

POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering



**Politecnico
di Torino**



Master's Degree Thesis

Development of Models for Thermal and Environmental Control and Life Support Systems of a Lunar Pressurized Rover

Supervisors:

Prof. Giuseppe Palaia
Prof. Erasmo Carrera
Prof. Alfonso Pagani
Prof. Rodolfo Azzara

Candidate:

Salvatore Testagrossa

July 2026

Abstract

Lunar surface exploration is expected to play a central role in future human space-flight missions, requiring advanced mobility systems capable of supporting long-duration operations. This thesis presents the development of analytical design models for the Thermal Control System (TCS) and the Environmental Control and Life Support System (ECLSS) of a lunar pressurized rover within the framework of the Space It Up! project.

The study begins with the definition of the problem, including the mission context, operational requirements, environmental conditions, and vehicle parameters that drive subsystem sizing. Based on these inputs, a parametric modeling approach is developed and implemented in MATLAB to support system design activities.

The TCS is modeled by combining a Multilayer Insulation (MLI) sizing approach with a dynamic thermal model based on the rover energy balance, enabling the estimation of heat fluxes and the prediction of rover temperature evolution under representative lunar conditions. In parallel, the ECLSS is modeled through analytical sizing relationships to estimate the resources required to maintain a habitable internal environment and support crew operations throughout the mission.

The integrated modeling approach enables the estimation of subsystem mass, power consumption, and thermal performance indicators, while also supporting scenario-based analyses and system-level trade-off studies. The proposed methodology provides a computationally efficient tool for the preliminary design of pressurized rover onboard systems and establishes a foundation for future refinement through higher-fidelity modeling and integrated vehicle-level analyses.

Contents

Abstract	II
Glossary	V
1 Introduction	1
1.1 Pressurized Rovers	1
1.2 Lunar Environment	2
1.3 Role of Onboard Systems	3
1.4 Evolution of Lunar Rovers	4
1.5 State of the Art	6
1.5.1 Pressurized Rover Architectures	6
1.5.2 ECLSS Architectures	7
1.5.3 TCS Architectures	11
2 Problem Definition	15
2.1 Mission Context	15
2.1.1 Lunar Environment	15
2.1.2 Mission Profile	16
2.2 System Requirements	16
2.3 Model Input Parameters	18
2.4 Operational Modes	20
3 Methodology	22
3.1 System Architecture and Modeling Assumptions	22
3.1.1 Mission Parameters	23
3.1.2 Vehicle Parameters	24
3.1.3 Environmental Parameters	25
3.1.4 Thermal Model Parameters	26
3.1.5 ECLSS Model Parameters	27
3.2 Thermal Control System (TCS) Modeling and Sizing	28
3.2.1 Multilayer Insulation (MLI) Model	28
3.2.2 Thermal Energy Balance Model	32
3.3 Environmental Control and Life Support System (ECLSS)	34
3.3.1 Architecture and Resource Flow	34
3.3.2 Modeling Approach	35
3.3.3 Consumable Mass Balance	36
3.3.4 Water Recovery Model	37
3.3.5 Emergency Scenarios and Failure Logic	38

3.3.6	Mass Estimation	39
4	Results and System Performance	41
4.1	Thermal Control System (TCS) Results	41
4.1.1	Multilayer Insulation (MLI) Model	41
4.1.2	Thermal Energy Balance Model	43
4.2	Environmental Control and Life Support System (ECLSS) Results . .	54
4.2.1	Nominal Regenerative Architecture	55
4.2.2	Effect of Water Recovery System	57
4.2.3	Emergency Scenario: WRS Failure	60
4.2.4	Emergency Scenario: Shelter Mode	63
4.3	Summary of Results	66
5	Sensitivity Analysis and System Trade-Offs	68
5.1	Thermal Control System Sensitivity Analysis	69
5.1.1	Radiator Area Sensitivity	69
5.1.2	Heater Power Sensitivity	70
5.1.3	Surface Absorptivity Sensitivity	71
5.1.4	Internal Heat Generation Sensitivity	72
5.1.5	Ground View Factor Sensitivity	73
5.1.6	Thermal Capacitance Sensitivity	74
5.1.7	Uninsulated Surface Emissivity Sensitivity	75
5.1.8	MLI Penetration Parameter Sensitivity	76
5.2	Environmental Control and Life Support System Sensitivity Analysis	77
5.2.1	Mission Duration Sensitivity	78
5.2.2	Water Recovery System Failure Scenario	79
5.2.3	Shelter Emergency Scenario	80
5.3	Trade-off Analysis	82
5.3.1	Thermal Control System Optimization	82
5.3.2	Environmental Control and Life Support System Optimization	84
6	Conclusions and Future Work	86
6.1	Summary of Results	86
6.2	Key Findings	87
6.3	Limitations	87
6.4	Future Work	88
	List of Figures	89
	List of Tables	91
	Bibliography	92

Glossary

AVS

Avionics System.

CDRA

Carbon Dioxide Removal Assembly.

COMMS

Communications System.

ECLSS

Environmental Control and Life Support System.

EPS

Electrical Power System.

EVA

Extravehicular Activity.

LUR

Light Utility Rover.

LVR

Lunar Roving Vehicle.

MLI

Multilayer Insulation.

PLR

Pressurized Lunar Rover.

SEV

Space Exploration Vehicle.

TCS

Thermal Control System.

WRS

Water Recovery System.

Chapter 1

Introduction

1.1 Pressurized Rovers

The Moon represents a unique challenge for human exploration: a hostile environment, lacking an atmosphere, with extreme temperature variations, intense radiation, and rough terrain. The renewed interest in returning humans to our satellite has led to a rethinking of the role of surface vehicles in lunar missions, which are no longer considered simple robotic exploration tools but fundamental elements of an operational ecosystem capable of supporting crews during long-duration missions. The ability to cover significant distances, transport complex scientific instruments, and operate in areas difficult to access on foot greatly enhances the efficiency and scope of missions. In this context, different classes of surface mobility systems are being considered, ranging from unpressurized rovers to more advanced crewed platforms designed to extend human presence on the lunar surface.

Within this range of surface mobility solutions, pressurized rovers play a central role in enabling sustained human operations on the lunar surface.



Figure 1.1: Concept of the JAXA Lunar Cruiser pressurized rover [1].

A pressurized rover is a small mobile habitat designed to temporarily accommodate the crew during surface activities. Unlike open or unpressurized vehicles, it provides a protected and controlled environment that allows astronauts to work without bulky spacesuits. This, in turn, reduces fatigue and increases operational autonomy, enabling longer and more complex missions, exploration of geographically challenging areas, and scientific experiments requiring extended durations on the surface.

Beyond transportation and scientific support, a pressurized rover represents an extension of the human habitat on the Moon. It integrates multiple onboard subsystems, including environmental control and life support, thermal control, power management, avionics and communications, ensuring crew safety, vehicle functionality, and mission continuity. In this sense, the vehicle becomes not only a means of transport but also an integrated mobile laboratory capable of expanding crew operational capabilities and supporting the development of increasingly ambitious lunar missions.

1.2 Lunar Environment

The Moon presents an extreme environment, profoundly different from Earth, characterized by conditions that strongly influence the design, operations, and performance of surface vehicles [2]. The main environmental factors affecting lunar mission systems include:

- **Extreme thermal variations:** the surface temperature is dominated by direct solar illumination. In the absence of an atmosphere, the soil heats up rapidly during the day and cools just as quickly during the long lunar night, generating very large thermal swings, ranging from approximately $-170\text{ }^{\circ}\text{C}$ to $+120\text{ }^{\circ}\text{C}$ [2]. These variations impose strong constraints on thermal control design and material selection.
- **Vacuum environment:** the vacuum eliminates convective heat transfer, making radiation and conduction the dominant mechanisms. This significantly affects thermal design, as well as the behavior of lubricants, seals, and exposed mechanical interfaces.
- **Regolith and micrometeoroid environment:** the lunar soil consists of fine, abrasive particles that are easily mobilized. In addition, continuous micrometeorite impacts contribute to dust production and surface fragmentation. These effects can degrade moving parts, optical surfaces, and thermal systems over time.
- **Radiation and energetic particles:** the absence of a magnetic field and atmosphere exposes the surface to cosmic radiation, solar wind, and potential high-energy solar particle events. This environment is particularly relevant for electronics reliability and, in crewed missions, for radiation shielding requirements.

- **Extended lunar day-night cycle:** the lunar day-night cycle lasts approximately 29.5 Earth days, resulting in long periods of continuous illumination followed by equally long periods of darkness. This strongly impacts energy storage strategies and the sizing of power and thermal systems.

These extreme conditions make the proper design of onboard systems essential: each subsystem, from thermal control to energy management, must be adequately sized and integrated to ensure continuous and reliable operation of the pressurized rover, allowing the crew to operate effectively on the lunar surface.

1.3 Role of Onboard Systems

The ability of a pressurized rover to operate safely on the lunar surface depends not only on its structural design and mechanical performance, but also on the reliability and integration of its onboard systems. In practice, mission success or failure is often determined by how these systems interact with each other under extreme conditions: wide temperature variations, intense radiation, the absence of an atmosphere, and long day-night cycles. Without proper integration and reliable operation, even a well-designed vehicle could become ineffective or potentially unsafe for the crew.

Unlike unpressurized rovers, which have more limited roles and usually focus on mobility and scientific instruments, a crewed rover must function almost like a small, mobile habitat. This implies that its onboard systems need to be designed with operational continuity, redundancy, and stability in mind, maintaining safe and comfortable conditions inside even when the external environment changes drastically. The performance of each subsystem, together with the level of their integration, directly influences important design aspects such as mass, power consumption, internal volume, and mission operations.

The main onboard systems contributing to rover operations can be summarized as follows:

- **Environmental Control and Life Support System (ECLSS):** Maintains habitable conditions inside the pressurized cabin by regulating atmospheric composition, pressure, humidity, and contaminant control, ensuring crew safety throughout the mission.
- **Thermal Control System (TCS):** Maintains both cabin and subsystem temperatures within acceptable operational limits for human habitation and onboard electronics through insulation, heat transport, heat rejection, and protection against the extreme lunar thermal environment.
- **Electrical Power System (EPS):** Manages the generation, storage, and distribution of electrical energy, ensuring a continuous power supply to all onboard subsystems, including operations during extended periods without sunlight.
- **Mobility System:** Includes wheels, suspension systems, actuators, and control components required to safely traverse rough lunar terrain while maintaining traction, stability, and maneuverability.

- **Communications System (COMMS):** Provides communication links with habitats, surface assets, or orbital infrastructure, supporting data transfer, operational coordination, and remote monitoring activities.
- **Avionics System (AVS):** Includes onboard computers, sensors, software, and control electronics responsible for system monitoring, data handling, automation, and coordination of rover operations.

The combination of these systems defines the rover’s functional architecture and determines its true capability to operate autonomously, reliably, and safely on the lunar surface. In this thesis, the Environmental Control and Life Support System (ECLSS) and Thermal Control System (TCS) are the systems investigated through the development of dedicated models. The goal is to provide useful tools for the early design stages, supporting system sizing, thermal and resource assessments, and helping to define the preliminary operational capabilities of a pressurized rover for human exploration of the Moon.

1.4 Evolution of Lunar Rovers

The evolution of lunar rovers has followed a discontinuous path, characterized by phases of rapid technological development followed by periods of consolidation and experimentation. Over time, the focus has progressively shifted from simple surface mobility to the broader problem of enabling human presence on the lunar surface in safe and efficient conditions.

The development of lunar rovers began during the Apollo program in the late 1960s and early 1970s with the Lunar Roving Vehicle (LVR), designed to extend the exploration range of astronauts. Used during the Apollo 15, 16, and 17 missions between 1971 and 1972, the LVR was a lightweight, unpressurized, battery-powered vehicle intended for short-duration surface operations. It allowed astronauts to cover larger distances than on foot and to transport scientific instruments and samples, demonstrating the importance of surface mobility for planetary exploration missions.



(a) Apollo 15 [3].



(b) Apollo 17 [4].

Figure 1.2: Photographs of the first lunar rovers used during the Apollo missions for surface exploration.

Following the Apollo era, roughly from the mid-1970s to the early 2000s, interest in crewed lunar surface vehicles decreased due to a reduced focus on human lunar exploration. During this period, rover development continued mainly through robotic planetary missions. From the 1990s onward, several autonomous or remotely operated rovers were developed for Mars exploration, including missions such as Sojourner, Spirit and Opportunity, and Curiosity. These missions led to significant advances in mobility systems, navigation, power management, autonomy, and environmental protection technologies. Although not designed for human transportation, they later influenced more advanced lunar rover concepts, especially in terms of autonomy and subsystem integration.

At the same time, and partly in parallel with the development of robotic planetary rovers, several studies during the 1980s and 1990s began to investigate the concept of pressurized and crewed lunar rovers capable of supporting astronauts inside a habitable environment during surface traverses. Among the most notable concepts are the Pressurized Lunar Rover (PLR) proposed by Creel et al. [5] and Bhardwaj et al. [6]. These studies introduced rover-habitat concepts with higher autonomy and improved protection against the lunar environment, integrating key subsystems such as life support, thermal control, and power management. Although many of these concepts remained at a preliminary level, they played an important role in defining the architectural principles adopted in more recent pressurized rover designs.

During the 2000s and 2010s, several technology demonstrators and field tests were developed to advance lunar surface mobility systems, including terrestrial prototypes and robotic rovers tested in lunar-analog environments, such as the desert campaigns reported in [7]. These activities focused on validating mobility performance on rough terrain and assessing key subsystem functions such as energy management, thermal protection, and autonomous navigation under realistic operational conditions, providing input for future system design.

Modern rover concepts are no longer limited to transportation tasks but are increasingly designed to support long-duration missions and sustained human presence on the lunar surface. Since the early 2020s, space agencies and private companies have proposed new pressurized rover architectures for future lunar exploration campaigns, driven by programs such as Artemis. A representative example is the Lunar Cruiser developed by JAXA and Toyota, which is designed to support multi-day missions with high autonomy, safety, and operational flexibility, evolving from a mobility system into a mobile habitation platform.

Overall, lunar rover development reflects how evolving mission goals and technologies have shaped surface vehicle design. However, the available literature remains limited and is mostly based on technical reports, early studies, and conceptual documents. Information is often fragmented and focused on individual subsystems rather than integrated rover architectures, showing that pressurized rover systems are still an active research area with several open aspects.

1.5 State of the Art

1.5.1 Pressurized Rover Architectures

The state of the art in pressurized lunar rover systems is not represented by a single reference vehicle, but rather by a set of conceptual and preliminary designs developed by different space agencies, industries, and research groups. Over the years, these studies have explored a wide range of mission scenarios and operational approaches, resulting in significant differences in vehicle size, crew capacity, autonomy, subsystem integration, and power architecture.

Table 1.1 summarizes some of the most representative rover concepts proposed throughout the evolution of planetary surface exploration. Most of the data reported in the table are adapted from [8]. The comparison includes the Apollo LVR, NOMAD, Light Utility Rover (LUR), Rover First, the Pressurized Lunar Rover (PLR) concepts V1 and V2 proposed by Creel et al. [5] and Bhardwaj et al. [6], respectively, the Arno rover, the Hoffman rover, the Daylight Rover, Space Exploration Vehicle (SEV), and the recent Lunar Cruiser developed by JAXA and Toyota.

