POLITECNICO DI TORINO

Master's Degree in Management Engineering

MASTER's Degree Thesis

Project Management Methodologies Applied to a Pressurized Lunar Rover

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Abstract

This thesis explores the application of project management methodologies to the planning and assessment of Pressurized Lunar Rover (PLR) missions, employing structured tools to analyze risks, costs, and quality, and to compare alternative mission profiles. With the growing importance of the space economy and the increasing participation of commercial actors, cost-efficiency, risk management, and mission reliability are vital to the success of lunar operations. The work presents two mission profiles: a Semi-Stationary Rover designed for localized scientific exploration, and a Transport Rover aimed at long-range mobility and surface logistics. For each, a structured project plan is developed using the PMBOK framework and tools such as Microsoft Project, incorporating Work Breakdown Structures (WBS), Gantt charts, and the Critical Path Method (CPM). Risk analysis is performed through a custom Risk Breakdown Structure (RBS), followed by mitigation planning and a Failure Modes, Effects, and Criticality Analysis (FMECA) for quality assurance. Cost estimation and resource planning are included to evaluate the financial viability of both mission profiles. The results highlight the trade-offs between complexity, autonomy, and cost, offering a comparative foundation for strategic decision-making in future lunar rover programs.

Acknowledgements

"Advancing lunar exploration means
advancing the frontier of human possibility;
this thesis seeks to be part of that effort"

Table of Contents

List of Tables

List of Figures

Acronyms

LRV
Lunar Roving Vehicle

PM
Project Management

PMBOK
Project Management Body of Knowledge

FMECA
Failure Modes, Effects, and Criticality Analysis

SPR
Small Pressurized Rover

EVAs
Extravehicular activities

ECLSS
Environmental Control and Life Support Systems

PLR
Pressurized Lunar Rover

LSS
Life Support System

ARM
Air Revitalization Module

WMM
: Water Management Module

FPM
: Food Provision Module

WDM
: Waste Disposal Module

CHM
: Crew Health Module

TCS
: Thermal Control System

VOCs
: Volatile Organic Compounds

DIPS
: Dynamic Isotope Power System

CBC
: Closed Brayton Cycle

HSUs
: Plutonium-powered Heat Source

M2M
: Moon to Mars

EGS
: Exploration Ground System

EMU
: Energy Management Unit

PMI
: Project Management Institute

CPM

Critical Path Method

WBS

Work Breakdown Structure

RBS

Risk Breakdown Structure

SPEs

solar particle events

GCRs

galactic cosmic rays

SSPR

Semi-Stationary Pressurized Rover

TPR

Transport Pressurized Rover

LIDAR

Light Detection and Ranging

IMUs

inertial measurement units

PCMs

Phase-change materials

FEA

Finite Element Analysis

NDT

non-destructive testing

Chapter 1
Introduction

1.1 Space Economy

The Space Economy is rapidly emerging as an innovative sector that is reshaping not only the way we approach space exploration but also the commercial point of view within the space industry.
Historically dominated by government agencies like NASA, space exploration has evolved into a competitive and innovative area. Companies such as SpaceX, Blue Origin, and Lunar Outpost now play an increasingly crucial role in pushing the boundaries of space technology. With this shift, there is a new emphasis on the economic feasibility and sustainability of space missions, with a continued technological innovation. This shift highlights a fundamental aspect: space exploration is no longer only about advancing human knowledge, but also about creating viable commercial opportunities.
In recent years, significant initiatives in commercial lunar missions and the expansion of autonomous exploration capabilities have opened new paths for private sector participation in space exploration. Although lunar missions have historically been led by government entities, commercial organizations are increasingly playing an important role in the exploration of the Moon. These efforts aim not only to explore, but also to lay the groundwork for the development of a commercial lunar economy. Rovers, such as the pressurized lunar rover, have evolved from simple tools for scientific exploration into essential vehicles that will help create sustainable infrastructure on the Moon.
With growing interest in lunar resource extraction, these projects are set to serve as the foundation for an economy extending beyond Earth's orbit, beginning with the Moon as a launchpad for Mars exploration and beyond.

1.2 Cost Efficiency and the FY 2025 Budget

At the heart of these efforts is a significant focus on cost efficiency, which has become a determining factor in modern space exploration. The FY 2025 Budget Request Summary from NASA [1] reflects this new priority. For fiscal year 2025, NASA has allocated $7.618 billion to the Deep Space Exploration Systems account, directly supporting the Moon to Mars (M2M) Program. This program focuses on returning humans to the Moon, conducting pioneering research, and enabling future missions to Mars.
The program covers several critical initiatives, including the development of lunar systems and transportation infrastructure essential for supporting human missions to the Moon and Mars. Particularly significant is the M2M Lunar Systems Development, which is focused on developing the systems required to land humans on the lunar surface and establish the infrastructure necessary for resource exploration.
Looking into the future, missions like Artemis will continue to push the boundaries of lunar exploration. The Artemis II mission, slated for launch in April 2026, will prepare the way for human landings, with subsequent missions such as Artemis III in 2027 and Artemis IV in 2028 aimed at establishing a permanent human presence on the Moon.
These missions will largely depend on Exploration Ground Systems (EGS) and the Orion crew vehicle to ensure safety and operational success.

1.3 Cost Estimation and Optimization for Pressurized Lunar Rovers

Cost estimation for Pressurized Lunar Rovers (PLR) is an essential component of mission planning. These estimations help determine the financial viability of lunar exploration projects, especially as they involve complex, innovative technologies and long-duration missions. The task of estimating the costs for space missions, particularly for systems as intricate as a PLR, is burdened with challenges due to the high degree of uncertainty, the lack of historical data, and the need for future-focused designs. The intricacy of the mission parameters, such as mobility, life support, power systems, and crew safety, increases the unpredictability of cost projections.
Two methods are employed to estimate space mission costs:

- Bottom-up approach: assessing material, labor, and production costs for each system component, is used when substantial design details are available.
- Analogy-based estimation: the costs of similar past missions are scaled to reflect the size and complexity of the current mission.

Trivailo et al. (2012) [2] offer a comprehensive review of these methods, discussing how parametric and analogy-based techniques are particularly useful in the early phases of mission planning when design details are still vague. They highlight that for space missions like PLR, estimating costs early is crucial for budgeting, as it sets constraints that guide the design process to stay within financial limits. They also point out that uncertainties in cost estimation are intensified in missions involving such technologies as those used in PLRs, where risk factors and technological development can significantly change cost projections.

1.4 Lunar Rovers and the Evolution of Planetary Exploration

The historical evolution of these Lunar Roving Vehicles (LRV) is marked by innovations in mobility systems, energy sources, and autonomous navigation, all of which are critical for the design of future lunar pressurized rovers. As detailed in recent studies [3], the first rovers were constrained by technological limitations, focusing primarily on simple tasks such as sample collection and surface exploration. Over time, rovers have improved to include more sophisticated systems, such as enhanced autonomous navigation and scientific payloads, making them essential tools for planetary science and the establishment of sustainable human presence.
Key technological challenges, such as lunar dust accumulation, extreme temperature variations, and the difficult terrain of the Moon's surface, have driven much of the rover development. These vehicles are now designed not only for scientific research but also to support the broader objectives of lunar resource extraction and the establishment of infrastructure needed for human missions to Mars. Future lunar rovers, particularly the pressurized rovers envisioned for NASA's Artemis program, will be fundamental to lay the base for a commercial lunar economy, offering both scientific and economic benefits.

Table 1.1: Rovers - Basic Configuration

Name	**Institution**	**Size (m^3)**	**Weight (kg)**	**System**
Lunokhod 1	NPO Lavochkin	1.6 × 2.22 × 1.35	756	Differential
Apollo XV	NASA	3.1 × 2.3 × 1.1	210	Ackerman
Apollo XVI/XVII	NASA	3.1 × 2.3 × 1.1	210	Ackerman
Lunokhod 2	NPO Lavochkin	1.7 × 2.15 × 1.35	840	Differential
Sojourner	JPL (NASA)	0.65 × 0.48 × 0.3	11	RB
Spirit/Opportunity	JPL (NASA)	2.3 × 1.6 × 1.5	174	RB
Curiosity	JPL (NASA)	2.9 × 2.7 × 2.2	900	RB
Yutu	CNSA	1.5 × 1.0 × 1.1	136	RB
Polaris	Astrobotic Technology/NASA	1.67 × 2.13 × 2.43	150	Differential

Name	Institution	Size (m^3)	Weight (kg)	System
Chandrayaan-2	ISRO/Roscosmos	0.6 × 0.5 × 0.4	27	RB
ExoMars	ESA/Roscosmos	1.2 × 1.1 × 2.0	219	3B
Mobile MAV	NASA	2.7 × 3.0 × 2.2	1050	RB
MELOS	JAXA	1.2 × 1.0 × 0.5	150	3B

Table 1.2: Rovers - Basic Configuration

Name	Wheels	Speed (cm/s)	Distance (km)	Year
Lunokhod 1	8	55	10.5	1970
Apollo XV	4	330	27.8	1971
Apollo XVI/XVII	4	330	27.1 / 35.74	1972
Lunokhod 2	8	55	37	1973
Sojourner	6	1	0.1	1997
Spirit/Opportunity	6	5	7.7 / 43.44[a]	2004
Curiosity	6	5	14.4[a]	2012
Yutu	6	5.5	0.1 out of 10	2013
Polaris	4	30	0.5 projected	2015
Chandrayaan-2	6	10	150 projected	2017
ExoMars	6	–	–	2018
Mobile MAV	6	TBD	–	2020
MELOS	6	0.75	50	2020

RB = Rocker-Bogie; **3B** = Three-Bogie; **TBD** = To be determined.
[a] = Ongoing

As shown in table 1.1 and 1.2, taken from [3], progress in rover design have significantly improved mobility, autonomy, and power systems, with each new generation of rovers addressing the limitations faced by previous models. These tables highlight the ongoing technological evolution, particularly in the areas of terrain traversal capabilities and energy storage systems.
According to recent studies [4], modularity in rover design will be crucial in meeting the demands of these missions. The paper emphasizes that modular systems will allow for greater flexibility and adaptation, making future vehicles more versatile and cost-effective. Modular components can evolve from unmanned vehicles to pressurized systems. This approach not only maximizes the functionality of the rover but also ensures that it can meet the diverse needs of both short and long-term lunar and Mars exploration missions.

1.5 Technology landscape

1.5.1 Mobility System for the Pressurized Lunar Rover

The mobility system of a Pressurized Lunar Rover (PLR) is one of the most critical components, as it directly affects its ability to operate efficiently on the surface of the Moon. Lunar terrain presents unique obstacles, including uneven ground, rocks, craters, and dust-covered areas, which demand a highly adaptive and reliable mobility system. The primary objective of the mobility system is to ensure that the rover can navigate these obstacles while maintaining stability, maneuverability, and traction, especially given the variable conditions of the lunar surface. The rover's mobility system must also be capable of carrying out long-duration missions, performing scientific experiments, and transporting astronauts and their equipment across large distances.

Six-wheeled configuration

A key feature of the PLR's mobility system is its six-wheeled configuration coupled with a rocker-bogie suspension system. This design has proven effective in previous planetary rovers, including the Lunar Roving Vehicle used during the Apollo missions, and is still an important example in new designs for both lunar and Mars rovers [5], such as the Spirit and Opportunity rovers.
The rocker-bogie suspension system is designed to keep all six wheels in constant contact with the lunar surface, regardless of the terrain's irregularities. This feature is particularly critical for preventing the rover from being stuck, especially in lunar regolith or other challenging terrain, by maintaining consistent traction and reducing the risk of the rover losing its stability. The rocker-bogie suspension also provides better ground clearance, enabling the rover to easily pass over rocks or small craters, ensuring the rover stays in motion.
In the design of the Pressurized Lunar Rover I (PLR I), the suspension system provides an impressive ground clearance. This allows the rover to traverse large obstacles. The suspension system also uses simple pivot joints that allow for up-and-down motion, enabling the rover to adjust independently to terrain variations. The wheels of the PLR I are constructed from a composite flexible plastic matrix, which makes them both lightweight and durable, capable of resisting the harsh effects of lunar dust and the abrasive surface of the Moon. The rover's high-torque brushless motors, integrated in each wheel, allow precise control of the rover's movement, providing the necessary torque to handle difficult terrain.

Maneuverability

In terms of steering, by varying the speed of the wheels on either side of the rover, the system allows it to make sharp turns and navigate narrow paths or limited spaces-such as those found near craters or in narrow lunar valleys.
As the need for enhanced mobility grows, more advanced designs like the PLR II are being developed, which integrate even more sophisticated systems to deal with the unpredictable nature of the lunar environment. The PLR II incorporates dual cylindrical shells, which are connected by an articulated passageway, providing a more flexible and robust design that enhances the rover's operational range. This modular design extends the rover's overall length to 11 meters, significantly improving its versatility and efficiency during long-duration missions.
One of the most innovative features of the PLR II is its dual steering system, which combines Ackermann steering and articulated frame steering 1.1, image taken from [5].

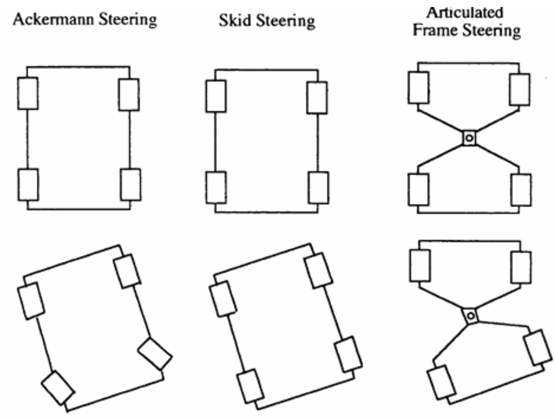


Figure 1.1: Steering system options

The Ackermann steering minimizes tire wear during turns, while the articulated frame steering allows for sharp turns in narrow spaces, such as inside craters or between large rocks. This combination allows the PLR II to achieve a minimum turn radius, improving its ability to maneuver in tight spaces and challenging terrain.
Additionally, the PLR's mobility system includes crabwise motion capabilities, which enable the rover to sidestep obstacles or traverse narrow passages without needing to turn. The rover's system is also designed to scale steps and climb inclines of up to 30 degrees.
These advancements in mobility system designs address critical development challenges outlined in various studies. For example, the implementation of modular systems, like the one used for the PLR II, provides not only enhanced flexibility

but also the potential for scalability, supporting future lunar and Mars missions with varying mission profiles 1.3, table taken from [6]. By designing systems that can evolve across missions, from short-duration to long-duration missions, the next generation of surface exploration vehicles will meet the growing demands of lunar exploration [4].

Table 1.3: Comparison between PLR I and PLR II Main Characteristics

PLR I		PLR II	
Nominal speed	10 km/hr	Nominal speed	10 km/hr
Maximum speed	18 km/hr	Maximum speed	14.7 km/hr
Maximum gradient	35 deg.	Maximum gradient	26.5 deg.
Ground clearance	0.85 m	Ground clearance	0.53 m
Minimum turn radius	7 m	Minimum turn radius	
Range		Neutral steer	8.6 m
at 10 km/hr	1680 km radius	Oversteer	6.6 m
at 18 km/hr	3192 km radius	Range	2000 km
Continuous power	6.5 kW	Continuous power	8 kW
Maximum power	9.5 kW	Maximum power	12 kW
Total mass	6,197 kg	Total mass	7,015 kg

In conclusion, the mobility system of the Pressurized Lunar Rover combines advanced suspension, wheel design, and steering mechanisms, ensuring that the rover can effectively navigate the harsh lunar terrain. Whatever it is, uneven surfaces, steep slopes, or rocky craters, the rover's mobility system provides the necessary stability, maneuverability, and traction for successful lunar missions. These systems are essential for extended lunar exploration, allowing the rover to support scientific research, resource exploration, and human exploration activities on the Moon, making it a key component of the Artemis program and future lunar missions [4].

1.5.2 Power System for the Pressurized Lunar Rover

The power system for the Pressurized Lunar Rover (PLR) is designed to ensure the rover's operational capability during long-duration lunar missions. It is a critical component for sustaining the rover's mobility, life-support systems, and scientific equipment. The lunar environment presents unique challenges, including long lunar nights, extreme temperatures, and dust accumulation, which require a carefully engineered power system capable of providing consistent energy under these harsh conditions. As detailed in recent studies, these challenges have driven the adoption of advanced power generation and storage systems that must balance energy efficiency, system reliability, and mission longevity, all of which are critical for ensuring that lunar rovers can perform effectively in unpredictable lunar environments [4].

Dynamic Isotope Power System (DIPS)

At the heart of the PLR's power system is the Dynamic Isotope Power System (DIPS), which utilizes Plutonium-238 as the heat source for a closed Brayton cycle (CBC) to generate electricity. This system will generate 8 kW of continuous power, essential for supporting the rover's core systems, such as life support, mobility, and communication. The DIPS offers several advantages, including a long operational life and the ability to function effectively during the lunar night when solar power is unavailable. The use of a Brayton cycle allows for a compact, efficient design, crucial for space-bound vehicles where mass and volume are tightly constrained.

Plutonium-powered heat source (HSUs)

The system is equipped with eight plutonium-238-powered heat source units (HSUs), which generate heat to drive the turbine and compressor assembly that powers the alternator, producing electricity for the rover's needs. Furthermore, to dissipate the heat produced by the DIPS, a thermal control system is implemented, featuring a large radiator. This system expels excess heat into space, ensuring that the rover's internal systems remain within their optimal operating temperature ranges. The radiator plays a critical role in preventing overheating during the rover's operations. Additionally, the rover is protected by a tantalum alloy shield, which safeguards the crew inside from harmful radiation emitted by the HSU, thus ensuring astronaut safety while meeting the strict radiation protection requirements for human space exploration [7].

Sodium-sulfur batteries

In addition to the primary power source, the PLR also features secondary power storage, provided by sodium-sulfur batteries. These batteries, capable of storing up to 4 kWh of energy, are used to meet short-term peak power demands, such as when the rover's mobility system requires up to 12 kW of power to drive all eight wheels simultaneously. The batteries are continuously charged by the DIPS, ensuring that the rover remains operational during the lunar night when solar power is unavailable. The integration of a secondary power storage system allows the rover to continue to function effectively throughout the mission, even if the primary power source faces problems. This combination of power generation and storage provides a reliable backup, allowing for extended operational periods on the Moon without the need for constant replenishment from external sources [8].

Further enhancing the system's reliability, the design incorporates redundant energy storage options. A small array, located on the rover's thermal control radiator shield, ensures that the batteries can still be charged if the primary power system is detached or becomes unavailable. This redundant system is vital for ensuring the rover's survival and functionality during extended lunar exploration missions, allowing it to operate independently if the main power system encounters a fault [8].

Energy management unit (EMU)

The DIPS with secondary sodium-sulfur batteries and solar panels is integrated in the PLR's power system.
A key point of the PLR's power system is the efficiency of energy distribution and consumption. The system is managed by an energy management unit (EMU), which regulates power distribution based on priority and operational need. For example, the mobility system demands significant power when crossing difficult terrain, while the life-support systems need continuous power for environmental control (e.g., air filtration, temperature regulation). Additionally, the rover's thermal control system requires power to maintain internal temperatures during the lunar night, highlighting the need for effective power management to ensure optimal system operation without risking energy shortages. These integrated energy management systems are essential for balancing power use between critical systems and ensuring that power is available when needed most.
The design of this power system is integral to the success of future lunar exploration missions, ensuring that the rover can perform its tasks reliably and efficiently without the risk of power failure [7].

1.5.3 Life Support Systems for the Pressurized Lunar Rover

The Life Support System (LSS) for the Pressurized Lunar Rover (PLR) is an intricate and vital network of interconnected systems designed to ensure the survival and operational efficiency of astronauts during extended lunar missions. The Moon's harsh environment presents unique challenges, including extreme temperature fluctuations, a lack of breathable atmosphere, and high levels of radiation, all of which require a sophisticated life support system capable of providing vital resources such as breathable air, drinkable water, and waste management. Additionally, the system must ensure crew safety and well-being while supporting the rover's scientific and operational tasks. As lunar missions grow longer, the need for reliable, autonomous life support systems becomes more pronounced, with advanced systems for air revitalization, water recycling, and radiation protection now at the forefront of rover designs [7], [8].

Air Revitalization Module (ARM)

At the heart of the PLR's LSS is the Air Revitalization Module (ARM), responsible for maintaining the rover's cabin pressure and oxygen levels, while removing harmful contaminants such as carbon dioxide (CO_2) and volatile organic compounds (VOCs). The ARM relies on chemical scrubbers, electrochemical cells, and oxygen generation systems to ensure that the air remains breathable and safe for the crew. Additionally, the ARM incorporates oxygen storage tanks to provide reserve oxygen for emergency use or during periods of heavy activity, such as extravehicular activities (EVAs), ensuring that the astronauts can rely on a stable oxygen supply [8].

Water Management Module (WMM)

Another crucial component is the Water Management Module (WMM), which handles the rover's water supply and recycling. Given the extended duration of lunar missions, efficient water management is critical. The WMM utilizes advanced filtration and distillation technologies to recycle urine and wastewater into drinkable water, minimizing the need for resupply from Earth. It also incorporates an integrated water recovery system, which can extract moisture from the rover's air, ensuring that water remains available for drinking, cooking, and hygiene. Additionally, the WMM assists in thermal management, absorbing excess heat from the rover's systems and helping regulate the internal temperature [7].

Food Provision Module (FPM)

The Food Provision Module (FPM) is designed to supply astronauts with the necessary nutrients for the duration of the mission. Given the constraints of food storage and preparation on the Moon, the FPM relies on dehydrated meals, which are rehydrated using the rover's water supply and heated with microwave systems. The FPM ensures that the crew receives balanced meals, with careful monitoring of nutritional needs to maintain astronaut health during the mission. Compact food storage systems are integrated into the rover, with enough capacity to support the crew for several weeks or months [8].

Waste Disposal Module (WDM)

The Waste Disposal Module (WDM) addresses the challenge of human waste management in space. The WDM is designed to safely contain liquid and solid waste, minimizing odor and potential biological hazards. For long-duration missions, the WDM must prevent contamination of the rover's living space, ensuring crew comfort and hygiene. The module may also integrate compaction technologies to reduce waste volume, which is critical for maximizing storage capacity on the rover [7].

Crew Health Module (CHM)

To ensure astronaut well-being, the Crew Health Module (CHM) plays a crucial role by providing exercise equipment, medical supplies, and health monitoring systems. This module is equipped with devices such as treadmills, resistance bands, and other fitness tools to help counteract the effects of prolonged low-gravity environments. Additionally, the CHM provides necessary medical provisions, such as first-aid kits and telemedicine systems, to enable remote consultation with medical professionals on Earth if needed [8].

Radiation protection

Radiation protection remains one of the most critical challenges for the design and operation of a Pressurized Lunar Rover. Unlike Earth, the Moon lacks both a magnetic field and a dense atmosphere, exposing astronauts to a significantly higher flux of cosmic rays, solar particle events (SPEs), and secondary radiation generated upon interaction with the lunar regolith [9].
While the current design of the PLR incorporates structural radiation shielding and radiation monitoring systems, there are still substantial limitations and challenges to be addressed.
One major limitation is the trade-off between shielding effectiveness and vehicle mass. Effective shielding, particularly against high-energy galactic cosmic rays (GCRs), often requires thick layers of dense materials, which would dramatically increase the rover's mass, negatively impacting launch and mobility capabilities [9].
Another significant challenge involves the unpredictability and intensity of solar particle events. While GCRs represent a chronic radiation exposure, SPEs can deliver dangerous doses within a few hours, requiring rapid protective measures. Current passive shielding designs may not be sufficient against extreme events without imposing extreme mass penalties.
Potential solutions to these challenges include:

- Use of advanced materials: Hydrogen-rich materials, such as polyethylene and specialized composites, offer promising shielding performance against both GCRs and SPEs while being significantly lighter than traditional metallic shields [10].

- Deployable radiation shelters: Another promising strategy is to include a compact, highly shielded radiation "storm shelter" within the rover. In the event of an SPE alert, astronauts could rapidly move into this confined space until the event subsides, drastically reducing required shielding mass for the entire vehicle [9].

- Predictive monitoring and early warning systems: Coupling the PLR with real-time space weather forecasting tools would allow crews to anticipate radiation events and take timely shelter actions, minimizing radiation exposure without relying solely on passive protection [9].

Thermal Control System (TCS)

Finally, the Thermal Control System (TCS) is integral to maintaining the rover's internal temperature, especially given the extreme temperature variations on the lunar surface, which can range from -173°C during the lunar night to +127°C during the lunar day. The TCS uses a combination of passive and active cooling mechanisms, such as heat exchangers, radiators, and phase-change materials, to regulate the internal temperature, ensuring the survival of both the rover's systems and the astronauts within [8].

In conclusion, the Life Support System for the Pressurized Lunar Rover is a highly integrated and essential system, ensuring that astronauts can live and work on the Moon for extended periods. With innovations in air revitalization, water management, waste disposal, radiation shielding, and health monitoring, the LSS is designed to meet the unique challenges of lunar exploration. These systems are fundamental to supporting the crew's health and safety while enabling the rover to operate autonomously and effectively in the harsh lunar environment [7].

1.6 Thesis Objectives and Structure

The management of resources and the cost estimation of such advanced systems are pivotal in ensuring that these missions remain economically viable. The integration of PMBOK methodologies for cost planning and risk management in the development and operation of lunar rovers will be essential for their success, ensuring that mission objectives are met while adhering to budget and timeline constraints.
However, despite the growing interest in pressurized lunar rovers, several aspects remain insufficiently addressed in current studies. Technical literature often focuses primarily on design solutions, while cost estimation, integrated risk management, and quality assurance are treated only marginally. Moreover, the absence of a unified project management framework limits the ability to systematically balance

schedule, cost, and reliability in the early phases of rover development.
To address these shortcomings, this thesis applies structured Project Management (PM) methodologies and tools to the conceptual development of a Pressurized Lunar Rover (PLR). After an overview of the role of PM in the context of space exploration, the work applies the PMBOK framework to structure the project phases, manage risks, control costs, optimize resources, and ensure mission success through standardized processes and knowledge areas.
Following this, Microsoft Project is used to create a detailed schedule representation of the mission development, utilizing both Gantt charts and the Critical Path Method (CPM). A Work Breakdown Structure (WBS) is also constructed to organize and define the scope of work for both mission profiles. Subsequently, a risk analysis is performed, identifying major risks through the development of a Risk Breakdown Structure (RBS) and defining appropriate mitigation strategies. Finally, a quality analysis is carried out using Failure Modes, Effects, and Criticality Analysis (FMECA) techniques to systematically identify potential failure points, assess their impact, and propose corrective actions.
Through this structured approach, the thesis aims not only to demonstrate how project management methodologies can be integrated into the early development phases of complex space systems such as a Pressurized Lunar Rover, but also to fill existing gaps by providing a comparative analysis of two mission profiles-a Semi-Stationary and a Transport Rover-thus supporting informed decision-making in future lunar exploration programs. Gantt charts, CPM, RBS, and FMECA to the conceptual design and mission planning of pressurized lunar rovers. By comparing two mission profiles, a Semi-Stationary and a Transport Rover, the work aims to provide a comprehensive foundation for strategic decision making in future lunar exploration programs.

Chapter 2
Project Planning and Launcher Selection for Pressurized Lunar Rover Missions

In the context of the Space Economy, the success of space missions, particularly those aimed at lunar exploration, depends not only on technological advancements but also on the effective management of complex projects. Project Management (PM) has become a critical discipline that ensures that these efforts are executed efficiently, on time, and within budget. As space exploration becomes increasingly commercialized, with growing participation from private entities, the need for robust PM frameworks has never been more pronounced.
The development and execution of space missions involve a variety of interconnected features, including research and development, resource management, budgeting, and risk management. These projects also require coordination among many stakeholders, including government agencies, private companies, contractors, and international partners. The complexity of such missions require systematic planning, monitoring, and control of all aspects of the project. A single misstep in timing, budgeting, or technical execution can lead to mission failure, wasted resources, or a significant delay in objectives.
According to NASA's Project Management Handbook (2020) [11], effective project management is crucial for ensuring that space missions meet their objectives while adhering to budget constraints and timelines. The document outlines several key principles for managing space projects, including the need for clear project goals, stakeholder coordination, and continuous risk assessment throughout the mission lifecycle.

2.1 Project Management Methodologies in Space Exploration

2.1.1 The PMBOK

The role of Project Management is particularly pronounced in space exploration projects, where technological innovations must be integrated with rigorous schedule and cost controls. Among the most widely recognized frameworks is the PMBOK (Project Management Body of Knowledge), which emphasizes the importance of scope management, risk management, cost control, and time management and provides a structured approach to the planning and execution of large-scale projects like lunar missions.
The PMBOK, developed by the Project Management Institute (PMI), offers a comprehensive framework for managing complex and multidisciplinary projects. It is organized into five process groups-initiating, planning, executing, monitoring and controlling, and closing-and ten knowledge areas, including scope, schedule, cost, risk, and quality management, as show in figure 2.1. These provide a structured approach to project execution, ensuring that every phase is guided by clear objectives, consistent procedures, and measurable outcomes.

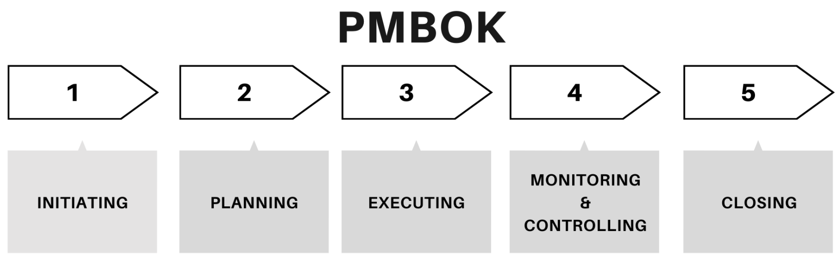


Figure 2.1: PMBOK phases

This framework supports the integration of engineering and management processes. In this thesis, tools derived from the PMBOK-such as the Work Breakdown Structure (WBS), Critical Path Method (CPM), Risk Breakdown Structure (RBS) and Failure Modes, Effects, and Criticality Analysis (FMECA)-are applied to support the planning and reliability assessment of the Pressurized Lunar Rover missions' profiles.

2.1.2 Microsoft Project

Microsoft Project is a widely used project management software developed to support the planning, scheduling, and monitoring of complex projects across a variety of industries. Its structured and visual interface makes it particularly suitable for technical domains such as aerospace and space systems engineering, where the management of task dependencies, resource allocation, and time constraints is essential. The software provides a wide range of features, including the definition of work packages, resource assignments, cost tracking, and time management, all integrated within an interactive Gantt chart. One of its key strengths lies in its ability to model complex project networks using task linkages, constraints, and lag times, which enables accurate schedule forecasting and the identification of critical paths.

In this thesis, Microsoft Project serves as a key tool for developing a structured and visually traceable project plan for the realization of a Pressurized Lunar Rover (PLR). The software is employed to simulate the design and development phases of the two distinct mission scenarios: the Semi-Stationary Mission and the Transport Mission. These mission concepts, while differing in their operational profiles, both involve the design, integration, and deployment of a complex rover system to support crewed lunar surface exploration.

The planning is structured by a Work Breakdown Structure (WBS) for both missions. The WBS defines the scope of work in a hierarchical structure, breaking down the significant deliverables into manageable, bite-sized components. Each WBS item is the equivalent of a set of activities in Microsoft Project and forms the foundation for the Gantt charts and Critical Path Method (CPM) analysis.

Microsoft Project is used for both missions to:

- Define and outline all major development phases (e.g., conceptual design, subsystem integration, testing, qualification).
- Identify task dependencies, durations, and milestones.
- Allocate hypothetical resources (e.g., labor hours, materials, system integration teams).
- Estimate costs involved through resource allocation and cost assignment at the task level.
- Identify critical paths (CPM) to identify the sequence of tasks that directly affect the project duration and possible bottlenecks in the project schedule.

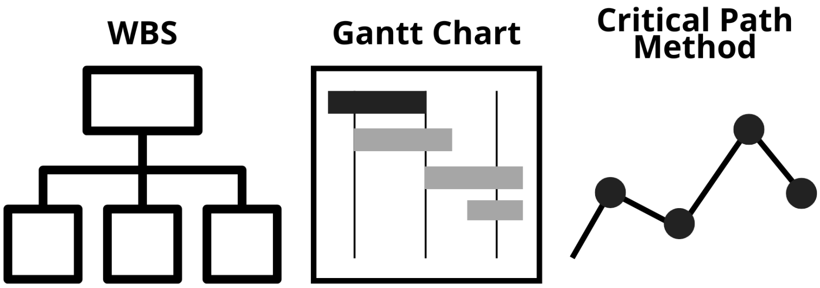


Figure 2.2: Microsoft Project tools

By structuring the project in this way 2.2, the tool enables a detailed simulation of the project schedule, establishing the basis for an initial cost estimation of the two missions. It also allows comparison of the two mission profiles on both a schedule and cost basis.

2.1.3 Risk Analysis

As part of the overall project management methodology, a structured risk analysis will be conducted to assess the potential threats that may compromise the successful development and deployment of the Pressurized Lunar Rover (PLR). This analysis is fundamental to identifying uncertainties early in the project, evaluating their possible impacts, and establishing mitigation strategies. To support this process, the Risk Breakdown Structure (RBS) will be employed as the primary tool for the systematic identification and classification of risks.
The RBS is a useful model for project management in breaking down and classifying risks hierarchically. It is used to identify systematically sources of risk throughout the project life cycle. In high-risk, high-complexity systems like space missions, where uncertainty cannot be avoided and the error margin is low, the use of a solid RBS is essential.
RBS format is a tree diagram, where every branch represents a separate category of risks. Risks are first categorized at the top level-internal risks and external risks. Then these categories are progressively subdivided into more detailed subcategories and specific-risk events. For example, there can be a Safety and Mission Assurance branch with sub-branches like "propulsion system failures," "software integration faults," or "thermal control breakdowns." rover risks can have "radiation incidents," "lunar dust interference," or "temperature extremes."
The role of the application of an RBS within this thesis is twofold. First, it provides for comprehensive and systematic enumeration of the risks associated with the design and deployment of a Pressurized Lunar Rover (PLR). Second, it provides

for the prioritization and thereafter qualitative and quantitative analysis of the identified risks.
The RBS will be used in:

- Classify the various risks by source and nature and provide a clear-cut framework for analysis.
- Highlight major risk areas most likely to have a substantial impact on mission cost, schedule, or performance.
- Facilitate successful stakeholder communication by allowing a common terminology and format for defining risk.
- Enable decision-making by focusing attention and resources on the most critical and probable threats.

In addition, the hierarchical nature of the RBS makes it scalable and flexible. When the mission concept evolves or new information becomes available, new levels or branches of detail can be added to the structure without ruining the overall risk architecture.

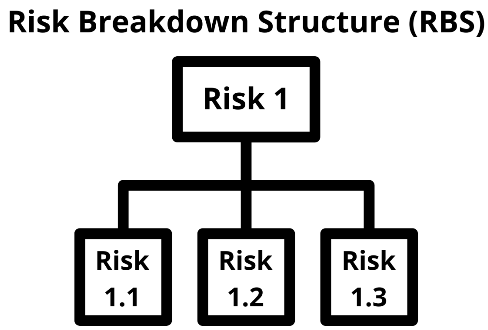


Figure 2.3: Risk Breakdown Structure

In summary, the RBS 2.3 will act as a basis of the risk management strategy of this thesis. In providing a clear and structured summary of potential risks for both mission types, it ensures that risk identification is complete, traceable, and aligned with project objectives. It further provides a basis for further analysis and well-supported decision-making in later phases of the thesis, including risk mitigation planning and reliability analysis.

2.1.4 Quality Analysis

As a complement to the risk management process and system robustness of performance, this thesis consists of a formal quality analysis by means of the Failure Modes, Effects, and Criticality Analysis (FMECA) method. Space project quality management goes beyond being compliant with specifications; it is being proactive in finding potential failure modes in an effort to maximize reliability, safety, and mission success. FMECA provides a formal method of studying how and why a system might fail, what the failure consequences would be, and how critical they are within the operating environment.
FMECA is an old, commonly applied engineering tool, particularly in defense and aerospace industry projects. It is intended to:

- Identify potential modes of failure in a system, subsystem, or component;

- Study each failure's impact on the system performance, safety, and mission requirements;

- Estimate the severity and probability of occurrence of each failure so that its criticality can be assessed;

- Prioritize the modes of failure for action against it to be scheduled and carried out later.

Analysis procedure would generally be as stated below:

1. System Decomposition: The system is broken down into manageable subsystems or units, which could relate to the Work Breakdown Structure (WBS).

