with and without lights.

Figure 3. NASA LaRC Lunar South Pole Visualization

Early concept design parameters were derived from years of changing mission direction and physical prototype testing, whereas the more recent designs appeared to have more of a “clean sheet” starting point. Both concepts have internal requirements and functional goals that create significant divergence in designs, despite both vehicles being meant to fill the same role within the Artemis lunar infrastructure. For example, one rover has a smaller internal volume and meets lunar night survival goals. The reduced volume is most likely from the lessons learned from earlier full-scale ground-tests. The NESC assessment team performed a high-level review of overarching requirements, or “requirement-like” information identified in the available documentation. A table was generated to compare the concepts with respect to identified “requirements” as interpreted by the NESC assessment team.

At the time of the assessment, from an integration perspective, some of the requirements are vague enough that they may have a significant impact on mass—either an increase or a decrease. Several requirements fall into this category, including the requirement for onboard autonomy during crewed and uncrewed periods. Both are early enough in development that many requirements have yet to be properly accounted for. The concept differences in methodology and experience produced varying areas of strength and definition. A lack of specificity at this point in a life cycle is not necessarily negative, but some thought should be given as to how the flow down of requirements could affect mass, particularly if the impact could be significant. For example, one design has a goal of 5 years without maintenance and a 10-year life expectancy, but no data were provided to help understand the effects of dust on external surfaces and how it affected maintenance time. The early requirements and some suggested requirements, though some values are still to be determined, from the team's review are shown in Table 1.

Table 1. Early Revisions and Suggested New Key Requirements

ID	Title	Key Driving Requirement
PR.2	Vehicle Life	Support 10-year, 10,000 km life
PR.3	Launch Vehicle/Lander	Fit within a TBD-diameter dynamic envelope and survive TBD launch and landing loads
PR.4	Mass	Have a TBD mass no greater than _TBD kg (TBR)
PR.5	Crewed Duration w/o Resupply	Support 2-crew for 14 days on the surface without resupply
PR.24	Maintenance	5 yrs no maintenance, 10 yrs with maintenance
Suggested new	Mass Specification	Launch mass vs. landed mass vs. operational mass (roving with 14 days of logistics) vs. wet mass without the 14 days of logistics for this case we assume the number of value is wet mass of operational vehicle minus logistics/GFE (O_2/N_2, potable, Crew, food/ clothes/ EVA, etc.) (regenerative fuel cell (RFC) and the food hydration station (FHS) water should be included)
Suggested new	w/o Resupply Specification	This requirement is vague. Should specify resupply mean all 14 days of outfitting is included inside and/or attached to the PR throughout the entire span.
Suggested new	Vehicle Maintenance	Expected maintenance over the vehicle life should be limited to TBD hrs or TBD interchangeable components (Discern EVA maintenance vs intravehicular activity (IVA)

Some generic observations and suggestions with respect to the vehicle level lunar rover designs were noted and presented in Table 2. Additional observations and suggestions at the hardware category level are presented in Section 3.0.

Table 2. General Observations and Suggested Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
Mass Management	Significant risk associated with designating MGA and margin at 15% across all hardware categories this early in the design maturity for the mission system, as one design team proposed.	Mass growth allowance and mass margin are inextricably linked to design maturity. See AIAA S-120A [ref. 2] and consider the recommendation of the review team that a some-what tailored MGA table is called for.

Fault Tolerance (FT) Requirement	There is a proposed 2-FT requirement for Loss of Crew. It was unclear if this was considered in the mass and power estimates as it could be a driver of mass growth. Also, FT requirements do not typically apply to emergency systems and clarity should be given to the FT requirement - common cause fault that can affect multiple strings for redundancy are often drivers.	Ensure mass and power estimates are consistent with FT requirements. Consider a 1-FT requirement with systems (built for high reliability), 2-FT for safety critical systems plus emergency systems in the trade space.
Assumptions impacting landed mass	A surface service life of 10 years on the moon is not trivial. The lunar environment is generally harsher than Mars (larger temperature swings, more radiation, more abrasive dust), particularly for soft goods.	A robust materials and processes (M&P) and tribology review is warranted, based on lessons learned from Mars rovers and landers experience.
Offloading Devices Allocation	A 500-kg Offloading Device allocation is ~6% of the payload predicted mass". Recent JPL work for a Mars sample return rover egress system was ~50% of the mass of deployed payload, prior heritage systems approached 100%. Understand that this % gets lower as the payload mass climbs, but <10% allocation at this phase appears inadequate.	Obtain lessons learned from JPL rover work with respect to payload device mass.
Architectures and System Modeling	An architecture description is a best practice for system development and no system architectures were made available.	Traditional documents may suffice, but a vehicle system model, and subsequent subsystem models, may ease the translation challenges of different points of reference, applications of requirements, and mass properties management.

3.0 Hardware Category Assessments

3.1 Theme "4" Results

Following the initial review of the material provided, the SMEs on the NESC assessment team provided additional insights, lessons learned, and best practices from their respective disciplines to each of the concept teams to further aid them in their design and development efforts. Identified as "Theme 4" (apparent disconnect between best practices, lessons learned, NASA, and U.S. industry requirements), the review team submitted inputs to Theme 4. The NESC team included JPL SMEs with experience and expertise, and many lessons learned, from the Mars rover campaigns. The team also included NASA Technical Fellows in the areas of human factors, human systems integration, environmental control and life support systems, structural and mechanical systems, active and passive thermal control, avionics, radiation protection, and systems engineering.

3.2 Electrical/ Electronic Components

Additional avionics mass is sometimes bookkept with other systems (e.g., lights/cameras with guidance, navigation, and control (GNC)). One approach performed a bottoms-up mass estimate based on their current design. Maturity levels for avionics vary from Layout-level (E2) to

Preliminary Design Review (PDR)-level (C2). Avionics boxes and systems are at the PDR-level while communication systems and harnessing are at a lower level of maturity. Without knowing the details of each system, it is not possible to fully understand project maturity classifications, but they appear to be reasonable. The recommended AIAA S-120A [ref. 2] mass growth allowances are added to the estimated masses to obtain best- and worst-case mass predictions.