Concept		Mission Type	Crew	Mass [t]	Range [km]	Main Features
Apollo (1971)	LVR	Lunar un-pressurized	2	0.21	30	First crewed lunar rover enabling short-range surface mobility during Apollo missions.
NOMAD (1997)		Terrestrial robotic	0	0.73	220	Autonomous long-range rover tested in analog environments (Atacama, Antarctica).
LUR (1990)		Lunar un-pressurized	2	0.98	–	Lightweight utility rover for cargo and surface support operations.
Rover (1992) [9]	First	Lunar pressurized	2	4.3	80	Small pressurized rover concept capable of direct landing without a dedicated lander.
PLR V1 (Creel et al., 1992) [5]		Lunar pressurized	4-6	6.2	500	Pressurized rover-habitat with integrated onboard systems for crew support and surface operations.
PLR (Bhardwaj et al., 1992) [6]	V2	Lunar pressurized	4	7.0	2000	Pressurized articulated rover-habitat with improved operational capability and mobility performance.
Arno (1999)		Lunar pressurized	3	6.08	100	Pressurized rover concept for polar missions including support for drilling and excavation payloads.
Hoffman (1997) [10]		Mars pressurized	2-4	16.5	500	Large pressurized rover concept for extended Mars surface exploration sorties.
Daylight Rover (1990)		Lunar pressurized	2-4	25	1000	Dual-module pressurized rover concept designed for extended mission duration with enhanced energy autonomy.
SEV (2008) [11]		Lunar pressurized	2-4	3	125	Multi-purpose pressurized rover concept for mobility and short-duration habitat functions.
Lunar Cruiser (2020s–present)		Lunar pressurized	2-4	-	-	Modern pressurized rover concept intended for Artemis missions with integrated habitation and mobility capabilities.

Table 1.1: Comparison of representative lunar and planetary rover concepts.

1.5.2 ECLSS Architectures

Environmental Control and Life Support System (ECLSS) represent one of the most critical subsystems in human space exploration vehicles and habitats. Their primary purpose is to maintain environmental conditions compatible with crew survival and

operational performance by controlling cabin atmosphere composition, pressure, air quality, humidity, and resource availability. In pressurized lunar rovers, the importance of ECLSS becomes particularly significant because the vehicle operates as a compact mobile habitat isolated from the external environment and exposed to extreme lunar conditions.

Unlike short-duration unpressurized missions, where astronauts rely mainly on portable life support systems integrated into EVA suits, pressurized rover missions require a stable and controlled internal environment for extended operations. Consequently, ECLSS architectures directly influence crew safety, mission duration, operational autonomy, and overall vehicle design. Furthermore, these systems are closely coupled with thermal control and power subsystems, since atmosphere conditioning and resource recovery processes introduce additional thermal loads and energy requirements.

The complexity of ECLSS architectures generally increases with mission duration and crew size. From a system engineering perspective, life support architectures can be classified according to the level of resource recovery implemented within the system:

- **Non-regenerative systems:** these architectures rely primarily on stored consumables and expendable components. Oxygen, water, and carbon dioxide removal materials are carried onboard and progressively depleted during the mission. Typical examples include lithium hydroxide (LiOH) canisters used for carbon dioxide absorption during early crewed missions. Non-regenerative systems are generally simpler and highly reliable, but their dependence on consumables leads to significant mass penalties as mission duration increases.
- **Regenerative systems:** these architectures employ technologies capable of recovering and processing part of the consumed resources, reducing the need for continuous resupply. Examples include water recovery systems, regenerative carbon dioxide removal units based on molecular sieves, and oxygen generation systems using water electrolysis. Regenerative approaches improve mission sustainability and reduce dependence on consumables, but introduce increased system complexity, additional power requirements, and higher operational constraints.

Modern exploration systems generally adopt partially regenerative architectures, combining resource recovery technologies with conventional consumable-based subsystems. This approach provides a compromise between reliability, mass reduction, and operational complexity, making it particularly suitable for long-duration exploration missions.

Atmosphere Management and Revitalization

One of the primary functions of an Environmental Control and Life Support System is atmosphere revitalization, namely the maintenance of breathable air composition and acceptable cabin air quality throughout mission operations. This process includes oxygen supply, carbon dioxide removal, humidity regulation, air circulation, and trace contaminant control. Depending on mission duration and required

autonomy, these functions can be implemented through either non-regenerative or regenerative technologies.

Oxygen Supply Oxygen supply systems compensate crew metabolic oxygen consumption and maintain the cabin oxygen partial pressure within acceptable limits. In non-regenerative architectures, oxygen is typically stored in high-pressure tanks and progressively consumed during the mission. Although this approach is simple and highly reliable, it introduces significant mass penalties for long-duration missions due to the required consumable storage.

Regenerative architectures instead employ technologies capable of producing oxygen onboard. One of the most mature examples is the **Oxygen Generation Assembly (OGA)** used onboard the International Space Station (ISS), which generates oxygen through water electrolysis. By splitting water into oxygen and hydrogen, the system reduces dependence on stored oxygen and contributes to increased mission sustainability.

Carbon Dioxide Removal Carbon dioxide removal is an essential ECLSS function because increased CO_2 concentration can rapidly become hazardous for crew health and cognitive performance.

Traditional non-regenerative systems commonly employ **Lithium Hydroxide (LiOH)** canisters, where carbon dioxide is chemically absorbed through expendable sorbent materials. LiOH systems were extensively used during Apollo missions and remain attractive for short-duration missions due to their simplicity, reliability, and limited operational requirements. However, their consumable nature makes them unsuitable for extended exploration missions.

Modern regenerative architectures increasingly adopt reusable sorbent technologies based on molecular sieves and regenerable adsorption beds. The ISS **Carbon Dioxide Removal Assembly (CDRA)** uses zeolite molecular sieves capable of adsorbing carbon dioxide and subsequently regenerating through pressure and temperature cycling. These technologies are considered key elements for long-duration exploration systems because they significantly reduce consumable requirements.

An additional technology associated with advanced atmosphere revitalization architectures is the **Sabatier reactor**. In this process, carbon dioxide reacts with hydrogen to produce methane and water. The recovered water can then be reused by oxygen generation systems, partially closing the oxygen recovery loop and reducing overall resource consumption.

Trace Contaminant Control In addition to oxygen and carbon dioxide regulation, ECLSS architectures must control trace contaminants generated by materials, equipment, and crew activities. Volatile organic compounds, ammonia, and other airborne contaminants can accumulate inside confined environments and negatively affect crew health and equipment reliability.

For this reason, spacecraft typically employ dedicated **Trace Contaminant Control Systems (TCCS)**, which combine activated carbon filters, catalytic oxidation systems, and particulate filtration devices to maintain acceptable air quality levels

inside the habitable volume. Although fundamental in complete ECLSS architectures, trace contaminant control is outside the scope of the present subsystem mass and performance model.

Air Circulation and Ventilation Air circulation and ventilation are fundamental aspects of atmosphere management. In confined environments, forced ventilation is required to avoid stagnant air regions and ensure uniform distribution of oxygen concentration, temperature, and humidity.

Ventilation systems provide continuous cabin airflow through fans, ducts, and air distribution systems, supporting crew comfort and enabling humidity removal and thermal conditioning functions. In complete spacecraft architectures, ventilation is integrated with atmosphere revitalization and thermal control systems.

Water Management and Recovery Systems

Water management represents another fundamental ECLSS function, particularly for long-duration missions where resupply opportunities are limited. Water is required for crew consumption, hygiene, food preparation, oxygen generation, and other onboard processes. As mission duration increases, the mass associated with stored water becomes a major driver, motivating the development of regenerative water recovery technologies.

From an architectural perspective, water management systems can be classified according to the level of resource recovery implemented. Non-regenerative solutions rely on stored consumables, while regenerative systems enable recovery from multiple onboard sources.

In non-regenerative configurations, water is stored in dedicated tanks and supplied directly for crew and operational needs. These architectures are simple and robust but lead to increasing mass penalties with mission duration. Main components include potable water storage tanks, distribution lines, and conditioning systems.

Regenerative architectures recover water from different waste streams, including cabin humidity condensate, hygiene wastewater, and urine. These systems reduce consumable requirements and are essential for long-duration exploration missions, although they introduce additional complexity and operational constraints.

The current state of the art in regenerative water processing is represented by the ISS **Water Recovery System (WRS)**, which integrates the **Water Processor Assembly (WPA)** and the **Urine Processor Assembly (UPA)**. These systems recover water through a combination of filtration, distillation, catalytic oxidation, and purification processes.

The main functional components of regenerative water systems include **condensing heat exchangers (CHX)**, responsible for extracting water vapor from cabin air; **water separators**, used to collect condensed liquids; **filtration units**, which remove contaminants; and **storage and treatment tanks**, ensuring water quality before reuse.

Urine processing represents one of the most important recovery pathways because urine contains a significant fraction of the recoverable water onboard. The **Urine Processor Assembly (UPA)** employs vacuum distillation and phase separation

techniques to extract water from waste streams. Despite its high recovery efficiency, this subsystem introduces additional complexity related to contamination control, microbial growth prevention, and energy requirements.

The selection of water management architecture is strongly mission-dependent. Short-duration missions typically adopt non-regenerative solutions due to their simplicity and reliability, whereas long-duration lunar and planetary missions require regenerative approaches to reduce resupply requirements and improve mission sustainability.

Interface Between ECLSS and Thermal Control

In a pressurized rover, ECLSS and TCS are closely coupled through cabin environmental regulation. The ECLSS is responsible for maintaining acceptable atmospheric conditions and generating internal heat and humidity loads associated with crew metabolism and onboard equipment. The TCS provides the mechanisms required to remove and reject the resulting thermal loads.

Humidity control is a key interface between the two subsystems. Cabin air is typically processed through **condensing heat exchangers (CHX)**, which remove water vapor by cooling the airflow below its dew point. The recovered condensate can then be routed to the water recovery system, creating a direct connection between humidity control and regenerative ECLSS architectures.

Within the present modeling framework, ECLSS defines the environmental and metabolic loads affecting the cabin, while the physical implementation of heat transport and rejection is addressed through the TCS model.

Fire Detection and Suppression

Fire detection and suppression represent additional safety functions included in complete ECLSS architectures. These systems are required to identify and control combustion events in confined pressurized environments, where rapid intervention is necessary to protect crew safety.

Typical solutions include smoke detectors, multi-sensor atmospheric monitoring systems, and fire suppression devices based on gaseous extinguishing agents. These functions are outside the scope of the present modeling framework and are not explicitly considered in the subsystem mass and performance evaluation.

1.5.3 TCS Architectures

Thermal Control Systems (TCS) are among the most critical subsystems in crewed spacecraft, planetary habitats, and surface exploration vehicles. Their primary function is to maintain equipment and habitable volumes within acceptable temperature ranges despite variable internal and external thermal loads. In space and planetary environments, where convective heat transfer is absent or strongly limited, thermal control relies mainly on conduction and radiation mechanisms, making thermal management a key factor for system reliability, crew safety, and mission performance. From a system engineering perspective, thermal control architectures are generally divided into two main categories:

- **Passive Thermal Control Systems (PTCS)**, which exploit material properties, surface characteristics, and geometric configurations to regulate heat exchange without continuous power consumption.
- **Active Thermal Control Systems (ATCS)**, which employ mechanical or fluid-based devices to actively transport and reject heat generated by onboard systems and crew activities.

Modern spacecraft and exploration vehicles typically adopt hybrid architectures combining passive and active solutions. Passive technologies provide baseline thermal stability and reduce heat transfer with the external environment, while active systems provide additional control capability when thermal loads exceed passive management limits.

Passive Thermal Control Systems

Passive Thermal Control Systems regulate heat transfer by exploiting the physical properties of materials and surfaces without requiring active energy consumption. They represent a fundamental component of spacecraft thermal design because they reduce the requirements imposed on active thermal control hardware.

One of the most widely adopted passive technologies is **Multi-Layer Insulation (MLI)**, which is particularly effective in vacuum environments where radiative heat exchange dominates. MLI consists of multiple low-emissivity layers separated by spacer materials, reducing radiative coupling between external surfaces and the spacecraft interior [12]. This technology is extensively used in spacecraft and exploration vehicles to limit heat losses during cold environments and reduce external heat absorption during hot conditions.

Surface optical properties also play a fundamental role in passive thermal design. **Thermal control coatings** allow the modification of absorptivity and emissivity values, enabling the adjustment of the radiative balance according to mission requirements and environmental conditions [12].

Another passive approach involves the use of materials with high thermal inertia. **Thermal storage materials** can absorb and release heat over time, reducing temperature fluctuations and improving thermal stability in environments characterized by cyclic thermal conditions, such as the lunar surface.

Thermal conduction paths are also used to redistribute localized heat loads. **Thermal straps** and conductive structural interfaces provide efficient heat spreading between components, reducing temperature gradients and preventing local overheating.

Active Thermal Control Systems

Active Thermal Control Systems are required when passive technologies are insufficient to maintain the desired thermal conditions. These systems actively transport heat from internal sources toward dedicated heat rejection devices, enabling controlled thermal regulation.

A common active thermal control architecture is based on fluid loops, where a working fluid circulates through the system to collect and transport heat. In crewed

spacecraft, **pump-driven fluid loops** are widely used because they provide accurate control of heat transport capability. Typical components include pumps, valves, accumulators, heat exchangers, and radiators.

Depending on the required performance, active systems may operate through single-phase or two-phase heat transport mechanisms. Single-phase systems transfer heat through sensible temperature variation of the working fluid, whereas two-phase systems exploit latent heat associated with phase change to increase thermal transport capability.

Advanced passive-active solutions include **Loop Heat Pipes (LHP)** and **Capillary Pumped Loops (CPL)**, which exploit capillary forces to transport heat with reduced power requirements compared with conventional pumped systems. These technologies are particularly attractive for spacecraft applications requiring high reliability and reduced mechanical complexity.

Heat rejection to the environment is ultimately achieved through **radiators**. Their performance depends on surface optical properties, effective radiating area, orientation, and interaction with the surrounding environment. For planetary surface missions, additional considerations include environmental contamination and thermal cycling effects that may influence long-term performance.

In pressurized exploration vehicles, active thermal control is closely coupled with Environmental Control and Life Support Systems (ECLSS), since crew metabolism, electronic equipment, and atmospheric conditioning processes represent significant internal heat sources. Consequently, thermal management must be considered at system level, where internal loads generated by other subsystems are balanced through appropriate heat transport and rejection strategies.

Thermal Control Challenges for Lunar Surface Vehicles

Lunar surface vehicles present particularly demanding thermal conditions due to the combination of vacuum environment, extreme temperature variations, and long-duration exposure to solar and deep-space radiative conditions. During illuminated periods, absorbed solar radiation and lunar surface infrared emission can generate significant external heat loads, while during shadowed conditions the vehicle experiences strong radiative heat losses toward deep space.

These characteristics make insulation and heat rejection strategies critical design drivers. In particular, the optimization of passive insulation systems such as MLI requires balancing heat retention during cold conditions with the capability of rejecting internally generated heat during hot conditions.

For this reason, state-of-the-art thermal architectures for lunar exploration vehicles rely on integrated passive and active solutions, where insulation, surface properties, heaters, and radiators are designed together to maintain acceptable internal temperatures throughout the mission.

System-Level Considerations

State-of-the-art thermal control architectures are therefore based on hybrid solutions combining passive and active technologies. Passive systems provide robustness and reduce the thermal exchange with the environment, while active systems provide

adaptability and precise control under varying mission conditions.

In lunar and planetary exploration scenarios, additional constraints such as long thermal cycles, extreme environmental variations, and surface contamination increase system complexity. As a result, modern rover designs increasingly rely on integrated thermal management approaches where the TCS is considered a key element of the overall vehicle architecture.