2. Failure Mode Identification: For each component, potential ways in which it can fail (failure modes) are listed.

3. Effect Analysis: The impact of each failure mode is evaluated at the local level, subsystem level, and mission level.

4. Criticality Assessment: Each failure mode is rated using a Risk Priority Number (RPN) derived from ratings for severity, chance of occurrence, and detectability.

5. Prioritization and Action: High RPN failure modes are brought to attention for corrective design action, redundancy, or additional testing.

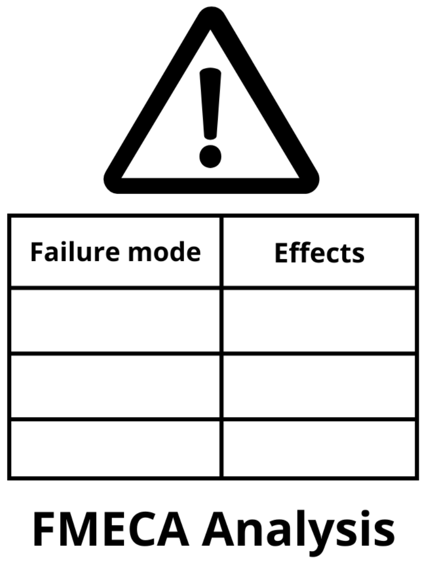


Figure 2.4: FMECA Analysis

In this thesis, FMECA 2.4 will be applied jointly to the Semi-Stationary Rover and the Transport Rover. Due to their similarity in operational profiles, subsystems, failure modes and their related impacts.
The objectives of the FMECA for this project are:

- To determine and assess most critical failure locations in the rover systems;
- To aid in the design and realization of mitigation measures to minimize the likelihood or impact of these failures;
- To improve overall mission reliability by correcting vulnerabilities at the conceptual design phase;
- Strengthen the integrity of the project planning system through integration of risk and quality factors.

The FMECA will be traceable in a good tabular form, correlating each component with its failure modes, effects, severity levels, probability ratings, and proposed measures to mitigate the failure. This organized documentation will enhance decision-making and allow for immediate corrective action, going straight to ensuring the reliability of the rover designs.
In summary, the application of FMECA throughout this thesis is not only to forecast failure, but to guide system design choices for maximizing overall mission

quality and safety.

In this chapter, a comprehensive overview of the project planning strategy for the Pressurized Lunar Rover missions has been presented, emphasizing the integration of structured project management methodologies with technical mission design. By adopting the PMBOK framework and employing Microsoft Project as the primary planning tool, a rigorous and traceable approach to scheduling, resource allocation, and cost estimation has been developed for both the Semi-Stationary and Transport Rover missions.
The application of Work Breakdown Structures (WBS), Gantt Charts, and Critical Path Method (CPM) enabled the decomposition of complex development activities into manageable phases, supporting clarity in task sequencing and identification of critical dependencies. These tools have been instrumental in simulating the overall project timeline and forming the foundation for budgetary analysis and cost comparisons between the two mission profiles.
In parallel, risk and quality management frameworks have been established as essential pillars of the planning process. The introduction of the Risk Breakdown Structure (RBS) provided a hierarchical means of classifying and analyzing potential threats, tailored separately for each mission concept. This structure ensures that mission-specific risks-are identified early and addressed systematically.
To complement the risk analysis, the Failure Modes, Effects, and Criticality Analysis (FMECA) methodology was introduced as a proactive tool to assess system reliability and mission robustness. Through the identification of critical failure points, assessment of their impacts, and prioritization based on severity and likelihood, the FMECA supports the refinement of system designs and enhances mission assurance.
Together, these planning and assessment tools form a comprehensive management architecture capable of guiding the development of the Pressurized Lunar Rover from conceptualization through execution. They ensure that each mission is approached with both technical rigor and strategic foresight, aligning engineering objectives with the broader economic and operational goals of contemporary space exploration. The frameworks established in this chapter will serve as the analytical foundation for the subsequent mission design, cost modeling, and reliability evaluation detailed in the following chapters.

Chapter 3
Mission Concepts for Pressurized Rover Operations

3.1 Potential launch vehicles for pressurized lunar rover missions

In the framework of this thesis, two distinct mission concepts for a Pressurized Lunar Rover (PLR) will be developed. The first concept, refer to a Semi-Stationary Mission, focuses on localized exploration with limited travel distances and smaller payload requirements. The second concept, the Transport Mission, involves longer-range operations, demanding a larger rover configuration and increased mission support capacity.
Considering that launch costs represent a major component of the overall mission budget [12], selecting the most appropriate launch vehicle is critical for optimizing both technical feasibility and economic efficiency. Table 3.1 and 3.2 summarize the main characteristics of potential launch vehicles assessed for these missions, including payload capacity, operational status, and estimated costs.
Following the list of available launch vehicles, an evaluation was carried out to align the launch system selection with the operational requirements of the two pressurized rover missions.

Table 3.1: Launchers - Mass and Volume Characteristics

Launcher	LEO Capacity	GTO Capacity	Payload Volume (Fairing)
Saturn V	140,000 kg	95,000 kg	10.1 m × 20 m
Titan IV	21,700 kg	5,800 kg	5.1 m × 17 m

Table 3.1: Launchers - Mass and Volume Characteristics

Launcher	LEO Capacity	GTO Capacity	Payload Volume (Fairing)
Proton-M	23,000 kg	6,900 kg	5.2 m × 17.6 m
Soyuz-FG	7,800 kg	3,000 kg	2.7 m × 8 m
Delta IV Heavy	28,790 kg	14,220 kg	5 m × 13 m
Atlas V	18,850 kg	8,900 kg	5.4 m × 20 m
Ariane 5 ECA	21,000 kg	10,500 kg	5.4 m × 17 m
Falcon 9	22,800 kg	8,300 kg	5.2 m × 13.2 m
Long March 5	25,000 kg	14,000 kg	5.2 m × 12 m
GSLV Mk III	10,000 kg	4,000 kg	5 m × 10 m
Vulcan Centaur	27,200 kg	13,000 kg	5.4 m × 19 m
SLS Block 1	95,000 kg	26,000 kg	8.4 m × 20 m
Starship	100,000 kg	21,000 kg	9 m × 22 m

Table 3.2: Launchers - Technical and Operational Characteristics

Launcher	Thrust Level	Est. Cost	Transfer Capability	Status
Saturn V	Very High	$1.16B	Direct Injection	No
Titan IV	Medium	$0.43B	Requires TLI stage	No
Proton-M	Medium	$0.65B	Requires TLI stage	Yes
Soyuz-FG	Low	$0.48B	Limited	No
Delta IV Heavy	High	$0.45B	Direct Injection	Yes*
Atlas V	Medium	$0.18B	With Centaur upper stage	No
Ariane 5 ECA	Medium	$0.17B	With cryo upper stage	No
Falcon 9	High	$0.067B	Proven via Falcon 9 upper	Yes

Table 3.2: Launchers - Technical and Operational Characteristics

Launcher	**Thrust Level**	**Est. Cost**	**Transfer Capability**	**Status**
Long March 5	Medium	$0.20B	Planned for TLI	Yes
GSLV Mk III	Medium	$0.05B	Under development	Yes
Vulcan Centaur	High	$0.25B	Planned	2024
SLS Block 1	Very High	$2.00B	Direct Injection	Yes
Starship	Medium	$0.05B	Planned with Starship HLS	Testing

* = Almost retired

3.2 Evaluation of Launch Options for Semi-Stationary and Transport Rover Scenarios

The first fundamental aspect to be considered before identifying the most suitable launch vehicle is whether the pressurized lunar rover will be delivered to the Moon fully assembled in a single launch, or whether it will be transported in modular components across multiple launches and assembled on the lunar surface. This decision directly influences the mission architecture, particularly in terms of launch logistics, operational risk, timeline, and overall cost.
This issue applies to both rover configurations proposed, the semi-stationary rover and the transport rover. While the two differ in size, range, and structural complexity, their core subsystems-such as the pressurized cabin, Environmental Control and Life Support System and internal workspace-are assumed to follow a similar architecture, scaled accordingly. This includes shared requirements for habitability, radiation protection, thermal control, and internal power management. For example, for the semi-stationary rover, although its propulsion requirements for lunar surface navigation are minimal due to its localized mission scope, it would still require electric drive capability components able of supporting mobility over short distances and uneven terrain. However, its internal power supporting systems like oxygen generation, temperature control, pressure control, data processing, and communication would remain comparable to the larger transport rover, as both must sustain a habitable environment for crew operations, onboard experiments, and emergency scenarios.

The choice between deploying a fully assembled rover in a single launch or delivering it in modular parts for lunar surface assembly significantly impacts both logistical complexity and launch vehicle selection. The modular launch scenario would require multiple launches, increasing the cumulative risk, cost, and mission duration. Each additional launch introduces new possibilities of failure, including launch delays and in-orbit integration issues.
In addition, on-site assembly on the lunar surface creates considerable challenges. The reduced gravity of the Moon, the lack of atmospheric protection, and the high radiation exposure would significantly complicate any astronaut, who performed mechanical operations.
Lunar regolith, known for its abrasiveness and electrostatic behavior, further interferes with the equipment. The absence of sterilization procedures, controlled clean-room environments, and fine assembly tools would make structural integration of critical systems (e.g., pressurized modules, power lines, control lines) very difficult, if not infeasible, especially while wearing Extravehicular Mobility Units.
Moreover, assuming a reusable launcher is employed, the vehicle would need to undergo extensive turnaround operations when returning to Earth before being sent again. These include thermal shield inspection, propellant tank reconditioning, recalibration, structural integrity testing, and potential revalidation for flight-procedures that would significantly extend the mission timeline. Each of these steps involves labor, time, and ground infrastructure, which directly translate into increased cost.
Therefore, this thesis adopts the first scenario as its baseline assumption: that the pressurized lunar rover-regardless of scale-is launched fully assembled in a single mission. This approach minimizes launch-related risk, reduces mission complexity, and aligns with NASA's Artemis logistics.
More in detail, the two mission profiles envisioned are:

- Semi-Stationary Mission, featuring a rover dedicated to limited mobility and short-range lunar surface operations, with an estimated mass of approximately 4,000 to 5,000 kg and an estimated occupy volume of 30-40 m^3.

- Transport Mission, involving an extended-range rover with larger structural dimensions, with an estimated mass of approximately 7,000 to 8,000 kg and an estimated occupy volume of 55-60 m^3.

These estimates mass and volume are based on reference values from historical pressurized rover concepts, such as NASA's Pressurized Rover [8], [7] and the PLR prototypes discussed in Table 1.1, 1.2.

3.2.1 Launcher Selection for the Semi-Stationary Mission

Considering both the moderate mass and the estimated volume of the Semi-Stationary Pressurized Rover, a medium-lift launch vehicle with a spacious fairing, proven lunar capabilities, and cost-efficient performance is required. The selected launch system must be capable of delivering the rover-fully assembled-to a trans-lunar injection (TLI) trajectory or to a staging orbit for subsequent lunar transfer.

Figure 3.1: Falcon 9

Among the available launchers, Falcon 9, in figure 3.1, by SpaceX emerges as the optimal solution [13]. Its payload fairing, measuring 5.2 meters in diameter and 13.2 meters in internal height, comfortably accommodates the estimated envelope of the semi-stationary rover (30–40 m^3), with additional margin for launch adapters, insulation, and support structures. From a performance perspective, Falcon 9 provides a LEO capacity of 22,800 kg and a GTO capacity of 8,300 kg, offering a substantial mass margin for both the rover and potential auxiliary systems such as transfer stages or communication payloads.

Moreover, Falcon 9 has a proven track record in supporting missions beyond Earth orbit. Notably, it successfully launched CAPSTONE toward a Near-Rectilinear Halo Orbit (NRHO) around the Moon, validating its compatibility with lunar injection maneuvers when used in conjunction with third-party upper stages (e.g., Photon). Falcon 9 is also part of future logistics chains supporting NASA's Artemis program, reinforcing its technical credibility for lunar-bound missions.
From a financial standpoint, the Falcon 9 offers a highly favorable cost-performance ratio, with an estimated cost of approximately \$67 million per launch-significantly lower than legacy systems such as Proton-M or Delta IV. Its high launch cadence, partially reusable design, and mature ground infrastructure make it an accessible and low-risk option for near-term lunar exploration payloads.
Other potential alternatives, including Proton-M [14] and GSLV Mk III [15], are less favorable in this context. While similar in fairing dimensions (5.2 $\times$ 17.6 m and 5 $\times$ 10 m, respectively), both suffer from limited heritage in lunar injection missions, higher relative costs, and in the case of GSLV, lower payload maturity and reduced mass margins. Their lower operational cadence and absence of integrated lunar support infrastructure further reduce their viability for early-stage crewed exploration scenarios.
In conclusion, Falcon 9 stands out as the preferred launcher for the Semi-Stationary Mission, offering unmatched flexibility, flight heritage, and cost-efficiency. It provides ample volume and mass capacity for a fully integrated rover, supports compatible TLI solutions, and aligns with broader lunar program logistics-making it a robust and reliable enabler for surface mission deployment.

3.2.2 Launcher Selection for the Transport Mission

For the Transport Pressurized Rover (TPR), the greater mass (7,000–8,000 kg) and the internal pressurized volume (55–60 m^3), combined with the need of a fully integrated launch, require the use of a heavy-lift launch vehicle with both high payload capacity and a large fairing volume. The launcher must not only accommodate the structural dimensions of the rover but also provide sufficient performance for trans-lunar injection (TLI) or support compatibility with a dedicated upper stage.
Among current and near-future options, Delta IV Heavy [16] stands out as a technically viable solution. With a LEO capacity of 28,790 kg and support for direct lunar injection, it meets all performance requirements for the TPR. Its payload fairing-measuring 5.0 meters in diameter and 13 meters in length-offers sufficient internal volume to house the transport rover, its deployment structure, and auxiliary support modules. However, despite its proven reliability and lunar capability (e.g., Orion EFT-1), the Delta IV Heavy is nearing retirement, and its extremely high cost (estimated at \$450 million per launch) makes it economically less viable, particularly for repeated or non-critical missions.

Figure 3.2: Vulcan centaur

As a successor, Vulcan Centaur, in figure 3.2, by United Launch Alliance (ULA) presents the most promising long-term solution [17]. Designed to replace the Delta family, Vulcan offers comparable mass performance (27,200 kg to LEO, ~13,000 kg to GTO) and supports planned lunar transfer trajectories using a Centaur upper stage. Its payload fairing-available in configurations up to 5.4 meters in diameter and 19 meters in height-comfortably accommodates the TPR's dimensions, including thermal clearance and structural isolation. Although still completing early flight milestones, Vulcan benefits from ULA's extensive launch heritage and is designed for high reliability, rapid turnaround, and integration with NASA's Artemis architecture.

While SLS Block 1 [18] and Starship [19] technically surpass all performance requirements-with fairings of 8.4 × 20 meters and 9 × 22 meters, respectively-their inclusion poses other constraints. The Space Launch System (SLS), although human-rated and capable of direct Moon missions, suffers from an exceptionally high cost (over $2 billion per launch) and very limited availability due to its alignment

with flagship Artemis missions. Starship, developed by SpaceX, offers unmatched potential in terms of capacity and reusability, but remains in early development and test phase, with no confirmed operational record for lunar injection or large cargo recovery. As such, it cannot yet be considered a baseline option for near-term missions requiring high assurance.
In conclusion, Vulcan Centaur is identified as the preferred launch system for the Transport Mission, offering the right balance between capability, cost, and availability. Its performance matches the TPR's dimensional and mass requirements, and its fairing options ensure compatibility with a fully integrated payload. Delta IV Heavy may serve as a transitional or contingency option, particularly in early flights or if Vulcan's development timeline is delayed. However, long-term mission planning should prioritize Vulcan for its scalability, integration with existing lunar infrastructure, and strategic alignment with commercial and governmental launch ecosystems.

3.3 Semi-Stationary Pressurized Rover Mission

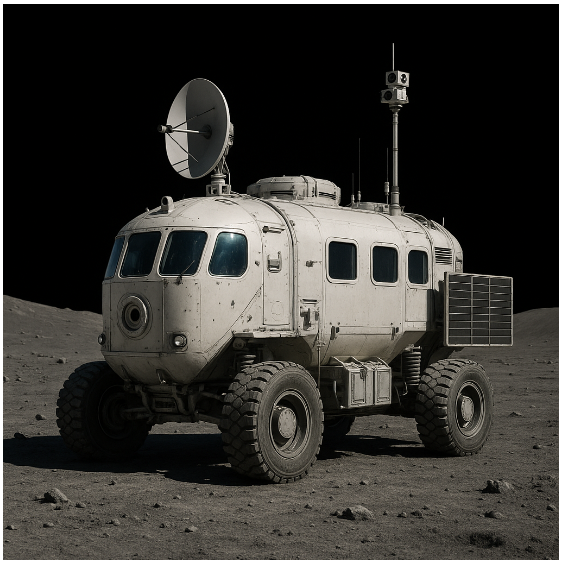


Figure 3.3: Possible representation of PR

The Semi-Stationary Mission, in figure 3.3, created by the author using Artificial Intelligence (AI), represents a preliminary step in lunar surface exploration, focused on enabling short-term human presence and localized scientific research. The core of the mission is a pressurized lunar rover designed for minimal mobility, operating at a very low speed on the order of a few centimeters per minute. This reduced

locomotion profile allows the vehicle to reposition slightly, when necessary, to optimize environmental conditions, solar exposure, or sample collection operations, while maintaining a largely fixed base of operations.
Unlike transport-oriented rovers, which are engineered for long-range exploration, the semi-stationary platform prioritizes habitat stability, energy efficiency, and scientific analysis on board. It acts as a temporary outpost for astronauts, supporting essential life support functions and enabling early-stage analysis of samples collected. The mission's objective is to demonstrate the feasibility of human activity in a constrained and controlled area, the possibility of traveling away from the primary base, and reducing the time needed for exploration and analysis by eliminating the necessity to return to the base camp after each sample is collected, serving as a technology and operations test base for more ambitious future missions.

3.3.1 Mission Objectives and Requirements

Enable crewed access to unexplored lunar regions with a semi-stationary pressurized rover capable of minimal surface mobility, and manage a preliminary analysis of collected samples.

To ensure the successful execution of the Semi-Stationary Mission, a comprehensive functional analysis has been conducted. This process identifies the core capabilities that the pressurized lunar rover must possess in order to meet mission objectives while operating within the constraints of the lunar environment. The following list outlines the key functions derived from the mission concept, emphasizing human survivability, system autonomy, scientific performance, and integration with broader lunar operations.

- Ensure crew survival through a complete life support system (oxygen, CO_2 removal, pressure, humidity)
- Maintain internal thermal stability
- Monitor and control internal environmental parameters (air composition, temperature, humidity)
- Enable safe ingress and egress of astronauts during lunar operations (EVA compatibility)
- Support minimal mobility for local repositioning on the lunar surface
- Enable onboard preliminary analysis of collected samples
- Storage and preserve collected samples

- Provide continuous communication with mission control and interoperability with other lunar assets (e.g., rovers, landers)
- Detect and respond to system anomalies or failures autonomously or via ground support
- Enable power generation and storage for all onboard systems for the entire mission duration
- Distribute and manage power across all critical subsystems (mobility, life support, communications, etc.)
- Navigate and maneuver over uneven terrain within a limited area
- Provide structural protection against micrometeorites, lunar regolith, and radiation

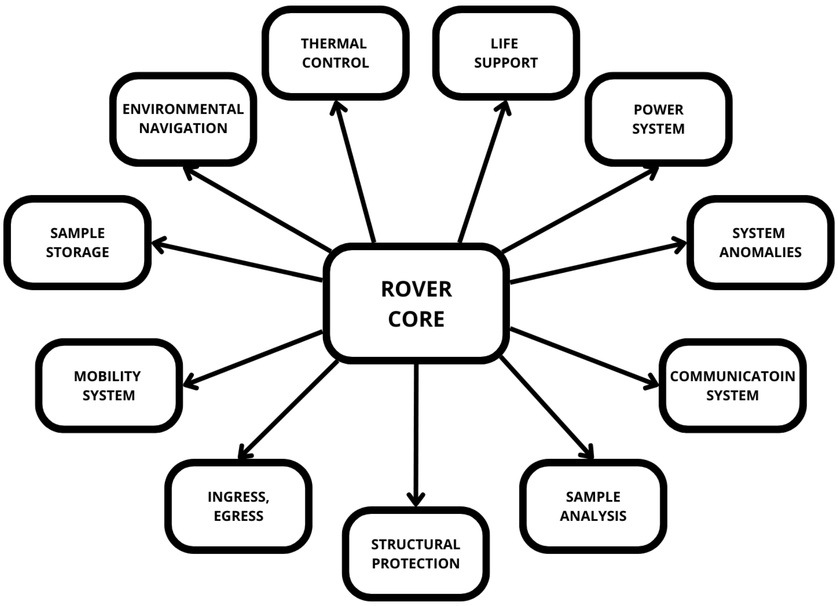


Figure 3.4: Semi-Stationary Rover Core

The following table 3.5 outlines the specific mission requirements corresponding to each primary functional capability of the Semi-Stationary Pressurized Rover. These requirements are derived from the mission objectives and environmental constraints of lunar surface operations.

Table 3.3: Functions and Corresponding Requirements

Function	**Requirement**
Crew survival through a complete life support system	The rover shall maintain habitable conditions by providing breathable air, pressure regulation, CO_2 removal, humidity control, and emergency oxygen backup for the entire mission duration.
Internal thermal stability	The rover shall maintain internal temperatures between 18°C and 26°C under varying external lunar conditions.
Monitor and control internal environmental parameters	The rover shall include sensors and control systems to continuously monitor and regulate temperature, humidity, air composition, and cabin pressure.
Safe ingress and egress of astronauts	The rover shall provide a pressurized docking interface and EVA-compatible hatch system to allow safe entry and exit in lunar surface suits.
Support minimal mobility	The rover shall be capable of local repositioning on the lunar surface with speeds up to a few centimeters per minute to optimize operational conditions.
Onboard preliminary analysis of collected samples	The rover shall be equipped with a basic scientific payload capable of performing initial compositional or structural analysis of lunar soil and rock samples.
Storage and preserve collected samples	The rover shall include dedicated sealed containers for storing geological samples in a controlled environment to prevent contamination or degradation.
Continuous communication with mission control and interoperability with other lunar assets	The rover shall maintain continuous bidirectional communication with mission control and support local communication protocols for coordination with other rovers or landers.
Detect and respond to system anomalies or failures autonomously or via ground support	The rover shall be equipped with diagnostic and fault detection systems capable of issuing alerts, initiating safe modes, and responding to faults with predefined actions.

Function	Requirement
Enable power generation for all onboard systems for the entire mission duration	The rover shall generate at least 8 kW of continuous power via a Dynamic Isotope Power System (DIPS) to ensure full operational autonomy.
Distribute and manage power across all subsystems	The rover shall include an energy management unit (EMU) capable of allocating power based on subsystem priority and load balancing under varying demand.
Navigate and maneuver over uneven terrain	The rover shall incorporate a low-speed, high-torque mobility system capable of traversing minor obstacles, slopes up to 30°, and regolith-covered surfaces.
Provide structural protection against micrometeorites, lunar regolith, and radiation	The rover shall be constructed with multilayer shielding to protect the crew and critical systems from radiation, dust intrusion, and micrometeorite impacts.

3.3.2 System Overview

The Semi-Stationary Pressurized Rover (SSPR) is designed as a short-range, low-mobility habitat and operations platform for initial crewed lunar surface missions. Unlike transport rovers, the SSPR functions primarily as a fixed scientific outpost, positioned at a preselected site within proximity to the primary lunar base. Its purpose is to support preliminary exploration, crew habitation, and surface analysis in environments not directly accessible from the base.

Mission Duration and Operational Profile

The mission duration for the SSPR is projected to be 14 Earth days, corresponding to one full lunar daytime cycle. This choice avoids the need for survival during the 14-day lunar night, significantly simplifying energy storage and thermal design. Power is supplied by a Dynamic Isotope Power System (DIPS), providing 8 kW of continuous power, sufficient to support all critical subsystems: life support, communication, mobility, thermal regulation, and scientific instruments. A sodium-sulfur battery array, with a capacity of 4 kWh, ensures short-term peak load support.

The rover will remain within a 500-meter operational radius from the landing zone or main lunar base, where it will arrive in approximately 5.5 hours if it maintains an average speed of 2.5 cm/s. This slow traversal during the first day allows for controlled movement, initial system diagnostics, and safe terrain navigation without consuming significant power or inducing mechanical stress. Its mobility system allows repositioning at speeds of 2-3 cm/s, or about 1.7-2.6 km/day. Over a 14-day mission, the theoretical maximum range is approximately 24-36 km, though actual movement is expected to be under 1 km, limited to micro-adjustments for thermal optimization, solar exposure, or access to scientific targets. [1]

Life Support and Habitability

The SSPR is designed to accommodate two astronauts in a pressurized, thermally regulated environment. The Air Revitalization Module (ARM) supports oxygen generation, CO_2 scrubbing, and humidity control, with redundant systems to ensure safety. The Water Management Module (WMM) recycles wastewater and provides thermal exchange support. Food is stored in dehydrated form, rehydrated onboard using recycled water. The Crew Health Module (CHM) includes basic exercise equipment and medical kits, enabling crew well-being over the mission duration.
Temperature within the pressurized cabin is maintained between 18°C and 26°C using a combination of active and passive thermal control systems (TCS). These include external radiators and multi-layer insulation, that buffer against the Moon's extreme surface temperatures. The compact internal volume also improves thermal efficiency, reduces surface area exposed to radiation and dust, and simplifies structural integrity, contributing to overall system robustness under lunar conditions.
The internal volume is approximately 30–40 m^3, a range carefully selected to balance crew habitability, system integration, and mass constraints. This volume provides 12.5–15 m^3 per astronaut, meeting the recommended minimum for short-duration missions while offering enough space for workstations, sleeping accommodations, environmental control systems, and sample processing. The configuration supports all necessary operations for a 14-day surface mission without introducing unnecessary structural.
The SSPR has a compact, yet functional, geometry optimized for both launch constraints and internal crew operations. The total external dimensions are approximately 4.5 m in length, 3.0 m in width, and 3.0 m in height. This provides adequate space for: a crew compartment with two foldable sleeping beds and workstations, a glovebox-based science bay for handling and analyzing geological samples, an Environmental Control and Life Support System (ECLSS) compartment housing environmental control and life support systems and storage modules are integrated into the walls for food, tools, and emergency gear.

[1] $14 days \cdot 24h \cdot 60s \cdot 60s \cdot (0.00002 km/s)$

Sample Handling and Scientific Capabilities

A key function of the rover is to support preliminary scientific investigations. To this end, it is equipped with an internal glovebox or sample handling unit, enabling non-invasive spectrometric analysis, imaging, and cataloging of lunar regolith and rock samples. The rover can store up to 20 kg of samples in sealed compartments for return to Earth. The sample storage capacity of is selected based on a trade-off between scientific return, mass constraints, and storage system complexity. This value aligns with historical missions such as the Apollo missions, which returned between 21.5 kg (Apollo 11) and 110.5 kg (Apollo 17) of lunar material. Furthermore, storing more than 20 kg would require reinforced containment, more complex thermal and radiation protection for volatile components, and potentially larger robotic handling systems, which contradict the nature of this early-stage mission.

Communication and Autonomy

The SSPR maintains continuous S-band or Ka-band communication with the mission control center via a direct line-of-sight high-gain antenna. It also supports short-range communication protocols for coordination with other lunar assets (e.g., autonomous rovers or landers).
The rover is equipped with autonomous health monitoring systems, capable of diagnosing system anomalies and activating safe-mode procedures in case of hardware failures or environmental hazards. Non-critical operations can be overridden by remote ground support when necessary. This functionality ensures mission resilience by allowing the rover to react in real time to internal malfunctions or external threats, such as excessive heat, mechanical wear, or radiation spikes, without requiring immediate human intervention. At the same time, ground operators retain the ability to control or adjust non-critical systems remotely, ensuring flexibility in mission planning and fault recovery.

Structural and Environmental Protection

The external shell of the rover is constructed using a multilayered composite shield, specifically engineered to provide robust protection against micrometeorite impacts, abrasive lunar dust, and ionizing radiation. This shield combines layers of carbon fiber composites, aluminum honeycomb structures, and hydrogen-rich materials such as polyethylene, which are effective at attenuating both galactic cosmic rays (GCRs) and solar particle events (SPEs).
Given the Moon's lack of atmosphere and magnetic field, astronauts face continuous exposure to space radiation, making radiation protection one of the most critical challenges in rover design. To address this, the rover incorporates an internal

storm shelter, a compact volume within the crew cabin lined with enhanced shielding-potentially future-generation materials such as boron-nanotube-doped polyethylene. In the event of a high-intensity SPE, astronauts can take refuge in this shelter for several hours, drastically reducing their effective radiation dose without overburdening the entire vehicle with excessive shielding mass.

More advanced approaches are currently in experimental stages. For instance, research supported by NASA and ESA is exploring the use of active radiation shielding based on magnetic or electrostatic fields. These systems theoretically deflect charged particles but face significant engineering constraints, including power consumption, system mass, and reliability in variable space environments. Other proposals involve hybrid passive-active materials or self-healing composites that dynamically respond to radiation exposure.

In addition to passive materials, the rover integrates predictive radiation monitoring and alert systems, connected to space weather forecasting networks. This allows early detection of solar activity, providing crews with actionable warning times to initiate safe-mode protocols and enter the storm shelter before the most dangerous particles arrive.

While GCRs pose a chronic exposure risk over time and are more challenging to shield due to their high energy, the chosen combination of localized heavy shielding (in the storm shelter) and lightweight distributed shielding (in the hull) offers a balanced approach. It reduces cumulative crew dose while keeping the overall mass of the rover within acceptable launch and mobility limits.

Despite ongoing efforts, no existing technology has yet demonstrated consistent, deployable protection against high-fluence SPEs in operational space conditions. As such, current mitigation strategies must rely on a combination of early warning systems, predictive models, and localized shielding. The rover's radiation monitoring and alert systems are connected to space weather forecasting networks, allowing timely detection of solar activity and enabling astronauts to initiate safe-mode protocols and enter the storm shelter before particle fluxes peak.

Future upgrades to this protection strategy could include deployable shielding panels, electrostatic deflection systems, or hybrid passive-active materials, offering enhanced protection for extended lunar missions or potential Martian expeditions.

Power Budget Calculation

Given that the DIPS system provides a continuous 8 kW, the power allocations across subsystems are defined as follows:[2]

[2] Power consumption values for the Semi-Stationary Pressurized Rover are based on scaled reference data from previous NASA crewed systems and ISS-derived life support modules. The estimates assume two astronauts operating continuously in a confined pressurized environment

Table 3.4: Subsystem Power Consumption Summary

Subsystem	**Power Consumption**	**Notes**
Life Support Systems (ECLSS)	2.5 kW	Continuous
Thermal Control (TCS)	1.0 kW	Variable load
Communication	0.5 kW	Intermittent
Lighting and Internal Systems	0.3 kW	Continuous
Mobility System	1.5 kW peak	0.3 kW avg
Scientific Payload	1.0 kW	Intermittent
Power Management / Redundancy	0.4 kW	Overhead

The total average power load of the rover is approximately 6.0 kW, based on the continuous operation of life support, thermal control, communications, internal systems, and scientific instrumentation. With a Dynamic Isotope Power System (DIPS) capable of delivering 8 kW, this configuration leaves an available margin of about 2.0 kW. This buffer ensures operational robustness, allowing the system to absorb unexpected demand spikes or temporary increases in power consumption due to subsystem anomalies, without compromising mission continuity or crew safety.
Unlike solar-based systems, which would require approximately 30-40 m^2 of high-efficiency photovoltaic panels and a battery array capable of storing up to 7,000 kWh to survive the 14-day lunar night, the DIPS offers continuous, reliable power generation both day and night. It also enables operation in permanently shadowed regions or during early mission phases when mobility and positioning are limited. Additionally, the system's compactness, dust-resilient design, and lack of exposed moving parts make it particularly well-suited for the lunar environment. While DIPS introduces additional challenges in terms of radiation safety and handling,

over a 14-day mission. Life support and internal systems are modeled for continuous operation, while communication and scientific payloads are considered intermittent. Thermal control requirements reflect the need to stabilize a small internal volume under lunar surface temperature fluctuations. Mobility-related values are minimized due to the rover's semi-stationary profile, with only low-speed repositioning expected.

its use significantly reduces mass, complexity, and operational risk, making it an optimal solution for early-stage lunar surface infrastructure.

Oxygen Demand Estimation

Oxygen consumption is estimated based on NASA's standard metabolic rates, which indicate a daily requirement of approximately 0.84 kg of O_2 per person at rest, and around 1.0 kg per person during light activity, such as laboratory work or routine rover operations. For mission planning purposes, an average consumption of 1.0 kg/day/person is assumed. Over a 14-day mission with two astronauts, the total oxygen demand amounts to 28 kg. Therefore, the rover must be equipped with storage tanks capable of holding at least 30 kg of oxygen, providing a small operational margin. Additional redundancy could be achieved through onboard oxygen generation via electrolysis, contingent upon the availability of water within the system.

Thermal Load

Given that external temperatures during the lunar daytime can reach up to +127°C, maintaining a stable internal environment at approximately 22°C requires effective thermal regulation. The estimated total thermal load inside the rover is in the range of 4–5 kW, composed of approximately 2.5-3 kW from equipment waste heat, 0.25 kW from human metabolic activity, and an additional 1 kW of solar heat gain-partially mitigated by multilayer insulation. To reject this excess heat, the rover is equipped with radiative panels positioned on its shaded side, allowing passive emission of thermal energy into space. During peak thermal loads, phase-change materials (PCMs) are employed to buffer heat spikes, ensuring internal temperatures remain within habitable limits without overloading the cooling system.

3.3.3 Work Breakdown Structure (WBS) for the Semi-Stationary Rover

The Work Breakdown Structure (WBS) for the Semi-Stationary Pressurized Rover was developed using Microsoft Project and reflects a hierarchical decomposition of all activities required to design, manufacture, integrate, and validate the rover system. The structure follows PMBOK best practices, using a WBS divided into 11 major components:

1. Mission Definition and System Requirements
2. Structural Design and Manufacturing
3. Environmental Protection Systems

4. Thermal Control System (TCS) Integration
5. Power System Integration
6. Mobility System
7. Life Support System (ECLSS)
8. Communication & Autonomy Systems
9. Crew Interface & Habitability
10. System Integration & Testing
11. Documentation, Verification & Delivery

Each branch is subdivided into work packages and individual tasks, allowing traceability of scope, schedule, cost, and dependencies. In figure 3.5 presents a visual overview of the WBS hierarchy up to the work package level, deducted from the Microsoft Project environment. The representation aims to highlight the sequence of steps and operations required to develop the Semi-Stationary Rover. The technical analysis has reached the third level of detail, and each WBS element up to this third level can be viewed in the appendices at the end of the document.