An avionics architecture diagram was not provided as part of the review materials but from discussion it was stated that they considered fault-tolerance and redundancy in their estimate. The MEL seems to support this claim at some level with (e.g., 3x computers, 3x network switches). For communications, redundancy is less clear, but communications may not be considered a critical system that could lead to loss of mission or crew.

In general, the lack of an architecture diagram does add some uncertainty in understanding MEL line items (avionics boxes, computers, switches, transceivers, etc.). For example, a mass of 3 kg for a computer and 12.5 kg for an avionics box is in the documentation provided. The box mass seems reasonable but the assumptions about the computer mass contain uncertainty.

Despite the uncertainties discussed, the Avionics MEL line items are in line with SME expectations, and the overall estimate seemed reasonable for the concept being reviewed (251.4 kg (electronics) plus 136 kg (harness)) plus the MGAs (15% to 100%, respectively) that is applied at this early stage.

With respect to a different concept, there were uncertainties about lighting and display architecture, but in general, they were considered a small impact to overall mass and were deemed to remain in the range specified in S-120A.

3.3 Primary Structure

The MEL of one concept shows a design maturity code of A5 for the hatches, suggesting this is existing hardware. This code would be appropriate if the architecture included part numbers of previously flown hatch assemblies. If this design is merely based on other hatches, or if there are prototypes of hatches being used, then the maturity code would be lower (approximately C3). This would add to the needed MGA for hatches.

A key consideration in the primary structure approach is whether and how the rover can land and perform a 14-day mission without resupply. Often, in rover design, parts of the rover extend beyond the payload adaptor; this will lead to cantilevered loads on the vehicle during launch. In numerous cases, the approach references the launch vehicle payload manual, but it is not clear if a preliminary launch loads analysis has always been done. The potential exists for significant mass increases if not already provided for in other estimates. As mentioned previously, requirements for habitable volume, headroom, and storage may drive significant mass growth with respect to primary structure, as well.

3.3.1 Solar Array

In one innovative concept the solar array system is dual-use; as a radiator to assist with both thermal control and power generation. However, since the solar array energy collection is not required for the standard day power balance, this hardware category is rated “N/A” in this study. On the other hand, in a different concept, the solar array amounts to less than 3% of the power generation unit total mass, so it is a negligible contributor to overall mass, as well. The NESC assessment team estimate was 45% higher than that provided, including contingency.

3.3.2 Battery

The battery energy density on one of the concepts was overly optimistic based on knowledge of the current state of the technology. The provided mass estimate was 23% lower than the NESC assessment team determined with contingency. A short summary of lessons learned with respect to battery and power systems is shown in Table 3.

Table 3. Battery Systems Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
Battery Safety	Address planned design controls/ technical standard to be used to mitigate battery safety hazards: fire/explosion, chemical exposure, electrical shock, and touch temperature, thermal runaway propagation, cell shorts, overcharge/over discharge, electrical shock, arc-flash, loss of power to critical safety systems, extreme temperature.	Develop and document battery safety requirements and design practice to be implemented for battery safety. NASA has a battery safety technical standard for human spaceflight, JSC 20793.
Battery Lithium Ion Mass Estimate	Battery mass table is optimistic when compared to known GS YUASA cell parameters and NASA experience with battery designs (Goddard Space Flight Center (GSFC) experience, unmanned science – human spaceflight (HSF) battery safe designs may be higher due to passively propagation resistant (PPR) design). There is some risk that the mass requirements may be higher than assumed at this phase of design. Battery package energy density is also optimistic, NASA experience is that battery energy density equates to roughly 0.5 of the cell energy density, due to harnessing and housing, etc. So, for an LSE190 battery we would estimate the full-up battery to be 0.5*165 Whrs.kg; 82 Whrs/kg vs 116 Whrs/kg estimated in table.	Develop and document basis for proposed mass solutions. We have found that the battery level energy density is reduced by structure and harness mass, so we have seen a sizeable drop from a cell energy density (Whrs/kg) to battery level. Batteries designed for HSF will have some accommodation to prevent hazards associated with known lithium-ion battery chemistry, some of which may impact the structural design like failure propagation resistance and venting.

3.3.3 Thermal Control

If radiator property degradation, largely due to lunar dust accumulation, is not considered, it could result in additional heat input and reduced heat rejection. This might result in the need for increased radiator area to meet heat rejection requirements. No historical data are available for mass growth allowance for a hybrid system such as the dual-use concept, and it was difficult to fully quantify mass growth. On analysis of performance with respect to environmental factors, the analysis would need to be reviewed to assess the conservatism in the results and the impact on mass growth and was not provided.

If articulation is required to maintain heat rejection and power generation needs but are not accounted for in the mass, it could add additional mass to the system to appropriately stiffen the hardware. Articulation hardware would need to be added which would add mass.

Thermal control of the windows, if not already accounted for, may add heater mass and associated wiring but probably not enough to push it out of AIAA standard predictions. If more than a single string of heaters is required, this could add mass, but it is unclear how much.

Another concept under assessment had several potential thermally related mass impacts identified with respect to thermal control. However, insufficient information was presented in the design summary to determine the magnitude of the impacts for either concept. Additional information is required before a determination can be made. The high-level thermal control best practices are listed in Table 4.

Table 4. Thermal Control Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
NASA Thermal Guidance	NASA recently published guidance on lunar thermal analysis.	It would be appropriate to cross check the assumptions against those in the NASA document: Human Landing System Thermal Analysis Guidebook, HLS-UG-001, Baseline Release, January 4, 2021, [ref. 3] available from: HLS-UG-001 Lunar Thermal Analysis Guidebook Baseline_STI.pdf (nasa.gov)
Solar Array Dust Effects	Dust effects on solar array performance degradation were apparently not considered.	Dust mitigation and dust effects on rover mechanisms and surfaces such as solar arrays should be addressed early in design.
Environmental Control and Life Support Systems (ECLSS)/Thermal Control System (TCS) Loss Contingency Scenario	This contingency operation scenario covers loss of ECLSS or TCS. One of the steps in the response is “Ground crew will remotely operate and drive the HMP to a designated site for keep alive.” However, if any components required to operate the human mobility platform (HMP) remotely require thermal control (batteries, comms, etc.), this may not be possible unless the system is designed to survive and operate for a specified period without thermal control.	Perform detailed integrated systems analysis and develop ConOps to address the contingency scenario of loss of ECLSS or TCS.