Within the present work, the thermal control problem is addressed through a parametric modeling approach focused on passive insulation performance and overall thermal balance. The developed model evaluates the influence of environmental conditions, surface properties, insulation characteristics, and heat rejection capability on the rover thermal behavior.

Chapter 2

Problem Definition

This work starts by defining the scope of the study and the operating conditions of a pressurized lunar rover, translating the mission context into engineering inputs required for the subsequent modeling of the Thermal Control System (TCS) and the Environmental Control and Life Support System (ECLSS).

The mission context is introduced through the description of the lunar environment and the operational profile of the vehicle, which establish the boundary conditions governing subsystem behavior and identify the main factors influencing thermal management and life support performance.

Based on this context, the main design assumptions and modeling parameters are established. These assumptions translate mission-level objectives into quantitative inputs and constraints, providing the basis for defining the mission and environmental cases used in the analysis.

The chapter then introduces the operational modes and the formulation of the problem under different mission scenarios and operating conditions, providing the basis for the modeling approach presented in the following chapter.

It is important to note that the chapter does not aim at defining a final system architecture, but rather at establishing a simplified and consistent modeling framework for parametric analysis. The development process is iterative, allowing assumptions and conditions to be refined as the modeling progresses.

2.1 Mission Context

2.1.1 Lunar Environment

The lunar environment imposes a set of boundary conditions that directly affect the performance of the onboard TCS and ECLSS. These two systems are closely related and jointly contribute to maintaining a safe and habitable internal environment for the crew.

The absence of an atmosphere results in vacuum conditions, eliminating convective heat transfer and making radiative exchange the dominant thermal mechanism. This directly affects the TCS, which must rely on conduction and radiation for heat transport and rejection, and requires a controlled pressurized environment supported by reliable atmospheric management and consumable control strategies for the ECLSS.

Extreme spatial and temporal variations between illuminated and shadowed regions lead to highly dynamic thermal loads. For the TCS, this results in long-duration thermal cycling conditions that must be managed to maintain acceptable internal temperatures. The limited heat transfer capability of the lunar environment increases the reliance on insulation and active thermal control strategies.

The absence of a global magnetic field and atmospheric shielding exposes the system to solar radiation, charged particles, and micrometeoroid impacts. These factors influence design choices related to shielding, material selection, and long-term system reliability.

Finally, lunar dust represents a critical contamination and degradation risk for exposed surfaces and interfaces, potentially affecting the long-term performance of radiators, seals, and moving parts, with consequences on both thermal and environmental control subsystems.

2.1.2 Mission Profile

The mission profile is defined as the temporal input framework for the system-level simulation of the pressurized lunar rover. Its primary role is to establish a consistent time-dependent structure that drives the variation of subsystem loads in the integrated MATLAB model.

The analysis is based on a representative lunar surface mission scenario in which the rover supports crewed exploration activities. The system is assumed to operate according to a representative 24-hour operational cycle, which is used as the fundamental time horizon for defining crew activities and subsystem loads.

This cyclic assumption allows the definition of time-dependent boundary conditions for the TCS and the ECLSS, as well as the estimation of subsystem resource demands. Each cycle represents a nominal operational day in which subsystem demands vary according to the current operational state of the system.

Within this framework, the mission profile defines a sequence of time intervals associated with different levels of system activity, such as crew habitation, surface mobility, extravehicular activity support, and low-power operation. These intervals are not treated as system states, but as temporal segments used to drive the activation of operational modes defined in Section 2.4.

The mission profile therefore acts as the time scheduler of the simulation, providing the input signals required to compute thermal loads, consumable consumption, and subsystem performance indicators over time.

2.2 System Requirements

The system requirements define the main performance targets and operational constraints adopted as reference conditions for the modeling and simulation of the TCS and ECLSS. They are derived from the mission profile, environmental conditions, and operational modes introduced in this chapter and provide consistent and traceable inputs for the system-level MATLAB model.

The requirements are expressed as measurable constraints on subsystem behavior rather than detailed design specifications, in order to preserve modeling flexibility

and ensure compatibility with the adopted parametric simulation framework. In particular, they are structured to support the definition of time-dependent inputs associated with the operational modes of the rover.

They are organized following a systems engineering approach inspired by ECSS practices [13] and are divided into performance, operational, and environmental categories.

ID	Requirement
R-PERF-01	The TCS shall maintain the cabin air temperature within the range 18-27°C under all operational modes [14].
R-PERF-02	The TCS shall provide sufficient thermal control capability to balance internally generated and externally absorbed heat loads during mission operations.
R-PERF-03	The ECLSS shall provide the required consumables and environmental control functions to support a crew of N_{crew} throughout the mission duration under nominal and contingency scenarios.
R-PERF-04	The ECLSS shall maintain a habitable internal environment for the crew throughout all mission phases [14].

Table 2.1: Performance requirements.

ID	Requirement
R-OP-01	The system behaviour shall be described through a set of discrete operational modes as defined in Section 2.4.
R-OP-02	The system shall operate according to a representative 24-hour operational cycle used as the basis for time-dependent simulation.
R-OP-03	The transition between operational modes shall preserve the required crew support conditions and subsystem functionality.
R-OP-04	Each operational mode shall define a distinct set of thermal loads, metabolic loads, and subsystem demand conditions used as inputs for the model.

Table 2.2: Operational requirements.

ID	Requirement
R-ENV-01	The system shall operate in lunar vacuum conditions, where convective heat transfer is negligible.
R-ENV-02	The system shall withstand external temperature variations associated with the lunar day-night cycle and surface illumination conditions.
R-ENV-03	The system shall operate under lunar gravity conditions ($g = 1.62 \text{ m/s}^2$ [2]).
R-ENV-04	The system shall be designed considering the effects of the lunar environment, including radiation exposure and charged particle effects.
R-ENV-05	The system shall tolerate lunar regolith dust contamination affecting external surfaces and thermal hardware.

Table 2.3: Environmental requirements.

2.3 Model Input Parameters

This section defines the set of input parameters used to drive the subsystem modeling framework developed in this thesis. These parameters describe the mission configuration, crew conditions, and external environment, and constitute the input set required to evaluate the performance of the Environmental Control and Life Support System (ECLSS) and the Thermal Control System (TCS) models.

The modeling approach is based on a parametric representation of the mission scenario, in which operational activities are decomposed into representative time intervals. This allows the evaluation of time-dependent subsystem loads and resource consumption, enabling the comparison of different operational conditions and design scenarios.

The first group of parameters defines the mission configuration and crew-related characteristics. These parameters determine the internal loads of the rover, including metabolic heat generation, consumables consumption, and life support requirements.

The number of crew members inside the rover, N_{crew} , represents one of the main drivers of the system model. It directly affects oxygen consumption, carbon dioxide production, water demand, food requirements, waste generation, and metabolic heat release, influencing both ECLSS and TCS performance.

The total mission duration, $t_{mission}$, defines the simulation time horizon over which subsystem behavior is evaluated. It is used to compute cumulative consumables consumption and assess system performance over the mission timeline.

Crew activities are distributed over the mission duration into different operational modes, including surface mobility, stationary operations, EVA support, and sleep phases. Each mode is associated with different crew activity levels and corresponding subsystem demands.

Emergency scenarios are defined through dedicated operating conditions, including contingency cases such as life support failures or shelter modes. These scenarios are used to evaluate the robustness of the system under degraded operating conditions.

These mission-related input parameters are summarized in Table 2.4.

Parameter	Description
N_{crew}	Number of crew members inside the rover.
$t_{mission}$	Total mission duration.
$t_{mobility}$	Duration of surface mobility operations.
$t_{stationary}$	Duration of stationary operations.
t_{EVA}	Duration of EVA support operations.
t_{sleep}	Duration of crew sleep phase.

Table 2.4: Mission input parameters.

The second group of parameters defines the external environmental conditions acting on the rover during lunar surface operations. These parameters are particularly relevant for the thermal behavior of the system and define the boundary conditions used in the TCS model.

The external thermal environment is characterized by radiative heat exchange due to the absence of atmosphere. The solar radiation, lunar albedo contribution, regolith infrared emission, and deep-space temperature define the external thermal loads acting on the rover.

The rover geometry and surface properties, including absorptivity and emissivity values, determine the interaction between the vehicle and the surrounding environment. These parameters are used to evaluate the thermal balance and the effectiveness of passive and active thermal control strategies.

These environmental input parameters are summarized in Table 2.5.

Parameter	Description
S_{sun}	Solar radiation flux at lunar distance.
$T_{ground,day}$	Lunar surface temperature during illuminated conditions.
$T_{ground,night}$	Lunar surface temperature during shadowed conditions.
T_{space}	Deep-space background temperature.
α	External surface solar absorptivity.
ϵ	External surface emissivity.

Table 2.5: Environmental input parameters.

Together, the mission and environmental input parameters define the complete set of boundary conditions used in the subsystem modeling framework. These parameters are directly used in the MATLAB-based models to compute power consumption, thermal loads, and life support requirements under different operational conditions. The operational modes governing the application of these inputs are defined in the following section.

2.4 Operational Modes

The operational concept of the pressurized rover is represented through a set of discrete operational modes describing the main mission phases expected during lunar surface operations. These modes are introduced to capture the variations in crew activity, subsystem utilization, and resource consumption occurring throughout the mission.

Rather than representing different vehicle configurations, the operational modes provide a framework for translating mission activities into model inputs. Each mode is associated with different levels of crew metabolic activity, internal heat generation, and subsystem demand. As a result, the operational mode directly affects the inputs used in the ECLSS and TCS models, enabling the evaluation of time-dependent and averaged subsystem loads.

Four operational modes are considered in this work: Surface Mobility Mode, Stationary Operations Mode, Extravehicular Activity (EVA) Support Mode, and Sleep Mode.

- **Surface Mobility Mode** represents nominal rover traversal activities. During this phase, the crew is actively engaged in mission operations while the rover moves between different locations. The increased crew activity results in higher metabolic loads, oxygen consumption, carbon dioxide generation, and internal heat release compared to low-activity phases.
- **Stationary Operations Mode** corresponds to periods in which the rover remains stationary while mission activities continue inside the pressurized cabin. Typical activities include mission planning, scientific operations, data analysis, and housekeeping tasks. Although mobility-related activities are not active, the crew remains operational and subsystem demands remain significant.
- **EVA Support Mode** represents mission phases in which extravehicular activities are supported by the rover. In the present modeling framework, EVA operations are represented as a dedicated operational condition with modified subsystem demands. Transient airlock depressurization and repressurization processes are not explicitly modeled; therefore, the mode is evaluated through steady-state variations in crew activity and resource consumption.
- **Sleep Mode** corresponds to crew rest periods. During this phase, metabolic activity is reduced, resulting in lower oxygen consumption, carbon dioxide production, water demand, and metabolic heat generation. Consequently, reduced thermal and environmental control loads are expected compared with active operational phases.

The qualitative influence of the operational modes on the subsystem models is summarized in Table 2.6.

Operational Mode	Crew Activity	ECLSS Load	TCS Load	Subsystem Power Demand
Surface Mobility	High	High	High	High
Stationary Operations	Medium	Medium	Medium	Medium
EVA Support	High	Low	Medium	Medium
Sleep	Low	Low	Low	Low

Table 2.6: Qualitative influence of operational modes on subsystem loads.

The operational modes are combined with the mission input parameters defined in the previous section to construct the mission duty cycle adopted by the MATLAB-based modeling framework. Through this approach, the subsystem models evaluate the variation of thermal loads, consumable consumption, and subsystem performance indicators under different mission conditions, allowing the estimation of representative average and peak values over the mission duration.

Chapter 3

Methodology

This chapter represents the core of the present work, as it describes the development of the engineering model used to analyze the Thermal Control System (TCS) and the Environmental Control and Life Support System (ECLSS) of a pressurized lunar rover.

The model is developed to translate mission-level requirements into subsystem-level engineering equations, enabling the assessment of thermal behavior, resource consumption, and system sizing under representative operational conditions. In this context, the physical system is represented through simplified but consistent formulations that capture the dominant governing effects while maintaining computational efficiency.

The modeling approach includes:

- definition of system boundaries at the mission, vehicle, and subsystem levels;
- identification and justification of modeling assumptions used to reduce complexity;
- representation of the system through lumped-parameter thermal models and mission-based mass balance formulations;
- formulation of the governing relationships for thermal exchanges, resource flows, and subsystem performance indicators;
- implementation of the complete model in a MATLAB environment.

Overall, the methodology describes how the mission scenario is translated into a coherent set of engineering equations and computational models, which form the basis for the analysis presented in the following results chapter.

3.1 System Architecture and Modeling Assumptions

The engineering model developed in this work relies on a set of assumptions and input parameters that define the operational scenario of the pressurized lunar rover

and establish the boundary conditions of the analysis. These assumptions are required to represent the system with an appropriate level of fidelity while maintaining a computationally efficient framework suitable for preliminary design and sizing activities.

The selected parameters describe the mission scenario, the rover configuration, the external lunar environment, the crew metabolic loads, and the main engineering quantities governing the behavior of the TCS and ECLSS. Together, they define the reference operational scenario adopted for the analysis and provide the basis for the formulation of the analytical models presented in the following sections.

3.1.1 Mission Parameters

The crew size represents one of the primary drivers of the onboard systems, as it directly affects internal heat generation, resource consumption, and overall subsystem sizing. A nominal crew of 2 astronauts is adopted as the baseline configuration, consistent with current concepts for pressurized lunar exploration rovers.

Emergency scenarios are also considered in the analysis by increasing the crew size to 4 astronauts, representing a contingency condition in which additional crew members may temporarily occupy the vehicle. This approach allows the evaluation of the impact of increased metabolic loads and resource demand on the ECLSS and thermal environment while maintaining consistency with the considered rover architecture.

Mission duration represents another fundamental parameter affecting consumable requirements and subsystem performance. A reference mission duration of 14 days is adopted as the baseline scenario, representing an extended surface exploration campaign for a pressurized lunar rover. All analyses presented in this work are performed considering this mission duration, while the developed model maintains a parametric structure that allows future investigations of different mission lengths. The operational behavior of the rover is represented through a mission profile based on four operational modes: Surface Mobility, Stationary Operations, EVA Support, and Sleep. Rather than reproducing a specific mission timeline, the profile is intended to represent a typical operational day and provide representative average thermal and environmental loads for the preliminary sizing and performance assessment of the onboard systems.

Operational Mode	Duration [h/day]	Fraction of Day [%]
Surface Mobility	4	16.7
EVA Support	4	16.7
Stationary Operations	8	33.3
Sleep	8	33.3
Total	24	100

Table 3.1: Nominal daily allocation of operational modes

The adopted time allocation is based on human factors guidelines for space missions. In particular, NASA recommendations for crew scheduling indicate an average sleep period of approximately 8.5 hours per day [15]. In the present work, this value

is approximated to 8 hours in order to maintain a consistent 24-hour discretization of the operational cycle.

The remaining time is distributed between operational and EVA-related activities. 4 hours per day are assigned to Surface Mobility, representing rover traversal phases associated with exploration activities, crew transportation, and external operations. An additional 4 hours are allocated to EVA Support activities, which include preparation and post-processing phases associated with extravehicular operations.