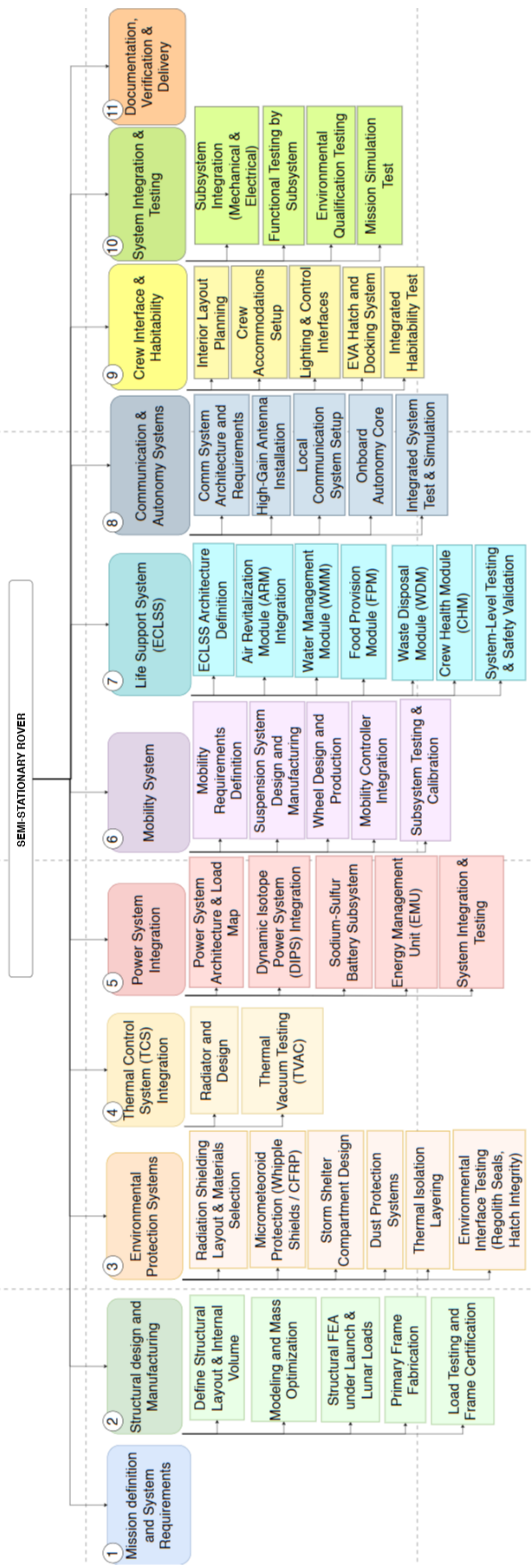


Figure 3.5: Stationary Rover WBS

Each branch of the WBS corresponds to a mission system:
The first phase of the project, **Mission Definition and System Requirements**, lays the foundation for the entire rover development process. It begins with the definition of the mission profile, which outlines the overarching objectives of the Semi-Stationary Rover. This includes the operational context, mission duration, crew needs, and scientific or logistical goals.
Following this, the process continues with the definition of system-level requirements. At this stage, the project team translates the mission objectives into concrete engineering constraints and performance parameters, such as structural limits, power autonomy, habitability, and environmental tolerances.
Once these requirements are established, the team conducts a series of preliminary design reviews, where early architectural concepts and subsystem configurations are evaluated for feasibility, traceability, and alignment with mission goals. These reviews often involve interdisciplinary inputs and iterative refinement of proposed solutions. The phase concludes with a formal System Architecture Design Freeze, marking the point at which the overall system configuration is locked. This milestone ensures that all downstream design and development activities proceed from a stable and validated reference baseline.

The second phase starts with The **Structural Design and Manufacturing** phase, which represents a core pillar in the development of the Semi-Stationary Rover, as it defines and realizes the physical architecture upon which all subsystems are mounted. This WBS is broken down into five major sub-phases, each encompassing specific technical steps that transition the design from conceptual layout to tested and certified structure.
The process begins with the definition of the structural layout and internal volume, where the team conducts internal zoning activities to allocate space for the ECLSS, crew cabin, mobility components, and hatch interfaces. In parallel, the design must ensure compliance with launch vehicle constraints, assessing payload envelope limitations and mass distribution. The launch load path concept is also defined at this stage to ensure proper force transmission during liftoff and landing.
Next, the focus shifts to modeling and mass optimization, a critical phase where the structural mesh is developed (covering shell, frame, and floor) and thoroughly analyzed. This includes interface checks with major systems such as thermal control, power, and ECLSS, as well as detailed planning of assembly sequences and fastener specifications to ensure ease of fabrication and integration.
Structural performance is then evaluated through Finite Element Analysis (FEA) under both launch and lunar conditions. Here, the design is validated against static loads (such as gravitational, crew ingress, and mobility loads), launch-induced vibrations and dynamic profiles, and localized stress points that may become critical under cyclic or concentrated forces.

Following successful analysis, the rover enters the Primary Frame Fabrication phase. This includes the forming of the pressure shell, integration of bulkheads and floor plates, and non-destructive testing (NDT)-such as weld inspections and joint integrity verification-to guarantee that the structural components meet safety and performance standards. Completion of this phase is marked by the formal milestone “Structure Completed.”
The final stage is Load Testing and Frame Certification, where the entire frame is subjected to vacuum chamber testing to validate leak-tightness and outgassing profiles, followed by physical load tests to confirm structural resilience. The process concludes with a final assembly sign-off and delivery to the integration floor, where the structure becomes the backbone for all subsequent subsystem installation.

The **Environmental Protection Systems** is the third phase, and it is critical for ensuring crew survivability and hardware reliability in the harsh conditions of the lunar environment. This WBS encompasses the design, integration, and validation of all protective barriers against radiation, micrometeoroids, dust, and extreme thermal fluctuations. It also includes the definition of emergency isolation zones and the verification of environmental seals.
The process begins with the Radiation Shielding Layout and Materials Selection, where GCR (Galactic Cosmic Rays) and SPE (Solar Particle Events) exposure levels are modeled based on mission duration and surface location. Based on the dosage analysis, suitable materials and thicknesses are selected, and integration zones are identified, focusing on high-priority areas such as the crew cabin and electronics bays.
Next, Micrometeoroid Protection is addressed through the implementation of Whipple Shields and CFRP (Carbon Fiber Reinforced Polymer) outer panels. This includes panel layering, mounting and sealing operations, and ballistic testing against simulated impact conditions to ensure certification for micrometeoroid defense.
The third functional area is the Storm Shelter Compartment Design, which involves the creation of an internal refuge space with reinforced walls. This compartment includes shielded wall installation, the routing of emergency oxygen and power lines, and the integration of modular shielding panels, offering last-resort protection during extreme radiation events.
Dust mitigation is handled through a dedicated Dust Protection System, which combines regolith-resistant external coatings with passive capture filters located near sensitive subsystems, especially around the mobility units. These passive barriers reduce mechanical wear and prevent sensor degradation due to fine lunar dust.
Thermal control is supported by Thermal Isolation Layering, where multi-layer insulation and heat isolation strategies are applied to the structural surface. This

ensures stable internal temperatures despite high surface thermal gradients, particularly during lunar day-night cycles.
The final step is Environmental Interface Testing, which includes a radiation attenuation test using a simulated source, dust ingress testing with regolith analogs, and a full visual and infrared inspection of the integrated protective systems. The phase concludes with a Subsystem Preliminary Design Review (PDR) to validate compliance and readiness for integration.

The fourth phase is the **Thermal Control System (TCS) Integration** which is essential for maintaining the operational temperature range of the rover's subsystems and its pressurized cabin under the extreme thermal conditions of the lunar surface. This WBS phase is structured to define the system architecture, validate heat transfer performance, and integrate thermal management components with the broader power system infrastructure. The process begins with the TCS Architecture Definition, in which the team outlines the thermal pathways, control loops, and key subsystems (such as radiators and thermal buffers) that will regulate heat flow during both active operations and dormant phases. This is followed by a Heat Load Analysis and Simulation, where transient and steady-state thermal behaviors are modeled based on mission scenarios, equipment dissipation, and environmental exposure.
Once the architecture is validated, attention shifts to the Radiator and Design block. This includes the design and testing of the radiator panel deployment mechanism, enabling passive heat rejection once the rover is on the lunar surface. The system undergoes infrared thermography testing to verify its ability to effectively dissipate waste heat in vacuum and low-gravity conditions.
Thermal storage and regulation are further enhanced through the integration of PCM (Phase Change Material) Containers, whose design and placement must be optimized for balancing thermal inertia. The components are then physically realized in the Thermal Control Subsystem Fabrication step and subsequently integrated with the EMU (Energy Management Unit) to ensure synchronized power-thermal behavior during both normal and contingency operations.
The final phase is Thermal Vacuum Testing (TVAC), during which the complete thermal system is subjected to vacuum chamber simulations replicating lunar environmental conditions. This test validates heat rejection efficiency, thermal gradients, and overall system stability under cycles of exposure and shadow.

The fifth phase is the **Power System Integration**, and it is central to ensuring that all onboard systems receive stable, regulated, and redundant energy throughout the mission. This WBS guides the process from system-level load definition through the physical integration of multiple power sources, including advanced batteries, dynamic isotope modules, and energy control units.

The first step is the Power System Architecture & Load Map, which involves determining nominal and peak loads for each subsystem, ensuring that energy demands are met even under stress or fault conditions. This includes defining redundancy strategies and emergency fallback options, which are critical for mission assurance, and specifying the interface requirements with the Energy Management Unit (EMU).
Next, the team focuses on the Dynamic Isotope Power System (DIPS) Integration. This segment begins with the fabrication of a mechanical mounting frame for the DIPS core, followed by the inclusion of radiation shielding to ensure crew and electronics safety. A thermal control link is then established between the DIPS and the main radiator system, allowing passive dissipation of waste heat. Finally, the electrical output is routed to the EMU, creating a seamless power transfer path from generation to distribution.
In parallel, the Sodium-Sulfur Battery Subsystem is developed. This includes the design and thermal insulation of the battery pack enclosure, configuration of the charging logic and interface with DIPS, and routing of power taps along with voltage regulation circuits. Before deployment, the system undergoes battery stress testing and safety validation to mitigate risks of overheat, leakage, or electrical failure.
The Energy Management Unit (EMU) acts as the central controller, regulating energy flow based on operational mode. Tasks include defining switching priorities for nominal, EVA (extravehicular activity), and fault scenarios, implementing firmware control logic, and conducting subsystem interface verification to ensure communication and safety across all power sources.
Finally, the entire system is brought together in the System Integration & Testing phase. This includes a functional test of power cycles, overload simulations, and verification of EMU failover behavior under abnormal loads. The last step is an EMI (Electromagnetic Interference) and safety compliance review, confirming that the integrated power system is ready for operation. Once completed, the milestone "TCS and Power Integrated" marks the successful conclusion of this critical subsystem.

The sixth phase is the **Mobility System**, which is responsible for enabling controlled, reliable movement of the Semi-Stationary Rover across the lunar surface. This WBS encompasses the definition of system-level mobility requirements, mechanical design of suspension and wheels, integration of control electronics, and final subsystem-level testing and calibration.
The process begins with the Mobility Requirements Definition, where the team evaluates power demands, defines speed profiles for nominal and contingency scenarios, and accounts for structural constraints such as rover mass, balance, and stability on rugged terrain.

Next comes the Suspension System Design and Manufacturing, starting with FEA simulations for terrain-induced loading and torque distribution. These analyses inform the fabrication of the rocker and bogie suspension system, which is essential for maintaining wheel-ground contact. The assembly then undergoes vacuum chamber testing of joints and hinges to verify mechanical reliability under space-like conditions.
In the Wheel Design and Production phase, motors are physically integrated into the wheel assemblies, and power harnesses are routed through the structure to interface with the Energy Management Unit.
Attention then shifts to the Mobility Controller Integration, where software and hardware work together to manage redundant control logic for motor synchronization. The system also incorporates terrain sensing and adaptive torque distribution, improving mobility performance over soft or uneven surfaces.
The final stage is Subsystem Testing & Calibration, consisting of several critical verifications: a load-bearing test under full rover weight, a drive endurance test for long-duration operation, and simulations of motor-overheat and fault scenarios to ensure safe system response. Once these tests are passed, the mobility system is fully installed, and an engineering model is completed, allowing integration with the rest of the rover.

The seventh phase is the **Life Support System (ECLSS)**, which ensures environmental control, atmosphere revitalization, water recovery, waste management, food provision, and crew health monitoring within the pressurized cabin. This system is crucial for supporting human presence on the lunar surface and is built around modular, integrated subsystems that operate in closed-loop or semi-closed-loop configurations.
The phase begins with ECLSS Architecture Definition, where engineers perform metabolic load analysis for oxygen, water, and food consumption based on mission duration and crew size. This is followed by subsystem placement and mass balancing, ensuring that the ECLSS layout is structurally feasible and thermally integrated.
The Air Revitalization Module (ARM) Integration includes the installation of O_2 tanks and a backup electrolysis system to ensure oxygen availability. A CO_2 scrubber system using lithium hydroxide or solid amine beds is implemented to remove carbon dioxide, along with filters for humidity and volatile organic compounds (VOC).
The Water Management Module (WMM) addresses water recovery and recycling. It includes greywater collection from the cabin and waste disposal system, a filtration and distillation unit, humidity condensing heat exchangers, and a refillable water tank for continuous crew hydration and hygiene.
The Food Provision Module (FPM) ensures mission sustenance with a 14-day

dehydrated food pack, rehydration and heating systems, and dedicated storage racks for food containment and weight distribution.
The Waste Disposal Module (WDM) includes a urine filtration loop, vacuum-sealed bags for fecal waste, and volume/mass sensors to track disposal cycles and storage capacity, minimizing contamination risks.
Crew wellness is maintained through the Crew Health Module (CHM). This comprises exercise equipment (e.g., treadmill or resistance bands), a medical kit with biometric monitoring, and telemedicine protocols for remote diagnostics and emergency interventions.
The final block is System-Level Testing & Safety Validation, involving a sealed ECLSS cabin test under nominal conditions, fault injection scenarios such as CO_2 buildup and water loss, and verification of crew safety procedures and emergency overrides.
Successful completion of this phase is marked by the "Life Support Ready" milestone, confirming the system's readiness for human occupation.

The eighth phase is **Communication & Autonomy Systems**, which encompasses all the components and operations required to enable the Semi-Stationary Rover to establish communication with external infrastructure and perform autonomous actions during the mission.
This phase begins with defining the Comm System Architecture and Requirements, including conducting a link budget analysis between Earth and the Moon to assess data transmission feasibility. Interfaces are established with the rover's central processing unit (CPU) and the Energy Management Unit (EMU), while developing standardized lunar communication protocols compatible with other lunar assets.
Once communication interfaces are defined, the High-Gain Antenna Installation phase begins. This includes the mechanical integration of the antenna into the rover structure and the signal routing to the CPU and EMU, ensuring both long-distance and internal data flow capabilities.
The next step is the Local Communication System Setup, where the radio modules are installed inside the rover. Antenna placement is optimized for reception and dust protection, and a pairing test with a mock lunar station is performed to validate communication reliability under simulated conditions.
The core of the autonomy capability is addressed in the Onboard Autonomy Core section. A diagnostic agent is developed to continuously monitor the health of vital systems such as the Thermal Control System (TCS), EMU, and ECLSS. A safe-mode script library is also included, offering predefined responses to common failure scenarios (e.g., overheating, communication loss). An override and manual control interface allows human operators to intervene when required.
Finally, all functions are validated during the Integrated System Test & Simulation. This includes mission communication scenario simulations, fault injection tests

(such as simulated sensor failure or thermal overload), and manual override and recovery drills, ensuring the rover can respond to both autonomous and operator-guided inputs.

The ninth phase is **Crew Interface & Habitability**, which focuses on ensuring that the internal environment of the Semi-Stationary Rover is functional, safe, and livable for crew operations during lunar missions. It balances technical layout with ergonomic comfort to support human needs in an enclosed, remote environment.
The phase begins with Interior Layout Planning, which defines the volume allocation of the cabin to prioritize accessibility and functional distribution. Safety path planning and reachability mapping are also developed, allowing astronauts to navigate the interior safely and efficiently, especially under emergency or constrained conditions.
Next, Crew Accommodations Setup is implemented, including the installation of sleeping/restraint systems, as well as food and equipment lockers to organize essential supplies and optimize weight distribution within the cabin.
The Lighting & Control Interfaces component ensures usability and visibility. It includes the installation of LED lighting strips for task and ambient illumination, and the setup of a main control interface (including a screen and physical buttons) to monitor and operate onboard systems.
A critical access point for lunar surface operations is developed through the EVA Hatch and Docking System. This includes a pressure equalization system, a fully airlock-rated EVA-compatible hatch, and an external docking ring designed for compatibility with a suitport or other docking systems.
Finally, a comprehensive Integrated Habitability Test validates the livability of the cabin. This includes a simulated 48-hour crew occupancy with full system usage, followed by emergency access drills simulating scenarios like fire or life-support failure. The phase concludes with the Flight Model Qualification Gate, which certifies the system as compliant for integrated crew use.

The tenth phase is **System Integration & Testing**, a crucial stage in which all subsystems previously developed and validated individually are brought together and tested as a unified whole to verify their correct interaction and overall functionality.
This phase starts with Subsystem Integration (Mechanical & Electrical). It includes structural and mechanical assembly, electrical harnessing, and subsystem wiring, ensuring that all physical and electronic interfaces are properly connected. Additionally, it involves EMI shielding, cable bundling, and connector stress relief to ensure robustness against environmental conditions and mechanical vibrations.
Following integration, the system undergoes Functional Testing by Subsystem. This step confirms that each major system works correctly when integrated. Specific

tests include: Power and EMU functional test, Life Support and Environmental systems test, Mobility and steering response evaluation, Communication and autonomy check and Lighting, human-machine interface (HMI), and interior usability test.
After the functional validation, the vehicle proceeds through Environmental Qualification Testing to verify its readiness for the space environment. This includes a thermal vacuum chamber run to simulate lunar temperatures and vacuum, a vibration and launch profile simulation to test launch survivability, and EMI/EMC validation to ensure electromagnetic compatibility.
The final step is the Mission Simulation Test, where the rover is tested in a full mission scenario. This involves a 72-hour sealed operational test, simulated EVA with docking and reentry, and contingency drills, such as failure injection to assess system response and crew readiness. Upon successful completion, the system reaches the Subsystem Integration Complete milestone, followed by the Launch Readiness Review, marking the transition from development to deployment preparation.

The eleventh and final phase is **Documentation, Verification & Delivery**, marking the culmination of the rover development process and ensuring the system is formally approved, properly archived, and prepared for launch logistics.
This phase begins with a comprehensive Quality Review & Verification, which revisits all technical and process requirements, checking that each has been met through documented tests, inspections, and verifications. It ensures no aspect of the rover's design, safety, or performance is left unvalidated.
Following this, the Final Documentation & Certification step compiles all engineering records, test results, risk mitigations, software versions, and configuration files into formal deliverables. These documents serve as the official record of the system's compliance with mission and safety requirements and are essential for mission authorities and launch providers.
With technical and administrative approval secured, the project proceeds to Shipping Preparation & Launch Integration Support, which includes the packaging of the rover with launch-specific constraints in mind, environmental conditioning, and coordination with launch interface teams for mechanical and electrical compatibility at the integration site.
The phase concludes with the Full System Qualified milestone, indicating that the Semi-Stationary Rover is officially ready for deployment and compliant with all mission requirements-structurally, functionally, and procedurally.

3.3.4 Project Milestones

In parallel with the hierarchical WBS, a set of key project milestones has been identified to mark the completion of major subsystems and critical integration tasks. Each milestone represents a logical validation point in the rover's development timeline, used to verify scope completion and coordinate cross-functional handoffs. As illustrated in Figure 3.14, the milestone plan spans across all major WBS branches:

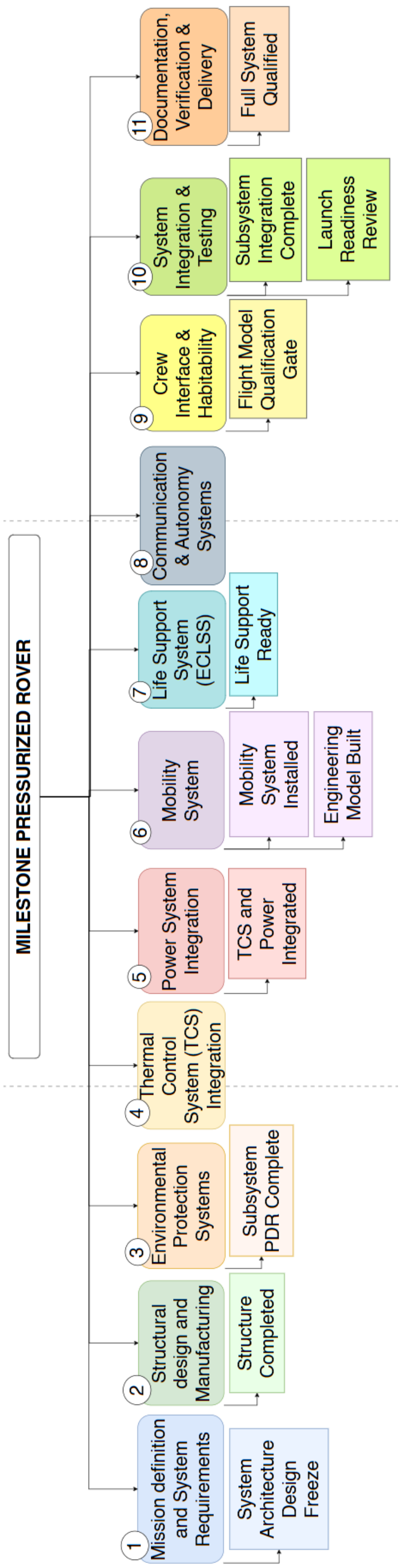


Figure 3.6: Stationary Rover Milestone WBS

Each of the milestones represented in the diagram is strategically placed within the Work Breakdown Structure to reflect a pivotal point in the development and verification of the Semi-Stationary Rover. The first milestone, **System Architecture Design Freeze**, marks the conclusion of Phase 1 and serves as the official lock-in of system-level requirements and architectural decisions. This freeze ensures consistency and traceability for all downstream engineering activities, forming the foundation upon which the structure and subsystems will be developed.

Following the completion of the structural design and manufacturing activities, the **Structure Completed** milestone validates that the primary mechanical frame and its key interfaces are ready for subsystem installation. This milestone is particularly critical as it enables physical integration to begin, moving the project from theoretical planning to tangible hardware assembly.

The third milestone, **Subsystem PDR Complete**, situated at the end of Environmental Protection Systems development, confirms that each environmental subsystem-such as shielding, micrometeoroid protection, and isolation-has passed its Preliminary Design Review. This indicates readiness to transition from concept to prototyping and integration, especially for safety-critical elements like radiation protection and storm shelters.

As the project progresses into thermal and electrical system integration, the **TCS and Power Integrated** milestone validates successful physical and logical coupling between the Thermal Control System and Power System. This milestone is crucial for ensuring that temperature regulation and power distribution are fully aligned and operational under combined test conditions.

In Phase 6, after installing actuators, suspensions, and the driving logic, the **Mobility System Installed** milestone confirms the completion of mechanical integration and initial checks. This is followed by the **Engineering Model Built**, which denotes that a functional prototype reflecting the final mobility configuration has been constructed and tested under representative conditions.

The **Life Support Ready** milestone at the end of Phase 7 is a decisive marker confirming that all ECLSS (Environmental Control and Life Support System) components-air, water, waste, food, and medical systems-are validated and operable. This milestone is fundamental for validating habitability and crew survivability.

Later, in Phase 9, **Flight Model Qualification Gate** acts as a checkpoint ensuring the internal interfaces, human factors systems, and crew accommodations meet launch-readiness and safety thresholds. It demonstrates that the pressurized volume and crew interface are aligned with EVA, docking, and safety requirements.

Phase 10 includes two major milestones. **Subsystem Integration Complete** confirms that all mechanical, electrical, and software subsystems have been successfully assembled and interfaced. Shortly thereafter, the **Launch Readiness Review** milestone certifies that the full rover is fully tested, qualified, and operationally prepared for delivery to the launch provider.

Finally, the milestone **Full System Qualified** in Phase 11 represents the closure of all verification processes, the finalization of documentation, and the handoff of the rover for transport and launch integration. It marks the formal end of the development lifecycle and the rover's transition to mission readiness.

Together, these milestones form a backbone of validation across the WBS. They allow the project to track progress, manage dependencies between engineering teams, and ensure system integrity throughout development. Their distribution is not arbitrary-they reflect key technical dependencies and integration logic, reinforcing the overall system architecture with structured check-points and decision gates.

3.3.5 Gantt Chart e Critical Path Method (CPM) for the Semi-Stationary Rover

Gantt Chart

The Gantt chart is a fundamental tool in project management used to visually represent the project schedule over time. It allows the project team to map out activities, assign durations, and sequence dependencies between tasks. Each activity is displayed as a horizontal bar along a time axis, making it easy to understand when each phase begins, how long it is expected to last, and how it overlaps with other phases. In more advanced stages of planning, it also enables tracking progress in terms of completion percentage.
Figure 3.7 provides a global view of the Gantt chart for the Semi-Stationary Rover project. The vertical axis lists the major Work Breakdown Structure (WBS) elements, while the horizontal axis shows the timeline extending from the start of 2026 through the mid-2030s. Each bar represents a specific task or WBS category, annotated with its planned duration and start/end dates. This visualization helps align interdisciplinary teams, identify critical overlaps, and plan for timely resource allocation across subsystems.

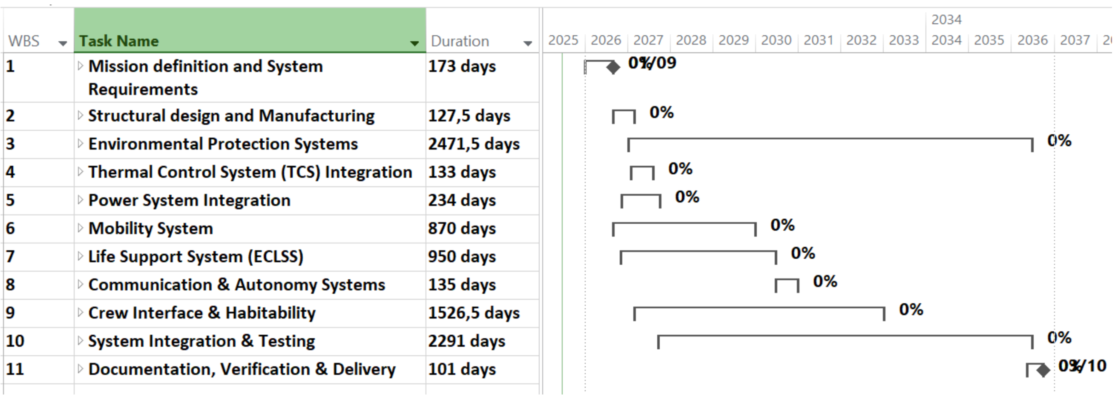


Figure 3.7: Gantt Chart Stationary Rover

As shown in Figure 3.7, the major phases-ranging from structural manufacturing to system integration. Milestones such as *System Architecture Freeze, Structure Completed,* and *Full System Qualified* punctuate the timeline and serve as reference points for project tracking.
The longest task is *Environmental Protection Systems*, which spans almost the entire duration of the project. It begins in late 2026 and remains active throughout, as it undergoes multiple adjustments and revisions following the completion of other subsystems. Its full integration occurs only at the final stages, since many of its operations depend on or must follow the completion of tasks that begin later in the schedule. The same can be said for the *System Integration & Testing* phase, which also spans multiple subsystems and depends on late-stage inputs. Each bar in the Gantt chart corresponds to a WBS element and reflects:

- Planned duration
- Start and end dates
- % completion (currently at 0% for all elements, as this is a baseline planning stage)

Critical Path Method

In Microsoft Project, the Critical Path Method (CPM) is used to identify the sequence of tasks that directly impact the project end date. These critical tasks have zero float and require careful monitoring. The critical path can be made visible within Microsoft Project by enabling the "Critical Tasks" view. Tasks on the critical path are highlighted in red in the software interface, in the figure 3.8 below it is represented using the color of each WBS to enable the link for each of them and the arrows are in red to identified the Critical Path. This path is essential for determining schedule flexibility and highlighting high-risk delay points. Based on the scheduling analysis, the critical path flows through the following major workstreams.

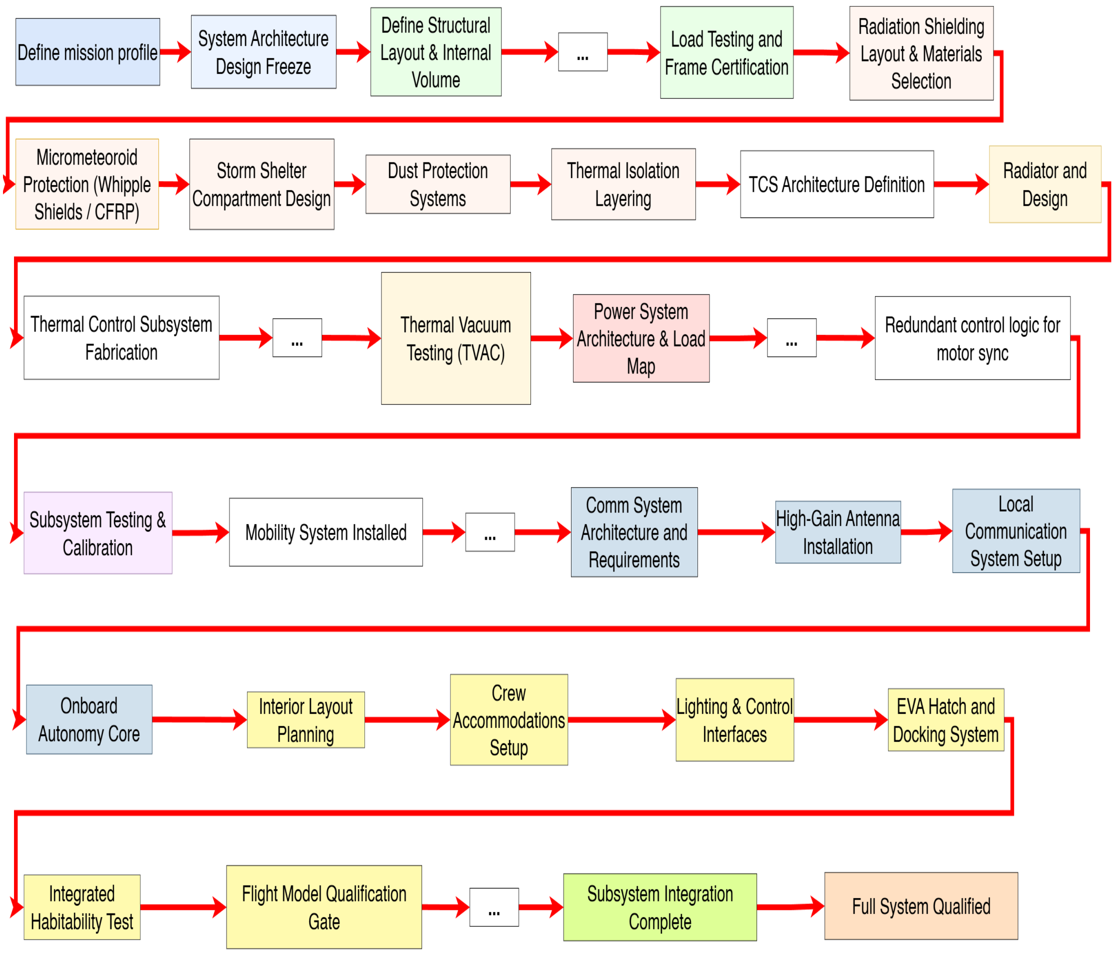


Figure 3.8: Critical Path Semi-Stationary

These activities span across multiple WBS components, forming a tightly connected chain of dependencies. The complexity arises from both intra-system sequences and cross-system integration points. Key project milestones such as:

- System Architecture Design Freeze
- Flight Model Qualification Gate
- Full System Qualified

are all located along the critical path, making them essential control points for progress tracking.

This analysis of the project timeline and critical dependencies not only supports informed decision-making and risk mitigation but also establishes a temporal framework upon which resource allocation and budget planning can be built. With the schedule baseline and critical path defined, the next step is to assess the Preliminary Cost Estimation, ensuring that each WBS element is supported by a realistic financial projection and aligned with mission feasibility constraints.

3.3.6 Preliminary Cost Estimation

The preliminary cost estimation of the Semi-Stationary Pressurized Rover was developed using a structured approach based on the project's Work Breakdown Structure (WBS), detailed resource allocation, and a set of validated benchmarks from prior aerospace programs. This analysis was carried out within Microsoft Project, allowing for a granular mapping of costs tied to each project phase-from mission definition through to final delivery. The cost modeling integrates both labor and material expenditures and is designed to span the entire engineering lifecycle.

To ensure the estimates reflect realistic and industry-aligned figures, data sources were carefully selected from reputable and applicable references. Among these were publicly available reports and documentation from space agencies such as NASA, ESA, and CNES, which included programs like Artemis, HERACLES, and MELiSSA. Additional guidance was drawn from key methodological references such as the ESA Cost Engineering Handbook [20] and the NASA Cost Estimating Handbook (CEH) [21], which offer structured methodologies for evaluating complex system costs. Academic studies and analog mission reports-such as the Mars Design Reference Architecture and ISS module development-provided further comparative grounding.

Labor costs were estimated based on average European engineering contract norms, ranging between €120 and €180 per hour depending on the expertise required. For hardware components, commercial values were approximated using market data on known items such as lithium battery packs, thermal radiators, and heat exchangers, ensuring a realistic representation of procurement costs in the aerospace sector.

Cost Distribution

WBS	Task Name	Duration	Start	Finish	Cost
1	Mission definition and System Requirements	222,5 days	Thu 23/10/25	Tue 01/09/26	594.800,00 €
2	Structural design and Manufacturing	127,5 days	Tue 01/09/26	Thu 25/02/27	100.379.000,00 €
3	Environmental Protection Systems	2471,5 days	Thu 07/01/27	Mon 30/06/36	221.193.600,00 €
4	Thermal Control System (TCS) Integration	133 days	Thu 28/01/27	Tue 03/08/27	91.005.320,00 €
5	Power System Integration	234 days	Tue 10/11/26	Mon 04/10/27	72.480.240,00 €
6	Mobility System	870 days	Tue 01/09/26	Tue 01/01/30	120.738.000,00 €
7	Life Support System (ECLSS)	950 days	Tue 03/11/26	Mon 24/06/30	50.473.200,00 €
8	Communication & Autonomy Systems	135 days	Tue 25/06/30	Mon 30/12/30	50.428.800,00 €
9	Crew Interface & Habitability	1526,5 days	Thu 25/02/27	Mon 03/01/33	50.179.600,00 €
10	System Integration & Testing	2291 days	Fri 17/09/27	Mon 30/06/36	200.322.160,00 €
11	Documentation, Verification & Delivery	101 days	Thu 15/05/36	Fri 03/10/36	672.000,00 €

Figure 3.9: Costs, durations of Stationary Rover

Figure 3.9 presents the synthesized output of the project planning phase, as derived directly from Microsoft Project. It displays the 11 primary WBS elements, each annotated with its planned duration (in working days), estimated start and finish dates, and the corresponding cost in euros. This table is not merely a static snapshot, but the result of dynamic modeling based on team assignments, resource loading, and system-specific requirements. The costs associated with each branch were calculated by aggregating the labor rates of assigned engineering teams and the material or component costs associated with each task.
Rather than pursuing a cost-minimization strategy, the estimation logic was guided primarily by schedule compliance. In fact, the underlying rationale favored compressing project timelines by increasing workforce capacity or parallelizing tasks when necessary. This means that in several branches, especially those with long durations or critical integration roles, higher costs are the direct result of allocating more personnel or overlapping engineering streams to meet overall delivery deadlines.
In other words, instead of extending timelines to save on workforce intensity, the project plan accepts higher short-term expenditure in order to secure on-time delivery of complex, interdependent systems. This design choice reflects a priority on feasibility and reliability within a constrained schedule, rather than purely budget-optimized execution.
The total cost across all major subsystems and project phases reaches a preliminary figure of approximately **1.0 billion euros**, with major contributors being:
Environmental Protection Systems, budgeted at approximately €221.2 million. The scope of this work package spans advanced shielding for radiation (GCR and SPE),

micrometeoroid protection (e.g., Whipple shields, CFRP panels), storm shelter systems, and regolith sealing. These subsystems require high-performance materials, iterative testing under simulated lunar conditions, and complex integration with the rest of the vehicle. Moreover, the environmental systems must be continuously validated as other subsystems evolve, leading to recurring design and verification cycles that compound the cost.

The System Integration & Testing phase follows closely with €200.3 million. This cost is attributable to the extensive effort required to assemble, wire, and verify all mechanical, electrical, and software subsystems. Functional testing, environmental qualification, fault injection scenarios, and full mission simulations are included within this WBS. Notably, these activities require the use of full-scale testbeds and sealed environments to emulate lunar operations, further raising the need for infrastructure and expert support.

Lastly, Structural Design and Manufacturing, which amounts to €100.4 million, includes the conception and fabrication of the rover's primary load-bearing architecture. This entails not only mechanical design and FEA validation, but also manufacturing of pressure vessels, bulkheads, and hatches using aerospace-grade alloys or composite materials. Non-destructive testing (NDT), vacuum chamber qualification, and frame-level certification are all part of this domain, demanding both precision and redundancy.

In summary, the elevated costs observed in these branches are not incidental, but rather the consequence of their technical complexity, criticality to mission safety, and reliance on specialized human and physical resources. They represent the backbone of the rover's operability and qualification for lunar deployment.[3]

Resources and Team Roles

The Microsoft Project plan includes a detailed resource sheet (figure 3.10) defining labor categories with hourly rates and maximum capacity levels:

[3]Notably, the Environmental Protection Systems (WBS 3) stand out as one of the most costly due to long-duration testing (e.g., regolith sealing, radiation shielding validation), while System Integration and Testing (WBS 10) includes high effort costs related to final reviews, and multi-system validation.