3.3.4 Mechanisms

The aft station of some rover concepts requires that the vehicle be able to move while the crew is outside, and accidental movement of the vehicle could endanger the crew. Having the drive system energized and capable of moving the vehicle while crew is outside introduces several new failure modes and risks. The crew must also have stations or seats on the outside that will allow them to safely operate the vehicle adding mass. This mass was not specifically identified. The articulating parts of a rover design will need to be locked in place during launch to prevent damage or excessive motion. Locking mechanisms are not discussed but should be included. These would provide a modest mass increase per locking mechanism if not already included. In addition, lifting/deployment mechanisms will be required for both suit port “porch” and experiment deployment/relocation. Mechanisms best practices arising from this assessment are listed in Table 5.

Table 5. Mechanisms Best Practices/Lessons Learned

Subject	**Observation**	**Best Practices/Lessons Learned**
Articulating Components	The articulating parts of a rover design will need to be locked in place during launch to prevent damage or excessive motion. Locking mechanisms are not discussed but should be included.	Locking mechanisms are not discussed but should be included. These would provide a modest mass increase per locking mechanism if not already included.
Lifting/Deployment Mechanisms	In addition, lifting/deployment mechanisms will be required for both suit port "porch" and experiment deployment/relocation.	Lifting/deployment mechanisms are required and present increased mass concerns for moving equipment and experiments on the lunar surface.

3.3.5 Suspension and Drive Train

The double-wheel/smaller-diameter design mechanism in one of the designs departs from rover experience and adds the complexity of a differential within the double-wheel assembly. Using a wheel design more like other previous rovers would reduce this complexity and would be more mass effective. Reviewers noted that the double-wheeled concept was likely over-capable (designed to perform in 1-g versus 1/6th-g lunar gravity) when compared to forthcoming trafficability requirements. The team noted significantly deficient MGA was applied to the mobility system basic mass. To assess the combined affect, reviewers rudimentarily modified the designer's MEL to essentially model a reduction to four mobility modules, then modified the MGA to 50%. The combined effect reflects potentially saving 50 kg or more when this mobility system is re-designed for flight, and neglects additional potential savings associated with reduced wheel count per mobility module and reduced dynamic loads. In general, this system was likely to get lighter when designed for flight.

For another rover concept the major mass increase threats identified were related to torque production and power dissipation to achieve the desired speed, though the team also identified a potentially significant mass reduction with respect to baselining a more traditional epicyclic (planetary) gearbox. Achieving the required design life has yet to be demonstrated for gearing and motors in this environment. Furthermore, JPL experience would indicate much higher MGA values are needed for immature, complex systems such as the pressurized rover, particularly when considering the immaturity of vehicle trafficability requirements and the concept of operations definition, to which mass will be highly sensitive. Table 6 outlines a short list of best practices and lessons learned with respect to suspension and drive systems. In concert, these observations point to our recommendation of MGAs more than the standard range identified in S-120A [ref. 2]. Note that there is significant overlap between these comments and the mechanisms category.

Table 6. Suspension and Drive Train Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
Drivetrain	Drivetrain reduction gearbox appears to be a 54:1 pressurized-oil-lubricated multi-stage spur gear reduction unit. Conventional aerospace design uses grease-lubricated planetary reduction gearboxes which feature small mass and volume.	• Consider a 3-stage grease-lubricated planetary reduction gearbox for high cycle application. • Consider a harmonic drive for low cycle robotic applications.

Driving	The drive ranges estimates appear high relative to experience, reflecting 16 to 20 km per day, with the low end being uncrewed/autonomous/remotely operated. That would be a tall order based on JPL’s current Mars autonomy experience even though pressurized rover will have high communication cadence compared to Mars, and demands a much higher drive rate than a lunar roving vehicle (LRV) was able to cover, in likely more difficult terrain.	Adjust drive range estimates based on lessons learned from JPL’s current Mars autonomous activities.
Drive locking hub	The locking hub feature is in the event of a drive actuator fault case to preserve trafficability, but what about in the event of a failed steer actuator? A steered wheel plowing into the regolith would almost certainly prevent forward motion, particularly if this happened to the front of the vehicle which has leading arms instead of trailing arms.	Drivability and trafficability details should be integrated to address all possible faults as well as their fault responses.
Rolling Resistance Requirement	This requirement is likely achievable given available state of art but would require a high-performance wheel design. These types of wheels may not be desirable as there are downsides and trades to consider.	Recommend understanding trade of need for low rolling resistance versus wheel design and system impacts.
Terrain Assessment to Define Needs	There was no terrain assessment or reference mission traverse provided. This or alternate approaches are typically needed to define terrain requirements and justify that the design can meet the traverse needs.	Perform terrain assessment including reference traverse at tentative landing/operating site.
Offline (Strategic) Planning	Long distance traverses will require significant resources for Strategic Path Planning and the corresponding terrain assessment. This may become quite arduous for the stated 16 to 20 km per day. Ground mission systems will need to support this.	Assess resources needed to support Strategic Path Planning. Strategic Path Planning would be needed to be in family with current best practices for rover flight operations.
Drive Train Actuation Torque	Wheel drive and steer torque capability may be insufficient in this design.	A rough rule of thumb that applies to four wheel and six-wheel rover platforms that has been empirically verified suggests an actuator torque capability of T = 0.5*mass*gravity*wheel radius. One of the designs was calculated to provide less than half the required torque capability.
Suspension configuration	Leading and trailing suspension arms will see very different loading.	To have similar loading (and mass efficiency) in all suspension modules and to potentially have a more desirable

		configuration (lower loading and better trafficability), consider implementing all suspension arms as trailing.
Tire Mu	The tire target max Mu (traction coefficient) of 0.5 may be difficult to achieve in widely accepted regolith analogs even with very high-performance wheels (LRV or similar new technologies).	Provide justification for stated 0.5 Tire Target Mu or assume a value below 0.35 to 0.4. Also recommend providing assumed regolith properties when listing Mu.