Stationary Operations account for the remaining 8 hours of the active period and represent a consolidated set of crew activities that typically dominate time expenditure in surface missions. These include meal preparation, personal hygiene, use of sanitation systems, mission planning, communication with Earth, scientific data handling, internal scientific activities, maintenance operations, system monitoring, mission preparation, and post-EVA activities. Although heterogeneous in nature, these tasks collectively occupy a significant fraction of the daily schedule and are therefore grouped into a single operational mode for modeling purposes.

The resulting mission profile is not intended to reproduce a specific mission timeline, but rather to provide a representative operational distribution for the reference mission scenario. This formulation is appropriate for preliminary system sizing and enables a consistent evaluation of thermal loads, metabolic consumption, and resource demands. Although actual mission activities may vary depending on operational constraints, the adopted profile provides a suitable reference case for the assessment of medium-duration lunar exploration missions.

3.1.2 Vehicle Parameters

Vehicle parameters describe the physical configuration of the pressurized rover and provide the geometric and structural basis for thermal and environmental modeling. As a preliminary design basis, representative values from existing literature and conceptual lunar rover studies are considered. In particular, the work presented in [16] provides a relevant reference for pressurized lunar rover configurations developed within the same mission framework. However, since these values are associated with preliminary design iterations, they are not treated as fixed design outputs in the present work. Instead, a bounded range is adopted in order to preserve generality and account for uncertainty in the final configuration.

The main geometric parameters are therefore defined as:

- rover radius: 1-1.5 m
- rover length: 5-6 m

Within the numerical implementation, a nominal baseline configuration is adopted for simulation purposes, with a rover radius $R = 1.3$ m and a rover length $L = 5.0$ m.

The total external surface area of the rover is computed assuming an ideal cylindrical geometry with two hemispherical end caps. The resulting expression is given by:

$$A_{tot} = 2\pi RL + 4\pi R^2$$

where the first term represents the lateral cylindrical surface and the second term accounts for the two hemispherical caps.

The rover mass is introduced as a design parameter and is used to characterize the overall thermal inertia of the vehicle. A mass range between 3000 and 7000 kg is considered, covering a variety of possible structural configurations and subsystem allocations for a pressurized lunar rover. Within the numerical implementation, a nominal rover mass $m_{rover} = 5000$ kg is adopted as the baseline value for the reference case simulations.

The vehicle mass is subsequently used in the thermal model to determine the equivalent thermal capacitance of the rover through an equivalent specific heat capacity approach. The details of this formulation are presented in the Thermal Model Parameters section.

The pressurization level is assumed to be 1 atm (101325 Pa), corresponding to an Earth-like internal environment. This assumption simplifies the environmental control modeling by avoiding the need for detailed partial pressure management and gas composition control.

3.1.3 Environmental Parameters

Environmental parameters define the external lunar thermal environment and are treated as fixed boundary conditions in the thermal model. These parameters are derived from established lunar environmental datasets and literature values and remain constant throughout the simulation, except for the distinction between day and night operational cases [2].

In particular, two primary environmental conditions are considered, corresponding to daytime and nighttime surface conditions. These conditions affect the incident solar radiation, the lunar surface temperature, and the radiative exchange between the rover and the surrounding environment.

The full set of environmental and radiative parameters used in the model is reported in Table 3.2.

Parameter	Symbol	Value
Solar constant	S_{day}	1361 W/m ²
Lunar albedo (day)	a_{day}	0.12
Ground emissivity	ϵ_{ground}	0.95
Ground temperature (day)	$T_{ground,day}$	390 K
Ground temperature (night)	$T_{ground,night}$	100 K
Deep space temperature	T_{space}	3 K
Stefan-Boltzmann constant	σ	5.67×10^{-8} W/m ² K ⁴

Table 3.2: Environmental and radiative parameters adopted in the thermal model.

The selection of these parameters is based on standard lunar surface models and widely used references in space thermal analysis. The lunar surface temperature values represent extreme hot and cold cases, while the view factors are used to approximate the fraction of radiative exchange between the rover and the lunar surface or deep space.

The solar constant and lunar albedo are relevant only during illuminated surface conditions, when direct and reflected solar radiation contribute to the thermal balance. In contrast, during lunar nighttime conditions, the thermal environment is dominated by radiative heat exchange with deep space, leading to significantly lower external heat input and increased radiative losses from the rover surface.

3.1.4 Thermal Model Parameters

The thermal model is governed by a set of design parameters describing the thermal characteristics of the pressurized rover. Unlike the environmental parameters presented in the previous section, these quantities depend on the vehicle design and may vary according to different architectural solutions. For this reason, each parameter is assigned a plausible range representative of preliminary lunar rover designs, while a nominal value is selected as the reference configuration adopted throughout the baseline analyses.

The Multilayer Insulation (MLI) coverage ratio, A_{MLI}/A_{tot} , defines the fraction of the external surface protected by multilayer insulation. Higher values improve thermal insulation by reducing radiative heat exchange with the environment, whereas lower values correspond to larger exposed areas. A range between 0.4 and 0.8 is considered, with a baseline value of 0.6 representing a balanced compromise between thermal protection and the need for exposed surfaces such as radiators, interfaces, and external equipment.

The ground view factor, F_{ground} , represents the fraction of the rover surface radiatively coupled with the lunar ground. Since the effective view factor depends on vehicle geometry and local terrain conditions, values between 0.2 and 0.5 are considered. A nominal value of 0.3 is adopted, representative of a rover operating on relatively flat terrain.

The optical properties of the external surfaces are characterized by the solar absorptivity, α , and the infrared emissivity of the uninsulated surfaces, ε_{unins} . The absorptivity is varied between 0.1 and 0.3 to account for different external coatings, while a nominal value of 0.15 is selected to represent a highly reflective surface suitable for lunar daytime operations. The emissivity of the uninsulated surfaces is assumed to range between 0.2 and 0.6, with a baseline value of 0.4 representing typical spacecraft external surfaces with moderate infrared emission characteristics. The thermal inertia of the rover is represented through an equivalent thermal capacitance, C_{th} , estimated from the rover mass and an equivalent specific heat capacity according to

$$C_{th} = m_{rover} \cdot c_{eq}$$

The rover mass is varied between 3000 and 7000 kg, while a constant equivalent specific heat capacity of $c_{eq} = 1000 \text{ J}/(\text{kg K})$ is assumed. This value is representative of a lightweight spacecraft structure including the contribution of onboard equipment, batteries, and internal subsystems. The resulting equivalent thermal capacitance ranges from $3 \cdot 10^6$ to $7 \cdot 10^6 \text{ J/K}$, with a nominal value of $5 \cdot 10^6 \text{ J/K}$.

The penetration factor, p , is introduced according to the MLI thermal model formulation to account for additional heat transfer paths caused by structural penetrations and imperfections. Since the actual thermal coupling depends on the detailed vehicle

design, values between 0.5 and 2.0 are considered, while the nominal configuration assumes $p = 1.0$.

The internal heat load, Q_{int} , represents the combined thermal dissipation generated by crew metabolism, avionics, electrical equipment, and onboard subsystems. Depending on the operational scenario and equipment activity, values between 500 and 2000 W are considered. The reference case adopts a constant internal heat generation of 1200 W.

Finally, the active thermal control system is characterized by the maximum heater power, $Q_{heater,max}$, and the radiator area, A_{rad} . The heater capacity varies between 1000 and 3000 W, while the radiator area ranges from 5 to 25 m², representing different active thermal control configurations. The nominal configuration assumes a heater capacity of 2000 W and a radiator area of 15 m².

The nominal values adopted in the reference thermal model are summarized in Table 3.3.

Parameter	Baseline value	Range
A_{MLI}/A_{tot}	0.6	0.4-0.8
F_{ground}	0.3	0.2-0.5
α	0.15	0.1-0.3
ε_{unins}	0.4	0.2-0.6
C_{th} [MJ/K]	5	3 – 7
p	1.0	0.5-2.0
Q_{int} [W]	1200	500-2000
$Q_{heater,max}$ [W]	2000	1000-3000
A_{rad} [m ²]	15	5-25

Table 3.3: Baseline values and variation ranges of the thermal model parameters.

3.1.5 ECLSS Model Parameters

The ECLSS model is governed by a set of parameters defining the metabolic loads, consumable requirements, and recovery characteristics of the life support system. These parameters represent the main inputs required to evaluate the evolution of onboard resources throughout the mission.

Unlike the thermal model parameters, which mainly describe vehicle and environmental characteristics, the ECLSS parameters are primarily related to crew resource consumption and internal mass flows. The adopted values are based on established human spaceflight life support references and selected assumptions required to represent the rover architecture at a preliminary design level.

The metabolic loads are represented through constant average daily consumption rates. Oxygen consumption, water demand, food consumption, carbon dioxide generation, humidity production, and urine generation are assumed constant throughout the mission. The adopted metabolic values are derived from NASA life support design references, in particular the values reported in [17], while hygiene water demand is based on the assumptions reported in the NASA Life Support Baseline Values and Assumptions Document [18]. This approach provides a simplified representation of crew-resource interactions while maintaining a suitable level of fidelity for prelimi-

nary system assessment.

Water management is characterized through recovery efficiency parameters associated with the main recovery processes. Unlike the metabolic loads, these parameters are not directly taken from a reference design but are introduced as model assumptions to represent different levels of regenerative capability. The condensation recovery efficiency is assumed equal to 0.9, representing an effective humidity recovery process, while the urine recovery efficiency is assumed equal to 0.8, consistent with the expected performance of regenerative water processing systems. The hygiene water recovery efficiency is assumed equal to 0.6, representing a lower recovery capability due to the contamination and treatment requirements associated with hygiene wastewater streams. These assumptions allow the evaluation of the benefits introduced by regenerative water recovery architectures compared to non-regenerative configurations.

The main parameters adopted in the reference ECLSS model are summarized in Table 3.4.

Parameter	Baseline value
Oxygen consumption [kg/(CM day)]	0.84
Water consumption [kg/(CM day)]	2.38
Hygiene water demand [kg/(CM day)]	2.70
Food consumption [kg/(CM day)]	1.77
CO ₂ generation [kg/(CM day)]	1.00
Humidity generation [kg/(CM day)]	2.28
Urine production [kg/(CM day)]	1.50
Condensation recovery efficiency	0.9
Urine recovery efficiency	0.8
Hygiene water recovery efficiency	0.6

Table 3.4: Baseline values adopted for the ECLSS model parameters.

3.2 Thermal Control System (TCS) Modeling and Sizing

3.2.1 Multilayer Insulation (MLI) Model

The thermal insulation of the rover is modeled through a MLI system, whose effect is represented by an equivalent effective emissivity formulation. This approach allows the complex combination of radiative exchange between layers, residual gas conduction, and solid conduction through spacers to be reduced to a single engineering parameter.

The effective emissivity model adopted in this work is based on the empirical correlation developed by Gilmore and reported in *Spacecraft Thermal Control Handbook* [19]. The formulation provides a first-order estimate of MLI performance for spacecraft applications in vacuum environments.

The radiative heat exchange between the rover external surface and the surrounding environment is modeled using the Stefan–Boltzmann law, where the effective emis-

sivity of the multilayer insulation directly influences the net radiative heat transfer. The resulting heat flux is expressed as:

$$Q = \varepsilon_{eff} \sigma A (T_h^4 - T_c^4) \quad (3.1)$$

The effective emissivity is expressed as:

$$\varepsilon_{eff} = \frac{0.000136 T_m^{0.667} + 0.000121 T_m}{4 f_i T_m^2} \cdot f_N \cdot f_A \cdot f_P \quad (3.2)$$

where:

- T_m is the mean temperature of the multilayer insulation blanket [K],
- f_N is a correction factor accounting for the number of layers,
- f_A is a correction factor accounting for blanket area effects,
- f_P is a correction factor accounting for penetrations and seams.

The mean temperature of the insulation blanket is defined as:

$$T_m = \left(\frac{T_h^4 - T_c^4}{4(T_h - T_c)} \right)^{1/3} \quad (3.3)$$

where T_h and T_c are the hot-side and cold-side boundary temperatures, respectively. The model is valid within a temperature range of:

$$-140^\circ C \leq T_m \leq +140^\circ C$$

which corresponds to typical spacecraft thermal operating conditions in vacuum environments.

The area correction factor is defined as:

$$f_A = \frac{1}{10^{(0.373 \log_{10} A)}} \quad (3.4)$$

where A is the blanket area in m^2 . This correlation is valid within the range:

$$0.05 m^2 \leq A \leq 3 m^2$$

For areas outside this range, the limiting values at the boundaries are adopted. The correction factor for the number of layers is defined as:

$$f_N = f_N(N)$$

where discrete values are provided in Table 3.5 based on experimental data reported in Gilmore.

Number of layers N	Correction factor f_N
5	2.048
10	1.425
15	1.164
20	1.000
25	0.905
30	0.841

Table 3.5: Correction factor for number of MLI layers.

The penetration correction factor f_P accounts for the degradation of thermal performance due to seams, penetrations, and non-ideal blanket assembly. It depends on the percentage of blanket area occupied by penetrations and on the emissivity of the internal MLI layers, as reported in Gilmore.

The corresponding correction values are summarized in Table 3.6.

Penetration p [%]	Correction factor f_P
0.1	0.756
0.2	0.783
0.5	0.865
1.0	1.000
1.5	1.133
2.0	1.266

Table 3.6: Penetration correction factor for MLI performance degradation (adapted from Gilmore).

In order to enable the use of the MLI model within a continuous numerical framework, the discrete values of the correction factors f_N and f_P reported in Tables 3.5 and 3.6 are interpolated to obtain continuous functions of the number of layers and penetration level, respectively.

This approach allows the thermal model to account for intermediate configurations not explicitly reported in the original experimental dataset, ensuring a smooth variation of the effective emissivity within the investigated design space. The resulting interpolated trends of the correction factors are shown in Figures 3.1 and 3.2, highlighting their dependency on the number of layers and penetration level, respectively.

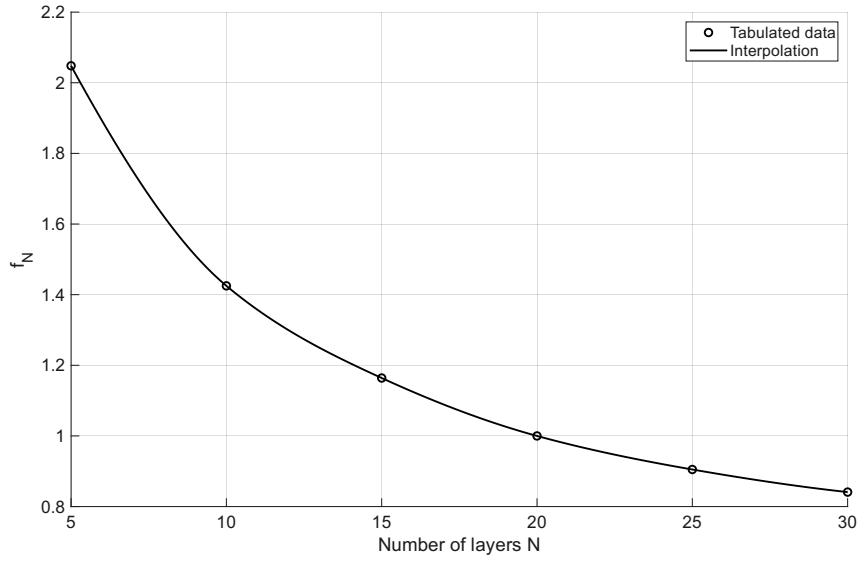


Figure 3.1: Interpolated layer correction factor f_N as a function of the number of MLI layers N .