	Resource Name	Type	Initials	Group	Max.	Std. Rate	Ovt. Rate	Cost/Use	Generic
	Structural Engineering Team	Work	S	Engineering	500%	150,00 €/hr	0,00 €/hr	0,00 €	Yes
	Thermal Systems Team	Work	TCS	Engineering	500%	160,00 €/hr	0,00 €/hr	0,00 €	Yes
	Power & Avionics Team	Work	P&A	Engineering	500%	170,00 €/hr	0,00 €/hr	0,00 €	Yes
	Mobility & Suspension Team	Work	M	Engineering	500%	140,00 €/hr	0,00 €/hr	0,00 €	Yes
	ECLSS Integration Team	Work	ECLSS	Environmental Systems	500%	180,00 €/hr	0,00 €/hr	0,00 €	Yes
	Communications & Autonomy Team	Work	CA	Software & Systems	500%	160,00 €/hr	0,00 €/hr	0,00 €	Yes
	Crew Systems & Habitability Team	Work	CH	Human Factors	500%	130,00 €/hr	0,00 €/hr	0,00 €	Yes
	QA & Testing Team	Work	QA	Quality Assurance	500%	140,00 €/hr	0,00 €/hr	0,00 €	Yes
	Project Management Office	Work	PROJ	Management	500%	180,00 €/hr	0,00 €/hr	0,00 €	Yes
	Assembly Technician	Work	A		500%	120,00 €/hr	0,00 €/hr	0,00 €	Yes

Figure 3.10: Work Resources of Stationary Rover

Each row represents a different specialized team involved in the engineering and verification phases of the mission, while the columns define key properties used in cost and schedule estimation.
The Resource Name identifies the team or functional unit, such as the Structural Engineering Team or the QA & Testing Team. These are logical resource groupings rather than individual personnel, aligning with major engineering domains from the WBS.
The Type of all entries are set as “Work” resources, which means they are human resources contributing labor hours to tasks. This is in contrast to material or cost resources, which are used for expendables and fixed charges.
The Group column organizes each resource under its broader discipline, such as Engineering, Human Factors, or Software & Systems. It aids in sorting and filtering resources during analysis or workload balancing.
The Max.is set to 500% for all resources, this field defines the maximum availability of the resource. In Microsoft Project, 100% corresponds to one full-time equivalent (FTE). Thus, 500% indicates a team of 5 full-time staff members available concurrently. This value is not derived from empirical staffing data but is a design assumption made to ensure project timelines remain within a plausible execution window. A smaller team would reduce costs but significantly increase project duration, which was not aligned with the planning objectives of this study.
The Std. Rate is the standard hourly rate (in euros) assigned to each resource. The values range from €120/hr for general technicians to €180/hr for high-skilled teams such as project management or ECLSS integration. These figures are based on typical European space engineering labor rates and serve as the basis for all labor cost calculations.
This configuration balances a realistic modeling of labor intensity and cost, while retaining flexibility in planning assumptions. It enables scalable project simulations and cost analyses without requiring precise headcounts or personnel rosters at this stage.

Material and Fixed Costs

The project budget also includes a predefined set of critical material elements, represented in the figure 3.11.

Composite Materials	Material	CM	25.000,00 €	CFRP, bulkhead, shell
Lithium Batteries	Material	L	100.000,00 €	Sodium-sulfur modules
Heat Pipes	Material	H	50.000,00 €	Thermal loop components
Oxygen Tanks	Material	O	40.000,00 €	For ARM system
Radiators	Material	R	3.000,00 €	Passive heat rejection
PCM Modules	Material	PCM	3.000,00 €	Thermal buffering
Environmental Testing	Cost	E		TVAC, EMI, regolith chamber
Launch Integration Services	Cost	LIS		Final prep before shipment
Software Licenses	Cost	SL		CAD, FEM, FMEA tools

Figure 3.11: Material Resources of Stationary Rover

This figure captures the non-labor resources allocated for the Semi-Stationary Rover project in Microsoft Project, encompassing both material and fixed cost resources. These entries complement the human resource configuration and represent all the tangible components and contracted services necessary for the design, assembly, and qualification of the vehicle.

The top portion of the table outlines the material resources, which include critical components integrated into various rover subsystems. Each entry specifies a fixed unit cost, reflecting a one-time expenditure per component rather than an hourly rate. For instance, composite materials are listed with a cost of €25,000, intended for high-performance structural elements like the CFRP (carbon fiber reinforced polymer) bulkhead and shell. Similarly, the lithium battery pack-necessary for power autonomy and emergency backup-is priced at €100,000, representing a tailored sodium-sulfur module designed for lunar applications. Additional components such as heat pipes (€50,000) and PCM modules (€3,000) support the thermal control system, ensuring heat rejection and buffering capacity under vacuum conditions. Items like oxygen tanks (€40,000) are associated with life support, specifically the ARM subsystem, and are costed according to both capacity and reliability standards. These values were drawn from a mix of commercial aerospace vendor pricing and analog projects documented in ESA and NASA procurement records.

The lower section of the figure lists cost-type resources, which are used to represent services or licenses that are charged per occurrence or project phase. “Environmental Testing” covers complex operations such as TVAC (Thermal Vacuum Chamber) tests, EMI shielding validation, and regolith exposure chambers—key activities required before subsystem qualification. “Launch Integration Services” refers to operations such as final system inspection, shipment packaging, and compatibility

check with launch systems—typically outsourced to a contractor during the mission delivery phase. Finally, “Software Licenses” bundles access to mission-critical digital tools (CAD platforms, FEM solvers, FMEA databases) necessary for design, simulation, and risk analysis throughout the engineering workflow. These are modeled as fixed charges and not tied to task durations.
All of these resource entries follow a structured logic based on realistic unit cost assumptions, allowing Microsoft Project to estimate total subsystem costs as soon as these resources are assigned to WBS tasks. Importantly, this data bridges the gap between design abstraction and cost forecasting, offering planners a quantitative sense of the capital investment associated with subsystem complexity and technological readiness.

3.4 Transport Pressurized Rover Mission

Figure 3.12: Possible representation of PR

The Transport Pressurized Rover Mission, in figure 3.12, created by the author using Artificial Intelligence (AI), represents a significant statement in crewed lunar surface operations, enabling long-range exploration, sample retrieval, and logistical flexibility across different lunar areas. Unlike the Semi-Stationary Mission, which focuses on localized analysis and habitat stability, this mission relies on a high-mobility rover platform engineered to traverse extended distances at speeds of up to 10-15 km/h. This mobility capability allows astronauts to access remote geological sites, transport equipment or samples, and support distributed exploration strategies far beyond the immediate vicinity of the main lunar base.

The core design of the transport rover prioritizes range, endurance, and surface coverage over onboard analysis and station-keeping. Scientific activities are supported primarily through sample acquisition and preservation, with detailed analysis expected to occur post-mission or in dedicated lab environments. The rover must therefore be equipped with robust navigation systems, long-duration life support, advance mobility system and sufficient storage capacity to sustain multi-day transfers without requiring constant return to the primary outpost. Through its extension of lunar mission operational capabilities, the Transport Pressurized Rover plays a key role in enabling scalable surface exploration, preparing the road for in-situ resource utilization, permanent surface infrastructure, and inter-base connectivity for future lunar settlement operations.

3.4.1 Mission Objectives and Requirements

Enable crewed access to unexplored and remote lunar regions with a transport pressurized rover capable of advanced surface mobility and vision's instruments, supporting extended traverses, and collected samples.

To make sure that the Transport Mission will be successfully completed, there has been an in-depth functional analysis. The exercise identifies the core capabilities the pressurized lunar rover must possess to meet mission objectives when operating under the constraints of the lunar environment. The following list constitutes the primary functions identified from the mission concept based on human survivability, advance mobility, extended traverses, advance instruments of vision and storage samples.

- Ensure crew survival through a complete life support system (oxygen, CO_2 removal, pressure, humidity)
- Maintain internal thermal stability
- Monitor and control internal environmental parameters (air composition, temperature, humidity)
- Enable safe ingress and egress of astronauts during lunar operations (EVA compatibility)
- Support advance mobility for extended surface traverses
- Navigate and maneuver across uneven, sloped and variable terrain
- Ensure sufficient ground clearance and traction control for rough or regolith paths
- Enable mobility speeds up to 10–15 km/h to support timely access to distant sites

- Provide visual navigation support through forward-facing windows, cameras, and terrain imaging systems
- Storage and preserve collected samples
- Provide continuous communication with mission control and interoperability with other lunar assets (e.g., rovers, landers)
- Detect and respond to system anomalies or failures autonomously or via ground support
- Enable power generation and storage for all onboard systems for the entire mission duration, both lunar day and extended periods of darkness
- Distribute and manage power across all critical subsystems (mobility, life support, communications, etc.)
- Provide structural protection against micrometeorites, lunar regolith, and radiation
- Guarantee operational autonomy for multi-day excursions without needing to return to the base

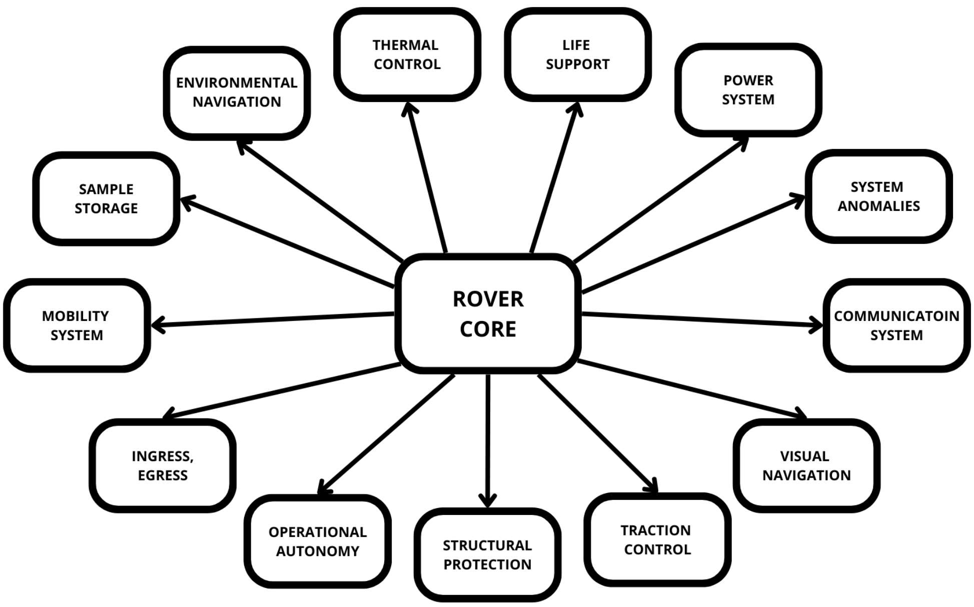


Figure 3.13: Transportation Rover Core

The following table outlines the specific mission requirements corresponding to each primary functional capability of the Transport Pressurized Rover. These requirements are derived from the mission objectives and environmental constraints of lunar surface operations.

Table 3.5: Functions and Corresponding Requirements

Function	**Requirement**
Crew survival through a complete life support system	The rover shall maintain habitable conditions by providing breathable air, pressure regulation, CO_2 removal, humidity control, and emergency oxygen backup for the entire mission duration.
Internal thermal stability	The rover shall maintain internal temperatures between 18°C and 26°C under varying external lunar conditions, including day/night cycles.
Monitor and control internal environmental parameters	The rover shall include sensors and control systems to continuously monitor and regulate temperature, humidity, air composition, and cabin pressure.
Safe ingress and egress of astronauts	The rover shall provide a pressurized docking interface and EVA-compatible hatch system to allow safe entry and exit in lunar surface suits.
Support advance mobility	The rover shall feature a drive system capable of sustained high-speed traversal, multi-wheel steering, and power distribution optimization for extended lunar driving.
Navigation and maneuver - ground clearance and traction control	The rover shall be equipped with an articulated suspension system and terrain-adaptive traction control, capable of clearing surface obstacles and maintaining stability on slopes up to 30°.
Mobility speeds up to 10-15 km/h	The propulsion system shall allow for continuous movement at speeds of up to 10-12 km/h over flat terrain, with controlled speed modulation based on terrain roughness.
Provide visual navigation support	The rover shall be equipped with forward-facing windows, panoramic external cameras, stereo vision sensors, and a terrain analysis system to support autonomous or assisted navigation.

Function	Requirement
Storage and preserve collected samples	The rover shall include dedicated sealed containers for storing geological samples in a controlled environment to prevent contamination or degradation.
Continuous communication with mission control and interoperability with other lunar assets	The rover shall maintain continuous bidirectional communication with mission control and support local communication protocols for coordination with other rovers or landers.
Detect and respond to system anomalies or failures autonomously or via ground support	The rover shall be equipped with diagnostic and fault detection systems capable of issuing alerts, initiating safe modes, and responding to faults with predefined actions.
Enable power generation for all onboard systems for the entire mission duration	The rover shall generate at least 8 kW of continuous power via a Dynamic Isotope Power System (DIPS) to ensure full operational autonomy during both lunar day and night.
Distribute and manage power across all subsystems	The rover shall include an energy management unit (EMU) capable of allocating power based on subsystem priority and load balancing under varying demand.
Guarantee operational autonomy for multi-day excursions	The rover shall support autonomous operation for missions lasting up to 18 days without returning to the base, including energy, life support, navigation, and communications. (The number is chosen to test its capability also during the lunar night).
Provide structural protection against micrometeorites, lunar regolith, and radiation	The rover shall be constructed with multilayer shielding to protect the crew and critical systems from radiation, dust intrusion, and micrometeorite impacts.

3.4.2 System Overview

The Transport Pressurized Rover (TPR) is designed to significantly extend the operational radius and flexibility of human exploration on the lunar surface. Unlike the semi-stationary rover, which remains largely fixed near a site, the TPR enables long-range traverses at an average speed of 12 km/h, allowing astronauts to reach and investigate remote targets, potential resource sites, and future base locations. The core goal of the mission is to validate technologies and operational procedures for extended surface mobility, independent navigation, and self-contained life support-key capabilities for future permanent lunar infrastructure and inter-outpost connectivity.

Mobility and Mission Duration

With its high-torque electric drive and adaptive suspension system, the Transport Pressurized Rover (TPR) is capable of traversing sloped, uneven, and regolith-covered lunar terrain with stability and control. The vehicle is engineered to sustain long-range mobility missions, enabling exploration far beyond the immediate vicinity of a fixed base.
The mission duration is projected at 18 Earth days, covering a full 14-day lunar daytime phase plus an additional 4-day buffer to validate rover performance under partial lunar night conditions. This extended profile allows comprehensive testing of power resilience, thermal regulation, and crew survivability across the widest range of environmental conditions likely to be encountered during future permanent operations.
Operating at a nominal cruising speed of 10-15 km/h, and assuming an average of 8-10 hours of traveling per day, the rover can cover between 80 and 120 km per day. While continuous travel over the full mission duration is not expected due to time allocated for EVA, rest, scientific documentation, and navigation planning, a conservative estimate assumes at least 10 days of active traversal. This results in a realistic mission range of approximately 800 to 1200 km. Depending on operational efficiency and surface conditions, this value may increase if the rover is used more intensively across additional days.
The assumption of 10 days of active movement within the 18-day mission window reflects a realistic operational balance. It accounts for alternating traverse and EVA days, rest and planning intervals, as well as contingency margins. This cadence ensures crew health, logistical feasibility, and flexible response to dynamic surface conditions, while still achieving a significant exploration range.

Navigation and Terrain obstacles

Due to its extended range and operational autonomy, the Transport Pressurized Rover is equipped with an advanced navigation and terrain sensing system. The rover uses a hybrid of (Light Detection and Ranging) LIDAR-based terrain mapping, stereo vision cameras, visual odometry, and inertial measurement units (IMUs) to perform accurate real-time localization and path planning, even in areas without line-of-sight to the base station.
Autonomous obstacle avoidance algorithms and terrain classification routines are

executed onboard, reducing reliance on ground control and enabling safe traversal across regolith-covered surfaces, slopes up to 30°, and rocky terrain. The system also includes redundant path recording, enabling safe return via previously validated routes in case of communication loss or emergent threats.

Operational Autonomy

Unlike the semi-stationary platform, the TPR is expected to operate independently from the primary base for up to 18 consecutive days, requiring robust planning and resource management. The mission concept includes multi-day excursions, with preplanned routes and objectives based on orbital scouting data, surface elevation maps, and scientific priorities.
The rover is equipped with onboard software for mission scheduling, energy and consumable tracking, and contingency response protocols. In case of unplanned deviations or resource consumption anomalies, the system can update return routes or initiate safe-mode operation until communication with mission control is re-established.

Emergency Return Capability

Given the extended distances from the main habitat, the TPR includes systems to support emergency return to base. Navigation software continuously evaluates the safe return paths, considering terrain, remaining oxygen and power, and crew fatigue.
The rover maintains an energy and consumable reserve margin specifically allocated for emergency use. In addition, a remote override protocol allows ground operators to take full control of mobility and navigation subsystems to guide the vehicle back in case of crew incapacitation.

Life Support and Habitability

The life support and habitability systems of the Transport Pressurized Rover (TPR) are based on the same architecture adopted for the Semi-Stationary Pressurized Rover (SSPR), with modifications reflecting the longer mission duration and the operational profile focused on mobility. The Environmental Control and Life Support System (ECLSS), including the Air Revitalization Module (ARM) and Water Management Module (WMM), ensures breathable air, CO_2 removal, humidity regulation, and water recycling for a mission lasting up to 18 days. Redundant systems are included to guarantee crew safety even in the event of subsystem degradation or partial failure.
While the core internal layout and crew accommodations remain comparable, a pressurized cabin of approximately 15-17.5 m^3, with workstations, foldable

sleeping berths, and storage modules-the science bay found in the SSPR has been removed. In its place, additional sample storage capacity and consumables have been integrated, supporting extended traverses and increased autonomy. The cabin remains thermally stabilized between 18°C and 26°C, using the same combination of active and passive thermal control systems, including external radiators, multi-layer insulation, and internal heat reserves.
The rover's geometry is adapted to support longer mission durations and extended traverses, with overall dimensions of approximately 7.5 meters in length, 3.0 meters in width, and 3.0 meters in height. This expanded form factor results in a pressurized internal volume of 55-60 m^3, providing ample space for crew accommodations, life support systems, equipment storage, and sample containment.

Sample Handling and Scientific Capabilities

Unlike the Semi-Stationary Rover, which includes onboard tools for preliminary sample analysis, the Transport Pressurized Rover is designed just for collection and transport of samples. No internal scientific processing systems are included, to maximize storage capacity and simplify operational workflows. The rover is equipped with sealed compartments capable of storing up to 30-40 kg of samples, this space can be used also for storage of water and basic life support resources. The compartment capability increased compared to the SSPR due to the longer mission duration and extended exploration range.
This mass is considered a balanced trade-off between scientific return and mass, volume, and thermal containment constraints, and remains well within the range of historical benchmarks such as the Apollo missions.

Communication and Autonomy

The TPR shares the same communication and autonomy architecture as the Semi-Stationary Rover. It maintains continuous S-band or Ka-band communication with mission control via a high-gain antenna and supports short-range protocols for connectivity with other surface assets.
The rover also incorporates autonomous health monitoring and fault detection systems, capable of triggering safe-mode procedures in case of subsystem anomalies or hazardous environmental conditions. Ground control retains full authority over non-critical functions, ensuring mission flexibility and safety even during long-range traverses.

Structural and Environmental Protection

The Transport Pressurized Rover adopts the same shielding strategy implemented in the Semi-Stationary configuration, including a multilayered composite hull

to protect against micrometeorite impacts, lunar dust, and ionizing radiation. Materials such as carbon composites, aluminum honeycomb layers, and hydrogen-rich polyethylene are employed for distributed protection.
Given the rover's extended autonomy and greater operational distance from the base, it also includes an internal radiation storm shelter, integrated into the crew module. This shelter is lined with enhanced shielding and is designed to provide temporary protection against Solar Particle Events (SPEs), without imposing mass penalties on the full structure. The system is provided with real-time radiation monitoring and alert integration with space weather forecasting tools.
As with the SSPR, this architecture provides an effective compromise between protection, mass efficiency, and operational mobility. Further upgrades for future missions may explore deployable shielding panels or active deflection technologies, particularly for long-term surface infrastructure or Mars transfer vehicles.

Power Budget Calculation

Given that the DIPS system provides a continuous 8 kW, the power allocations across rover subsystems for the Transport Pressurized Rover (TPR) are defined as follows: [4]

Table 3.6: Subsystem Power Consumption Summary

Subsystem	**Power Consumption**	**Notes**
Life Support Systems (ECLSS)	2.5 kW	Continuous
Thermal Control (TCS)	1.2 kW	Higher due to larger volume
Communication	0.5 kW	Intermittent

[4]The power consumption values are derived from NASA and ESA reference data for crewed surface systems, including analogues such as the Space Exploration Vehicle (SEV), ISS life support modules, and studies related to HERACLES and Desert RATS campaigns. Values have been scaled according to the increased internal volume (55–60 m^3), a mission duration of 18 days, and a two-person crew. Estimates for life support, thermal control, and internal systems assume continuous operation, while mobility and communication subsystems are dimensioned based on expected duty cycles. Peak values for propulsion reflect the demands of long-range traverses and uneven terrain, while redundancy and power management account for system overhead and diagnostic monitoring.

Table 3.6: Subsystem Power Consumption Summary

Subsystem	Power Consumption	Notes
Lighting and Internal Systems	0.5 kW	Continuous (expanded interior)
Mobility System	2.0 kW peak	0.5-0.7 kW average
Power Management / Redundancy	0.4 kW	Overhead

The total average power load of the rover is estimated at 6.4-6.6 kW, leaving an operational margin of 1.4-1.6 kW. This reserve ensures the system can accommodate redundancy needs, or temporary subsystem overloads without affecting overall mission integrity.
Solar arrays would require 30-40 m^2 of photovoltaic surface and substantial battery storage to sustain power during the lunar night, instead the DIPS ensures uninterrupted energy supply throughout the mission. Although only the final 3-4 days of the planned 18-day mission fall within the lunar night, this period presents significant thermal and energy challenges. DIPS must enable full functionality even in low-illumination conditions or permanently shadowed regions. It shall be design as compact, dust-resistant and which continuous output to be ideally suited for long-duration.

Oxygen Demand Estimation

Oxygen demand for the TPR is calculated using NASA's metabolic reference values, assuming light activity such as rover driving, EVA preparation, and routine operations. A nominal consumption of 1.0 kg O_2 per day per person is assumed. For two astronauts over an 18-day mission, the total oxygen required is 36 kg [5]. Therefore, the rover must carry at least 40 kg of breathable oxygen, allowing for a contingency margin. Additional oxygen may be regenerated through electrolysis, provided a compatible water source is integrated into the life support system.

Thermal Load

The TPR's enlarged interior and extended operating duration require enhanced thermal regulation strategies. With external temperatures reaching up to +127°C during lunar daytime and down to -173°C during lunar night, internal temperature

[5] $2 \cdot 1.0 kg/day \cdot 18 days = 36 kg$

must be maintained between 18°C and 26°C.
There is an estimation of heat that must be dissipated through radiative panels installed on the shaded side of the rover, ensuring continuous passive emission. Phase-change materials (PCMs) are integrated into the thermal control system to mitigate sudden increases in internal heat during EVA prep or when exposed to intense sunlight. The system is designed to maintain temperature stability throughout 18 days of operation, including partial exposure to lunar night conditions.

3.4.3 Work Breakdown Structure (WBS) for the Transport Rover

In line with the methodology adopted for the Semi-Stationary Rover, the project planning of the Transport Pressurized Rover has also been developed using Microsoft Project and is structured around a comprehensive Work Breakdown Structure (WBS). The same PMBOK-guided, deliverable-oriented approach has been applied, ensuring consistency in scope definition, schedule management, and resource allocation. This section will focus on highlighting the key structural and operational differences that distinguish the Transport Rover's WBS from that of the Semi-Stationary configuration-particularly about its enhanced mobility, extended mission duration, and additional system complexity driven by its long-range operational profile.
The Work Breakdown Structure (WBS) developed for the Transport Pressurized Rover follows the same hierarchical structure and methodological framework used for the Semi-Stationary Rover. At the first level, the WBS architecture remains identical, encompassing the same 11 macro areas based on system functions and mission deliverables (e.g., Power System Integration, Mobility System, ECLSS, System Integration & Testing, etc.). This ensures direct comparability between the two mission profiles and allows reuse of project management logic across configurations.
However, due to the increased operational complexity of the Transport Rover-designed for long-range traverses, high-speed mobility, and extended mission duration-several second-level work packages and task sequences have been refined or newly introduced. These updates reflect the enhanced technical requirements of a more autonomous mobile vehicle platform.

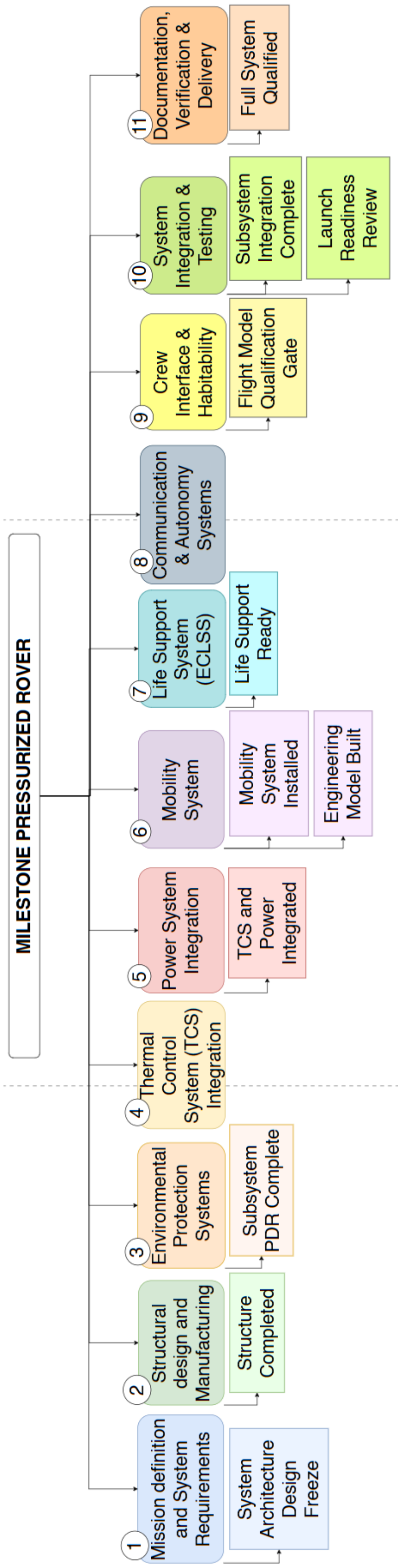


Figure 3.14: Stationary Rover Milestone WBS

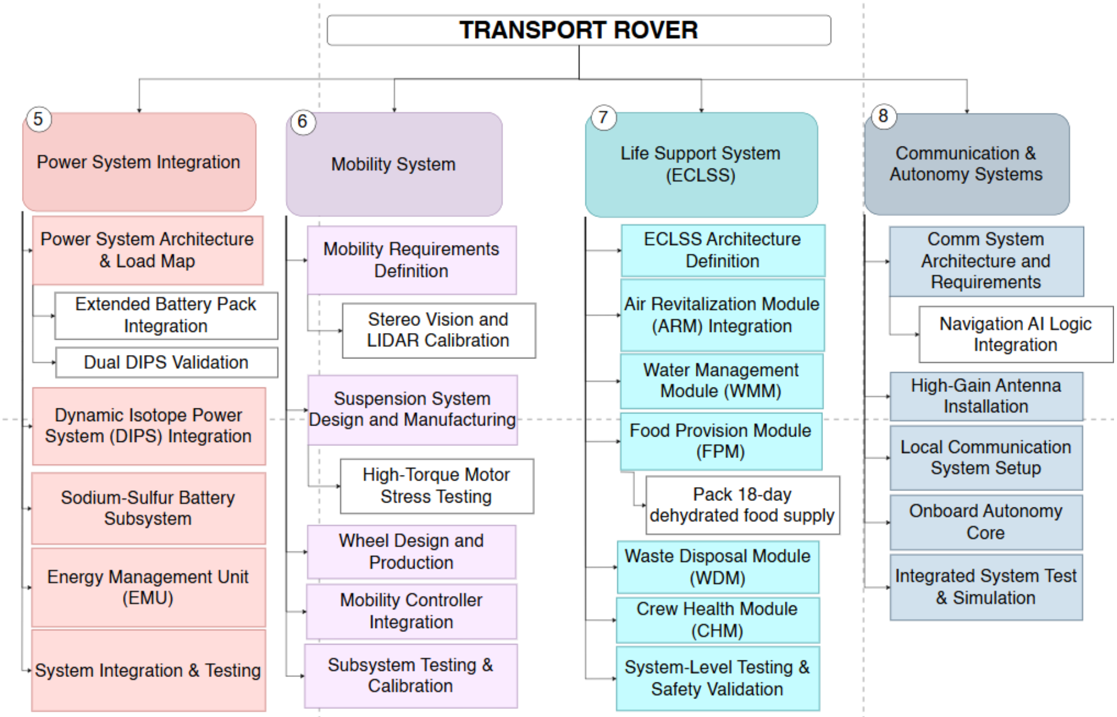


Figure 3.15: Difference subtasks between Stationary Rover & Transport Rover

As shown in Figure 3.15, the following subsystems have undergone significant updates:
The fifth phase of the Transport Rover-Power System Integration-follows the same structural layout as the Semi-Stationary Rover but introduces specific technical divergences that reflect the functional adaptations required for a vehicle optimized for mobility and extended range.
As shown in the image, the Power System Architecture & Load Map is developed first, including the definition of nominal and peak loads per subsystem. While this is consistent with the stationary rover, the Transport version introduces an Extended Battery Pack Integration, indicating a design emphasis on greater energy autonomy to support mobility across longer distances. This enhancement addresses the need for prolonged traverses, variable terrain resistance, and additional power for real-time navigation and obstacle negotiation.
Another key difference is the adaptation of the Dynamic Isotope Power System (DIPS) Integration. While both rovers include a DIPS subsystem, in the Transport version, the thermal control and electrical output routing are slightly adapted to accommodate the vehicle's dynamic envelope and higher operational duty cycles. The emphasis is on efficient radiator interfacing and robust shielding to withstand both vibration and thermal variations during motion.

The sixth phase of the Transport Rover's development focuses on the Mobility System, the process begins with Mobility Requirements Definition, which goes beyond static constraints. While both rovers undergo power requirement estimation and speed profile definition, the transport variant introduces Stereo Vision and LIDAR Calibration early in the development cycle. This inclusion reflects the system's reliance on real-time environment sensing and obstacle detection, which are essential for semi-autonomous navigation. These components are not just plug-ins but drive the logic and load demands for subsequent mobility components. The Suspension System Design and Manufacturing phase retains the same foundational elements as in the stationary rover (FEA for terrain impact, rocker-bogie design, vacuum testing), but the design assumptions are tuned for dynamic stress profiles. This includes rough terrain traversal, gradient climbing, and frequent motion cycles, which require both structural resilience and torque efficiency.

The seventh phase of the Transport Rover development is dedicated to the Life Support System (ECLSS), and while structurally similar to the Semi-Stationary counterpart, it incorporates important modifications to support the rover's longer autonomous mission capability. This is particularly evident in the Food Provision Module (FPM), which is designed to sustain a crew for up to 18 days, in contrast to the 14-day capacity of the semi-stationary rover. This extension reflects the transport vehicle's need to support missions such as emergency rescue, multi-site logistics, or scientific expeditions further away from a fixed habitat.

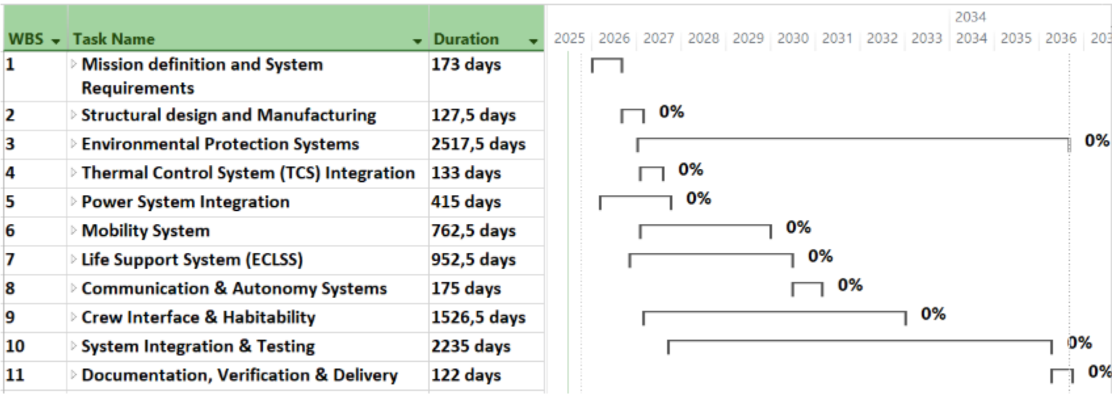
The eighth phase in the development of the Transport Rover focuses on Communication & Autonomy Systems, an area that sees significant advancements compared to its Semi-Stationary counterpart due to the transport rover's mobility and extended operational range. One of the most notable additions is the Navigation AI Logic Integration, which equips the vehicle with a higher degree of autonomous capability.
This task includes integrating algorithms for route planning, obstacle detection, localization, and dynamic re-planning in response to sensor feedback. The AI logic enables the rover to follow mission trajectories, avoid hazards, and even reroute itself in case of communication loss or unexpected environmental changes. This autonomy reduces the need for continuous ground control and enhances the vehicle's resilience during extended sorties.
These additions and refinements not only adapt the WBS to the Transport Mission's unique functional requirements, but also lay the groundwork for a differentiated project schedule and resource allocation strategy. By evolving the WBS while maintaining top-level coherence, the project ensures that each subsystem is both independently manageable and integrable within the larger system-of-systems logic

of the pressurized rover program.

3.4.4 Gantt Chart e Critical Path Method (CPM) for the Transport Rover

Gantt Chart

The Gantt chart developed for the Transport Pressurized Rover reflects the same project management structure and scheduling philosophy used in the Semi-Stationary configuration. As shown in Figure 3.16, all primary WBS components are plotted along a multi-year timeline, from mission definition and early structural design, through to final delivery and system qualification.



WBS	Task Name	Duration
1	Mission definition and System Requirements	173 days
2	Structural design and Manufacturing	127,5 days
3	Environmental Protection Systems	2517,5 days
4	Thermal Control System (TCS) Integration	133 days
5	Power System Integration	415 days
6	Mobility System	762,5 days
7	Life Support System (ECLSS)	952,5 days
8	Communication & Autonomy Systems	175 days
9	Crew Interface & Habitability	1526,5 days
10	System Integration & Testing	2235 days
11	Documentation, Verification & Delivery	122 days

Figure 3.16: Gantt Chart Transport Rover

Each top-level task is allocated a planned duration, with dependencies and start dates defined to preserve technical feasibility and integration logic. The baseline schedule spans from early 2026 to 2036, with certain phases-such as System Integration & Testing -extending significantly due to the added complexity of high-mobility and autonomy requirements.

Although the high-level Gantt structure closely mirrors that of the Stationary Rover, the underlying activities have been reconfigured in line with the unique demands of the Transport mission.

Most significantly, both the Power System Integration and the Mobility System begin earlier in the Transport Rover's timeline compared to their stationary counterpart. This scheduling adjustment is intentional and directly related to the nature and dependencies of a mobile system.

In a transport rover, mobility is not merely an auxiliary feature but a core functional capability, essential to mission fulfillment. To ensure early validation of terrain

handling, dynamic response, and navigation features, development of the mobility subsystem is prioritized. This early start allows for timely integration of LIDAR calibration, suspension testing, and motor control logic-crucial for autonomous movement across the lunar surface.
Similarly, Power System Integration is anticipated sooner, because mobility introduces higher power demands and operational peaks. Extended battery packs, dual DIPS units, and advanced energy management strategies must be tested early to support the autonomous movement and communication architecture that follow. Starting the power system integration earlier enables thorough testing of subsystem interaction and ensures a stable electrical baseline for the rest of the engineering workflow, especially for autonomy and environmental regulation.