3.3.6 Wire Harnesses

Harness mass for avionics was typically provided in the MEL with MGA. Both mass allocation and associated MGA appear reasonable for this stage for each design. Harness mass is a small percentage of vehicle mass and therefore not a key driver. Harness mass is also estimated, and is about 35% of the total avionics mass, a reasonable estimate for this phase. Harness MGA for the avionics and mobility (chassis) MELs often differ (more conservatism on the Mobility harnessing). Wire harness mass impacts were not addressed in the second rover concept and although wire harnesses were not specifically mentioned in the information given, they will be impacted by changes in thermal control, avionics, and electrical/electronic components. The changes were assessed to be minor and within the standard range outlined in S-120A [ref. 2].

3.3.7 Secondary Structure

There is a possibility of mass impact depending on required end effectors that enable autonomous operation and articulation discussed earlier, possibly rippling into other mass requirements like secondary structure and avionics. Another requirement states that the PR shall have interfaces to accommodate a range of payloads and associated structural, power, data, and fluid connections and that it will provide an interface for power, fluid, and gas transfers with other surface assets—all of which have yet to be identified. The impact on mass is unknown and depends on what interfaces will be required, which is unclear in this requirement.

Added protection for the mechanical devices would be expected to add mass, but it is unknown if they would be necessary. There was insufficient information available to assess secondary structure required to survive launch loads and thus mass could vary significantly from the estimate.

Secondary structure assessed for the second concept determined that despite primary structure predicted to experience significant increases in mass, secondary structure is estimated to be changing mass within standard ranges.

3.4 Instrumentation

The instrumentation category discussed in S-120A [ref. 2] describes hardware whose primary purpose is to sense or measure the operating environment, such as thermocouples, strain gauges, and pressure sensors. The assessment concluded that mass growth will be negligible in this hardware category.

3.4.1 ECLSS, Crew Systems

ECLSS, Crew Equipment, and Tankage were combined in the "ECLSS/Crew Systems" hardware evaluation. Several items were identified as missing from the MELs including toilet/feces collection hardware, urine pretreat hardware, and all tank isolation valves identified on the schematic. Based on waste management hardware from a current NASA program, the added mass for toilet and urine pretreat is approximately 62 kg. Using values for other isolation valves in the system, the total additional mass for tank isolation valves was 6.0 kg. Graphics within the presentation showed redundant tanks, but the MEL in the first concept evaluated included mass for only single tanks across the system. While the review package does not indicate what packaging factor was assumed in sizing the external tankage volumes for EVA, potable, and wastewater, experience would suggest the packaging factors assumed by the designer were too optimistic. Concepts should be refined based on functional designs, which will likely add mass.

Upon reviewing available system schematics, the system is zero fault tolerant. Additional mass for redundant tankage and corresponding lines/components is approximately 113 kg. It was unclear if O_2/N_2 regulators and valves have filters, but this will likely to be required to protect from contamination based on historical experience. Five solenoid valves are shown external to the habitable volume in the schematic (10 if redundancy is assumed). These valves, particularly potable water valves, are at risk of freezing in the lunar environment. This may require design modifications (e.g., heaters) that could increase mass.

Similarly, pressure and temperature sensors outside the pressurized cabin may require environmental protection. CO_2 removal redundancy was not clearly shown. This may require a secondary method which will add more mass. In a related note, the use of amine beds for various forms of contaminant removal such as ambient temperature catalytic oxidizers (ATCOs) are expected to release CO_2 as they oxidize contaminants. A dedicated CO_2 bed may be necessary at the outlet of these beds unless plumbing allows for recirculation to the rapid cycle amine (RCA) beds (not shown schematically in the proposed designs). RCA beds are at risk of off-gassing ammonia. No ammonia filtration is shown to mitigate this risk.

Per the above, known mass that needs to be added to the dry mass MEL totals is approximately 180.9 kg, for an increase of 24.7% above the current estimate for this specific design. Accounting for areas for concern identified above plus unknown mass increases, it is likely that the mass of the final vehicle ECLSS design will exceed the 30% MGA estimate called out in S-120A [ref. 2].

The ECLSS system for another rover concept was significantly different and required assessment from that perspective. Significant anticipated mass growth noted includes water required for EVA thermal water losses and 2-day contingency water (total additional 131 kg), LiOH canisters (up to 73.5 kg, depending on usage and architecture), and medical equipment (up to 15 kg). Moderate to minor mass growth may come from water separation hardware, additional gas consumables in a modified cabin environment, support for potential decompression sickness treatment, additional lighting to support EVA, exercise hardware, and contingency consumables to support an emergency return to the landing site. Known mass increases (for significant contributors) yields approximately 28% mass growth over the initial estimate. Given the additional moderate/minor increases anticipated, it is likely that the total mass increase for ECLSS and crew systems will exceed the current upper limit of 30%. The best practices and lessons learned with respect to ECLSS systems in human space flight highlighted during this assessment are captured in Table 7.

Table 7. Environmental Control and Life Support Systems Best Practices/Lessons Learned

Subject	Observation	Best Practice/Lesson Learned
CO_2 Production	CO_2 level of 3 mmHg is adequate but higher production during light exercise should be considered.	Perform integrated ECLSS systems analysis to address all operational phases, including exercise and quiescence.
Food and Water Allocation	2.5 L/day is appropriate with no EVAs – adding EVAs 3 to 5 times per week requires additional water. Additional Calories will be consumed on days with EVAs (~25% more on EVA days). No hot water, as proposed in one concept, for 30 days is an issue.	Refer to NASA-STD-3001 Volume 2, Rev C [ref. 4].
Human Waste	Human Waste production and disposal management should be considered.	Human waste management systems should be integrated into the habitable volume design.
Medical System	Medical System power/data and mass should be considered.	Mass management should always include ALL medical power, data, and hardware requirements.
Lighting	Lighting – considered/mentioned for the cameras.	Designers should consider modeling and simulation of lighting environments during all phases of operations.
Low level vibration	Low-level vibration during traverse needs to be considered – Vibration Health & Comfort Limits.	Utilize the standards for vibration that were developed for the uncrewed lunar transfer vehicle (LTV).
Pressure/O2 Levels Decompression Sickness (DCS)	Habitable Pressure – HLS is planning at 8.2psia cabin atmospheres with a concentration of 34% O_2. To be compatible with HLS and the habitat of the Rover should be able to match pressures and O_2 concentration to minimize DCS protocols. Higher pressure may be required for DCS treatment.	The design of components of the HLS architecture should include an integrated ConOps.
Lack of Exercise Equipment	Agree that high intensity exercise is not required in the rover, but low-level exercise should be planned. Which would include light exercise/stretching/EVA warm up rehabilitation type activities.	NASA astronaut experience indicates that EVAs are not a substitute for exercise and that some level of exercise capability should be provided.