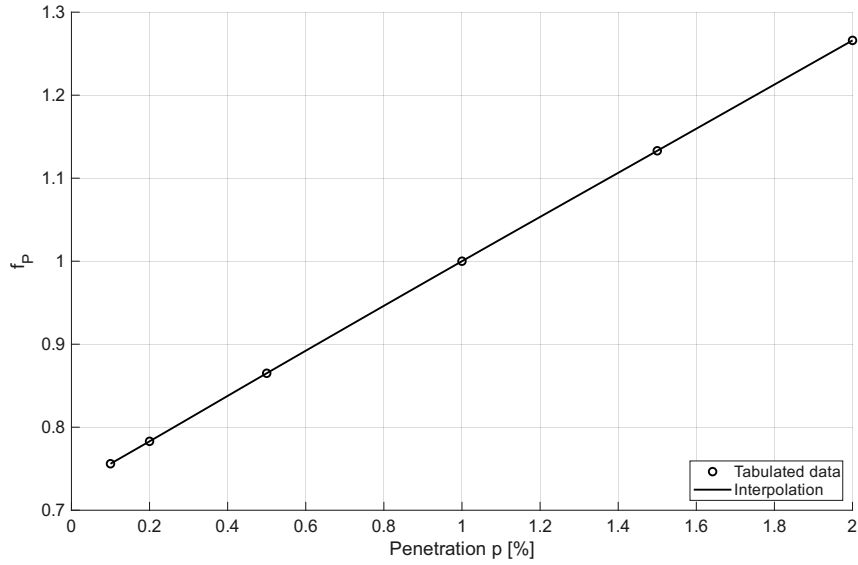


Figure 3.2: Interpolated penetration correction factor f_P as a function of the MLI penetration level p .

In particular, the penetration factor f_p is treated as an equivalent parameter representing the quality of the MLI assembly. The reference value $p = 1.0$ corresponds to the nominal configuration reported in the original Gilmore formulation. Values lower than unity represent improved insulation performance associated with high-quality MLI assembly, while values greater than unity account for degraded configurations with increased conductive coupling through penetrations and structural discontinuities.

The resulting effective emissivity is then used to compute the equivalent radiative heat transfer through the insulated surfaces, which is integrated into the global thermal balance of the rover.

3.2.2 Thermal Energy Balance Model

The thermal behavior of the pressurized rover is modeled through a lumped-parameter energy balance approach, assuming a uniform internal cabin temperature and neglecting spatial temperature gradients within the vehicle. This simplification allows the transient thermal response of the rover to be described through a single thermal node, which is suitable for preliminary system-level analyses.

The time evolution of the internal temperature is obtained by solving the global energy balance:

$$C_{th} \frac{dT_{int}}{dt} = \dot{Q}_{in} - \dot{Q}_{out} \quad (3.5)$$

where C_{th} is the equivalent thermal capacitance of the rover and T_{int} is the internal cabin temperature. The incoming and outgoing heat flows are defined as:

$$\dot{Q}_{in} = \dot{Q}_{sun} + \dot{Q}_{albedo} + \dot{Q}_{IR,ground} + \dot{Q}_{internal} + \dot{Q}_{heater} \quad (3.6)$$

$$\dot{Q}_{out} = \dot{Q}_{MLI} + \dot{Q}_{unins} + \dot{Q}_{rad} \quad (3.7)$$

The individual thermal contributions are described in the following sections.

Thermal capacitance The thermal inertia of the rover is represented through an equivalent thermal capacitance:

$$C_{th} = m_{rover} c_{eq} \quad (3.8)$$

where m_{rover} is the equivalent rover mass considered for thermal inertia estimation and c_{eq} is an equivalent specific heat capacity accounting for the aggregated thermal behavior of the structure, onboard equipment, and internal subsystems.

Internal heat generation The internal heat load includes crew metabolic contribution and heat dissipation from onboard equipment:

$$\dot{Q}_{internal} = \dot{Q}_{crew} + \dot{Q}_{equipment} \quad (3.9)$$

This formulation represents the average thermal dissipation associated with crew activity, avionics, electrical equipment, and environmental control systems.

External environmental heat loads The external heat inputs are represented by direct solar radiation, lunar reflected radiation, and infrared emission from the lunar surface.

The absorbed solar contribution is calculated as:

$$\dot{Q}_{sun} = \alpha S A_{tot} \sin(\theta) F_{space} \quad (3.10)$$

where α is the solar absorptivity, S is the solar constant, and θ represents the rover orientation with respect to the Sun.

The lunar albedo contribution is expressed as:

$$\dot{Q}_{albedo} = \alpha a_{lunar} S A_{tot} F_{ground} \quad (3.11)$$

where a_{lunar} is the lunar surface albedo.

The infrared exchange with the lunar ground is calculated considering both insulated and non-insulated surfaces:

$$\dot{Q}_{IR,ground} = (\varepsilon_{unins}A_{unins} + \varepsilon_{MLI}A_{MLI}) F_{ground}\varepsilon_{ground}\sigma T_{ground}^4 \quad (3.12)$$

where F_{ground} represents the rover-ground view factor.

Radiative heat losses Heat rejection through the passive external surfaces is separated between MLI-covered and exposed surfaces.

The radiative heat transfer through the MLI-covered area is:

$$\dot{Q}_{MLI} = \varepsilon_{MLI}\sigma A_{MLI} (T_{int}^4 - T_{env,eq}^4) \quad (3.13)$$

where $T_{env,eq}$ is the equivalent radiative temperature of the external environment.

The heat loss from non-insulated surfaces is expressed as:

$$\dot{Q}_{unins} = \varepsilon_{unins}\sigma A_{unins} (T_{int}^4 - T_{space}^4) F_{space} \quad (3.14)$$

where ε_{unins} is the infrared emissivity of the exposed external surfaces.

Active thermal control The active thermal control system includes electrical heaters and radiators.

The heater contribution is activated when the cabin temperature approaches the minimum allowable temperature:

$$\dot{Q}_{heater} = \begin{cases} Q_{heater,max} & T_{int} < T_{min} \\ 0 & \text{otherwise} \end{cases} \quad (3.15)$$

The active radiator provides heat rejection when the internal temperature exceeds the upper thermal limit:

$$\dot{Q}_{rad} = \begin{cases} \varepsilon_{rad}\sigma A_{rad} (T_{int}^4 - T_{space}^4) & T_{int} > T_{max} \\ 0 & \text{otherwise} \end{cases} \quad (3.16)$$

where A_{rad} is the radiator area and ε_{rad} is its infrared emissivity.

Numerical solution The resulting first-order ordinary differential equation is integrated numerically using a discrete time formulation:

$$T_{int}(i+1) = T_{int}(i) + \frac{\dot{Q}_{net}(i)}{C_{th}} \Delta t \quad (3.17)$$

where:

$$\dot{Q}_{net} = \dot{Q}_{in} - \dot{Q}_{out} \quad (3.18)$$

This formulation provides a simplified but physically consistent representation of the main thermal interactions governing the rover temperature evolution during lunar surface operations.

3.3 Environmental Control and Life Support System (ECLSS)

3.3.1 Architecture and Resource Flow

The Environmental Control and Life Support System (ECLSS) considered in this work is based on a simplified regenerative architecture designed to support crew operations inside a pressurized lunar rover. The system provides the functions required to maintain cabin habitability, including atmosphere revitalization, water management, consumable storage, and waste collection. The adopted architecture and the main resource flows considered in the model are shown in Figure 3.3.

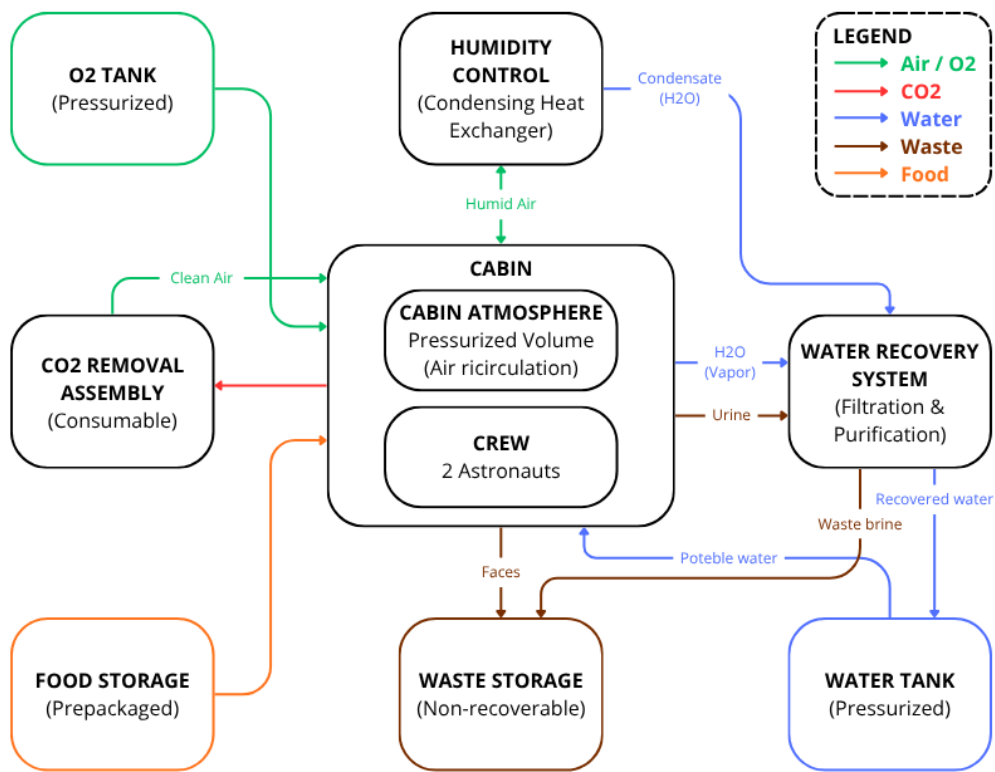


Figure 3.3: Simplified architecture and resource flows of the Environmental Control and Life Support System (ECLSS)

The pressurized cabin represents the central node of the system, where crew activities generate the main metabolic flows driving the ECLSS sizing. The crew consumes oxygen, water, and food while producing carbon dioxide, humidity, urine, and waste streams. These exchanges are represented through dedicated mass flows connecting the cabin with the different ECLSS subsystems.

The cabin atmosphere is continuously recirculated through an air revitalization loop. Oxygen is supplied from the onboard storage tank to compensate for crew consumption, while the produced carbon dioxide is extracted from the cabin atmosphere and directed to the Carbon Dioxide Removal Assembly (CDRA). After carbon dioxide removal, the regenerated air is returned to the cabin, closing the atmospheric loop.

In the present model, the oxygen inventory is represented as a consumable resource, whereas carbon dioxide removal is modeled through the consumption of lithium hydroxide ($LiOH$) cartridges.

Water management is based on a regenerative loop centered on the Water Recovery System (WRS). Different wastewater streams generated inside the cabin are collected and processed to recover part of the consumed water. Humidity generated by crew respiration and perspiration is removed from the cabin air through the Humidity Control subsystem, which includes a Condensing Heat Exchanger. The resulting condensate is transferred to the Water Recovery System (WRS), where filtration and purification processes convert it into reusable water returned to the onboard water tank. Similarly, urine produced by the crew is collected and processed by the WRS, and the recovered fraction is stored for subsequent use. Hygiene-related wastewater is also considered a recoverable stream through the same approach.

The consumable and waste management paths complete the system architecture. Food is supplied from the onboard storage directly to the cabin and is considered a non-regenerative resource. The residual products generated by crew activities, together with unrecovered fractions from the water processing loop, are accumulated in the waste storage.

The resulting architecture represents the main closed-loop resource exchanges of a pressurized rover ECLSS while maintaining a simplified system-level description suitable for preliminary sizing. The different flows shown in Figure 3.3 are subsequently translated into mass balance equations to evaluate the evolution of onboard resources during the mission.

3.3.2 Modeling Approach

The model developed in this work represents the rover life support functions through a time-dependent lumped-parameter formulation based on mass balance equations. The objective is to estimate the evolution of onboard resources during the mission and to evaluate the impact of different operational scenarios on the overall system sizing.

The adopted approach does not aim to reproduce the detailed physical behavior of individual hardware components but rather represents the overall exchange of resources between crew activities, storage units, recovery processes, and waste accumulation through equivalent mass flows. This level of abstraction is considered appropriate for preliminary design studies, where system-level trends and sizing drivers are of primary interest.

The crew metabolic activity is assumed to be the main source term governing resource consumption and waste generation. Oxygen consumption, carbon dioxide production, water demand, food consumption, humidity generation, and waste production are described through constant average daily rates. These quantities are scaled according to the crew size and integrated over the mission duration.

Each resource is represented through a dedicated state variable updated at each simulation time step. The model tracks the evolution of:

- oxygen storage;

- available water inventory;
- food storage;
- lithium hydroxide consumable for carbon dioxide removal;
- accumulated waste mass.

The resource evolution is obtained by applying discrete mass balance equations that account for consumption, recovery, and generation terms. This formulation enables the evaluation of consumable depletion trends, the benefits introduced by regenerative processes, and the total mass variation of the system throughout the mission.

3.3.3 Consumable Mass Balance

The evolution of the onboard consumables is evaluated through discrete mass balance equations applied at each simulation time step. The considered resources are oxygen, lithium hydroxide cartridges, food, and waste, which represent the main mass contributors associated with crew survival and consumable logistics.

The general formulation adopted for each consumable is based on the balance between the initial inventory and the cumulative consumption or generation rate:

$$m_i(k+1) = m_i(k) + \dot{m}_i \Delta t \quad (3.19)$$

where m_i represents the mass of the considered resource, $\dot{m}_i$ is the corresponding mass flow rate, and Δt is the simulation time step.

Oxygen consumption Oxygen is considered a non-regenerative consumable supplied by the onboard storage tank. The oxygen inventory is reduced according to the crew metabolic demand:

$$m_{O_2}(k+1) = m_{O_2}(k) - N_{crew} \dot{m}_{O_2} \Delta t \quad (3.20)$$

where $\dot{m}_{O_2}$ represents the average oxygen consumption rate per crew member. The model assumes a constant oxygen demand throughout the mission, neglecting variations associated with different crew activities.

Oxygen depletion is considered a critical condition, as the lack of available oxygen directly prevents continued crew operation. Therefore, the model identifies oxygen exhaustion as an immediate mission failure condition.

Carbon dioxide removal The carbon dioxide generated by crew metabolism is removed through a consumable-based process represented by lithium hydroxide ($LiOH$) cartridges. Rather than modeling the detailed behavior of the carbon dioxide removal assembly, the required consumable quantity is estimated through an equivalent conversion factor:

$$m_{LiOH}(k+1) = m_{LiOH}(k) - N_{crew} \dot{m}_{CO_2} k_{LiOH} \Delta t \quad (3.21)$$

where $\dot{m}_{CO_2}$ is the average carbon dioxide production rate per crew member and k_{LiOH} is the conversion coefficient that relates carbon dioxide generation to the equivalent lithium hydroxide consumption.

The available $LiOH$ inventory is therefore used as an indicator of the carbon dioxide removal capability. Similar to oxygen depletion, complete exhaustion of the consumable is considered a critical failure condition.

Food consumption Food is treated as a non-recoverable resource directly dependent on crew size and mission duration. The food inventory evolves according to:

$$m_{food}(k+1) = m_{food}(k) - N_{crew}\dot{m}_{food}\Delta t \quad (3.22)$$

where $\dot{m}_{food}$ represents the average daily food requirement per crew member.