Critical Path Method (CPM)

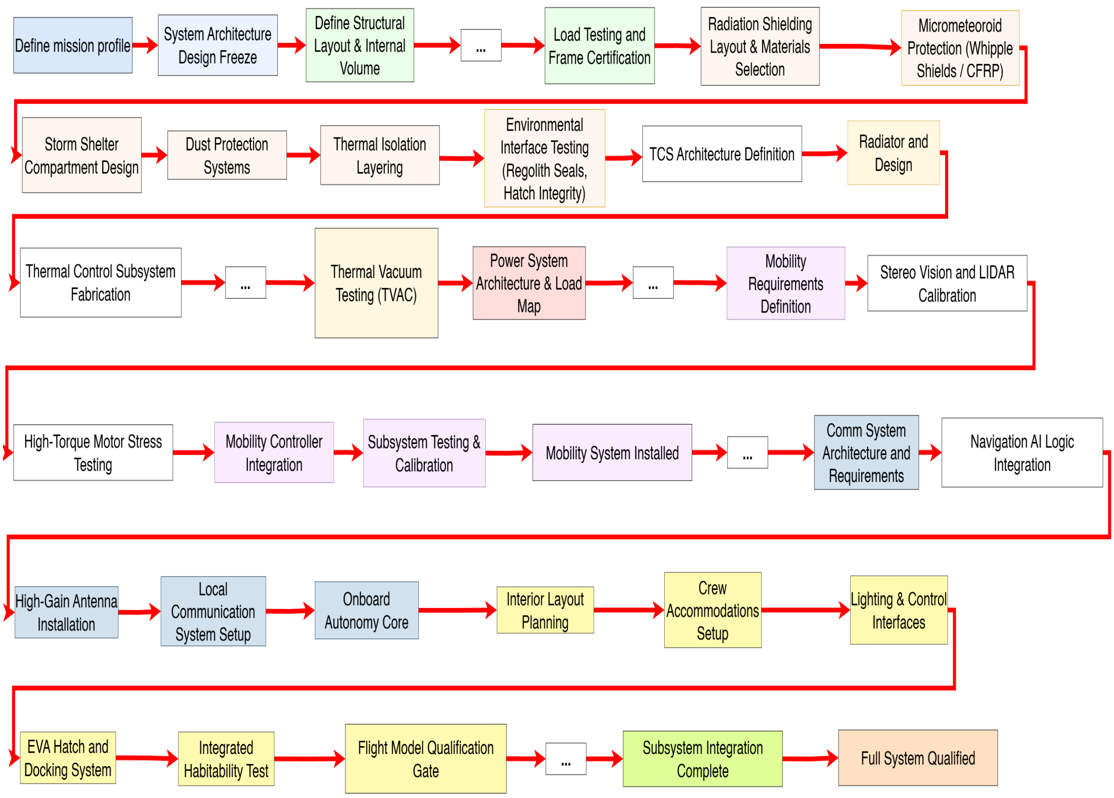


Figure 3.17: Gantt Critical Path Transport

Although the critical path was calculated using the same methodology as in the Semi-Stationary mission (via Microsoft Project), its specific composition reflects

the new sequence of high-dependency tasks, as it is show in the figure above 3.17. New activities as the Stereo Vision and LIDAR Calibration or the High-Torque Motor Stress Testing, are taking part to the critical path of the Transport rover. A new milestone is present, the Mobility System Installed WBS, all this due to the increased reliance on system autonomy and the importance of resilience during long-range missions. Testing phases are both longer and more interdependent, making them a core contributor to the critical path's structure.
This highlights the importance of front-loading risk mitigation, accelerating subsystem interfaces, and closely monitoring integration testing throughout the entire development lifecycle of the Transport Rover.

3.4.5 Preliminary Cost Estimation

The cost estimation for the Transport Pressurized Rover was developed using the same methodology applied to the Semi-Stationary Rover. However, due to enhanced capabilities, longer mission duration, and expanded system requirements of the Transport variant, several cost categories show significant increases. The estimation is derived from Microsoft Project using assigned labor resources, material components, and fixed-cost entries, and is mapped directly to the Work Breakdown Structure (WBS).
While the methodology remains consistent-leveraging aerospace benchmarks, analog mission data, and engineering assumptions-the Transport Rover introduces key cost-driving differences. These are primarily related to: increased system autonomy, the advanced mobility systems, the longer mission duration and the higher integration overhead for life support and power subsystems.

WBS	Task Name	Duration	Start	Finish	Cost
1	**Mission definition and System Requirements**	**173 days**	**Thu 01/01/26**	**Tue 01/09/26**	**594.800,00 €**
2	**Structural design and Manufacturing**	**127,5 days**	**Tue 01/09/26**	**Thu 25/02/27**	**100.379.000,00 €**
3	**Environmental Protection Systems**	**2517,5 days**	**Thu 07/01/27**	**Mon 01/09/36**	**221.193.600,00 €**
4	**Thermal Control System (TCS) Integration**	**133 days**	**Thu 28/01/27**	**Tue 03/08/27**	**91.005.320,00 €**
5	**Power System Integration**	**415 days**	**Mon 02/03/26**	**Mon 04/10/27**	**72.648.240,00 €**
6	**Mobility System**	**762,5 days**	**Thu 28/01/27**	**Tue 01/01/30**	**140.877.200,00 €**
7	**Life Support System (ECLSS)**	**952,5 days**	**Tue 03/11/26**	**Thu 27/06/30**	**50.475.800,00 €**
8	**Communication & Autonomy Systems**	**175 days**	**Thu 27/06/30**	**Thu 27/02/31**	**70.515.200,00 €**
9	**Crew Interface & Habitability**	**1526,5 days**	**Thu 25/02/27**	**Mon 03/01/33**	**50.179.600,00 €**
10	**System Integration & Testing**	**2235 days**	**Fri 17/09/27**	**Fri 11/04/36**	**200.322.160,00 €**
11	**Documentation, Verification & Delivery**	**122 days**	**Mon 14/04/36**	**Wed 01/10/36**	**672.000,00 €**

Figure 3.18: Costs, durations of Transport Rover

From the figure 3.18, the total Estimated Cost is **1.1 billion €**. This value represents an approximate 10% increase over the Semi-Stationary Rover cost baseline (~1.0 billion €), driven by extended mission scope and system complexity.

Cost Drivers

The increased cost of the Transport Pressurized Rover, estimated at approximately 1.618 billion euros, represents a 10% rise compared to the 1.0 billion euro baseline of the Semi-Stationary configuration. This difference is primarily attributed to a set of expanded technical requirements and longer mission duration, which directly affect resource engagement, testing scope, and system complexity.
One of the most significant cost contributors is the Mobility System, which sees a substantial increase due to the integration of high-torque motor stress testing, articulated suspension system development, and stereo vision/LIDAR calibration for autonomous long-distance traversal. These components were either simplified or entirely absent in the stationary version, whose mobility was limited to slow repositioning maneuvers.
Similarly, the Communication and Autonomy Systems register a notable increase in cost, driven by the inclusion of AI-based navigation logic, terrain mapping capabilities, and enhanced onboard computing resources. These additions reflect the need for real-time decision-making and operational independence in the Transport Rover, especially during multi-day excursions without base support.
The Power System Integration phase also sees a moderate increase, resulting from the validation of dual DIPS (Dynamic Isotope Power Systems), extended load profiling, and additional redundancy mechanisms to support both lunar day and partial night operations.
While the System Integration and Testing phase maintains a similar cost structure to that of the Semi-Stationary mission, its internal complexity is greater due to the larger number of interdependent systems. This requires longer simulation cycles and more comprehensive qualification protocols.
Together, these differences justify the increased budget and highlight how expanded performance capabilities translate into higher design, development, and validation costs.

Resource Allocation

All labor teams, material items, and cost entries remain the same as the Semi-Stationary configuration, as all the teams were assigned a maximum capacity of 500%. This value, which corresponds to a hypothetical deployment of 5 full-time workers per team, was deliberately chosen to maintain consistency across both rover development plans and ensure a comparable level of engineering throughput. By retaining identical workforce assumptions and cost baselines, any differences in overall cost and duration between the Semi-Stationary and Transport rovers can be directly attributed to structural and functional divergences, rather than fluctuations in labor policy or procurement. This approach simplifies comparative analysis and reinforces the modularity of the development framework adopted.

3.4.6 Comparative Evaluation of the Two Rover Missions

The development of the Semi-Stationary and Transport Pressurized Rovers represents two distinct but complementary approaches to lunar exploration. From a project management perspective, both missions were structured using the same methodological framework based on PMBOK guidelines and implemented through Microsoft Project. This allowed for a consistent and traceable comparison across their Work Breakdown Structures (WBS), Gantt charts, Critical Path Methods (CPM), and preliminary cost estimates.
Structurally, both rovers share a common WBS architecture at the first level, with eleven major branches encompassing the full spectrum of mission development-from mission definition to final delivery. However, the second and third levels of the WBS reflect their divergent operational roles. The Semi-Stationary Rover prioritizes stability, internal scientific analysis, and minimal locomotion, while the Transport Rover is optimized for long-distance traversal, autonomy, and logistical flexibility. As a result, task sequences related to mobility, autonomy, and energy management are significantly expanded in the Transport configuration, while certain elements like onboard scientific payloads are reduced or omitted.

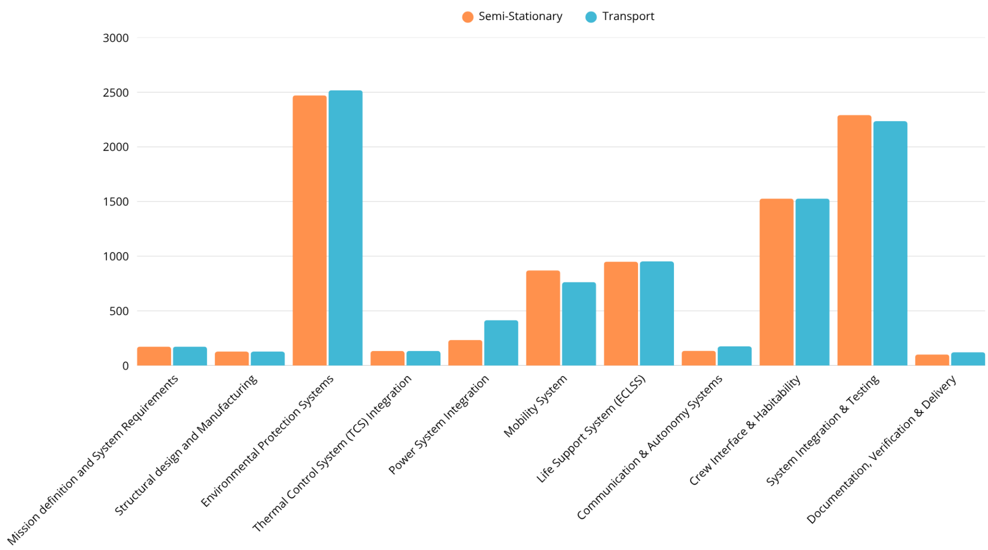


Figure 3.19: Duration Comparison

Based on the updated graph in Figure 3.19, it is evident that both missions adhere to a structured, phase-based development model, maintaining consistency in milestone progression and facilitating cross-phase coordination. However, key differences emerge in the duration of specific WBS elements. Notably, the Transport Rover requires significantly more time for the Power System Integration and Communication & Autonomy Systems phases, reflecting the added complexity of long-range energy management and autonomous navigation logic.
Conversely, durations for other critical subsystems such as Structural Design, Environmental Protection Systems, and System Integration & Testing remain comparable between the two configurations, as they share baseline architectural and functional foundations. Interestingly, the Mobility System, while slightly shorter in the Transport case, likely reflects an optimized development effort due to earlier initiation and focused calibration efforts-rather than reduced complexity. The Critical Path Method (CPM) analysis confirms this dynamic: while both rovers converge in the final validation and delivery phases, the Transport configuration introduces more risk-sensitive dependencies in earlier technical subsystems, particularly in control logic, fault tolerance, and power routing strategies. These variations underscore the impact of mission objectives on development timelines, with autonomy and endurance driving extended planning for the Transport Rover. In terms of cost, the Transport Rover exhibits an approximately 10% increase in total budget, driven by the need for advanced subsystems and longer design and testing cycles.

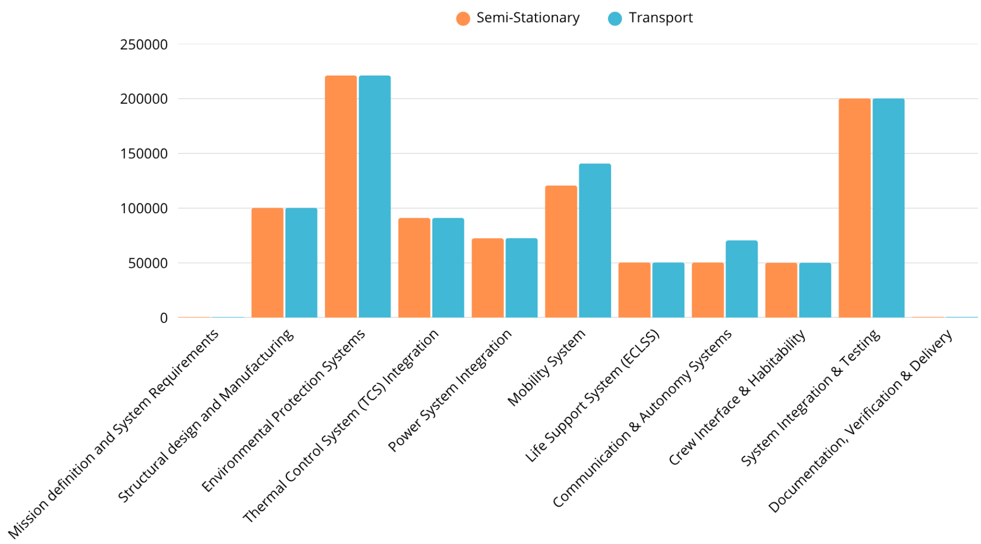


Figure 3.20: Costs Comparison

As clearly illustrated in the bar chart 3.20, this increase is primarily attributed to specific areas such as the Mobility System, where the requirements for high-torque motors, LIDAR calibration, and adaptive torque distribution elevate the cost significantly compared to the Semi-Stationary version. A noticeable increment is also seen in Communication & Autonomy Systems, reflecting the integration of Navigation AI Logic and more complex comms testing protocols.

While the Environmental Protection Systems and System Integration & Testing remain similarly costly across both configurations-highlighting their intrinsic complexity regardless of mission profile-the Semi-Stationary Rover allocates a marginally higher budget to Documentation, Verification & Delivery. This aligns with its tighter scope and earlier maturity, possibly requiring more up-front certification efforts. On the other hand, the Transport Rover maintains parity in most foundational categories, such as Structural Design, Thermal Control, and ECLSS, confirming that many core systems share baseline characteristics. Overall, the cost variation reflects strategic trade-offs in mobility and autonomy, emphasizing the Transport Rover's greater operational flexibility at a modest financial premium.

The overall comparison reveals a clear trade-off between complexity and capability. The Semi-Stationary Rover offers a cost-efficient, focused solution for short-term missions and localized scientific activity, minimizing risk and simplifying integration. In contrast, the Transport Rover demands greater investment and longer development time, but in return unlocks strategic value: it enables long-range exploration, in-situ resource scouting, and inter-base logistical support.

Ultimately, the choice between the two designs depends not only on technical feasibility or budget availability, but also on mission objectives. A semi-stationary platform may suffice for early human presence and scientific return; however, the long-term vision of a sustained lunar infrastructure will inevitably require the extended mobility and operational independence provided by the Transport configuration. These contrasting profiles emphasize the importance of modularity, scalability, and well-structured project planning in the design of lunar exploration assets.

Chapter 4
Risk Analysis for Pressurized Lunar Rover Missions

4.1 Risk Management Policy

The purpose of this chapter is to outline the methodology adopted for risk identification, classification, and evaluation in the development of pressurized lunar rovers, with a focus on the two mission profiles: the Semi-Stationary Rover and the Transport Rover.
To structure and streamline the identification process, a Risk Breakdown Structure (RBS) was implemented. This hierarchical framework categorizes risks starting from Level 0 (overall mission risks), then branching into Level 1 to distinguish between internal and external sources of risk. Internal risks refer to threats that arise directly from within the mission, such as technological choices, engineering challenges, or operational misalignments. External risks stem from influences beyond the control of the mission team, such as environmental conditions, supply chain issues, or geopolitical changes. Figure 4.1 illustrates the RBS, detailing all possible risk categories associated with both internal and external sources.

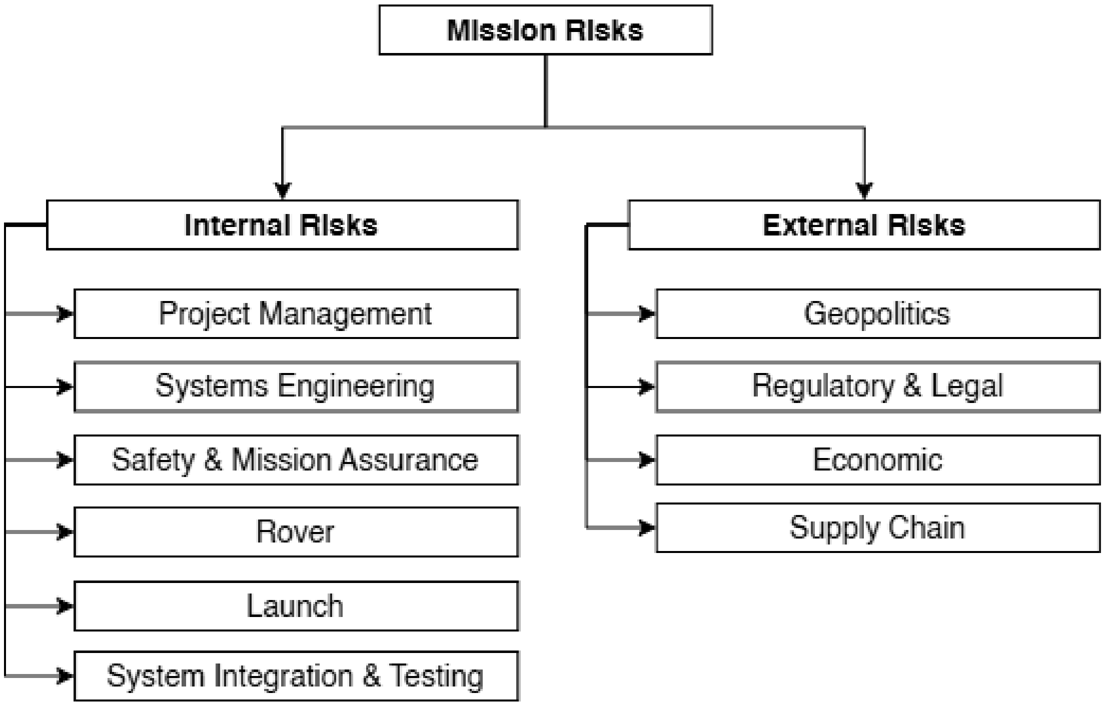


Figure 4.1: Risk Breakdown Structure

Internal Risks:

- Project Management: related to planning, scheduling, resource allocation, communication, and overall coordination of the project;
- Systems Engineering: related to the definition, analysis, integration, and management of system requirements and interfaces;
- Safety & Mission Assurance: related to the failure to meet safety standards or mission assurance processes, potentially compromising mission success;
- Rover: related to the design, development, and performance of the rover, including subsystems and components;
- Launch: related to the launch phase, such as vehicle availability, integration, weather conditions, and launch failure;
- System Integration & Testing: related to the integration of subsystems and during verification/validation activities;

External Risks:

- Geopolitics: related to international relations, political instability, or conflicts that may affect project continuity or partnerships;

- Regulatory & Legal: related to compliance with national and international laws, export controls, licensing, or regulatory changes;
- Economic: related to funds, inflation, or financial instability impacting project cost or schedule;
- Supply Chain: related to the availability, reliability, and delivery of components, materials, or services from external suppliers.

Each identified risk is assessed both quantitatively and qualitatively using two key indicators: the impact level and the probability of occurrence. These dimensions are then combined in a standard risk matrix to determine the overall severity of the risk. Figure 4.3 presents the criteria used to evaluate the probability level. Figure 4.2 describes the criteria adopted to assess the impact level. This indicator reflects the potential consequences should the risk materialize and is evaluated across three dimensions:

- Performance: the extent to which system functionality or mission objectives are compromised;
- Schedule: time delays resulting from the risk;
- Cost: additional project costs due to mitigation or recovery actions.

The five impact levels and their definitions are detailed in Figure 4.2.

Level	Impact	Performance Impact	Schedule Impact	Cost Impact
1	Negligible	Negligible or absent impact. No corrective measures are necessary.	Minimal or absent impact.	Minimal or absent impact.
2	Significant	No negligible impact. A small number of corrective actions are required.	Additional activites required (≤1 month).	Project costs increase slightly (≤5%).
3	Major	Moderate impact. A moderate number of corrective actions are required.	Additional activites required (tra 2 e 6 months).	Project costs increase sufficiently (≤10%)
4	Critical	Significant impact. A considerable number of corrective actions are required.	Additional activities required (tra 7 e ≤12 months).	Project costs increase significantly (≤20%).
5	Catastrophic	Unacceptable impact. Most planned activities require reformulation.	Major project milestones cannot be achieved. More than 50% of project activities need to be rescheduled, or the schedule is formerly interrupted.	Project costs increase s.t. possible project termination may follow (≥25%)

Figure 4.2: Impact Levels criteria

Figure 4.3 shows the criteria used to determine the probability level, which indicates the likelihood of the risk occurring. The five-level probability classification is summarized in the same figure.

Level	Probability	Definition
1	Minimum	The risk is extremely unlikely to occur (p ≤ 0.1%).
2	Low	The risk is very unlikely to occur (0.1% ≤ p < 1%).
3	Medium	The risk might occur (1% ≤ p < 10%).
4	High	The risk may occur frequently (10% ≤ p < 100%).
5	Maximum	The risk will definitely occur (p = 100%).

Figure 4.3: Probability Levels criteria

These two indicators are then combined using the risk matrix shown in Figure 4.4 to determine the overall severity of each risk. The severity is classified as Very Low, Low, Medium, High, or Very High, and serves as the basis for defining mitigation strategies and prioritizing risk responses.

Risk Matrix			Impact				
			1	2	3	4	5
Probability	Minimum	1	Very Low	Very Low	Very Low	Very Low	Low
	Low	2	Very Low	Very Low	Low	Low	Medium
	Medium	3	Very Low	Low	Low	Medium	High
	High	4	Very Low	Low	Medium	High	High
	Maximum	5	Low	Medium	High	High	Very High

Figure 4.4: Risk Matrix

4.2 Risk Identification for the Pressurized Rover

Identifying and analyzing potential risks is a critical step in ensuring the success and safety of a lunar pressurized rover mission.
This section presents a structured identification of all known risks associated with the pressurized rover, regardless of mission profile (Semi-Stationary or Transport). Each risk is categorized according to its origin-internal or external-and is further assigned to a specific domain such as Project Management, Systems Engineering, Safety & Mission Assurance, Rover, Launch, System Integration, or Geopolitics, Regulatory & Legal, Economic, Supply Chain, following the hierarchy defined in the Risk Breakdown Structure (RBS).
For each identified risk, a concise description is provided in the table 4.1, along with a summary of the potential impact on mission performance, cost, schedule, or safety.

Table 4.1: Risk Breakdown Structure (RBS)

Category	**ID**	**Description**	**Impact**
Project Management	R-M-1	Lack of quality control during development, procurement, and integration.	Undetected faults causing mission failure and rework during late phases.
	R-M-2	Failure to verify requirements throughout development.	Delivering systems not in align with requirements and performance and/or mission failures.
	R-M-3	Poor planning, estimation, or adherence to the project schedule.	Project delays, compression of critical phases. Cost overruns.
	R-M-4	Communication protocols between stakeholders were not sufficiently defined/implemented.	Misalignment of goals and increasing risk of errors and delays.
Systems Engineering	R-S-1	Inadequate definition or management of interfaces between rover subsystems can lead to mechanical, electrical, or functional incompatibilities.	Subsystems may fail to integrate properly, leading to critical malfunctions, testing delays, and potential system-level failures during the mission.
	R-S-2	The uncontrolled addition of new requirements during the development phase increases system complexity and engineering workload.	This can result in cost overruns, delays, integration issues, and a higher likelihood of introducing defects due to rushed or incomplete implementation.
Safety and Mission Assurance	R-SM-1	Lack of backup systems for critical functions.	Mission may fail in the event of a single-point failure, compromising safety and success.
	R-SM-2	Insufficient diagnostics or fault management algorithms.	Undetected anomalies could escalate, leading to partial or total mission failure.

Category	ID	Description	Impact
Rover	R-R-1	Mechanical or control issues in the wheel, suspension, or drive system caused by regolith buildup, terrain interaction, or wear.	Limited or lost mobility may prevent the rover from completing exploration objectives or returning to the base/habitat.
	R-R-2	Batteries may degrade under extreme lunar temperature cycles and vacuum exposure, especially during the lunar night.	Power supply interruptions could jeopardize life support, mobility, or communication functions, reducing mission duration or causing system loss.
	R-R-3	Scientific and navigation sensors may lose calibration over time due to radiation or temperature fluctuations.	Leads to inaccurate scientific measurements, misinterpretation of lunar data, or compromised autonomous navigation and obstacle detection.
	R-R-4	Inability of the thermal regulation system to maintain acceptable temperature ranges for critical components in the harsh lunar environment.	May lead to overheating or freezing of onboard electronics and life support systems, potentially causing partial or total mission failure.
	R-R-5	Exposure to lunar regolith, vacuum, and radiation may cause unexpected material wear, erosion, or structural weakness.	Risks include seal breaches, joint failures, or degradation of thermal coatings, potentially affecting crew safety and rover longevity.
	R-R-6	Breach or leak in the pressurized cabin due to impact, structural fatigue, or seal failure.	Immediate threat to crew safety, triggering emergency abort protocols and termination of activities.
	R-R-7	Micro-meteoroid impacts, temperature-induced stresses, or mechanical fatigue could degrade the rover's frame or subsystems.	May reduce load-bearing capacity, compromise safety systems, and increase risk during extended missions.

Category	ID	Description	Impact
	R-R-8	Errors in localization systems or terrain mapping (e.g., due to faulty sensors, software bugs, or loss of reference data).	Increased risk of collision, inability to follow mission routes or reach predefined way points, especially in complex terrain.
	R-R-9	Antenna damage, software faults, or electromagnetic interference can disrupt the rover's ability to transmit or receive data.	Loss of command, telemetry, or video feed; can force a mission halt or switch to autonomous fallback modes.
	R-R-10	Lunar regolith is extremely fine and abrasive, and can penetrate joints, actuators, and seals despite protective measures.	Causes mechanical wear, increased friction, or failure in moving parts such as robotic arms, airlocks, or wheels.
	R-R-11	Dust or off-gassing from internal components may contaminate sensitive optical, spectroscopic, or sampling instruments.	Compromises the quality and accuracy of scientific measurements, reducing mission value and objectives.
	R-R-12	Failure in air circulation, CO_2 scrubbing, or humidity control systems.	Poses a critical risk to crew health and safety during manned excursions; requires immediate corrective actions.
	R-R-13	The crew and onboard electronics of the pressurized rover are exposed to cosmic rays and solar particle events (SPEs).	Radiation can induce single-event upsets (SEUs), memory corruption, and long-term degradation of electronic components; may lead to acute health effects. In extreme events, an emergency retreat or mission abort may be required to ensure crew survival.

Category	**ID**	**Description**	**Impact**
Launch	R-L-1	Mechanical or electrical mismatches between the rover and the launch vehicle due to errors in interface specifications, testing oversight, or late design changes.	Could result in damage to the rover during launch preparation or ascent, potentially causing mission-critical systems to fail before even reaching lunar orbit.
	R-L-2	Failure to meet the scheduled launch window due to technical issues, weather conditions, or logistical complications.	Delays can impact the mission timeline, increase costs, and force rescheduling of landing slots or crew coordination, affecting integration with broader lunar exploration campaigns.
	R-L-3	Extreme mechanical loads and acoustic vibrations during launch can exceed design tolerances if not accurately predicted or mitigated.	May lead to microcracks, loosening of components, or latent defects in the rover that manifest later during operations on the Moon, jeopardizing reliability.
Systems Integration and Testing	R-T-1	Failure to simulate full mission scenarios during ground testing, such as EVA coordination, emergency protocols, or environmental conditions.	Undetected integration issues may emerge during lunar operations, leading to mission-critical failures or unsafe conditions for the crew.
	R-T-2	Subsystems may be individually tested but not sufficiently verified in combination, leading to physical, electrical, or software mismatches.	System-level malfunctions, miscommunication between modules (e.g., life support, power, navigation), and delays in mission readiness.
	R-T-3	Thermal vacuum, vibration, and radiation tests may not fully replicate the harsh lunar environment due to limitations in ground facilities.	Provides false assurance of system robustness; real mission conditions may trigger failures that were not detected during qualification.

Category	**ID**	**Description**	**Impact**
Geopolitics	R-G-1	Shifts in diplomatic relations or political tensions between collaborating nations or space agencies can disrupt joint missions or shared resources.	Could lead to restricted data access, withdrawal of technical support, or loss of funding and launch/logistics services provided by partner countries.
	R-G-2	Imposition of new export regulations or trade sanctions (e.g., ITAR or national security measures) affecting space-grade components or software.	Delays in procurement of critical parts, redesigns to replace restricted technologies, or legal limitations on collaboration with specific entities.
Regulations	R-RE-1	The mission must adhere to international treaties (e.g., Outer Space Treaty) and national space laws, which may impose constraints on operations, payload use, or surface activity.	Non-compliance could lead to legal disputes, mission delays, or reputational damage, and may require design or procedural modifications late in development.
	R-RE-2	Delays or complications in securing licenses for lunar mission operations, including communication frequency bands and launch approvals.	Can postpone launch schedules, disrupt coordination with ground systems, or cause loss of communication rights during critical mission phases.
Economic	R-E-1	Unexpected reductions in allocated funding or delays in disbursement due to shifting government priorities, economic downturns, or institutional policy changes.	Can cause re-planning of mission phases, downsizing of scope, postponement of critical activities, or even partial project cancellation.
	R-E-2	Rising costs for materials, specialized components, or contractor services due to inflation, supply chain instability, or scarcity of space-grade parts.	Increases the total mission expenditure, may force trade-offs in system capabilities, or lead to reallocation of funds from other mission areas.

Category	ID	Description	Impact
Supply Chain	R-SC-1	Delays or disruptions in the delivery of essential space-grade components (e.g., radiation-hardened electronics, propulsion valves) due to manufacturing issues or supplier dependency.	Can cause major schedule delays, require costly requalification of substitute parts, or even force redesigns of rover subsystems.
	R-SC-2	Reliance on a single supplier for key hardware or materials creates vulnerability if the vendor experiences financial, technical, or logistical problems.	Puts the entire project at risk of interruption, loss of quality control, or inability to meet integration timelines.

4.3 Risk Assessment and Severity Evaluation

In this section, as show in the figure below 4.5[1], a structured risk assessment is performed for all identified internal and external risks associated with the pressurized lunar rover. Each risk is evaluated along two critical dimensions:

- Probability (P): the likelihood that the risk will occur during the mission lifecycle, ranging from 1 (Minimum) to 5 (Maximum).

- Impact (I): the extent of consequences the risk would generate if it occurred, considering performance, schedule, and cost, ranging from 1 (Negligible) to 5 (Catastrophic).

The Severity (S) is calculated as the product of Probability and Impact ($S = P \times I$), and provides a quantitative indicator of the overall threat level posed by each risk. This value is used to prioritize the risks and guide the development of mitigation strategies in the following sections.

[1]The probability and impact values used in this risk assessment were estimated based on engineering judgment and aligned with methodologies described in standard references such as the NASA Risk Management Handbook [22] and ECSS-M-ST-80C [23]. These values do not derive from statistical mission data but represent a qualitative risk profiling tailored to the nature of the pressurized lunar rover mission under study.

			BM		
ID	**Category**	**Risk**	**Prob.**	**Imp.**	**Sev.**
R-M-1	Project Management	Quality Control Compliance	3	4	12
R-M-2		Requirements Compliance	3	4	12
R-M-3		Time & Scheduling Management	4	3	12
R-M-4		Communication Management	3	3	9
R-S-1	Systems Engineering	Interface Misalignment	2	3	6
R-S-2		Requirements Creep	3	2	6
R-SM-1	Safety and Mission Assurance	Insufficient Redundancy	2	5	10
R-SM-2		Inadequate Fault Detection	3	4	12
R-R-1	Rover	Mobility System Malfunction	3	5	15
R-R-2		Battery Performance	3	5	15
R-R-3		Sensor Calibration Drift	3	3	9
R-R-4		Thermal Control System Failure	3	5	15
R-R-5		Material Degradation in Lunar Environment	3	4	12
R-R-6		Pressurization Loss	2	5	10
R-R-7		Structural Integrity Degradation	3	4	12
R-R-8		Navigation and Guidance Failure	3	4	12
R-R-9		Communication System	3	4	12
R-R-10		Dust Infiltration into Mechanisms	4	5	20
R-R-11		Contamination of Scientific Instruments	3	3	9
R-R-12		Failure of Cabin Environmental Control	2	5	10
R-R-13		Radiation Exposure	3	5	15
R-L-1	Launch	Vehicle Integration Failure	2	5	10
R-L-2		Launch Delay or Window Miss	4	3	12
R-L-3		Vibration and Acoustic Stress	3	4	12
R-T-1	Systems Integration and Testin	Incomplete End-to-End Test Coverage	3	5	15
R-T-2		Interface Compatibility Errors	3	4	12
R-T-3		Environmental Test Gaps	3	3	9
R-G-1	Geopolitics	Deterioration of International Partnerships	2	4	8
R-G-2		Export Control and Sanctions	3	3	9
R-RE-1	Regulations	Compliance with Space Treaties and National Regulations	2	3	6
R-RE-2		Licensing and Frequency Allocation Delays	3	3	9
R-E-1	Economic	Budget Cuts or Funding Delays	3	4	12
R-E-2		Inflation and Cost Escalation	4	3	12
R-SC-1	Supply Chain	Critical Component Unavailability	4	4	16
R-SC-2		Single-Source Supplier Failure	3	4	12

Figure 4.5: Risk Assessment

As shown in the figure above, several risks stand out due to their high severity scores ($S \leq 20$), which represent the most critical threats to mission success:

			BM		
ID	**Category**	**Risk**	**Prob.**	**Imp.**	**Sev.**
R-R-10	Rover	Dust Infiltration into Mechanisms	4	5	20
R-SC-1	Supply Chain	Critical Component Unavailability	4	4	16
R-R-1	Rover	Mobility System Malfunction	3	5	15
R-R-2	Rover	Battery Performance Degradation	3	5	15
R-R-4	Rover	Thermal Control System Failure	3	5	15
R-R-13	Rover	Radiation Exposure	3	5	15
R-T-1	Systems Integration and Testing	Incomplete End-to-End Test Coverage	3	5	15

Figure 4.6: Risks with Higher Severity

These risks show in the figure 4.6 above, require special attention in the mitigation phase, as they carry significant potential for project delay, cost overruns, system failure, or even crew safety compromise.
The next section will focus on tailored mitigation strategies, targeting the highest severity risks and implementing proactive measures to minimize both likelihood and impact.

4.4 Risk Mitigation

Following the risk assessment and prioritization phase, a detailed mitigation strategy has been developed for each identified risk. As shown in the table 4.8 below, each risk is associated with a designated Risk Owner responsible for managing it throughout the project lifecycle. For every risk, a specific Response Strategy is selected-ranging from Accept, Mitigate to Transfer-depending on the nature of the risk, its controllability, and its severity score.
In addition, both a Contingency Plan and a Mitigation Plan are defined:

- Mitigation Plan: Preventive actions taken before the risk occurs to reduce either the probability or the impact.

- Contingency Plan: Corrective measures planned for activation in the event that the risk materializes.

The right-hand side of the table also displays the updated probability and impact levels (AM - After Mitigation), showing the residual severity scores after the mitigation measures have been applied. These reduced values confirm the effectiveness of the planned responses in managing mission risk.