3.4.2 Human Systems Integration/Human Factors

As with all crewed spaceflight activities, the PR is expected to be responsive to human factors requirements (e.g., cabin height, visibility, panels, and controls compatibility). The impacts on both designs and the resultant mass could be significant with one identified best practice presented in Table 8.

Table 8. Human Systems Integration/Human Factors Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
Automation	Human Interface for automated driving	Utilize the standards for automation that were developed for the LTV.

3.5 Radiation/Solar Particle Protection

The NESC assessment team evaluated a minimal amount of information related to radiation and solar particle event (SPE) protection. One design concept has a frozen water heatsink/radiator on the roof, which is horizonal when stowed. In addition to its primary role of power and heat dissipation, it provides additional SPE protection. Water tanks cover only the front half of each side in this proposed design. The skin of the pressure vessel, in this case, was aluminum with a honeycomb-style grid for support, which would not provide adequate protection. There is additional radiation protection from any mass between the crew and the Sun because some fraction of the isotropic SPE particle flux will be blocked. However, the SPE flux cannot be treated as "line of sight" to the Sun and charged particles during an SPE will appear to arrive from anywhere not blocked by the Moon. From the perspective of isotropic SPE particle flux, significant regions of the rover would not be protected by the frozen water radiator or water tanks, which may have varying liquid levels. Additional installed masses will provide radiation protection. However, a significant portion of the stored items and secondary structure is in the lower part of the rover and already largely shielded by the Moon. There is potential for unprotected regions inside the rover. Radiation protection has the potential to increase the mass of this design to a greater extent than a solid aluminum design, which may reduce overall mass based strictly on radiation protection. Adding additional shielding or establishing a safe-haven zone would have a mass impact.

A different design approach relies on an aluminum rover skin of 0.5-inch aluminum for primary structure and radiation shielding from SPE. Since this structure, based on information at the time of the initial review, has no windows and is completely enclosed, in theory it provides radiation protection in all directions. Regarding the 0.5-inch aluminum shielding, the designers estimated the SPE dose to blood-forming organs (BFOs) as 249.6 milli-gray-equivalent (mGy-Eq) for 12-mm aluminum (0.47-inch). NASA has a requirement to keep the 30-day dose limit to BFOs to ≤250 mGy-Eq, so the ~0.5-inch aluminum shielding approach would meet this requirement. All design approaches should consider shielding materials for all angles that do not intersect the lunar surface (i.e., the entire sky). Two significant lessons learned are documented in Table 9.

Table 9. Radiation/Solar Particle Protection Best Practices/Lessons Learned

Subject	**Observation**	**Best Practice/Lesson Learned**
Shielding	Radiation Protection – integrated shielding not needed for 30-day mission. Ability to reconfigure storable items should suffice.	Use Recommendations in NASA-STD-3001 Volume 1, Rev B [ref. 5].
Shielding	Initial designs often do not account for the fact that radiation and particle impact could arrive from a myriad of directions.	All design approaches should consider shielding materials for all angles that do not intersect the lunar surface.

4.0 Summary and Conclusions

One rover designer team approach used a unique process to address estimating mass. The approach incorporates design maturity, TRL, and low and high MGAs that are tied to design maturity at the subsystem or component level. The NESC assessment team reviewed that table, along with the provided documentation and information from a question-and-answer session and developed the tailored MGA table shown in Table 10.

Table 10. Color-Coded MGA Qualitative Assessment Summary – First Rover Concept

Major Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)												
			Electrical/Electronic Components			Primary Structure	Battery	Solar Array	Thermal Control	Mechanism	Suspension & Drivetrain	Wire Harness	Secondary Structure	Instrumentation	ECLSS, Crew System
			0-5 kg	5-15kg	>15kg										
			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟥
Concept 1 MEL often identified more than one level of maturity, at the system/subsystem level, within a hardware category. The review team selected a numerical MGA range from the S120A standard and assessed using expertise/experience/best judgement															

🟥 Exceeds Std Range

🟨 Unknown/Within Std Range

🟩 Estimated Lower Than Std Range

With respect to the provided material for this first concept that the NESC assessment team reviewed, we identified uncertainty in mass estimates:

1. Significant risk of mass growth (i.e., above S-120A [ref. 2] recommended range) exists in the ECLSS hardware category.
2. Minimal uncertainty and within-range mass growth (i.e., within S-120A [ref. 2] recommended range) are estimated for electrical/electronic components, thermal control, wire harness, battery, solar array, suspension and drive train, mechanism, primary and secondary structure categories.
3. Limited confidence exists for minimal (i.e., below S-120A [ref. 2] recommended range) mass growth in the instrumentation category.

The overall assessment of this rover concept indicated good progress and a sound preliminary MEL. There is a risk of high mass growth in ECLSS, significant uncertainty at this stage of design, and opportunities for improved design and possible MGA decreases exist.

It was clear to the review team that the next concept proposed is in the early stages of definition and design. Numerous questions from the NESC assessment team were unanswered, or the information was unavailable. The lack of detailed information provided prevented a more quantitative in-depth review. Some of the design approaches did not follow current best practices for rover system development. Most critically, the second concept material lacked an in-depth MEL or any basis of estimate information and lacked mass details by hardware category to the subsystem and component levels.