In contrast to oxygen and carbon dioxide removal capability, food depletion is not considered an instantaneous failure condition. The model introduces a predefined survival allowance after food exhaustion to represent the possibility of temporarily continuing the mission through stored reserves or operational constraints.

Waste accumulation Waste generation is evaluated as the accumulation of non-recoverable products generated during crew operations. The waste mass includes solid waste production and unrecovered fractions of liquid waste streams:

$$\begin{aligned} m_{waste}(k+1) = & m_{waste}(k) + N_{crew}\dot{m}_{solid}\Delta t \\ & + N_{crew}\dot{m}_{urine}(1 - \eta_{urine})\Delta t \\ & + N_{crew}\dot{m}_{hygiene}(1 - \eta_{hygiene})\Delta t \end{aligned} \quad (3.23)$$

where η_{urine} and $\eta_{hygiene}$ represent the recovery efficiencies associated with the water processing system.

The resulting waste inventory accounts for the fraction of generated material that cannot be returned to the resource cycle and therefore contributes to the final system mass.

3.3.4 Water Recovery Model

Water management represents one of the main drivers of the life support system mass budget, especially for medium and long-duration missions. In order to reduce the amount of water that must be initially stored onboard, the adopted architecture includes a regenerative water loop based on a simplified Water Recovery System (WRS).

The model does not reproduce the detailed behavior of the individual water processing units, such as filtration, purification, and phase separation processes. Instead, the WRS is represented through equivalent recovery efficiencies applied to the main water streams generated by crew activities. This approach allows the evaluation of the mass benefit associated with regenerative water management while maintaining a suitable level of complexity for preliminary design studies.

The water balance is calculated by considering the difference between the consumed

water and the recovered fraction returned to the onboard storage tank:

$$m_{water}(k+1) = m_{water}(k) - \dot{m}_{consumed}\Delta t + \dot{m}_{recovered}\Delta t \quad (3.24)$$

The total water consumption is divided into drinking and food preparation demand, and hygiene activities:

$$\dot{m}_{consumed} = N_{crew}(\dot{m}_{drinking} + \dot{m}_{hygiene}) \quad (3.25)$$

The recovered water contribution is obtained from three different recovery paths associated with the main wastewater streams generated inside the cabin:

$$\dot{m}_{recovered} = \dot{m}_{vapor} + \dot{m}_{urine} + \dot{m}_{hygiene} \quad (3.26)$$

Humidity generated by crew respiration and perspiration is removed from the cabin atmosphere through the Humidity Control subsystem. The condensed water collected by the Condensing Heat Exchanger is then processed by the WRS and returned to the water storage tank:

$$\dot{m}_{vapor} = N_{crew}\dot{m}_{vapor,crew}\eta_{vapor} \quad (3.27)$$

Similarly, urine generated by the crew is considered a recoverable water stream processed by the WRS:

$$\dot{m}_{urine} = N_{crew}\dot{m}_{urine,crew}\eta_{urine} \quad (3.28)$$

A fraction of the hygiene wastewater is also recovered through the same regenerative process:

$$\dot{m}_{hygiene} = N_{crew}\dot{m}_{hygiene,crew}\eta_{hygiene} \quad (3.29)$$

The recovery efficiencies η_{vapor} , η_{urine} , and $\eta_{hygiene}$ represent equivalent performance parameters of the complete recovery chain, including collection, processing, and purification losses. The adopted values are assumed based on typical regenerative life support system performances and represent a simplified estimation of the achievable recovery capability of a rover-scale WRS.

The model allows different water management architectures to be evaluated by modifying these efficiency parameters. In the regenerative configuration, the recovery processes are active and reduce the net water consumption. Conversely, the non-regenerative configuration is obtained by disabling the recovery contribution, representing a system relying only on initially stored water.

The evolution of the water inventory is therefore used as an indicator of system sustainability, allowing the evaluation of recovery benefits, resource depletion trends, and critical water availability conditions during the mission.

3.3.5 Emergency Scenarios and Failure Logic

In addition to the nominal operational condition, the model includes simplified emergency scenarios to evaluate the robustness of the resource management strategy under degraded conditions. These scenarios are introduced through a modification of the main system parameters and allow the assessment of the impact of failures or operational constraints on mission sustainability.

Two emergency conditions are considered:

- a WRS failure;
- a shelter mode scenario.

In the WRS failure case, the regenerative water loop is partially or completely degraded by reducing the recovery efficiencies associated with humidity condensation, urine processing, and hygiene wastewater recovery. As a consequence, the available water inventory decreases faster due to the loss of the regenerative contribution. At the same time, reduced water consumption rates are introduced to represent crew conservation procedures adopted during contingency operations.

The shelter mode represents a contingency condition in which additional crew members temporarily occupy the rover. In this scenario, the crew size is increased to the emergency value, while food, water consumption, carbon dioxide generation, and waste production rates are modified according to reduced operational conditions. This allows the evaluation of the impact of increased occupancy and resource constraints on the available consumables.

The activation of emergency conditions is implemented through a time-dependent event logic. Before the defined emergency time, the system operates according to the nominal configuration. Once the event occurs, the corresponding parameter modifications are applied and maintained for the remainder of the simulation.

The model also includes a failure detection logic to identify the exhaustion of critical resources and determine the corresponding mission outcome. Oxygen and carbon dioxide removal capabilities are considered immediate failure conditions since their depletion directly prevents continued crew survival. Conversely, water and food depletion are associated with a predefined survival allowance, representing the possibility of short-term operation through stored reserves, reduced consumption, or emergency procedures.

The failure time and failure cause are recorded during the simulation, providing an additional indicator for the evaluation of mission feasibility under different resource management scenarios.

3.3.6 Mass Estimation

The total mass contribution of the system is evaluated by combining the onboard consumables with the estimated hardware mass required by the life support architecture. The consumable mass is obtained from the final inventory of each stored resource:

$$m_{consumables} = m_{O_2} + m_{water} + m_{food} + m_{LiOH} + m_{waste} \quad (3.30)$$

where each term represents the remaining onboard mass of oxygen, water, food, carbon dioxide removal consumables, and accumulated waste, respectively.

The total mass of the system is then calculated as:

$$m_{tot} = m_{consumables} + m_{hardware} \quad (3.31)$$

where $m_{hardware}$ represents the fixed contribution associated with the physical components of the architecture, including storage tanks, processing units, and supporting equipment.

During the simulation, the evolution of the consumable inventory is tracked over time, allowing the evaluation of both initial and final system mass. The resulting mass variation is defined as:

$$\Delta m_{tot} = m_{tot,initial} - m_{tot,final} \quad (3.32)$$

This parameter provides an indication of the mass reduction achieved during the mission due to resource consumption and recovery processes.

The proposed formulation enables the comparison of different system architectures, such as regenerative and non-regenerative configurations, by evaluating their impact on initial mass requirements, resource depletion, and overall mission sustainability.

Chapter 4

Results and System Performance

This chapter presents the results obtained from the analyzes performed on the pressurized lunar rover models developed in this work. The objective is to evaluate the system behavior under representative lunar environmental conditions and to assess the performance of the main subsystems considered in the analysis.

The chapter is organized according to the models described in the previous methodology section. First, the results of the Thermal Control System (TCS) are presented, starting from the MLI thermal model to evaluate the insulation performance and its influence on the effective emissivity. Subsequently, the results of the transient thermal model are discussed, focusing on the evolution of the cabin temperature and the contributions of the different heat fluxes involved in the energy balance. The results obtained for the Environmental Control and Life Support System (ECLSS) are then presented, with particular focus on the evolution of consumable resources, the influence of regenerative technologies, and the subsystem performance under nominal and emergency operational scenarios.

The presented results allow the identification of the dominant physical phenomena affecting the rover behavior and provide a comprehensive evaluation of the subsystem performance. The sensitivity analyses and design trade-offs associated with the main system parameters are discussed separately in the following chapter.

4.1 Thermal Control System (TCS) Results

4.1.1 Multilayer Insulation (MLI) Model

The MLI system represents the primary passive thermal protection element of the rover and plays a fundamental role in limiting radiative heat exchange between the cabin and the external lunar environment. Within the Thermal Control System (TCS), the MLI is modeled through an equivalent effective emissivity formulation derived from empirical correlations reported in Gilmore's spacecraft thermal design literature.

The performance of the MLI system is evaluated through a parametric analysis considering two main design variables: the number of insulation layers N and the penetration level, which represents the quality of the blanket assembly and accounts for thermal degradation effects due to seams and structural discontinuities.

The variation of the effective emissivity ϵ_{eff} with the number of MLI layers and the penetration level is shown in Figure 4.1.

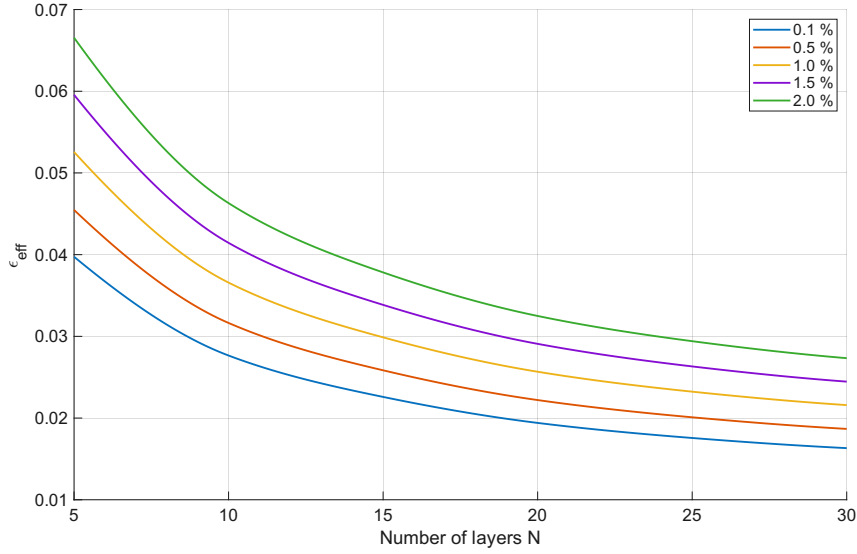


Figure 4.1: Effective emissivity ϵ_{eff} of the MLI system for different layer numbers N and penetration levels p

As expected, the effective emissivity decreases with increasing number of layers, indicating an improvement in the insulation performance. The results also highlight a clear sensitivity to the penetration level, which shifts the curves upward as penetration increases, reflecting a progressive degradation of the thermal insulation capability.

The corresponding heat flux exchanged through the MLI system is reported in Figure 4.2.

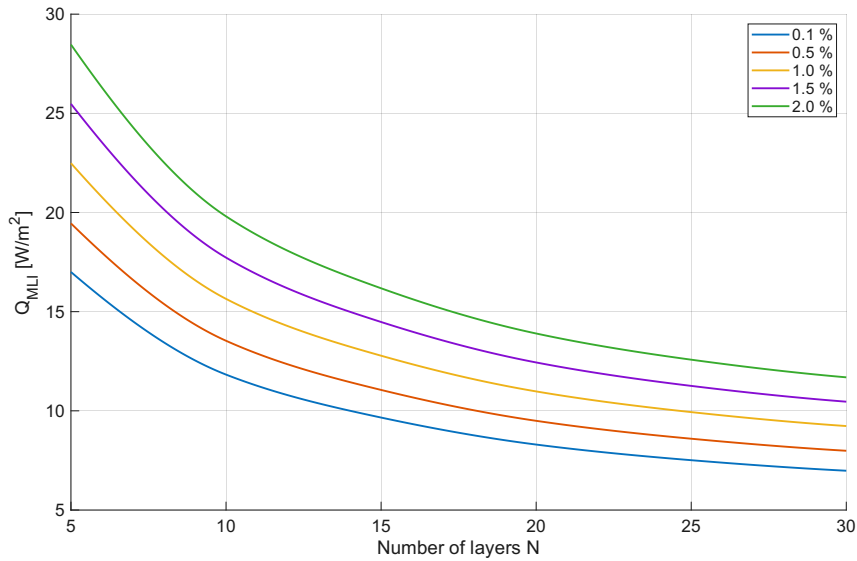


Figure 4.2: Heat flux through the MLI system Q_{MLI} for different layer numbers N and penetration levels p

The heat flux decreases significantly with increasing number of layers, confirming the expected reduction in radiative heat transfer. However, higher penetration levels lead to increased heat leakage, particularly evident in configurations with a large number of layers, where the potential benefit of additional insulation is partially offset by degradation effects.

The resulting specific thermal resistance of the MLI system is shown in Figure 4.3.

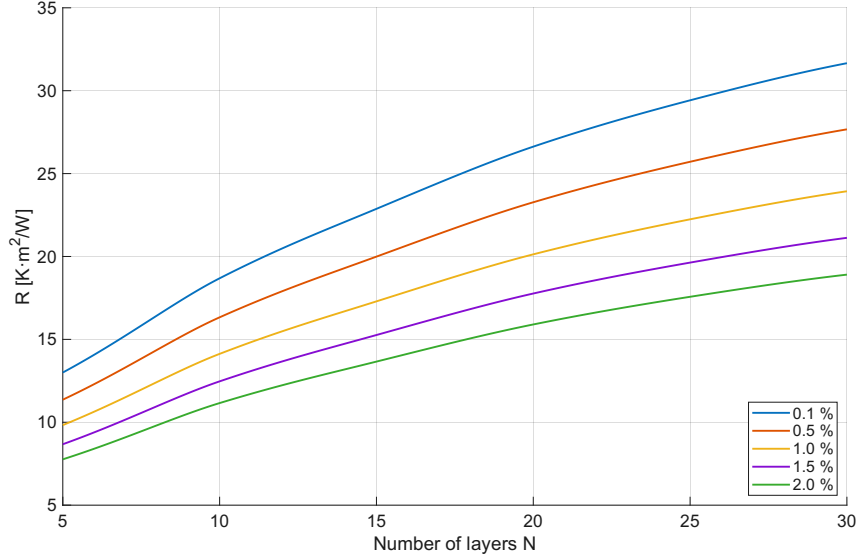


Figure 4.3: Specific thermal resistance R of the MLI system for different layer numbers N and penetration levels p

The thermal resistance increases with the number of layers, consistently with the expected behavior of multilayer insulation systems. Nevertheless, the penetration level limits the maximum achievable performance, introducing a saturation effect for degraded configurations where additional layers provide diminishing returns. Overall, the results demonstrate that the number of layers primarily governs the baseline thermal insulation capability of the MLI system, while the penetration level acts as a degradation parameter that significantly influences the effective performance. This distinction is crucial for the subsequent system-level thermal analysis of the rover.

4.1.2 Thermal Energy Balance Model

The thermal behavior of the rover is evaluated by progressively introducing the different Thermal Control System (TCS) elements in order to highlight their individual and combined effects on the cabin thermal balance. The analysis begins with the uninsulated configuration, which represents the baseline case and provides a reference for evaluating the contribution of the subsequent thermal control strategies. The following configurations are considered:

- Configuration 1: No MLI;
- Configuration 2: Passive thermal control with MLI;

- Configuration 3: MLI with active heating;
- Configuration 4: Complete TCS including MLI, heaters, and radiators.

Configuration 1: No MLI

The first case considers the thermal response of the rover without MLI during both lunar night and daytime conditions. In this configuration, the entire external surface is assumed to be uninsulated, resulting in direct radiative coupling between the cabin and the surrounding lunar environment.

During the lunar night, the thermal behavior is dominated by radiative heat losses toward deep space, which act over the full external surface area.