			Mitigation Strategy				AM		
ID	**Category**	**Risk**	**Risk Owner**	**Response Strateg**	**Contigency Plan**	**Mitigation Plan**	**Prob**	**Imp.**	**Sev.**
R-M-1	Project Management	Quality Control Compliance	Project Quality Manager	Mitigate	Trigger re-inspection and rework if non-compliance is found during final testing	Enforce multi-step QA checks and supplier certification	2	3	6
R-M-2		Requirements Compliance	Systems Engineering Manager	Mitigate	Activate corrective design loop and requirement back-trace in case of late misalignment	Implement regular requirement verification and change control process	2	3	6
R-M-3		Time & Scheduling Management	Project Manager	Mitigate	Reallocate resources and compress non-critical tasks if delays occur	Use detailed scheduling tools and monitor critical path regularly	2	3	6
R-M-4		Communication Management		Mitigate	Hold alignment meetings to resolve miscommunication issues	Define clear communication protocols and stakeholder responsibilities	2	2	4
R-S-1	Systems Engineering	Interface Misalignment	Lead Systems Engineer	Mitigate	Perform interface redesign and revalidation if mismatch occurs during integration	Use Interface Control Documents (ICDs) and early integration testing	2	3	6
R-S-2		Requirements Creep		Mitigate	Freeze scope and reject late-stage requirement changes	Enforce change control board and requirement baseline management	2	3	6
R-SM-1	Safety and Mission Assurance	Insufficient Redundan	Safety & Mission Assurance Lead	Mitigate	Activate backup procedures if primary system fails	Design and verify redundant systems for all critical functions	1	4	4
R-SM-2		Inadequate Fault Detection		Mitigate	Switch to manual or crew intervention if anomaly is undetected	Develop and test autonomous fault detection and isolation algorithms	2	3	6
R-R-1	Rover	Mobility System Malfunction	Rover Mechanical Subsystem Lead	Mitigate	Use alternate route planning or limited-range fallback mode	Test mobility system in regolith simulants and include fault-tolerant design	2	3	6
R-R-2		Battery Performance Degradation	Power Subsystem Lead	Mitigate	Switch to reduced power mode and prioritize essential systems	Use qualified batteries with thermal shielding and life-cycle testing	2	3	6
R-R-3		Sensor Calibration Drift	Avionics & Navigation Lead	Mitigate	Recalibrate using reference markers or backup data	Implement in-mission auto-calibration routines and environmental shielding	2	2	4
R-R-4		Thermal Control System Failure	Thermal Subsystem Lead	Mitigate	Isolate affected components and switch to emergency thermal mode	Use active/passive thermal control redundancy and extensive thermal vacuum testing	2	3	6
R-R-5		Material Degradation in Lunar Environment	Materials & Structures Lead	Mitigate	Limit exposure time or reconfigure mission plan if degradation is detected	Use qualified materials tested under lunar-like vacuum, dust, and radiation conditions	2	3	6
R-R-6		Pressurization Loss	ECLSS Lead	Mitigate	Immediate crew evacuation and cabin isolation	Use redundant seals, pressure sensors, and structural integrity monitoring	1	4	4
R-R-7		Structural Integrity Degradation	Structural Engineering Lead	Mitigate	Reduce operational loads and reroute non-critical functions	Use high-durability materials and perform fatigue/radiation lifetime analysis	2	3	6
R-R-8		Navigation and Guidance Failure	GNC Lead	Mitigate	Switch to manual control or predefined safe-mode path	Implement sensor fusion, redundant navigation sources, and fault detection logic	2	3	6
R-R-9		Communication System Malfunction	Communications Subsystem Lead	Mitigate	Use backup antenna or switch to autonomous mode	Include redundant comm paths and perform link margin analysis	2	3	6
R-R-10		Dust Infiltration into Mechanisms	Mechanisms & Seals Lead Engineer	Mitigate	Disable affected components and rely on redundant or manual alternatives	Use dust-tolerant designs, protective covers, and regolith-tested seals	2	3	6
R-R-11		Contamination of Scientific Instruments	Payload & Science Lead	Mitigate	Isolate or recalibrate contaminated instruments if degradation is detected	Seal sensitive instruments and integrate contamination monitoring	2	2	4

Figure 4.7: Risks Mitigation

R-R-12		Failure of Cabin Environmental Control	ECLSS Lead	Mitigate	Switch to backup life support mode or initiate crew evacuation	Use redundant ECLSS subsystems with real-time monitoring and diagnostics	1	4	4
R-R-13		Radiation Exposure	Mission Safety Officer	Mitigate	Shelter crew in shielded zone or abort surface operations during SPEs	Integrate radiation shielding and monitor space weather forecasts	2	3	6
R-L-1	Launch	Vehicle Integration Failure	Launch Integration Manager	Mitigate	Delay integration and apply corrective interface adjustments	Perform early interface verification and cross-check with launch provider specs	1	3	3
R-L-2		Launch Delay or Window Miss		Mitigate	Rebook next available launch window and adjust mission timeline	Build schedule margin and secure secondary launch options	2	2	4
R-L-3		Vibration and Acoustic Stress		Mitigate	Inspect and replace damaged components post-launch if anomalies are detected	Perform qualification testing under expected launch load profiles	2	3	6
R-T-1	Systems Integration and Testing	Incomplete End-to-End Test Coverage	Integration & Test Lead	Mitigate	Apply software updates or procedural workarounds during mission	Develop high-fidelity mission simulations and full-system integrated tests	2	3	6
R-T-2		Interface Compatibility Errors		Mitigate	Apply hardware/software patch or replace incompatible modules	Perform early interface validation and system-level integration tests	2	3	6
R-T-3		Environmental Test Gaps		Mitigate	Implement in-mission workarounds or limit affected operations	Supplement test campaigns with detailed simulations and heritage data	2	3	6
R-G-1	Geopolitics	Deterioration of International Partnerships	Program Director	Mitigate	Shift responsibilities to national partners or internal resources	Establish clear agreements and diversify partnership dependencies	1	3	3
R-G-2		Export Control and Sanctions	Legal & Compliance Officer	Mitigate	Replace restricted components with compliant alternatives	Monitor regulatory updates and pre-qualify export-compliant suppliers	2	2	4
R-RE-1	Regulations	Compliance with Space Treaties and National Regulations		Mitigate	Adjust mission scope or operations to align with legal constraints	Perform early legal review and continuous coordination with regulatory bodies	1	3	3
R-RE-2		Licensing and Frequency Allocation Delays		Mitigate	Use backup frequency bands or request emergency authorization	Submit licensing applications early and maintain continuous coordination with regulatory	2	2	4
R-E-1	Economic	Budget Cuts or Funding Delays	Program Finance Manager	Mitigate	Reprioritize tasks and defer non-critical activities	Secure multi-year funding and include financial buffers in planning	2	3	6
R-E-2		Inflation and Cost Escalation		Transfer	Adjust scope or postpone non-essential procurements	Lock key contracts early and include escalation clauses in budgeting	2	3	6
R-SC-1	Supply Chain	Critical Component Unavailability	Supply Chain Manager	Transfer	Use pre-qualified substitutes or adjust integration schedule	Identify alternate suppliers and place long-lead orders early	2	3	6
R-SC-2		Single-Source Supplier Failure		Mitigate	Activate backup supplier or initiate internal production	Qualify multiple vendors and establish framework agreements	2	3	6

Figure 4.8: Risks Mitigation

As evident from the updated severity values, most high-severity risks have been successfully reduced to moderate or low levels. As show in the figure 4.9 below:

			BM			AM		
ID	**Category**	**Risk**	**Prob.**	**Imp.**	**Sev.**	**Prob.**	**Imp.**	**Sev.**
R-R-10	Rover	Dust Infiltration into Mechanisms	4	5	20	2	3	6
R-SC-1	Supply Chain	Critical Component Unavailability	4	4	16	2	3	6
R-R-1	Rover	Mobility System Malfunction	3	5	15	2	3	6
R-R-2	Rover	Battery Performance Degradation	3	5	15	2	3	6
R-R-4	Rover	Thermal Control System Failure	3	5	15	2	3	6
R-R-13	Rover	Radiation Exposure	3	5	15	2	3	6

Figure 4.9: Risks Mitigation

- Mobility System Malfunction (R-R-1), Thermal Control Failure (R-R-4), and Radiation Exposure (R-R-13) originally scored high (Severity $\geq$ 15), but were mitigated to manageable levels.

- Dust Infiltration (R-R-10)-originally the highest with Severity 20-was substantially reduced thanks to robust mechanical design and redundancy.

- Critical Component Unavailability (R-SC-1) and Battery Performance Degradation (R-R-2) have been proactively managed through a combination of early supplier qualification, procurement planning, and subsystem-level testing.

These results demonstrate a proactive and structured approach to risk control, crucial to ensure the technical, financial, and operational robustness of the pressurized lunar rover missions.
The following figures 4.12 present a consolidated view of all identified risks, showing the severity evaluation both before (BM) and after mitigation (AM). Each risk is assessed with color-coded values to highlight relative criticality.

			BM			AM		
ID	**Category**	**Risk**	**Prob.**	**Imp.**	**Sev.**	**Prob.**	**Imp.**	**Sev.**
R-M-1	Project Management	Quality Control Compliance	3	4	12	2	3	6
R-M-2		Requirements Compliance	3	4	12	2	3	6
R-M-3		Time & Scheduling Management	4	3	12	2	3	6
R-M-4		Communication Management	3	3	9	2	2	4
R-S-1	Systems Engineering	Interface Misalignment	2	3	6	2	3	6
R-S-2		Requirements Creep	3	2	6	2	3	6
R-SM-1	Safety and Mission Assurance	Insufficient Redundar	2	5	10	1	4	4
R-SM-2		Inadequate Fault Detection	3	4	12	2	3	6
R-R-1		Mobility System Malfunction	3	5	15	2	3	6
R-R-2		Battery Performance Degradation	3	5	15	2	3	6

Figure 4.10: Risks Mitigation

R-R-3		Sensor Calibration Drift	3	3	9	2	2	4
R-R-4		Thermal Control System Failure	3	5	15	2	3	6
R-R-5		Material Degradation in Lunar Environment	3	4	12	2	3	6
R-R-6		Pressurization Loss	2	5	10	1	4	4
R-R-7	Rover	Structural Integrity Degradation	3	4	12	2	3	6
R-R-8		Navigation and Guidance Failure	3	4	12	2	3	6
R-R-9		Communication System Malfunction	3	4	12	2	3	6
R-R-10		Dust Infiltration into Mechanisms	4	5	20	2	3	6
R-R-11		Contamination of Scientific Instruments	3	3	9	2	2	4
R-R-12		Failure of Cabin Environmental Control	2	5	10	1	4	4
R-R-13		Radiation Exposure	3	5	15	2	3	6

Figure 4.11: Risks Mitigation

R-L-1	Launch	Vehicle Integration Failure	2	5	10	1	3	3
R-L-2		Launch Delay or Window Miss	4	3	12	2	2	4
R-L-3		Vibration and Acoustic Stress	3	4	12	2	3	6
R-T-1	Systems Integration and Testing	Incomplete End-to-End Test Coverage	3	5	15	2	3	6
R-T-2		Interface Compatibility Errors	3	4	12	2	3	6
R-T-3		Environmental Test Gaps	3	3	9	2	3	6
R-G-1	Geopolitics	Deterioration of International Partnerships	2	4	8	1	3	3
R-G-2		Export Control and Sanctions	3	3	9	2	2	4
R-RE-1	Regulations	Compliance with Space Treaties and National Regulations	2	3	6	1	3	3
R-RE-2		Licensing and Frequency Allocation Delays	3	3	9	2	2	4
R-E-1	Economic	Budget Cuts or Funding Delays	3	4	12	2	3	6
R-E-2		Inflation and Cost Escalation	4	3	12	2	3	6
R-SC-1	Supply Chain	Critical Component Unavailability	4	4	16	2	3	6
R-SC-2		Single-Source Supplier Failure	3	4	12	2	3	6

Figure 4.12: Risks Mitigation

This comparative evaluation enables a clear understanding of the effectiveness of the risk response actions taken. As illustrated, the majority of high-severity risks ($S \geq 12$) have been successfully reduced to moderate ($6 \leq S < 12$) or low ($S < 6$) levels after mitigation.

Chapter 5
Quality Analysis for Pressurized Rover Missions

5.1 Failure Modes, Effects and Criticality Analysis (FMECA)

The Failure Modes, Effects, and Criticality Analysis (FMECA) is a structured, bottom-up methodology used to evaluate the potential failure modes of components and subsystems within complex systems such as lunar rovers. Its primary goal is to identify weaknesses early in the design phase, assess their potential impact on system performance, and support the implementation of corrective or preventive measures to improve mission reliability and safety.

Given the structural and functional similarities between the Semi-Stationary Pressurized Rover and the Transport Pressurized Rover, and the shared nature of their critical subsystems (e.g., ECLSS, mobility, power, communication), this analysis will be conducted as a single integrated FMECA. This unified approach provides a comprehensive overview of the most significant failure scenarios while avoiding unnecessary duplication.

The FMECA table is structured as in figure 5.1:

Subsystem	Component	Failure Mode	Effect of Failure	S	Potential Cause of Failure	O	D	RPN	Recommended Action

Figure 5.1: FMECA Table

Each line in the FMECA represents a specific component within a subsystem, the way it can fail (failure mode), and the consequences of that failure (effect of failure). The table 5.1 includes the following columns:

Table 5.1: Description of the FMECA

Column	**Description**
Subsystem	The higher-level functional domain or system (e.g., Mobility, Power, ECLSS).
Component	The specific hardware or software element within the subsystem.
Failure Mode	A concise description of how the component could fail (e.g., "motor overheating").
Effect of Failure	The direct consequence of the failure on system performance, mission objectives, or crew safety.
Current Process Controls	Lists the tools or procedures currently in place to detect, prevent, or mitigate the failure. These include sensors, alarms, redundancy, diagnostics, or inspection protocols. To justify **D**.
RPN	The Risk Priority Number: **S** × **O** × **D**. This is used to rank the failure modes in terms of risk priority.
Recommended Action	Suggested mitigation measures to reduce the risk-this may include design changes, redundancy, alarms, or improved monitoring.

To quantify the risk associated with each failure, three key indices are assigned (Table 5.2):

Table 5.2: Severity, Occurrence, Detection

Parameter	**Description**
Severity (S)	The consequence of the failure on safety, mission success, or system performance.
Occurrence (O)	The estimated likelihood of the failure mode occurring during the mission.

Parameter	Description
Detection (D)	The ability to detect the failure before it impacts the mission.

Each parameter (S, O, D) is rated from 1 (least critical/frequent/detectable) to 10 (most critical/frequent/undetectable).

Table 5.3: Severity (S)

Severity	Description	Impact
1	No effect on mission or crew	Negligible
2–3	Minor degradation of performance	Limited functional impact
4–5	Moderate reduction in performance	Reduced mission efficiency
6–7	Subsystem failure, workaround possible	Major inconvenience
8–9	Mission objectives compromised, no recovery	Severe impact
10	Total system loss or crew safety compromised	Catastrophic

Table 5.4: Occurrence (O)

Occurrence	Description	Estimated Likelihood
1	Failure unlikely, never observed	$< 0.01\%$
2–3	Failure rare, occurs in edge conditions	0.1%–0.5%
4–5	Occasional failure in similar systems	1%–5%
6–7	Failure possible in operational use	10%–20%
8–9	Failure occurs frequently	30%–60%
10	Failure almost certain	$> 80\%$

Table 5.5: Detection (D)

Detection	Description	Likelihood of Detection
1	Failure always detected and reported	< 99%+
2–3	Failure usually detected by monitoring	80%–95%
4–5	Failure sometimes detectable	50%–70%
6–7	Failure rarely detected before system effect	20%–40%
8–9	Failure very unlikely to be detected before impact	5%–10%
10	Failure is undetectable until after system failure	< 1%

Table 5.6 below illustrates the components of the major subsystems considered in the Failure Modes, Effects, and Criticality Analysis (FMECA). This table support the identification and classification of critical elements subject to potential failure during rover operations [24], [25], [26].

Table 5.6: FMECA Analysis

Component	Failure Mode	Effect(s) of Failure	Potential Cause of Failure
Wheels	Structural damage or detachment due to regolith abrasion or mechanical stress	Loss of traction or complete immobilization of the rover; inability to reposition or complete traversal objectives	Prolonged exposure to sharp lunar regolith, overloading during terrain navigation, material fatigue
Motors	Overheating or torque loss leading to motor burnout or seizure	Partial or total loss of mobility; increased energy consumption; potential mission abort in case of terrain entrapment	Extended operation under load, poor thermal dissipation, dust infiltration in motor housing

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
Suspension	Mechanical joint failure or deformation in rocker-bogie suspension system	Reduced ability to maintain wheel-ground contact; loss of stability over uneven terrain; increased stress on other mobility components	Excessive mechanical stress, fatigue due to repeated loading, dust abrasion in articulations
Steering	Steering actuator malfunction or misalignment	Loss of directional control; increased turning radius; risk of being unable to avoid obstacles or align with desired path	Actuator wear, software error in steering control logic, or obstruction from lunar dust
Sensors	Sensor blackout, miscalibration, or data loss	Impaired terrain assessment; reduced obstacle detection; increased risk of collision or entrapment	Radiation effects, dust contamination on optics, or thermal cycling degrading sensor performance
DIPS	Power output drop or total shutdown	Loss of continuous power to life support, mobility, and communication systems; immediate mission abort; critical threat to crew survival	Mechanical failure in turbine assembly, thermal imbalance, fuel degradation, or radiator blockage
Batteries	Capacity degradation or thermal runaway	Reduced ability to handle power peaks or support emergency systems; risk of fire or internal damage in extreme cases	Repeated charge/discharge cycles under thermal stress; internal short-circuit; electrolyte leakage

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
EMU	Power routing failure or software malfunction	Incorrect or blocked power delivery to critical subsystems (e.g., life support, communication); system-wide power instability or cascading shutdown	Faulty control logic, processor crash, power line short circuit, or corrupted sensor input
Power distribution	Electrical short circuit or open circuit in power lines	Power loss to downstream subsystems; risk of overcurrent damage; possible fire hazard or full system blackout	Faulty connectors, wiring degradation, vibration-induced disconnection, regolith intrusion
Radiators	Reduced or blocked heat rejection due to surface contamination or mechanical damage	Overheating of onboard systems (e.g., electronics, power units, ECLSS); degradation or shutdown of critical functions	Regolith deposition, micrometeoroid impact, deployment failure of radiator panels
PCM modules	PCM degradation or failure to transition properly between solid and liquid phases	Reduced thermal buffering capacity; temperature spikes during peak loads; possible overheating of critical subsystems	Material fatigue after repeated thermal cycles, leakage, or improper encapsulation
Insulation	Loss of insulation effectiveness due to material degradation, tearing, or dust infiltration	Uncontrolled heat transfer to or from the environment; risk of thermal stress on internal systems; increased energy demand for temperature regulation	Micrometeoroid damage, regolith abrasion, delamination during thermal cycling

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
ARM	CO_2 scrubber saturation or oxygen generation failure	Accumulation of CO_2 and/or oxygen depletion in the cabin; immediate risk to crew health and mission continuity	Sorbent bed exhaustion, electrolyzer malfunction, contamination, system leak
WMM	Filtration or recycling failure, leading to water contamination or loss	Inability to supply clean water for drinking, hygiene, or system cooling; potential health hazard and interruption of thermal control	Filter clogging, microbial growth, distillation system breakdown, seal failure
FPM	Inability to rehydrate, heat, or access food supplies	Crew unable to receive sufficient nutrition; risk of fatigue, cognitive degradation, and mission interruption	Water supply failure, heating system malfunction, packaging breach, or mechanical obstruction
WDM	Failure to collect, contain, or process liquid/-solid waste	Unhygienic cabin conditions; odor, biological contamination risk; reduced crew comfort and possible medical hazard	Seal leakage, compactor jamming, fluid overflow, valve malfunction
CHM	Failure of exercise equipment or health monitoring systems	Reduced crew physical condition, inability to track vital signs; increased health risks during extended missions	Mechanical failure of exercise devices, software bug in biometric sensors, miscalibration, or data loss
High-gain Antenna	Signal transmission loss due to mechanical misalignment or hardware failure	Loss of long-range communication with mission control; inability to transmit telemetry or receive commands	Actuator failure, dust accumulation on antenna dish, cable disconnection, radiation-induced electronics degradation

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
Transmitters	Transmission failure due to amplifier burnout or circuit malfunction	Partial or complete loss of signal transmission; degradation of data quality or total comms blackout	Overheating, radiation damage to components, voltage surges, solder joint cracking due to thermal cycling
Protocol Stack	Corrupted data handling, loss of synchronization, or protocol misalignment	Inability to interpret or transmit valid data; dropped packets, command misinterpretation, or system timeouts	Software bug, memory corruption, desynchronization between systems, or incompatible error-correction configuration
Cameras	Image distortion, misalignment, or complete sensor failure	Loss or degradation of visual navigation, mapping, and obstacle detection capabilities; impaired autonomous mobility	Radiation damage to imaging sensor, lens contamination by dust, miscalibration, or thermal stress
Navigation software	Navigation error due to software bug, corrupted map data, or logic fault	Path deviation, obstacle collision, or inability to localize; autonomous operations compromised; increased mission risk	Faulty algorithm, memory overflow, degraded sensor input, or mismatched data fusion
Shell	Structural breach or degradation of pressurized hull	Loss of cabin pressure; immediate threat to crew safety; mission abort or emergency shelter activation	Micrometeoroid impact, material fatigue, regolith abrasion, or thermal cycling-induced cracks
Hatch	Inability to open/close or seal the hatch properly	Prevents crew ingress/egress; risks depressurization; obstructs EVA operations or emergency return to cabin	Mechanical jamming, seal damage, thermal expansion, actuator failure, or dust intrusion

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
EVA seal	Seal leakage or loss of integrity during or after EVA	Cabin depressurization; risk to crew safety; inability to perform or complete EVA; emergency return procedures required	Abrasion from lunar dust, thermal cycling fatigue, improper latching, or material degradation over time
Micrometeoroid Shield	Inability to absorb or deflect micrometeoroid impact	Penetration of structural layers or pressurized cabin; risk of system damage or depressurization	Impact by high-velocity debris larger than design tolerance, shield aging or delamination, or improper material selection
Shelter	Inability to maintain adequate radiation shielding during a solar particle event (SPE)	Crew exposed to hazardous radiation levels; potential for acute radiation sickness; mission interruption or emergency evacuation	Insufficient mass shielding, design miscalculation, shield degradation over time, or improper material distribution
Shielding panels	Degradation or detachment of shielding panels	Increased radiation exposure in cabin areas; reduced effectiveness during SPEs; long-term health risks to crew	Micrometeoroid impact, thermal cycling-induced delamination, material aging, or mechanical stress
Sample storage	Breach of containment or sample contamination	Loss of scientific integrity; invalid or unusable samples; risk of cross-contamination within the rover	Seal failure, improper handling, regolith abrasion, internal pressure imbalance, or mechanical jamming
Instruments	Instrument malfunction or calibration drift	Loss or degradation of scientific data; inability to perform in-situ analysis; delays or reduction in mission objectives	Radiation exposure, thermal drift, mechanical shock, software bug, or lens/sensor contamination

Component	**Failure Mode**	**Effect(s) of Failure**	**Potential Cause of Failure**
Diagnostic logic	Failure to detect or incorrectly classify system anomalies	Delayed or incorrect responses to critical faults; propagation of subsystem errors; increased risk of mission failure	Software bug, sensor fault, incomplete fault tree definitions, or unexpected failure modes
Safe Mode Controller	Failure to enter or maintain safe mode during system anomaly	Uncontrolled subsystem behavior; inability to isolate faults; risk of system-wide damage or cascading errors	Software corruption, improper fault detection handoff, timing error, or logic loop preventing mode activation
Health Monitoring	Incomplete, delayed, or inaccurate health data reporting	Missed early warnings of system degradation; reduced situational awareness for crew and ground control; delayed fault response	Sensor drift, data bus fault, time desynchronization, software crash

In the following table 5.7 [1] there will be the values of Severity, Occurrence and Detection of each component.

Table 5.7: S-O-D Components

Subsystem	**Component**	**S**	**O**	**D**	**RPN**
Mobility System	Wheels	8	5	4	160
	Motors	9	6	3	162
	Suspension	7	4	5	140
	Steering	8	5	4	160

[1] The severity, occurrence, and detection ratings in this FMECA analysis were defined using estimation and adapted from reference scales outlined in MIL-STD-1629A and ECSS-Q-ST-30-02C [26]. These values reflect anticipated performance in a lunar environment and were assigned to support a preliminary design-phase risk prioritization process.

Subsystem	**Component**	**S**	**O**	**D**	**RPN**
	Sensors	7	6	5	210
Power System	DIPS	10	3	3	90
	Batteries	8	5	4	160
	EMU	9	4	3	108
	Power distribution	9	4	4	144
Thermal Control System (TCS)	Radiators	9	4	4	144
	PCM modules	7	5	5	175
	Insulation	6	4	6	144
Life Support System (ECLSS)	ARM	10	3	2	60
	WMM	9	4	3	108
	FPM	8	3	4	96
	WDM	7	4	3	84
	CHM	6	4	3	72
Communication System	High-gain Antenna	9	4	3	108
	Transmitters	8	5	3	120
	Protocol Stack	7	4	4	112
Autonomy & Navigation System	Cameras	8	5	4	160
	Navigation software	9	4	4	144
Structural & Pressurized Cabin	Shell	10	3	2	60
	Hatch	9	4	3	108
	EVA seal	10	4	2	80
	Micrometeoroid Shield	9	3	5	135
Radiation Protection	Shelter	10	2	3	60
	Shielding panels	8	3	4	96
Scientific Payload / Sample Handling	Sample storage	7	4	3	84
	Instruments	6	5	3	90

Subsystem	Component	S	O	D	RPN
System Integration & Control	Diagnostic logic	8	4	4	128
	Safe Mode Controller	9	3	3	81
	Health Monitoring	7	4	4	112

The table summarizes the Severity (S), Occurrence (O), and Detection (D) values assigned to each component, with the Risk Priority Number (RPN) used to identify and prioritize the most critical failure modes.
As show in the figure 5.2 below, among the components, Sensors (RPN = 210), PCM modules (175), Motors (162), and Navigation software (144) show the highest RPN values. These high scores indicate a combination of severe consequences, high likelihood of failure, and limited detectability-suggesting that these areas require urgent attention and mitigation.
In contrast, components such as the Shelter (RPN = 60), CHM (72), and the EVA seal (80) have the lowest RPNs. While still important for mission safety and reliability, these elements currently present lower levels of risk and are likely well-controlled by the existing safeguards in place.

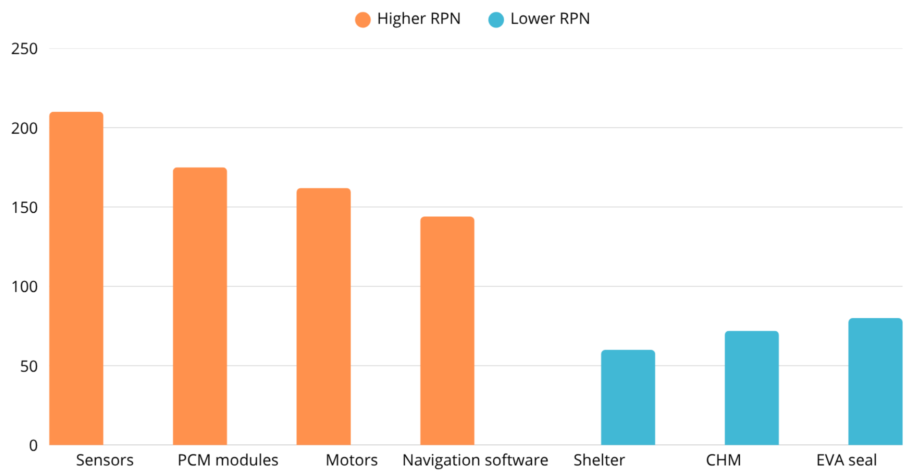


Figure 5.2: RPN before actions

5.2 Quality Assessment and Mitigation Strategies

The following table presents a revised risk analysis of each system component after the implementation of specific mitigation actions. While the Severity (S) rating remains unchanged-reflecting the inherent impact of the failure mode-the Occurrence (O') and Detection (D') values have been recalculated to reflect the expected improvements from the recommended corrective actions. As a result, the updated Risk Priority Number (RPN') provides a clearer indication of the reduced risk level for each component, allowing for better prioritization and decision-making in the design and operational planning of the system.

Component	**Recommended Action**	**S**	**O'**	**D'**	**RPN'**
Wheels	Design wheels with flexible composite mesh; implement regolith-deflecting shields; add redundancy in locomotion systems	8	3	3	72
Motors	Add heat shielding and thermal path to radiators; implement dust-proof motor enclosures; include software-based overload prevention routines	9	4	2	72
Suspension	Reinforce suspension arms; add articulation angle sensors; consider redundant linkages or a semi-passive damping system	7	2	4	56
Steering	Implement software limiters; design actuator housings to be dust-resistant; introduce redundant steering modes	8	3	3	72
Sensors	Add protective covers and auto-cleaning mechanisms; implement cross-checking algorithms between multiple sensor types	7	4	4	112
DIPS	Include high-capacity battery backup; monitor thermal conditions continuously; design failover logic for critical systems to switch to emergency mode	10	1	2	20
Batteries	Reinforce thermal shielding; include automated battery isolation switch; schedule power system diagnostics at regular intervals	8	1	1	8

Component	**Recommended Action**	**S**	**O'**	**D'**	**RPN'**
EMU	Implement watchdog timers and self-recovery routines; add manual override capability; isolate critical loads with hardware-level switches	9	2	2	36
Power distribution	Segment the power network with independent breakers; use self-healing fuses; include diagnostic software to localize faults automatically	9	2	1	18
Radiators	Add radiator cleaning mechanism or shielding; implement redundant radiative paths; enhance onboard temperature trend diagnostics	9	2	3	54
PCM modules	Use redundant PCM units; monitor thermal lag in affected zones; plan periodic recalibration of thermal response models	7	3	4	84
Insulation	Add localized temperature sensors near insulation-critical zones; reinforce MLI with impact-resistant outer layers	6	2	5	60
ARM	Include automatic CO_2 scrubber switchover; provide manual override for oxygen injection; add predictive diagnostics on sorbent health	10	1	1	10
WMM	Add spare filters and membranes; implement automated bypass for failed sections; integrate warning system for early indication of saturation	9	2	2	36
FPM	Provide emergency ration packs that do not require rehydration; implement status monitoring for heating elements; allow manual access to storage	8	1	3	24
WDM	Include redundant collection paths; provide crew with backup manual disposal kits; design for easy access and maintenance in EVA suits if required	7	2	2	28

Component	Recommended Action	S	O'	D'	RPN'
CHM	Include backup fitness tools (e.g., resistance bands); ensure offline data recording; perform regular system checks and calibrations	6	2	2	24
High-gain Antenna	Add mechanical and electrical redundancy; integrate auto-repointing logic; shield antenna head from dust and thermal cycling	9	2	2	36
Transmitters	Include backup transmitters with automatic switching; reinforce thermal control; apply radiation-hardened designs for RF components	8	3	2	48
Protocol Stack	Implement real-time protocol validation and watchdogs; use error-correction codes (ECC); develop rollback procedures for corrupted communication stacks	7	2	3	42
Cameras	Include backup camera arrays; integrate sensor fusion with LIDAR; add active cleaning system or transparent protective shutters	8	3	3	72
Navigation software	Apply formal software verification; implement fallback to manual teleoperation; include runtime self-correction and recovery protocols	9	2	3	54
Shell	Reinforce critical zones with impact-tolerant materials; add internal storm shelter; include localized pressure loss alarms and sealing kits	10	2	1	20
Hatch	Design for manual emergency operation; shield hinges from regolith; include seal health monitoring and backup closure mechanisms	9	3	2	54
EVA seal	Use dust-tolerant seal designs; include manual secondary seal; add localized pressure sensors and alarms for fast isolation in case of breach	10	3	1	30

Component	Recommended Action	S	O'	D'	RPN'
Micrometeoroid Shield	Enhance shielding in critical areas; install impact sensors on hull; include internal containment zones to limit effects of punctures	9	2	3	54
Shelter	Verify shielding effectiveness through periodic validation; store consumables and water around shelter walls to enhance passive protection	10	1	2	20
Shielding panels	Use layered shielding with overlapping coverage; monitor radiation flux inside cabin; install fault-tolerant panel attachments	8	2	3	48
Sample storage	Include redundant containment layers; isolate compartments to prevent cross-contamination; add sample integrity sensors if feasible	7	2	2	28
Instruments	Perform regular calibration with onboard standards; include backup instruments for key functions; design components to be swappable or serviceable	6	2	2	24
Diagnostic logic	Expand anomaly training datasets; apply machine-learning-assisted fault detection; implement conservative default actions for unclassified faults	8	2	2	32
Safe Mode Controller	Perform formal verification of transition logic; isolate safety-critical code from mission payload code; implement manual override from ground	9	2	1	18
Health Monitoring	Implement cross-validation between subsystems; log discrepancies for post-analysis; include backup telemetry paths and fallback health algorithms	7	2	3	42

After the implementation of the mitigation strategies, a general reduction in risk levels has been observed across all components. The recalculated RPN values reflect improvements in both Occurrence and Detection, while Severity remains unchanged.

The components with the highest residual risk (figure 5.3) are the Sensors (RPN = 112), followed by the PCM modules (84), Motors (72), and Navigation software (54), even if their values are lower than before. Despite improvements in Occurrence and Detection, these systems still maintain relatively high RPN values due to their inherently high Severity-particularly in the case of the Sensors, which remain the most critical element post-mitigation.

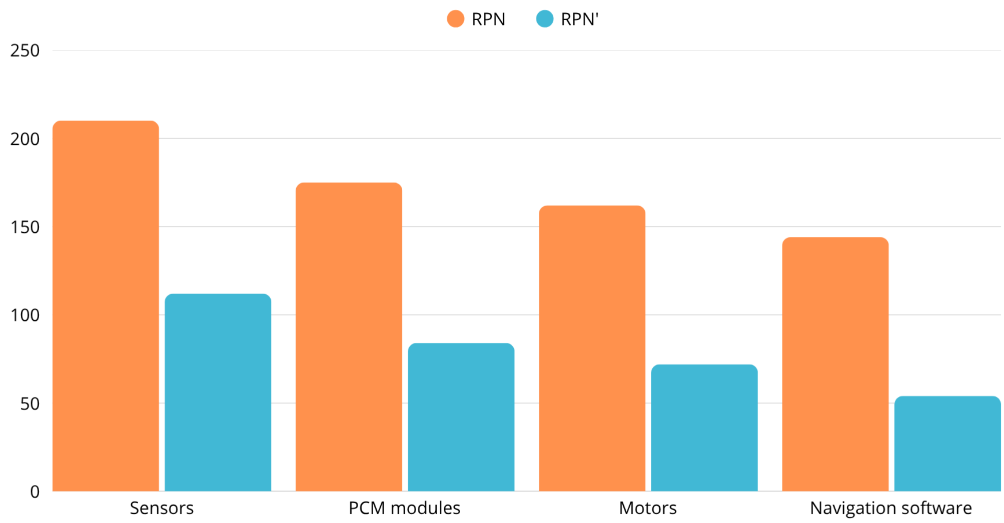


Figure 5.3: RPN higher after actions

Conversely, the lowest RPN values (figure 5.4) are now observed in the Batteries (8), ARM (10), Safe Mode Controller (18), and Shelter (20). These reductions demonstrate the effectiveness of the proposed actions in lowering both the likelihood of failure and improving detectability. As a result, these components can be considered well-managed under current design conditions and control strategies.

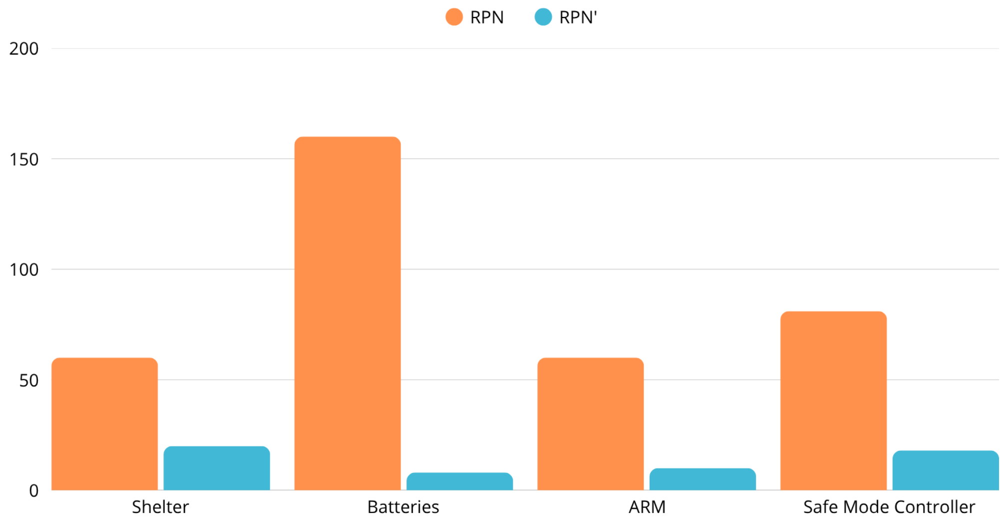


Figure 5.4: RPN new lower after actions

Chapter 6
Conclusions and future prospectives

This final part of the thesis reflects the outcomes of this research and the broader implications they may hold for the future of lunar exploration. The following sections first summarize the main findings of the thesis, highlighting the contributions and limitations of the applied project management methodologies. They then turn to possible future directions, outlining short-, medium-, and long-term perspectives for both technical development and methodological refinement.