This concept was larger in mass and volume and may reflect the desire to exceed the proposed lunar night survival duration. The crew cabin height appears to be derived from an assumed need for vertical donning and doffing of EVA suits. If the assumption of vertical donning/doffing of EVA suits becomes a requirement, the first concept the team reviewed may require revision with a likely increased mass. Environments inputs, optical property degradation, and other analysis assumptions should be developed and provided to any team designing and developing a pressurized, crewed, lunar rover. A thermal analysis review is required before a complete assessment can be made. Data on assumed degraded optical properties are required in conjunction with analysis to determine lifespan under those conditions.

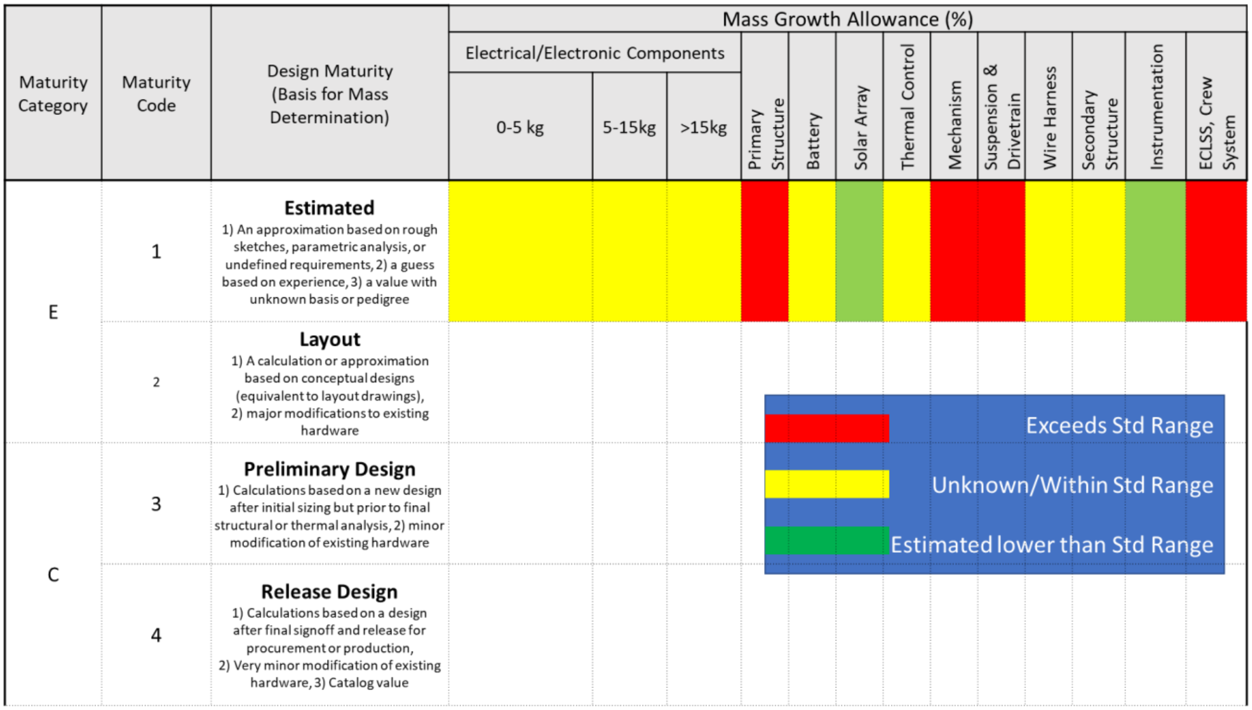
Based on the information provided, the proposed designs generally appear to meet structural requirements. However, none of the concepts reviewed provided information addressing launch loads and it is unknown whether the concept meets the requirement to survive launch conditions. An overarching finding in this assessment is that individual or cumulative mass increases could result in rover volume updates, and volume changes will impact mass. For the thermal subsystem, while the concepts seem reasonable, not enough information was presented to conclude that the design meets the requirements as they stand currently. From an ECLSS perspective, the second general design appears to meet the intent of requirements. However, some areas need to be addressed, such as a larger mass than concepts assume for ECLSS-related functions. Additionally, the second design does not yet meet requirements in areas such as two-fault-tolerance for catastrophic failures.

Without a consistently accepted modeling language for describing the design architecture, there is no fidelity to make estimates, understand nuance, and capture misses. For example, in one approach, avionics included computing systems, networking, data storage, displays and controls, instrumentation, lighting systems, audio and video systems, communication systems, and associated harnessing whereas in another, harnessing and lighting systems were unclear.

The second concept provides greater radiation protection, but design changes could produce a more mass-efficient structure. Designs could take advantage of the moon shadow to reduce thickness in the Moon-facing rover areas and consider using a combination of primary pressure vessel structure, lighter radiation absorptive materials, and distribution of other equipment.

The overarching mass growth posture for the second concept is captured in Table 11.

Table 11. Color-Coded MGA Qualitative Assessment Summary – Second Rover Concept



Maturity Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)												
			Electrical/Electronic Components			Primary Structure	Battery	Solar Array	Thermal Control	Mechanism	Suspension & Drivetrain	Wire Harness	Secondary Structure	Instrumentation	ECLSS, Crew System
			0-5 kg	5-15kg	>15kg										
E	1	**Estimated** 1) An approximation based on rough sketches, parametric analysis, or undefined requirements, 2) a guess based on experience, 3) a value with unknown basis or pedigree	🟨	🟨	🟨	🟥	🟨	🟩	🟨	🟥	🟥	🟨	🟨	🟩	🟥
	2	**Layout** 1) A calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) major modifications to existing hardware													
C	3	**Preliminary Design** 1) Calculations based on a new design after initial sizing but prior to final structural or thermal analysis, 2) minor modification of existing hardware													
	4	**Release Design** 1) Calculations based on a design after final signoff and release for procurement or production, 2) Very minor modification of existing hardware, 3) Catalog value													