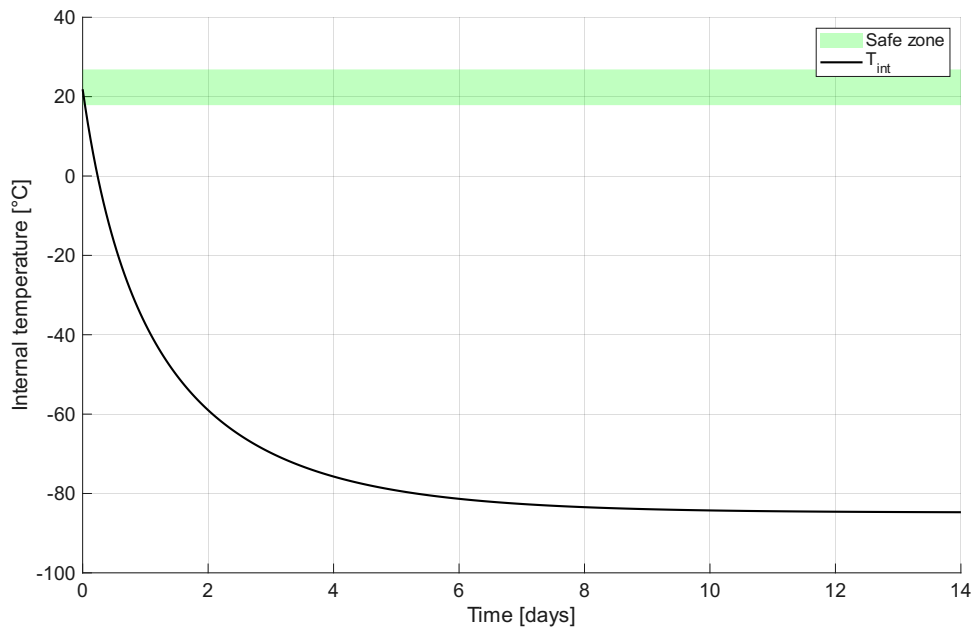


Figure 4.4: Cabin temperature evolution without MLI during the lunar night

As a consequence, the cabin temperature rapidly decreases, reaching values below -80°C . This behavior highlights the inability of the uninsulated structure to retain thermal energy under deep-space radiative conditions.

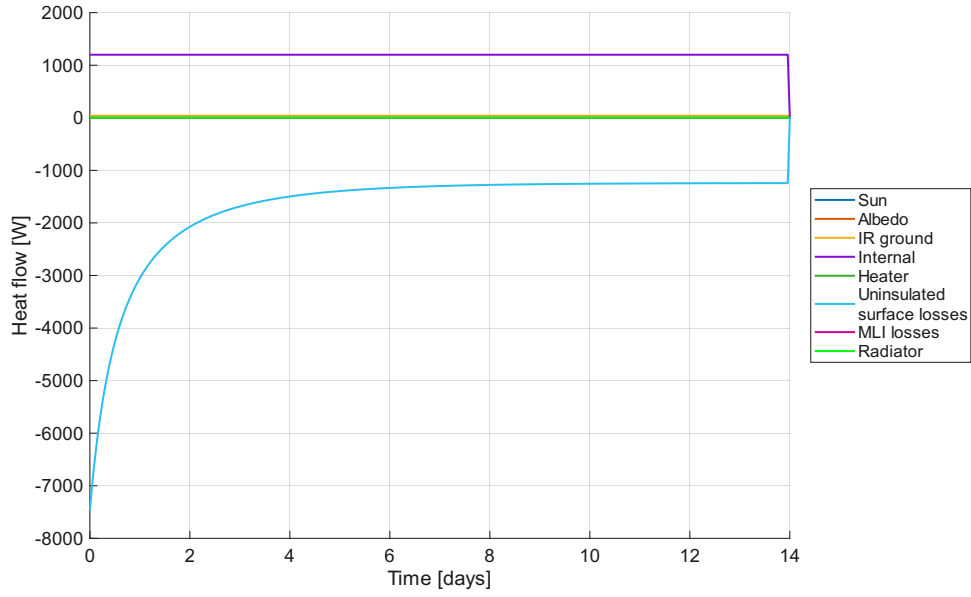


Figure 4.5: Heat balance components without MLI during the lunar night

The corresponding heat balance indicates that the dominant contribution is the radiative loss from the uninsulated surface, which represents the entire external area in this configuration. Internal heat dissipation is insufficient to compensate for these losses, while the absence of solar radiation and albedo during the lunar night results in negligible environmental heat inputs. Consequently, the energy balance is strongly dominated by radiative cooling.

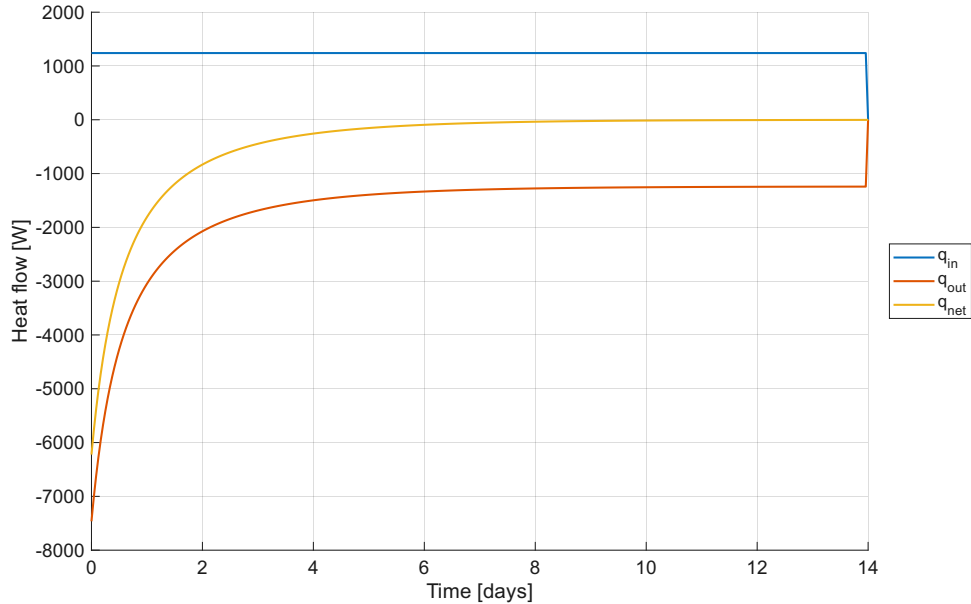


Figure 4.6: Net heat flow without MLI during the lunar night

The resulting net heat flow remains negative throughout the entire night period, producing a continuous depletion of the cabin thermal energy. During the lunar day, the absence of insulation exposes the internal volume to

significant external heat loads, primarily due to direct solar radiation and infrared emission from the lunar surface.

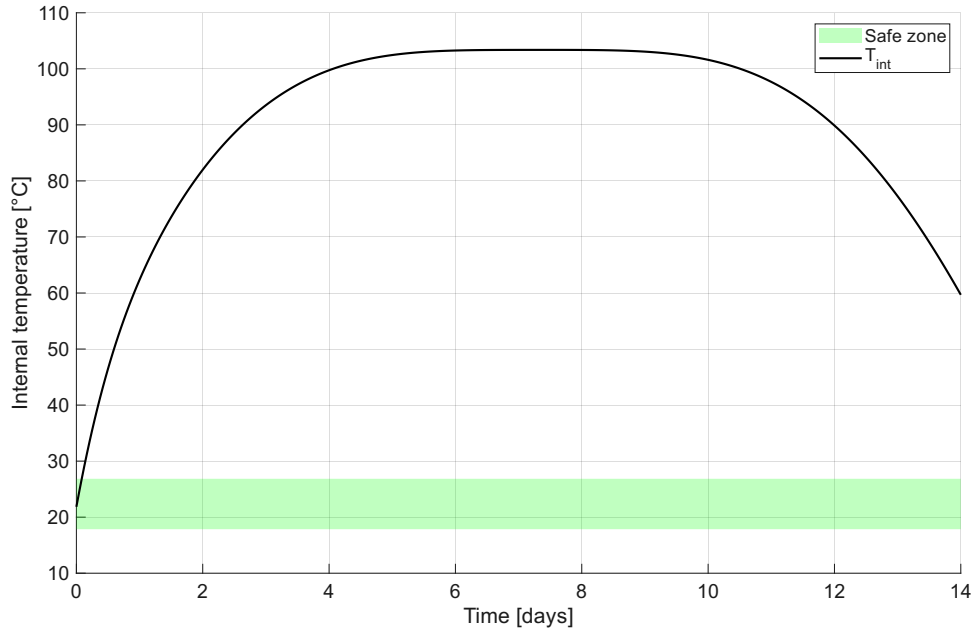


Figure 4.7: Cabin temperature evolution without MLI during the lunar daytime

As a result, the cabin temperature rapidly increases, exceeding 100°C during the illuminated phase. This overheating is driven by the direct absorption of solar and environmental infrared heat fluxes, which are not mitigated by any insulation layer.

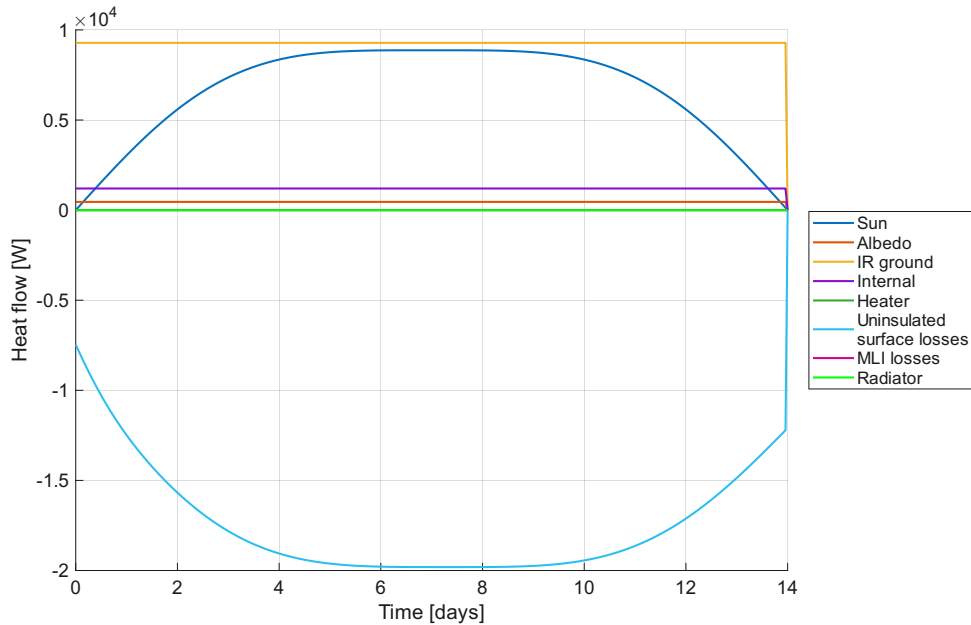


Figure 4.8: Heat balance components without MLI during the lunar daytime

The corresponding heat balance indicates that, although radiative losses from the uninsulated surface remain significant, they are insufficient to counterbalance

the incoming solar radiation and infrared emission from the lunar surface. These external heat loads therefore dominate the energy balance, producing a continuous heat gain by the cabin.

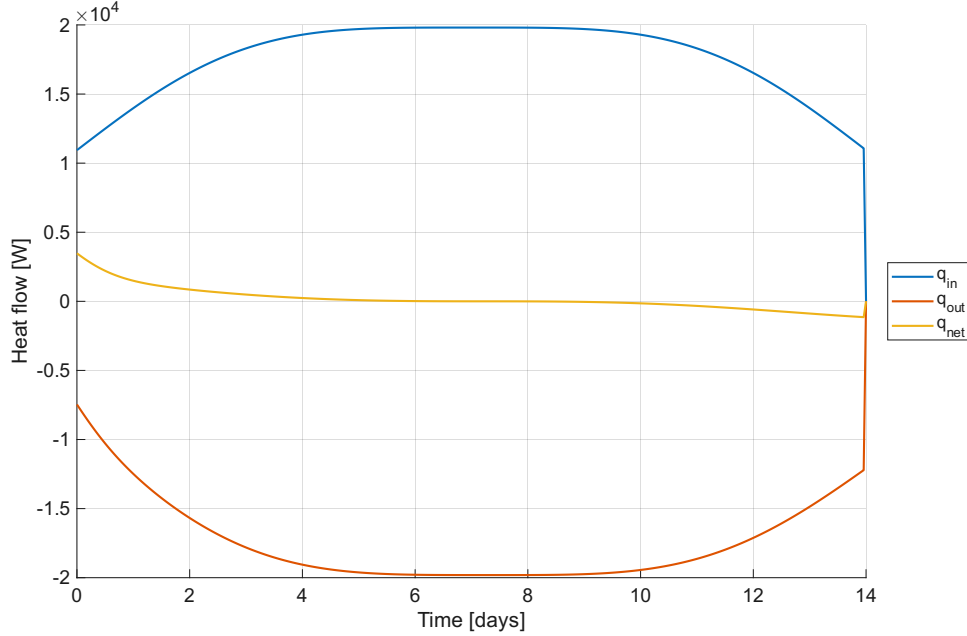


Figure 4.9: Net heat flow without MLI during the lunar daytime

The resulting net heat flow remains predominantly positive throughout the illuminated phase, leading to continuous thermal energy accumulation within the cabin.

Configuration 2: Passive Thermal Control with MLI

The introduction of the MLI system significantly modifies the thermal behavior of the rover during the lunar night by reducing the radiative coupling between the cabin and the external deep-space environment. The effect of the insulation system is evaluated by varying the number of MLI layers, in order to identify the influence of the insulation level on the cabin thermal response.

The temperature evolution obtained for different numbers of MLI layers is shown in Figure 4.10.

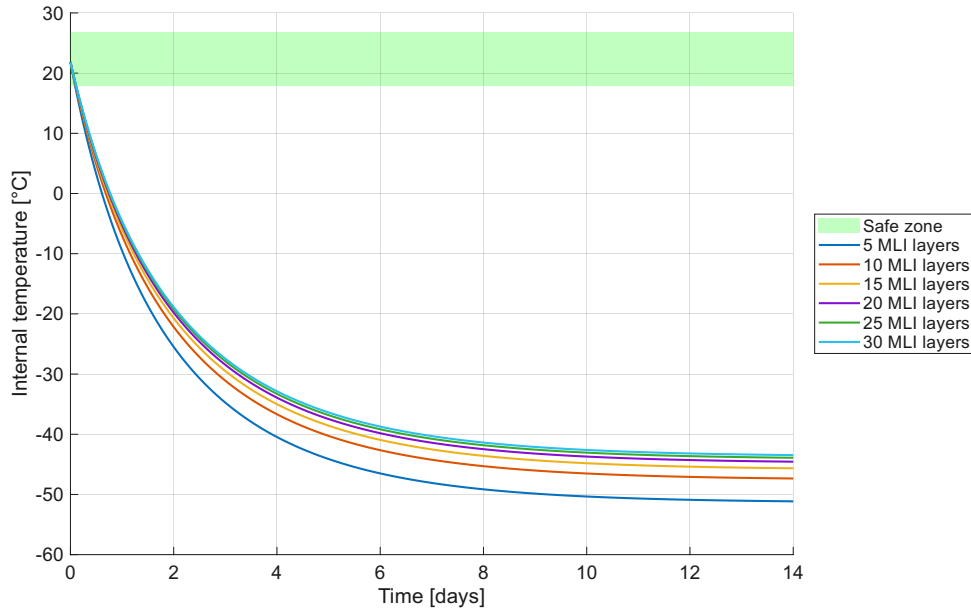


Figure 4.10: Cabin temperature evolution during the lunar night for different numbers of MLI layers

The results show that increasing the number of MLI layers progressively improves the thermal insulation performance by reducing the cabin temperature decrease during the lunar night. The largest improvement is obtained when introducing the first insulation layers, as the temperature difference between the configurations decreases significantly. For example, increasing the number of layers from 5 to 30 allows the minimum cabin temperature to improve from values below -50°C to values below -40°C . However, the improvement becomes progressively smaller as the number of layers increases, with limited temperature variations observed between 20 and 30 layers. This behavior highlights the diminishing returns associated with increasing the insulation thickness, where additional layers provide only marginal improvements in thermal performance.