6.1 Conclusions

This thesis has investigated the application of project management methodologies to the planning and development of pressurized lunar rover (PLR) missions, with a focus on two distinct mission profiles: the Semi-Stationary Rover and the Transport Rover. While the technical design of space systems has historically received most of the attention in the literature, this work has sought to demonstrate that structured project management (PM) approaches provide an equally critical contribution to the success of such missions. By applying frameworks and tools derived from the PMBOK guidelines, including Work Breakdown Structures (WBS), Gantt charts, Critical Path Method (CPM), Risk Breakdown Structures (RBS), and Failure Modes, Effects, and Criticality Analysis (FMECA), the thesis has created a comprehensive foundation for evaluating both the feasibility and the sustainability of PLR projects.
The comparative analysis carried out between the two mission profiles has provided several valuable insights. The Semi-Stationary Rover, designed to operate in a localized area, demonstrates advantages in terms of cost containment, operational simplicity, and reduced risk exposure. This mission profile benefits from a shorter critical path, fewer interdependent activities, and consequently a lower probability of schedule delays. The reduced operational range also minimizes exposure to

uncertainties such as power shortages, terrain unpredictability, and communication risks. Conversely, the Transport Rover, intended for long-range exploration and logistics, offers enhanced mission capability, greater autonomy for the crew, and the possibility of supporting more ambitious exploration goals. However, this comes at the expense of higher system complexity, a longer and more vulnerable critical path, and an increased number of high-severity risks identified in the RBS and FMECA analyses. Financially, the Transport Rover requires significantly greater investment both in development and in operations, reflecting the broader scope of its intended functionality. This trade-off underscores the necessity of adopting an integrated management perspective, where technical, financial, and operational factors are weighed against one another to identify the most appropriate mission strategy.

A major contribution of this work lies in the demonstration that even at the conceptual and preliminary stages of mission planning, project management tools are not merely supplementary but essential. The use of WBS and CPM enabled the structuring of mission phases and identification of the critical path, ensuring that scheduling and resource allocation could be evaluated with greater accuracy. For the Semi-Stationary Rover, the WBS revealed a relatively shallow hierarchy of tasks, reflecting a simpler scope of work and facilitating monitoring and control. For the Transport Rover, the WBS structure was deeper and more fragmented, reflecting the wider range of subsystems and operational requirements. This not only highlighted the different scales of complexity but also showed how project management tools provide early visibility of potential bottlenecks and cost drivers. The risk assessment process, carried out through the creation of a tailored RBS, systematically identified mission-specific risks and enabled the definition of mitigation strategies. The analysis revealed that risks related to mobility systems, power generation, and life support were the most critical across both mission profiles, although their severity and likelihood differed significantly between the Semi-Stationary and the Transport Rover. For the Transport Rover, the higher number of interdependencies amplified the occurrence of cascading risks, requiring more robust contingency planning. Similarly, the quality assurance step, conducted with FMECA, highlighted the vulnerabilities of the rover systems, supporting proactive measures to improve mission robustness. For instance, potential failure modes in power and life support subsystems were classified with high criticality indices, prompting the definition of redundancy strategies and preventive monitoring requirements. Such insights, while based on hypothetical values, nonetheless demonstrate the importance of embedding structured quality analysis into the project management framework from the earliest stages.

Another important result is the integration of cost estimation into the overall project management framework. By combining technical and managerial perspectives, the thesis has shown how cost evaluation can inform trade-offs between design

ambition and operational feasibility. The Semi-Stationary Rover emerged as the more cost-effective option, providing sufficient mission capability at a manageable investment level, whereas the Transport Rover, while more capable, raises questions about long-term sustainability unless justified by higher scientific or operational returns. This dimension is particularly relevant in the context of the space economy, where commercial actors are increasingly involved and efficiency becomes a decisive factor. The ability to demonstrate not only technical feasibility but also economic viability is crucial for gaining institutional and private sector support.
Naturally, this thesis also has certain limitations. The analysis is based on a restricted set of mission profiles and cannot be considered exhaustive of all possible alternatives for lunar exploration. The risk and quality parameters were estimated using hypothetical values due to the lack of experimental data or field testing of PLR systems. Furthermore, the absence of direct validation with industrial stakeholders or space agencies limits the immediate applicability of the findings. Despite these limitations, the work provides a structured framework and a replicable methodology that can be expanded in future research.
In conclusion, this thesis demonstrates the added value of project management methodologies in space exploration. By moving beyond purely technical considerations and integrating cost, risk, quality, and scheduling analyses, the study contributes to the establishment of a management-driven foundation for PLR development. The comparative analysis of two rover mission profiles provides not only a clearer understanding of their respective strengths and weaknesses but also a decision-making tool that can support the planning of future crewed lunar missions. The results show that structured project management does not merely support technical design but actively shapes strategic choices, highlighting how mission success depends as much on managerial discipline as on engineering innovation.

6.2 Future Work and Perspectives

Looking ahead, several avenues for future development and research can be identified, both in the short term and in the long term.
In the immediate future (1-3 years), research should focus on refining the assumptions made in this work. This includes developing more accurate cost models, validated through collaboration with industry and space agencies, and conducting early-stage prototyping of key rover subsystems such as mobility, power, and environmental control and life support systems (ECLSS). Field testing in terrestrial analog environments-such as deserts, volcanic terrains, and polar regions-would also be valuable for assessing the operational performance of rover designs under conditions that approximate those on the Moon. From a project management perspective, the adoption of digital tools for scheduling, simulation, and risk analysis

could further enhance accuracy and decision-making efficiency.
In the medium term (3-7 years), the growing involvement of commercial actors in lunar exploration will require the establishment of standardized project management practices across international and industrial partnerships. Future research could explore the integration of agile project management methodologies, which, when combined with digital twins and artificial intelligence (AI)-driven risk assessment tools, may improve flexibility and responsiveness in rover development. Additionally, comparative analyses could be extended to include a broader range of mission concepts, such as hybrid rovers or modular exploration vehicles, thereby providing decision-makers with a wider set of options.
In the longer term (beyond 7 years), pressurized lunar rovers are expected to evolve into operational assets that play a central role in sustained lunar presence. Their deployment as part of programs such as NASA's Artemis and international exploration initiatives will not only expand scientific capability but also create opportunities for commercial exploitation of lunar resources. From a methodological standpoint, the frameworks demonstrated in this thesis can be scaled to more ambitious missions, including Mars exploration and the establishment of permanent lunar bases. Expanding the scope of project management in these contexts will ensure that exploration initiatives remain cost-effective, reliable, and aligned with broader strategic goals.
Overall, the future development of pressurized lunar rovers will depend not only on technological innovation but also on the capacity to manage complexity effectively. This thesis has shown that structured project management methodologies can serve as a critical enabler in this process, bridging the gap between technical design and operational feasibility. By continuing to refine these approaches and adapting them to evolving mission needs, the space community can accelerate progress toward sustainable and economically viable human exploration of the Moon and beyond.