🟥 Exceeds Std Range

🟨 Unknown/Within Std Range

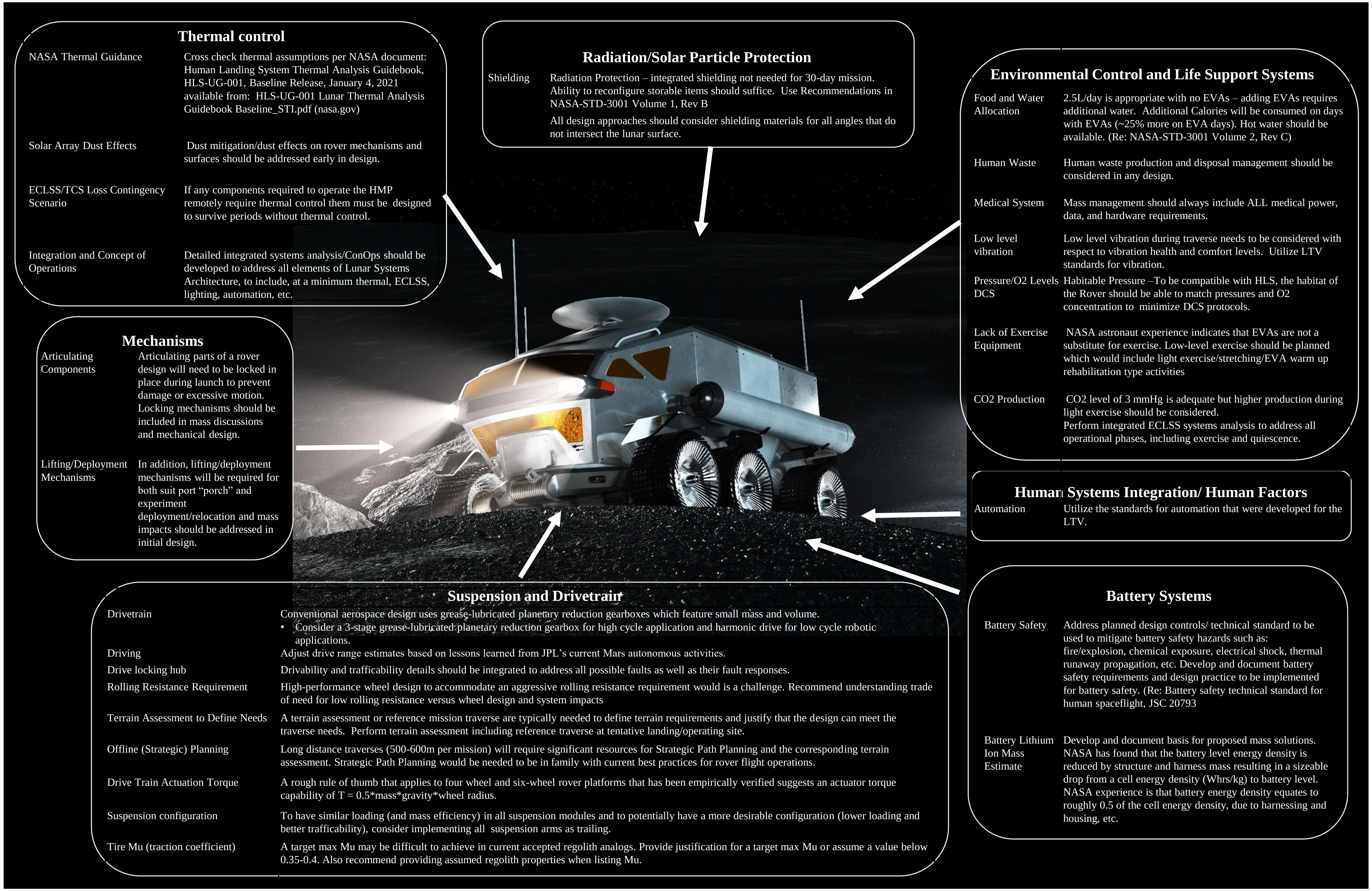
🟩 Estimated lower than Std Range

Following a review of available data, the NESC assessment team reached the following conclusions with respect to the second concept.

1. Significant risk (i.e., above S-120A [ref. 2] recommended range) exists for mass growth in the areas of primary structure, mechanisms, suspension and drive train, and ECLSS/crew systems.
2. Minimal uncertainty and within-range (i.e., within S-120A [ref. 2] range) mass growth is estimated for electrical/electronic components, battery, thermal control, wire harness, and secondary structure categories.
3. Limited confidence (i.e., less than S-120A [ref. 2] range) exists that solar array and instrumentation mass growth are acceptable.

Overall, the NESC assessment team's review of the second rover concept, summarized in the tailored MGA, indicates significant uncertainty and high risk of mass growth over the design process.

The lessons learned and best practices are depicted graphically in Figure 4.



Thermal control

NASA Thermal Guidance	Cross check thermal assumptions per NASA document: Human Landing System Thermal Analysis Guidebook, HLS-UG-001, Baseline Release, January 4, 2021 available from: HLS-UG-001 Lunar Thermal Analysis Guidebook Baseline_STI.pdf (nasa.gov)
Solar Array Dust Effects	Dust mitigation/dust effects on rover mechanisms and surfaces should be addressed early in design.
ECLSS/TCS Loss Contingency Scenario	If any components required to operate the HMP remotely require thermal control them must be designed to survive periods without thermal control.
Integration and Concept of Operations	Detailed integrated systems analysis/ConOps should be developed to address all elements of Lunar Systems Architecture, to include, at a minimum thermal, ECLSS, lighting, automation, etc.

Radiation/Solar Particle Protection

Shielding	Radiation Protection – integrated shielding not needed for 30-day mission. Ability to reconfigure storable items should suffice. Use Recommendations in NASA-STD-3001 Volume 1, Rev B All design approaches should consider shielding materials for all angles that do not intersect the lunar surface.

Environmental Control and Life Support Systems

Food and Water Allocation	2.5L/day is appropriate with no EVAs – adding EVAs requires additional water. Additional Calories will be consumed on days with EVAs (~25% more on EVA days). Hot water should be available. (Re: NASA-STD-3001 Volume 2, Rev C)
Human Waste	Human waste production and disposal management should be considered in any design.
Medical System	Mass management should always include ALL medical power, data, and hardware requirements.
Low level vibration	Low level vibration during traverse needs to be considered with respect to vibration health and comfort levels. Utilize LTV standards for vibration.
Pressure/O2 Levels DCS	Habitable Pressure –To be compatible with HLS, the habitat of the Rover should be able to match pressures and O2 concentration to minimize DCS protocols.
Lack of Exercise Equipment	NASA astronaut experience indicates that EVAs are not a substitute for exercise. Low-level exercise should be planned which would include light exercise/stretching/EVA warm up rehabilitation type activities
CO2 Production	CO2 level of 3 mmHg is adequate but higher production during light exercise should be considered. Perform integrated ECLSS systems analysis to address all operational phases, including exercise and quiescence.

Mechanisms

Articulating Components	Articulating parts of a rover design will need to be locked in place during launch to prevent damage or excessive motion. Locking mechanisms should be included in mass discussions and mechanical design.
Lifting/Deployment Mechanisms	In addition, lifting/deployment mechanisms will be required for both suit port "porch" and experiment deployment/relocation and mass impacts should be addressed in initial design.

Human Systems Integration/ Human Factors

Automation	Utilize the standards for automation that were developed for the LTV.

Suspension and Drivetrain

Drivetrain	Conventional aerospace design uses grease-lubricated planetary reduction gearboxes which feature small mass and volume. • Consider a 3-stage grease-lubricated planetary reduction gearbox for high cycle application and harmonic drive for low cycle robotic applications.
Driving	Adjust drive range estimates based on lessons learned from JPL's current Mars autonomous activities.
Drive locking hub	Drivability and trafficability details should be integrated to address all possible faults as well as their fault responses.
Rolling Resistance Requirement	High-performance wheel design to accommodate an aggressive rolling resistance requirement would is a challenge. Recommend understanding trade of need for low rolling resistance versus wheel design and system impacts
Terrain Assessment to Define Needs	A terrain assessment or reference mission traverse are typically needed to define terrain requirements and justify that the design can meet the traverse needs. Perform terrain assessment including reference traverse at tentative landing/operating site.
Offline (Strategic) Planning	Long distance traverses (500-600m per mission) will require significant resources for Strategic Path Planning and the corresponding terrain assessment. Strategic Path Planning would be needed to be in family with current best practices for rover flight operations.
Drive Train Actuation Torque	A rough rule of thumb that applies to four wheel and six-wheel rover platforms that has been empirically verified suggests an actuator torque capability of T = 0.5*mass*gravity*wheel radius.
Suspension configuration	To have similar loading (and mass efficiency) in all suspension modules and to potentially have a more desirable configuration (lower loading and better trafficability), consider implementing all suspension arms as trailing.
Tire Mu (traction coefficient)	A target max Mu may be difficult to achieve in current accepted regolith analogs. Provide justification for a target max Mu or assume a value below 0.35-0.4. Also recommend providing assumed regolith properties when listing Mu.

Battery Systems

Battery Safety	Address planned design controls/ technical standard to be used to mitigate battery safety hazards such as: fire/explosion, chemical exposure, electrical shock, thermal runaway propagation, etc. Develop and document battery safety requirements and design practice to be implemented for battery safety. (Re: Battery safety technical standard for human spaceflight, JSC 20793
Battery Lithium Ion Mass Estimate	Develop and document basis for proposed mass solutions. NASA has found that the battery level energy density is reduced by structure and harness mass resulting in a sizeable drop from a cell energy density (Whrs/kg) to battery level. NASA experience is that battery energy density equates to roughly 0.5 of the cell energy density, due to harnessing and housing, etc.

Figure 4. Significant Best Practices/Lessons Learned

5.0 References

1. *Moon to Mars Architecture Definition Document* (ESDMD-001), NASA/TP-20230017458, – Revision B
2. ANSI/AIAA Standard S-120A, “Mass Properties Control for Space Systems,” 2019. https://doi.org/10.2514/4.103858.001
3. “Human Landing System Thermal Analysis Guidebook,” HLS-UG-001, January 4, 2021.
4. NASA-STD-3001 Volume 2, Rev C, “NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health,” April 2022.
5. NASA-STD-3001 Volume 1, Rev B, “NASA Space Flight Human-System Standard: Volume 1: Crew Health,” January 2022.
6. International Society of Allied Weight Engineers (SAWE) RP A-3, “Recommended Practice for Mass Properties Control for Space Systems,” January 26, 2016.

Appendix A. Suggested Lesson-Learned for External Application

One final observation of the NESC lunar rover review team was that ANSI/AIAA Standard S-120A-2015_R2019 [ref. 2], Mass Properties Control for Space Systems, should be applied in context. S-120A and the International Society of Allied Weight Engineers (SAWE) RP A-3, Recommended Practice for Mass Properties Control for Space Systems [ref. 6], define the terminology and document common processes and approaches for managing mass of space systems. The lesson learned through the efforts of the NESC Pressurized Rover Red Team Assessment is that the standard has been developed and applies to space vehicles, upper stages, payloads, reentry vehicles, launch vehicles and ballistic vehicles. It does not specifically address space systems (e.g., rovers) that are operational on other surfaces, and it may not address hardware categories that those systems may employ (e.g., suspension and drive train assemblies). The overarching purpose of the NESC PR Red Team was to evaluate and assess the mass management activities of lunar rover design providers, assess the MGAs provided by the concept developers, and apply system and subsystem expertise to the proposed approaches, with an eye toward expected mass impacts of those design approaches. The team set out to use the S-120A MGA table [ref. 2] and soon found gaps in the hardware categories. For instance, although the standard's table cites "mechanisms" as a hardware category, and there are mechanisms on the rover, there is no reference information for the suspension and drive train required for a roving vehicle and these suspension and drive train designs have their own sets of design maturity and requirements, depending on the surface characteristics, trafficability, and concepts of operations.

In the early stages of the PR mass management assessment process the team learned that, although the S-120A MGA standard table provided a variety of ranges in a variety of typical space system hardware categories, it was important to use them only as a framework. The team developed additional hardware categories to address the suspension and drivetrain of a rover space system and used the "mechanisms" hardware category as a starting point. The application of system-specific experience required the development of different categories and adjusted approaches for this specific space system application and the development of a tailored MGA table that considered different hardware categories or systems from the typical designs for which S-120A is applied.

The team recommended that space system developers utilize the framework, concepts, and approaches outlined in S-120A and the recommended practices of SAWE RP A-3 as a guide, but tailor the MGA table for each system's specific ConOps and design.