Appendix

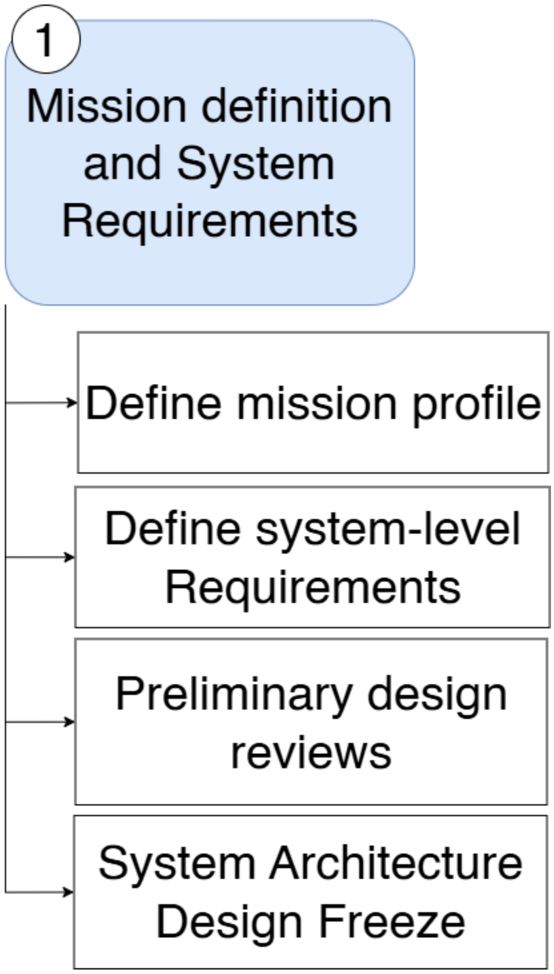


Figure A.1: WBS 1 - Stationary Rover

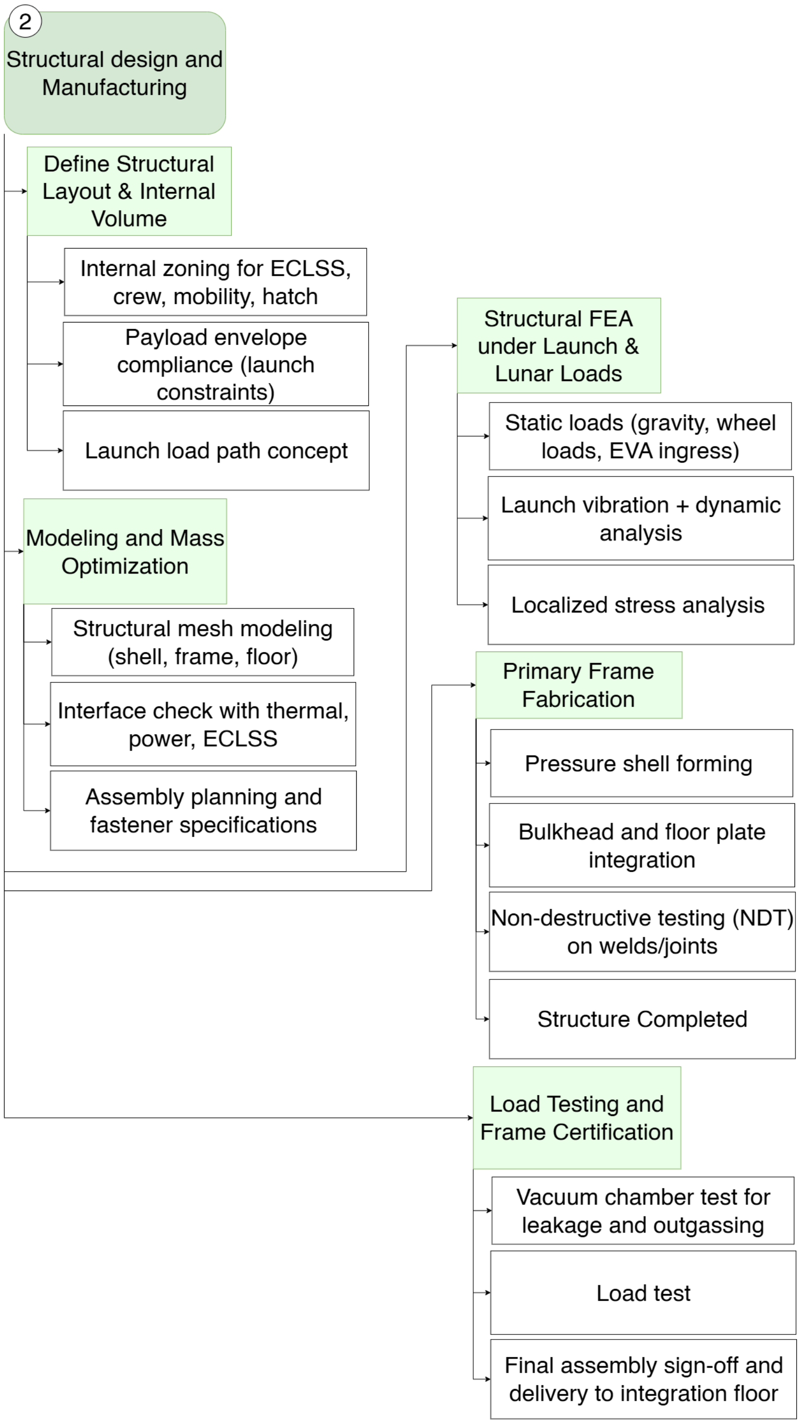


Figure A.2: WBS 2 - Stationary Rover

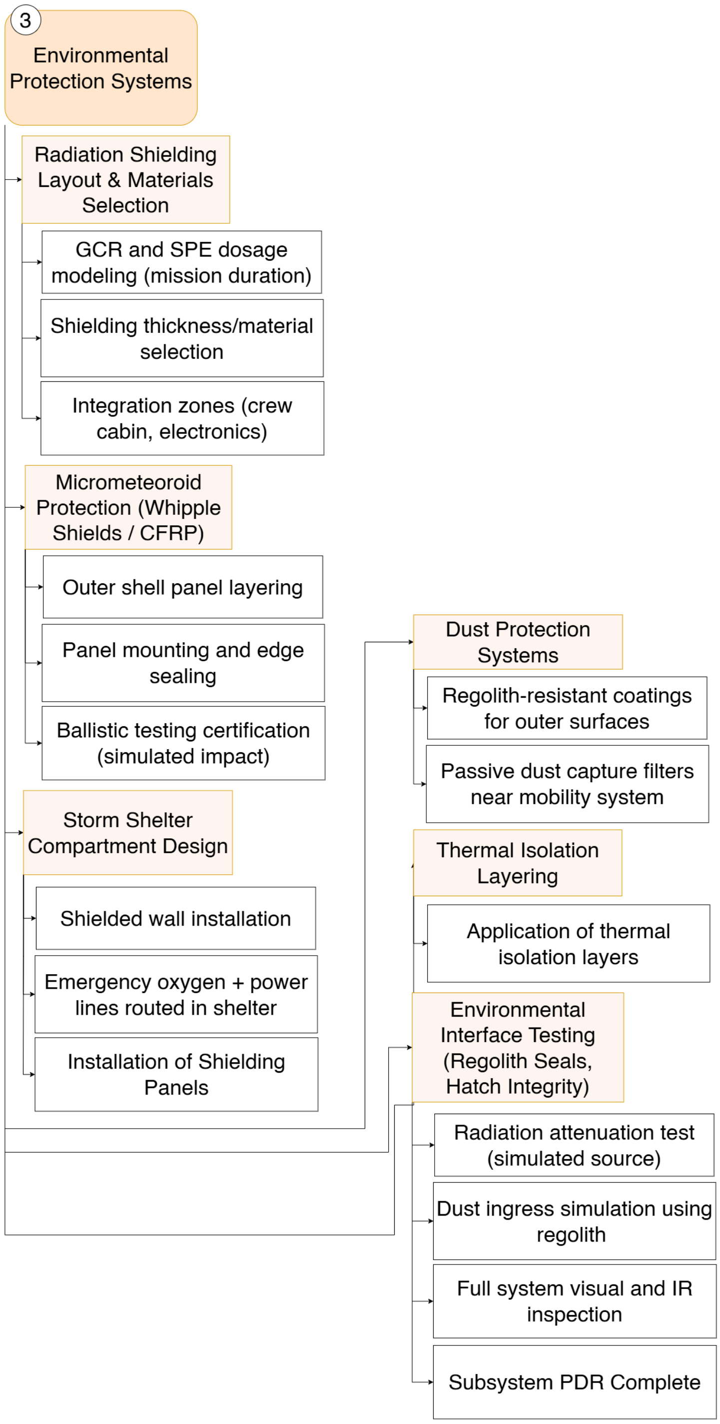


Figure A.3: WBS 3 - Stationary Rover

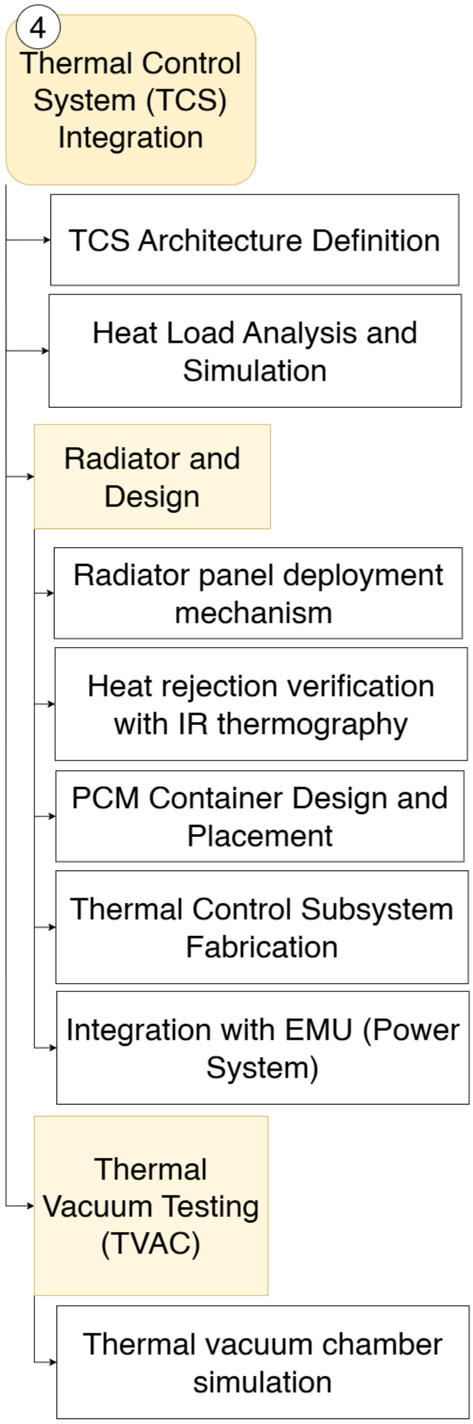


Figure A.4: WBS 4 - Stationary Rover

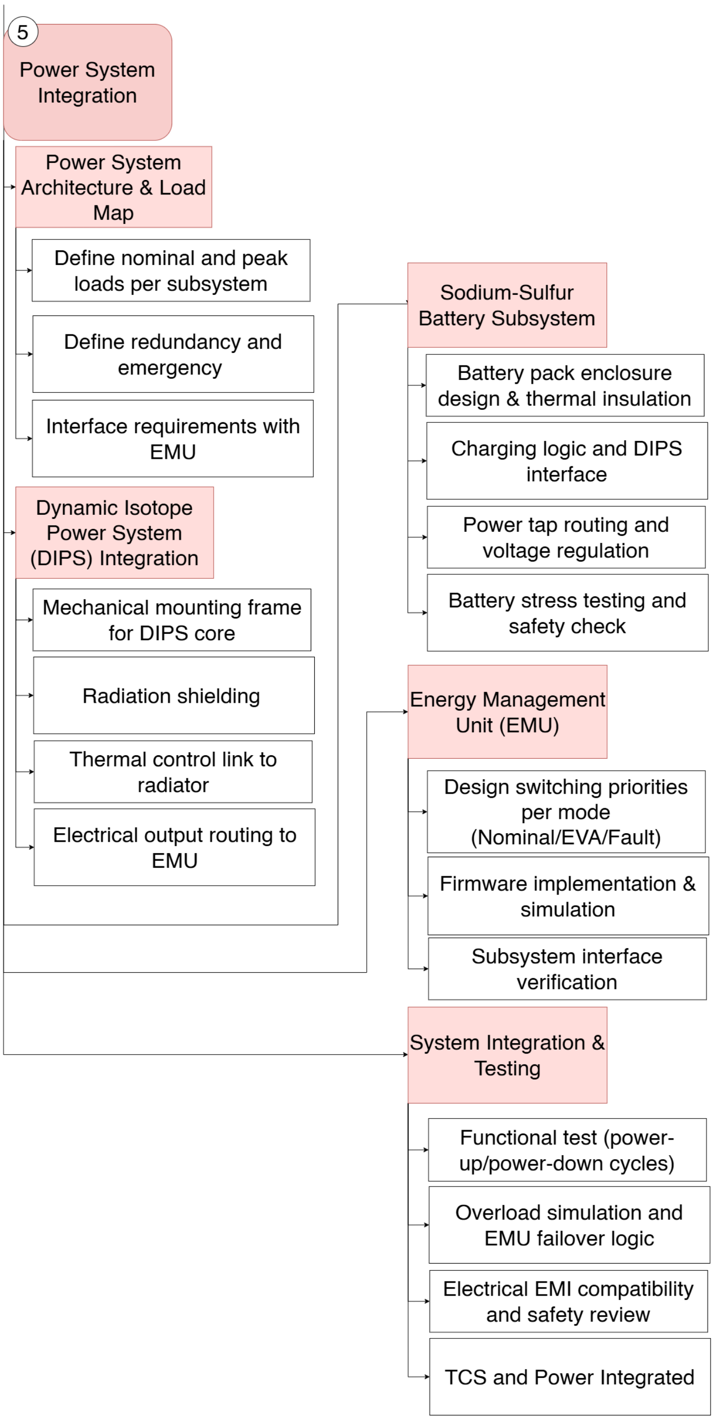


Figure A.5: WBS 5 - Stationary Rover

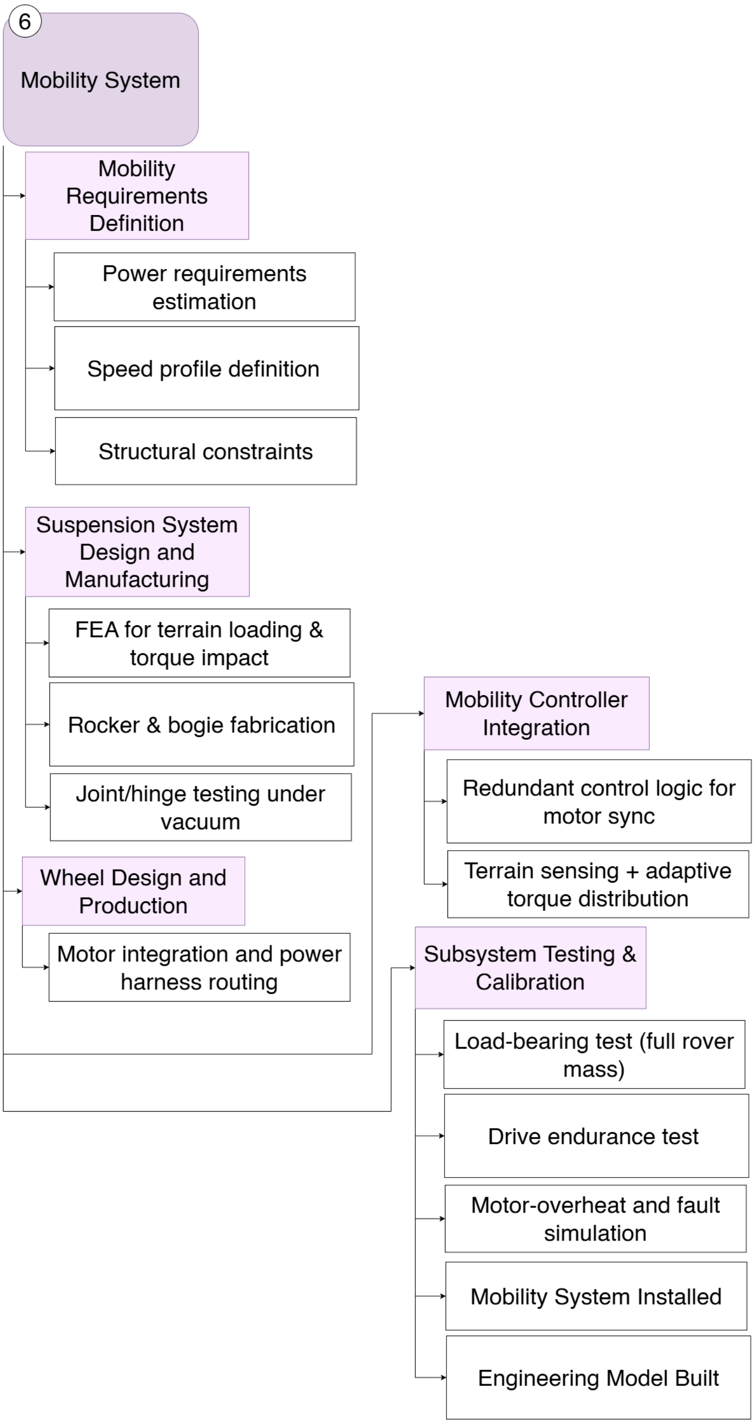


Figure A.6: WBS 6 - Stationary Rover

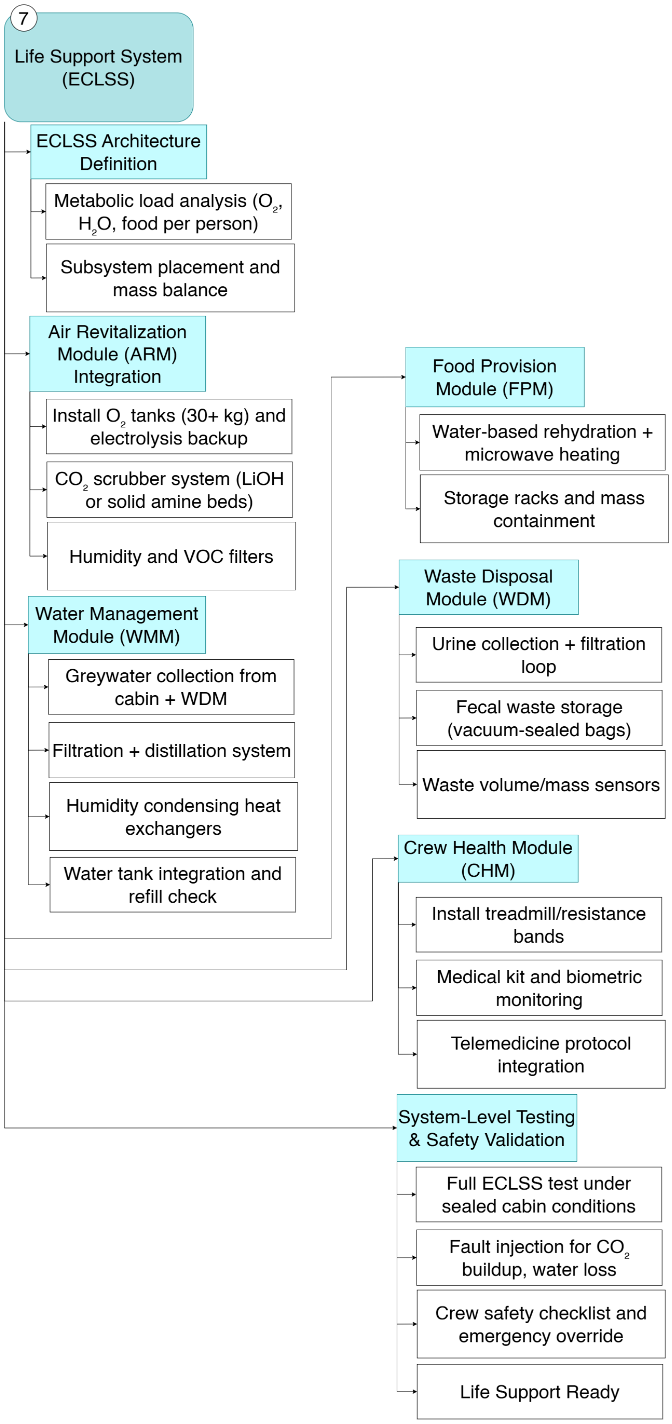


Figure A.7: WBS 7 - Stationary Rover

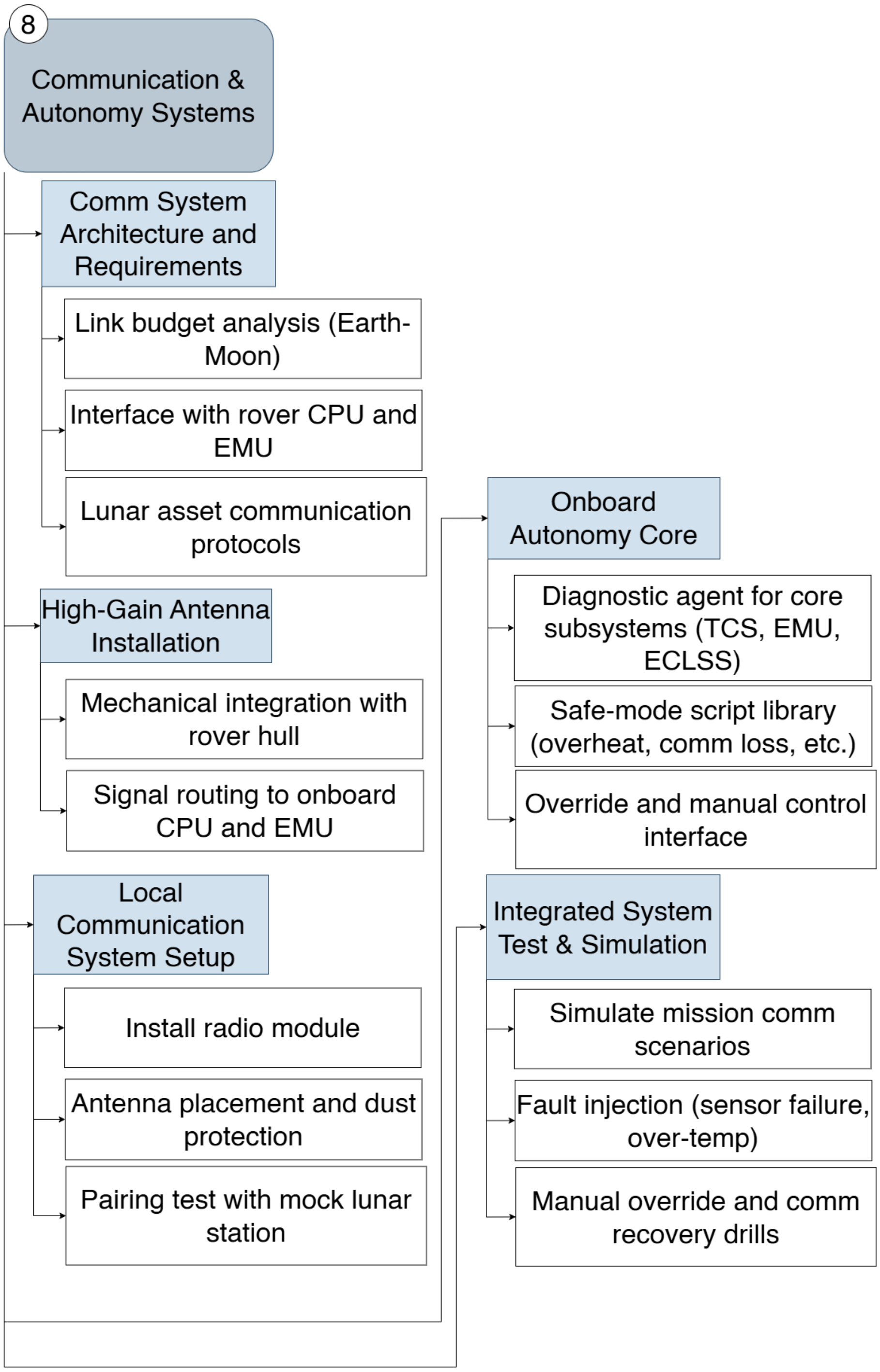


Figure A.8: WBS 8 - Stationary Rover

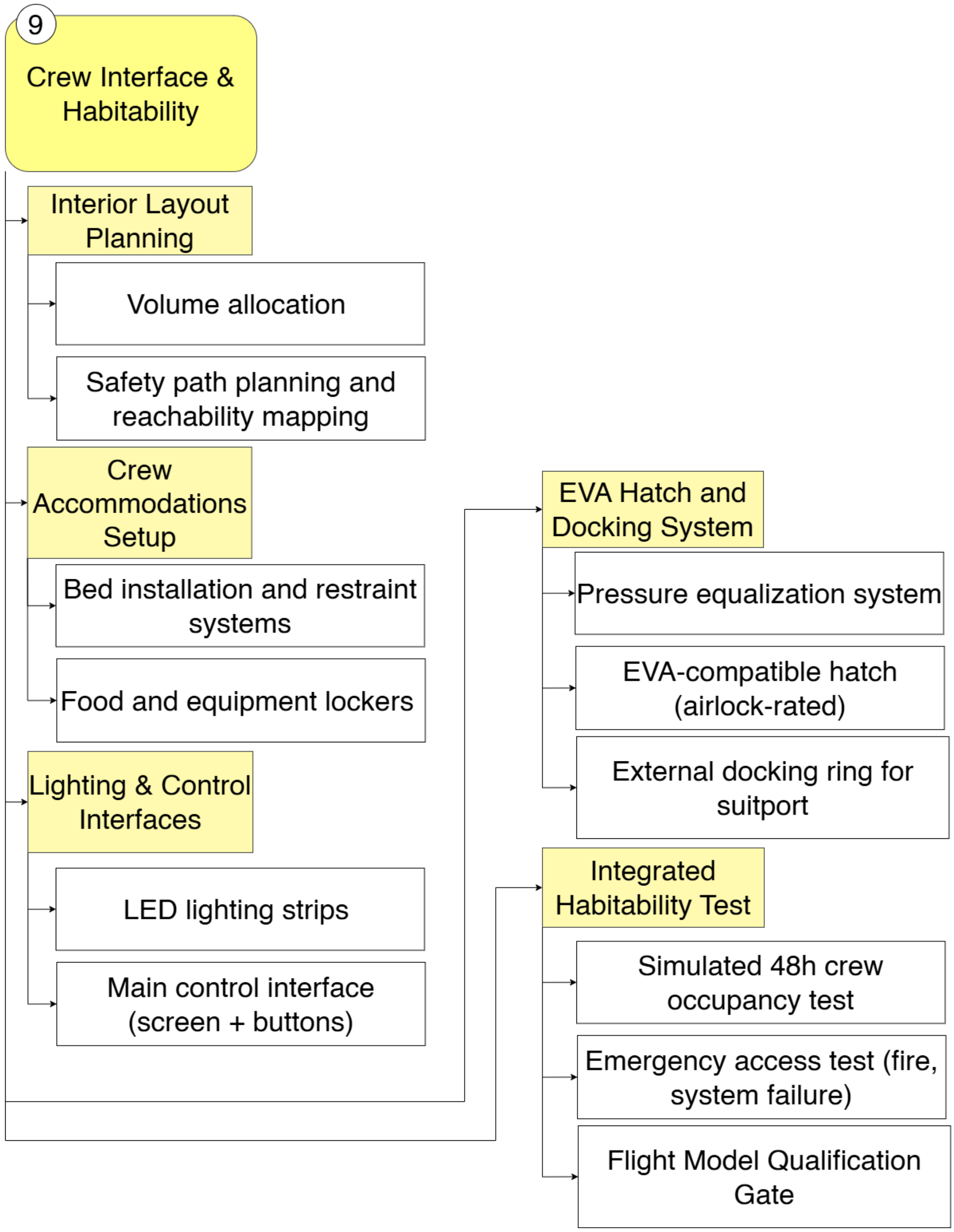


Figure A.9: WBS 9 - Stationary Rover

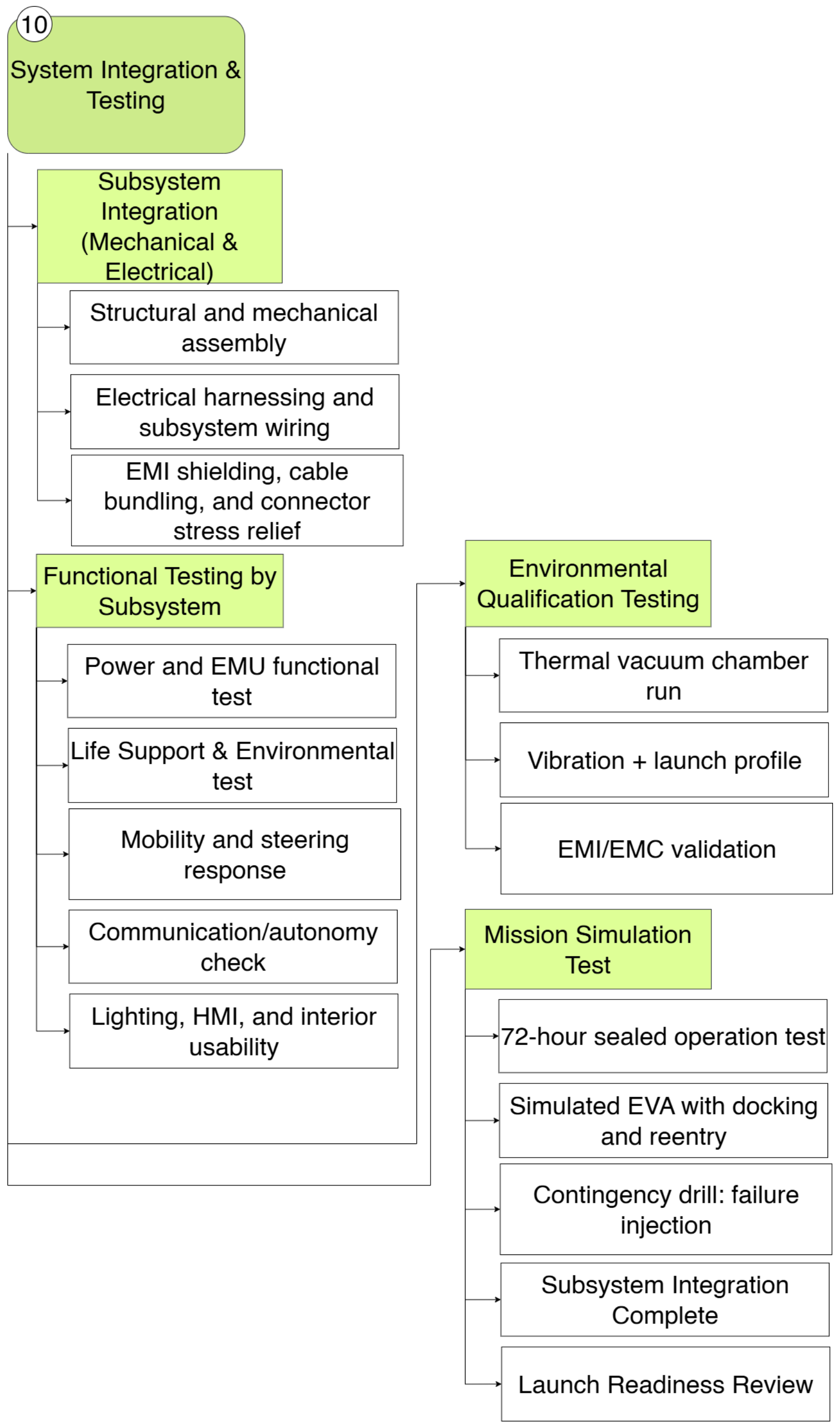


Figure A.10: WBS 10 - Stationary Rover

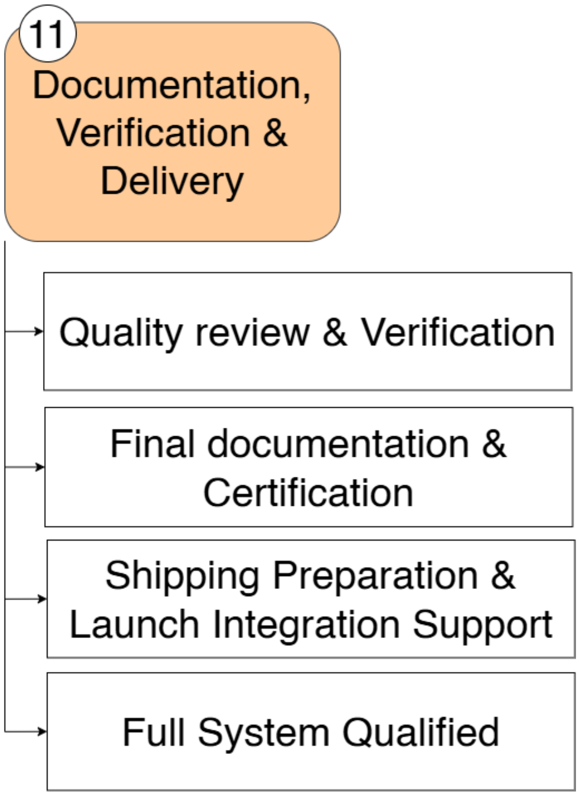


Figure A.11: WBS 11 - Stationary Rover

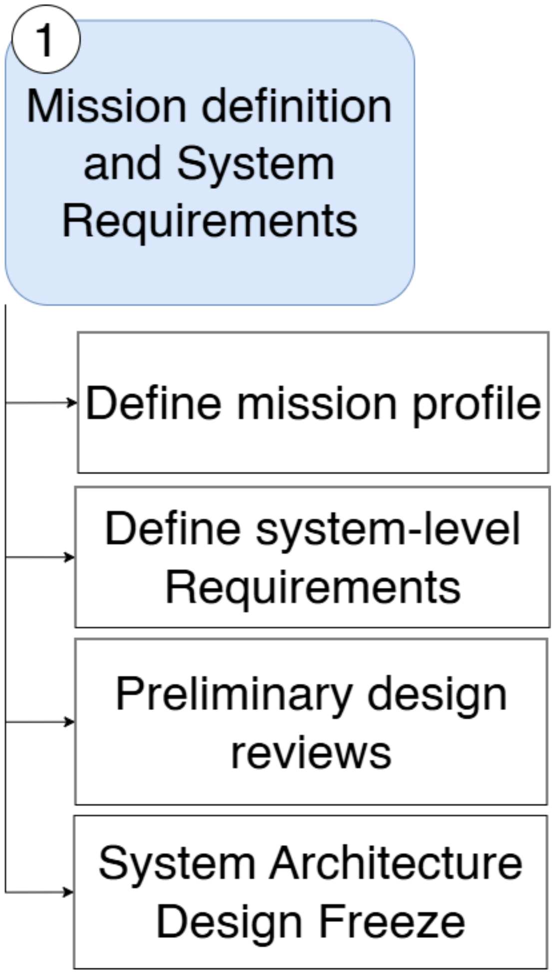


Figure A.12: WBS 1 - Transfer Rover

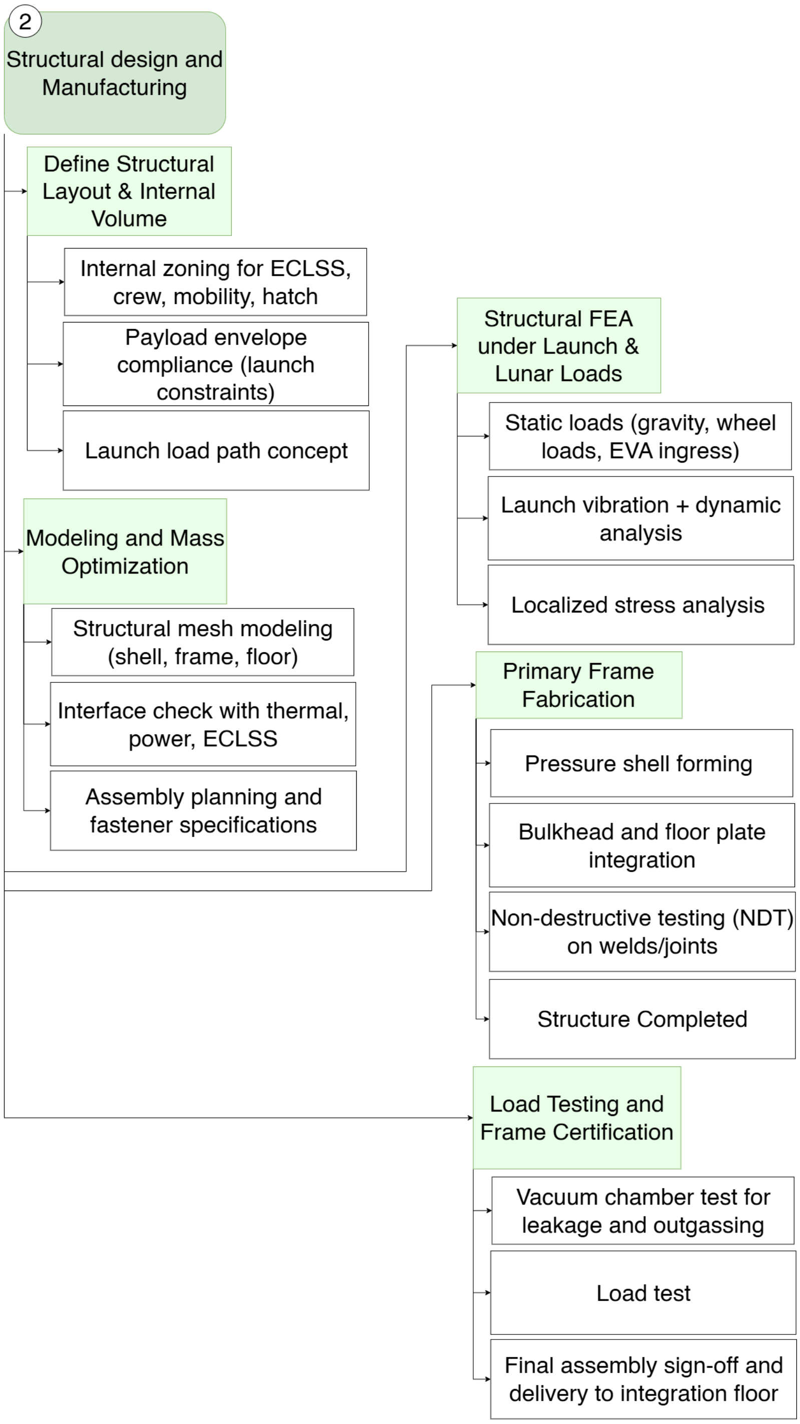


Figure A.13: WBS 2 - Transfer Rover

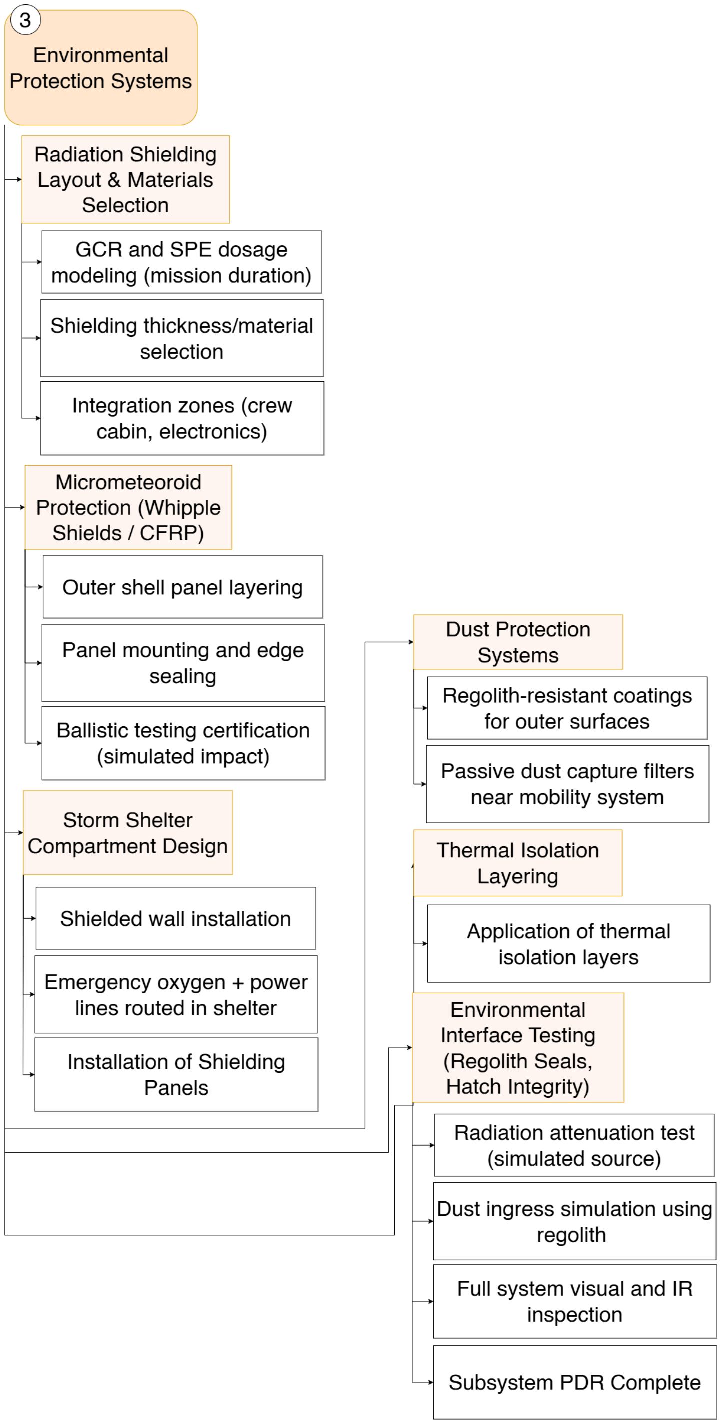


Figure A.14: WBS 3 - Transfer Rover

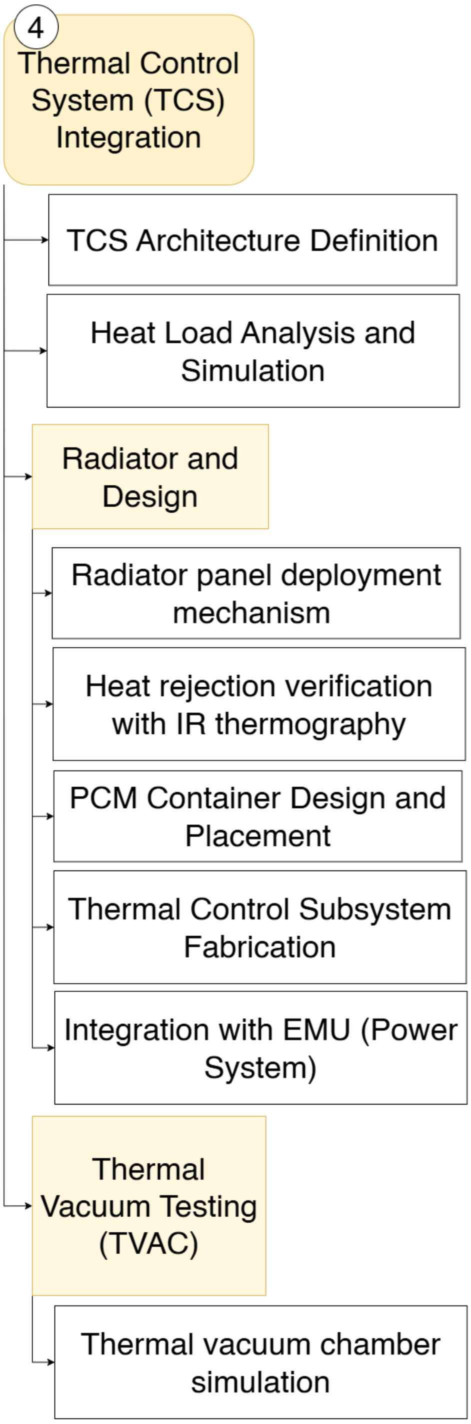


Figure A.15: WBS 4 - Transfer Rover

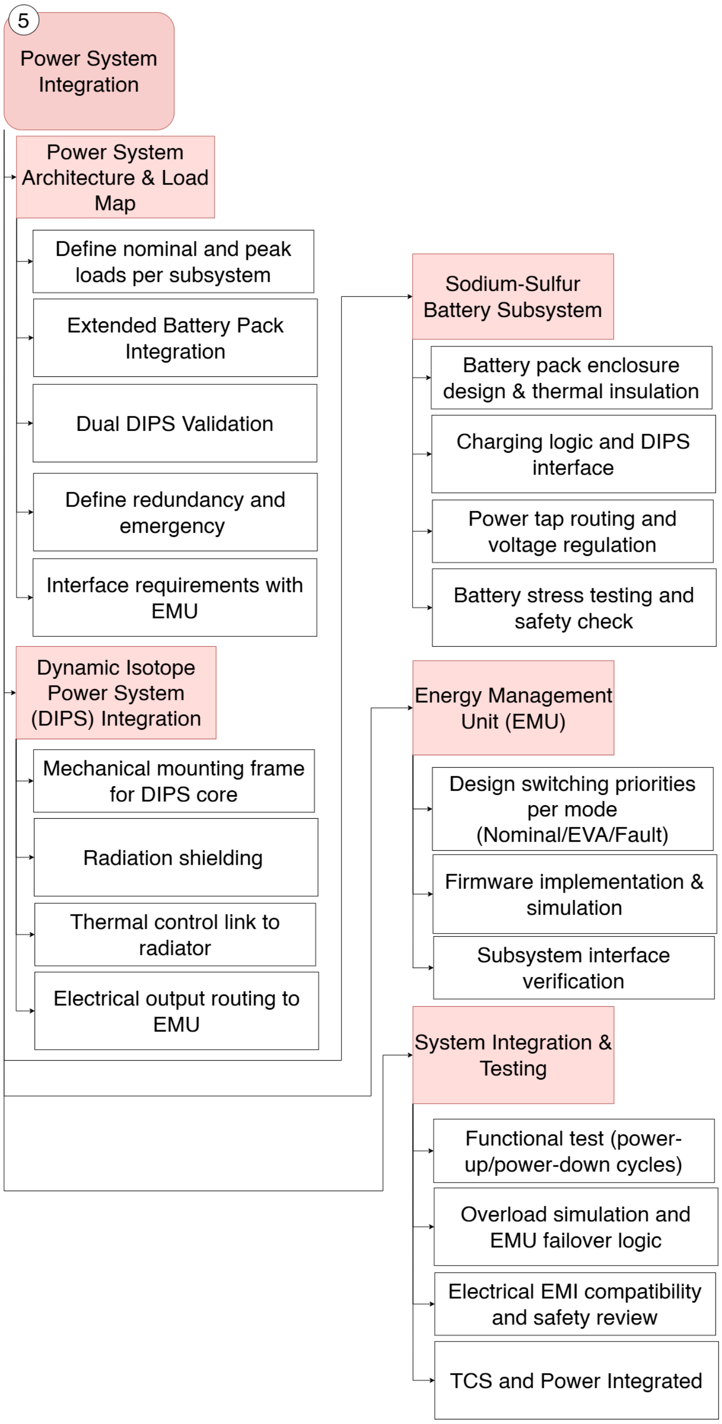


Figure A.16: WBS 5 - Transfer Rover

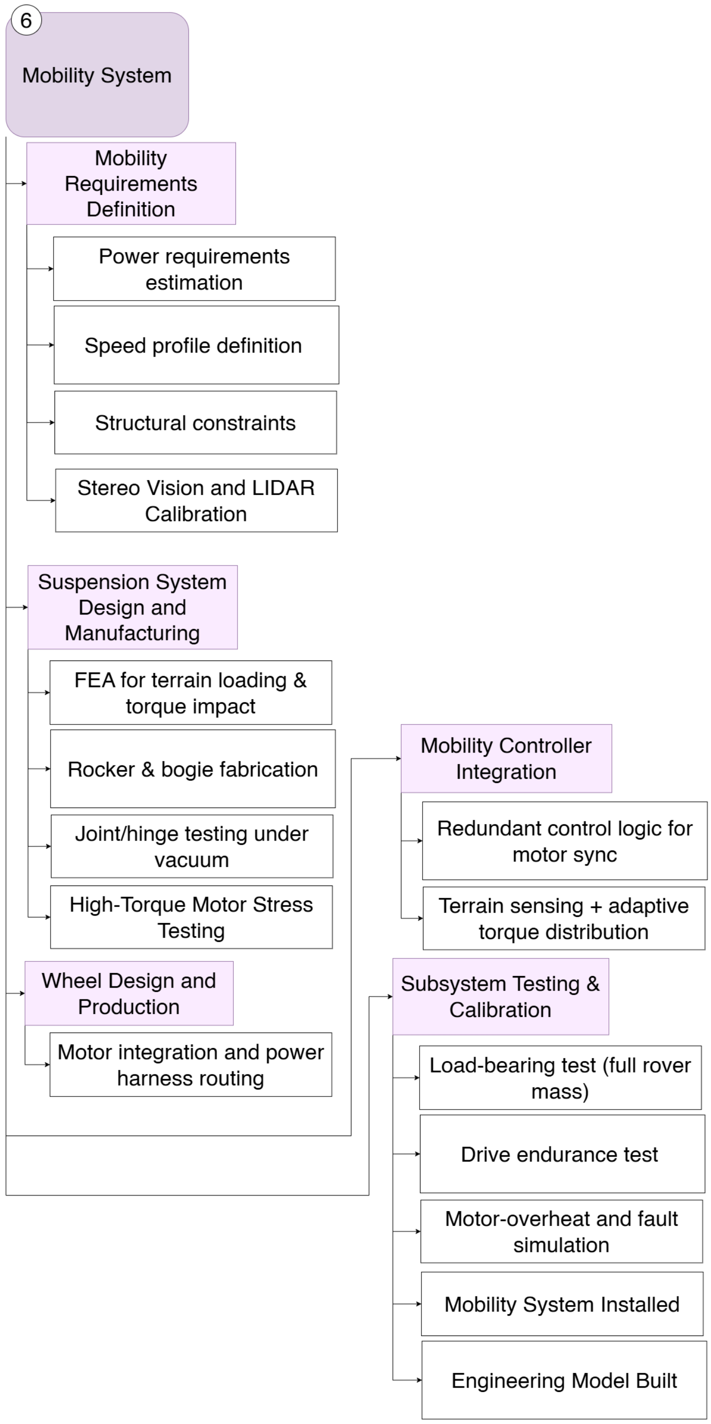


Figure A.17: WBS 6 - Transfer Rover

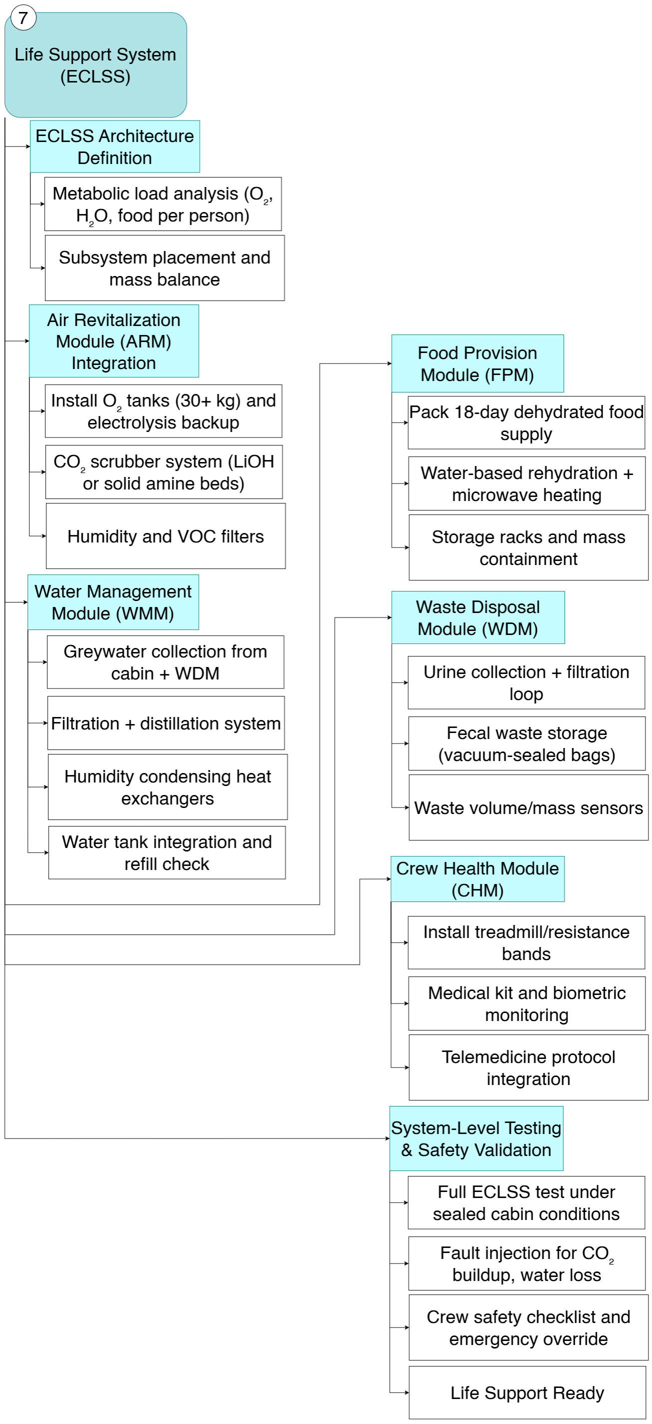


Figure A.18: WBS 7 - Transfer Rover

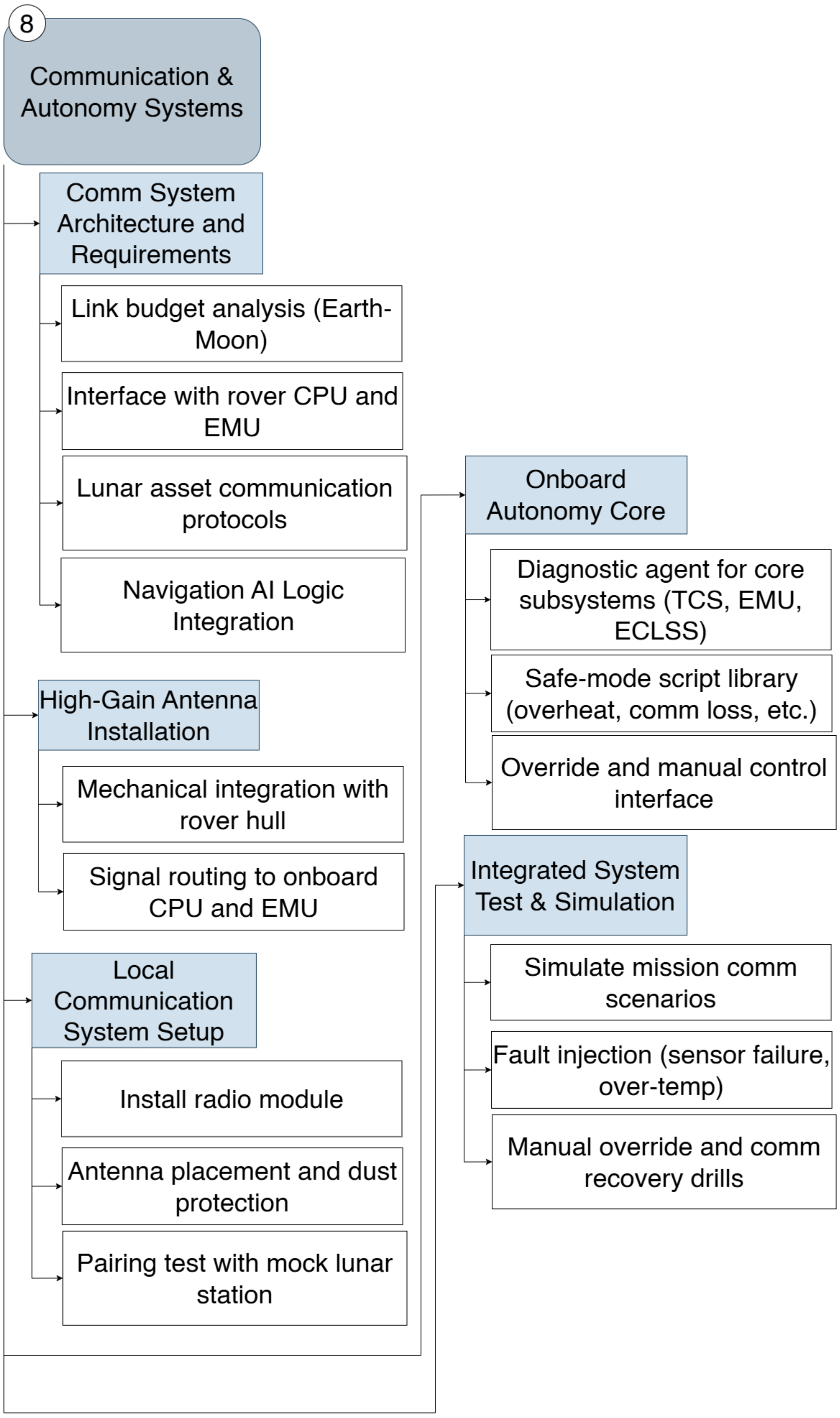


Figure A.19: WBS 8 - Transfer Rover

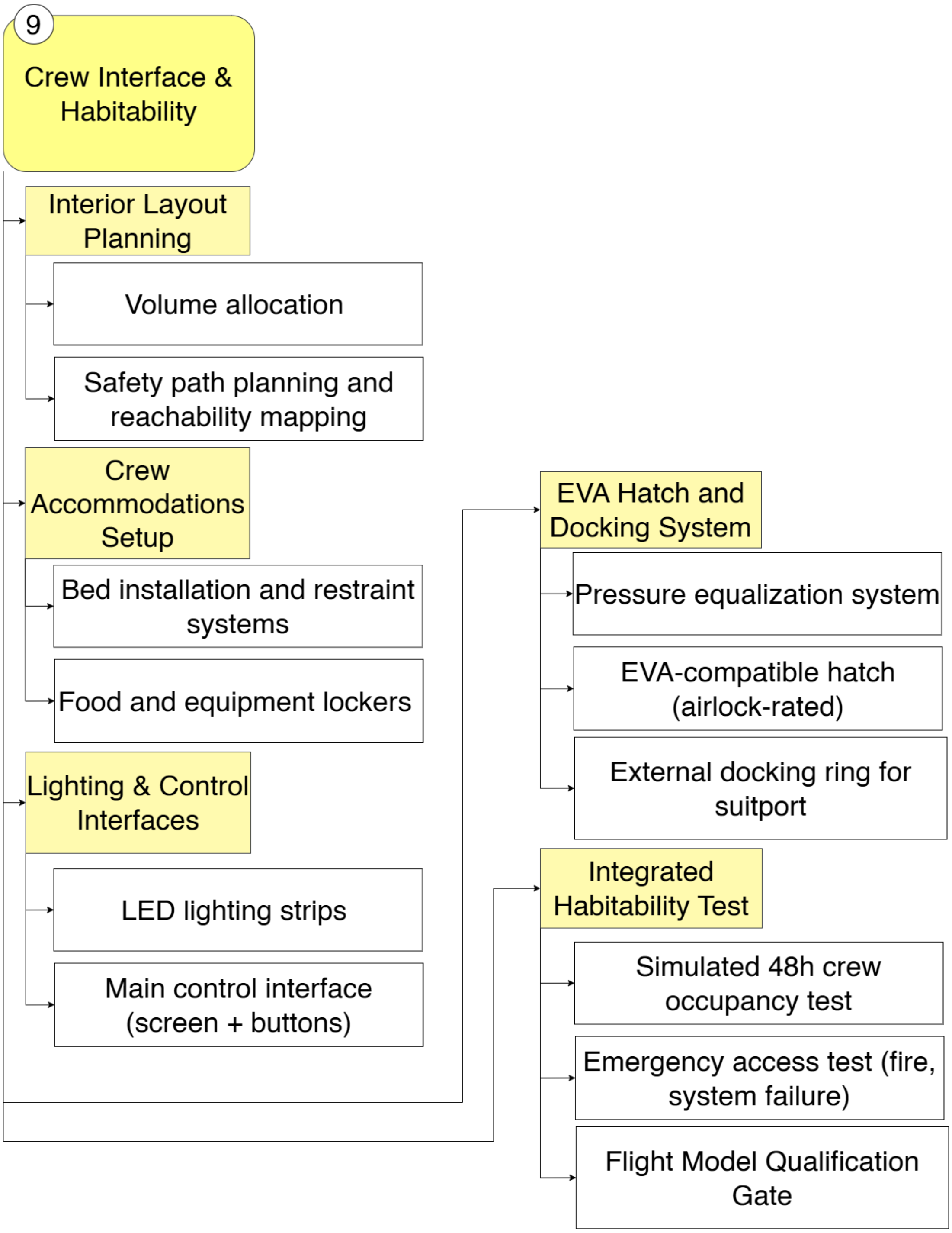


Figure A.20: WBS 9 - Transfer Rover

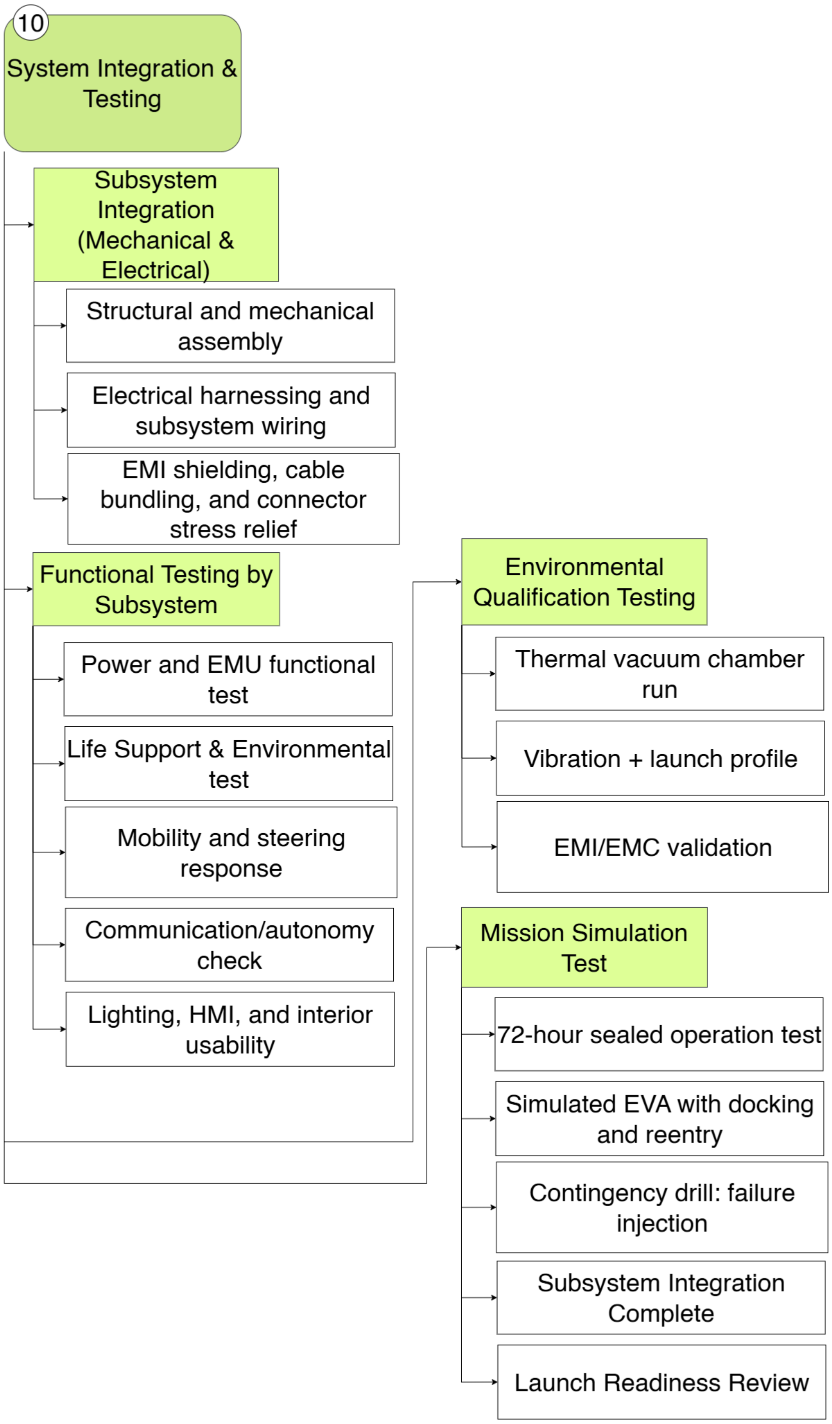


Figure A.21: WBS 10 - Transfer Rover

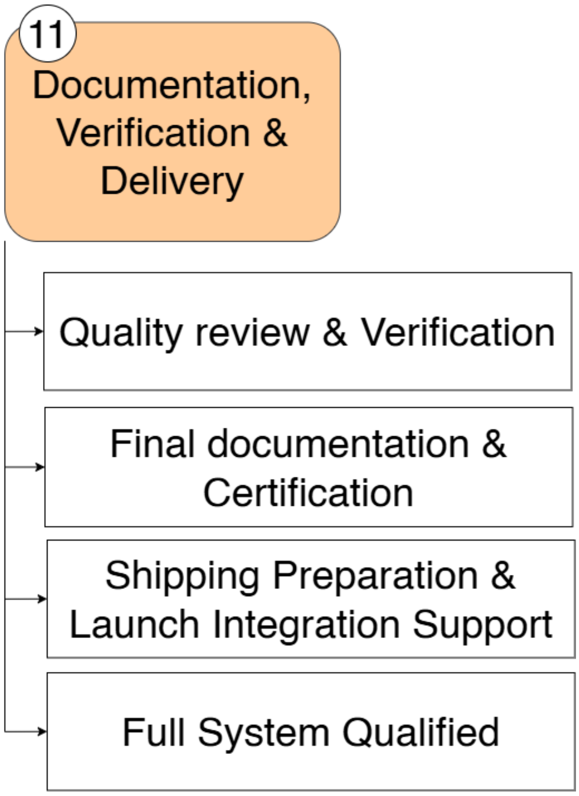


Figure A.22: WBS 11 - Transfer Rover

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