The heat balance analysis is performed considering the nominal MLI configuration with 20 layers, which is selected as representative of the rover design case.

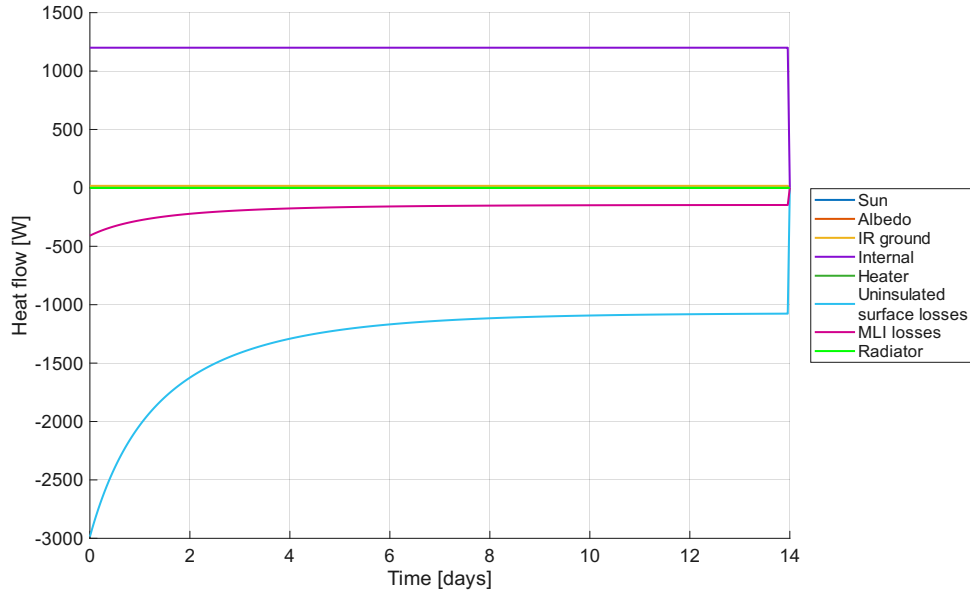


Figure 4.11: Heat balance components with 20 MLI layers during the lunar night

The heat flux breakdown confirms the physical mechanism responsible for the improved thermal performance. The presence of the MLI reduces the radiative heat losses from the external surface by introducing an effective thermal resistance between the cabin and the surrounding environment. As a result, the heat rejection toward deep space is significantly reduced compared with the uninsulated configuration.

Although the internal heat generation remains unchanged, its contribution becomes increasingly relevant due to the lower radiative losses. This reduced heat exchange with the external environment allows the cabin to maintain a higher equilibrium temperature during the lunar night.

Configuration 3: Active Thermal Control with MLI and Heater

The addition of the heater introduces an active thermal control strategy aimed at maintaining the cabin temperature within the prescribed operational limits during the lunar night. Unlike the passive MLI configuration, the system now includes an active heat input controlled by a feedback logic, which compensates for the residual thermal losses when the internal temperature decreases below the minimum allowable threshold.

The effect of the active thermal control system is evaluated by considering different numbers of MLI layers in order to assess the combined influence of passive insulation and active heating on the cabin thermal response.

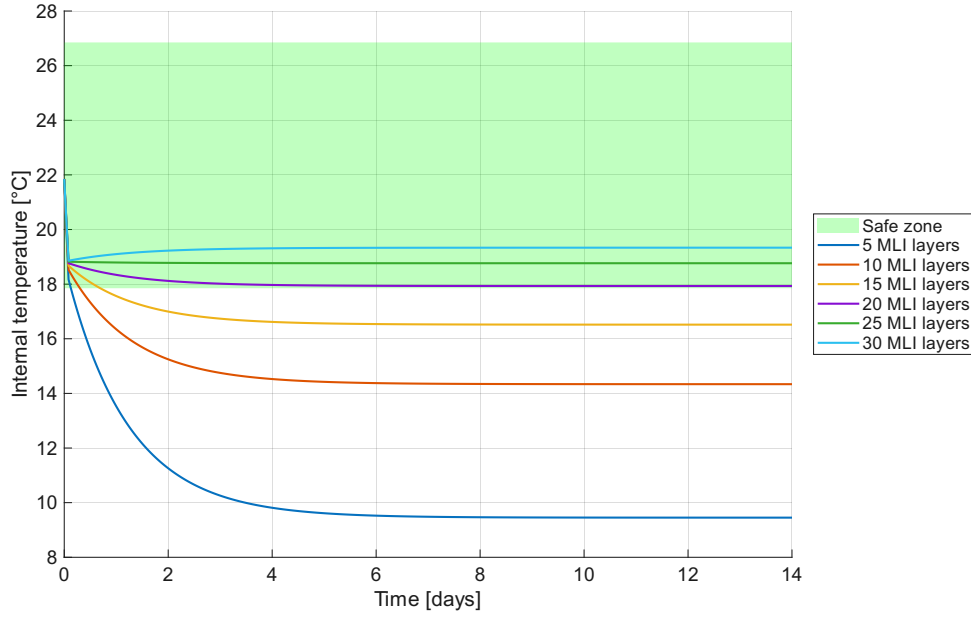


Figure 4.12: Cabin temperature evolution with heater during the lunar night for different numbers of MLI layers

The temperature evolution shows that the combined use of MLI and active heating significantly improves the thermal stability of the cabin compared with the passive insulation configuration. Increasing the number of MLI layers reduces the thermal losses and progressively increases the minimum cabin temperature reached during the lunar night. The considered configurations show an improvement from values around -10°C for lower insulation levels to temperatures approaching 20°C for higher numbers of layers. However, the benefit of additional insulation becomes progressively smaller as the number of layers increases. In particular, approximately 20 MLI layers are sufficient to maintain the cabin temperature within the defined safe operational range, while further increases provide only limited additional improvement.

The heat balance analysis is performed considering the nominal configuration with 20 MLI layers, which represents the selected design case for the integrated thermal control system.

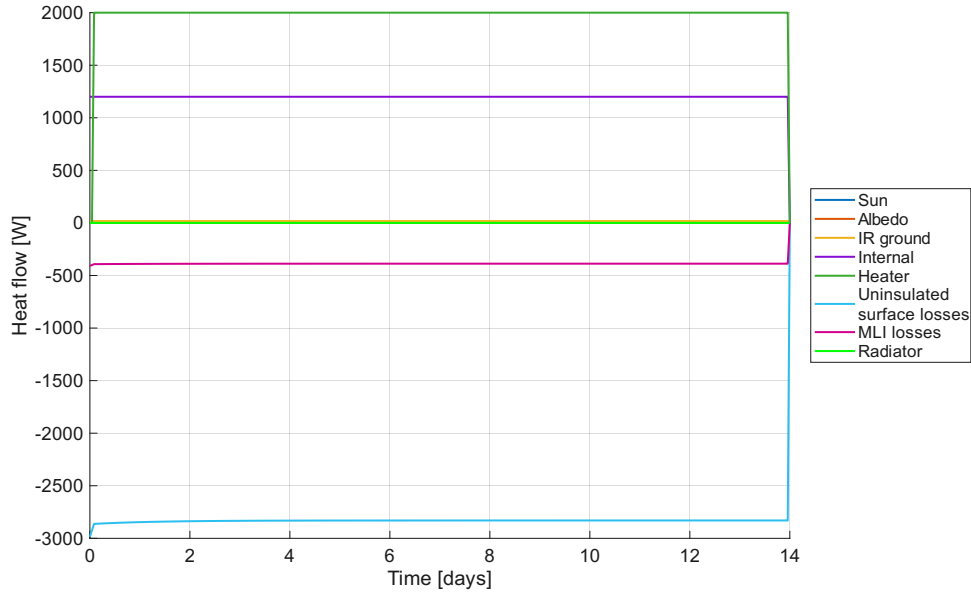


Figure 4.13: Heat balance components with heater and 20 MLI layers during the lunar night

The heat flux breakdown highlights the dynamic interaction between passive insulation and active thermal control. The heater contribution exhibits a discontinuous profile due to the on/off nature of the control logic, resulting in periodic variations in the thermal balance as the system alternates between heat injection phases and passive cooling periods. Despite these fluctuations, the overall energy balance remains controlled, allowing the cabin temperature to be maintained within acceptable operational limits.

The results demonstrate that the combined action of MLI and active heating provides the required thermal stability during the lunar night. The passive insulation reduces the heat rejection toward deep space, while the heater compensates for the remaining losses and ensures the maintenance of the target temperature range.

Configuration 4: Active Thermal Control with MLI and Radiators

The introduction of radiators in the daytime configuration provides an active mechanism for rejecting the excess thermal energy accumulated within the rover. Combined with the thermal protection provided by the MLI system, the radiator system represents the main active element responsible for controlling the cabin temperature during the lunar day.

The effect of the radiator system is evaluated by considering different numbers of MLI layers in order to assess the combined influence of passive insulation and active heat rejection on the cabin thermal response.

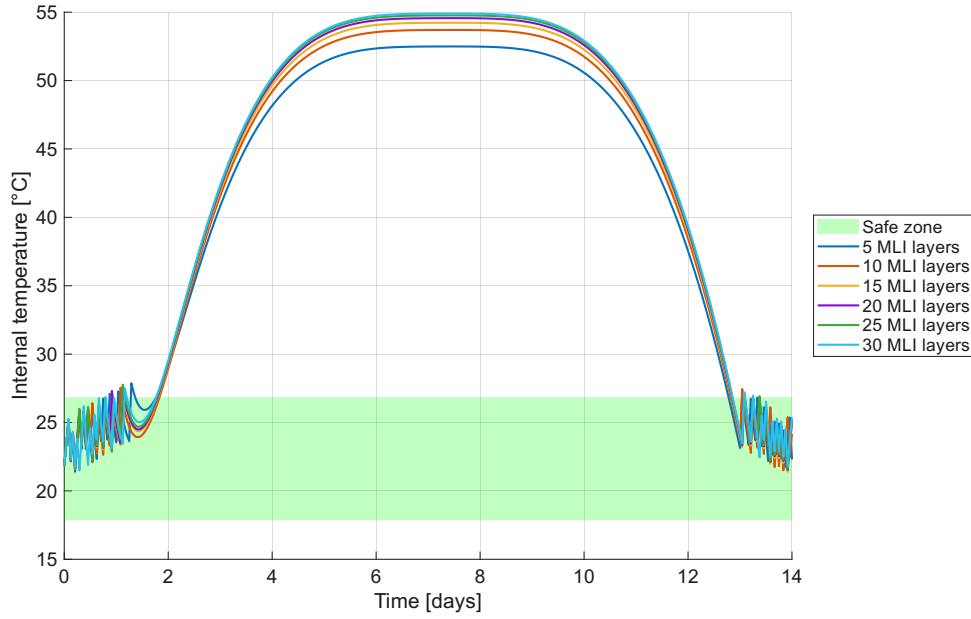


Figure 4.14: Cabin temperature evolution with radiators during the lunar daytime for different numbers of MLI layers

The temperature evolution shows that the influence of the number of MLI layers on the daytime thermal response is limited. The considered configurations result in maximum cabin temperatures ranging approximately between 52°C and 55°C, indicating that additional insulation provides only a marginal improvement under illuminated conditions. This behavior is mainly related to the dominant contribution of external heat loads, particularly solar radiation and lunar infrared emission, which are not significantly reduced by increasing the insulation level.

The figure also highlights the dynamic behavior of the radiator control system. During the initial and final portions of the lunar day, when the solar contribution is lower, the radiator is able to compensate for the incoming thermal loads and maintain the cabin temperature within the safe operational range. In these phases, the on/off control logic produces repeated activation and deactivation cycles, resulting in visible temperature oscillations. Conversely, during the central portion of the lunar day, the external thermal loads increase significantly and the radiator remains continuously active. Under these conditions, the heat rejection capability is insufficient to compensate for the absorbed energy, leading to a progressive temperature increase above the safe operational limits.

The heat balance analysis is performed considering the nominal configuration with 20 MLI layers, which represents the selected design case for the integrated thermal control system.

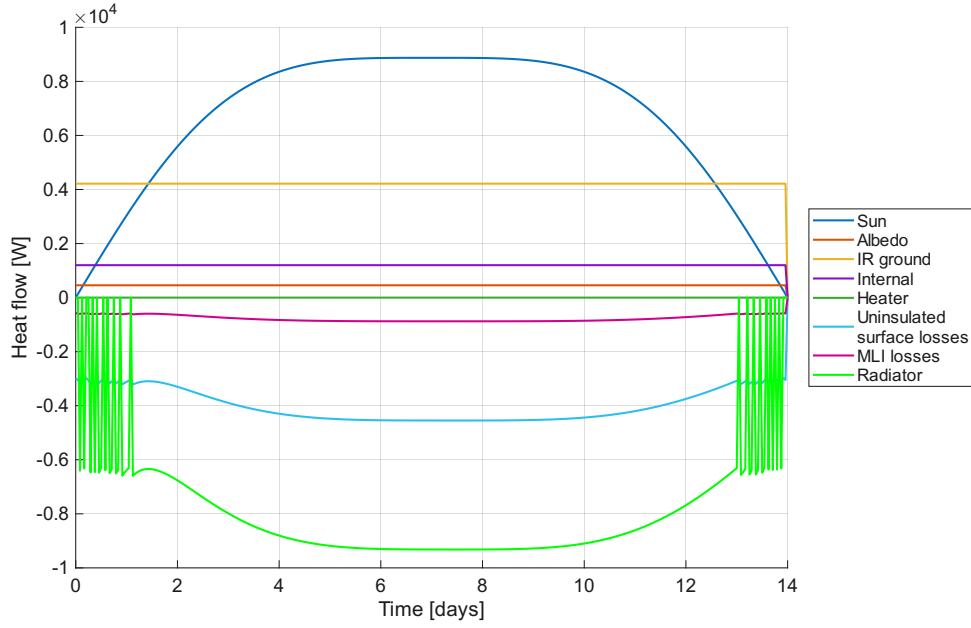


Figure 4.15: Heat balance components with radiators and 20 MLI layers during the lunar daytime

The heat flux breakdown provides further insight into the radiator control behavior. During the beginning and the end of the lunar day, the radiator contribution presents a discontinuous profile due to the on/off control logic. The active heat rejection alternates between zero and maximum values as the system switches between cooling and non-cooling periods to regulate the cabin temperature. These oscillations directly correspond to the temperature fluctuations observed in the previous figure.

During the central portion of the lunar day, the radiator heat rejection remains continuously active because of the increased external thermal loads. However, even with the maximum available rejection capability, the incoming solar and infrared heat fluxes remain dominant, preventing the system from reaching thermal equilibrium. The MLI contribution remains comparatively stable, confirming that insulation plays a secondary role during the illuminated phase with respect to active heat rejection.

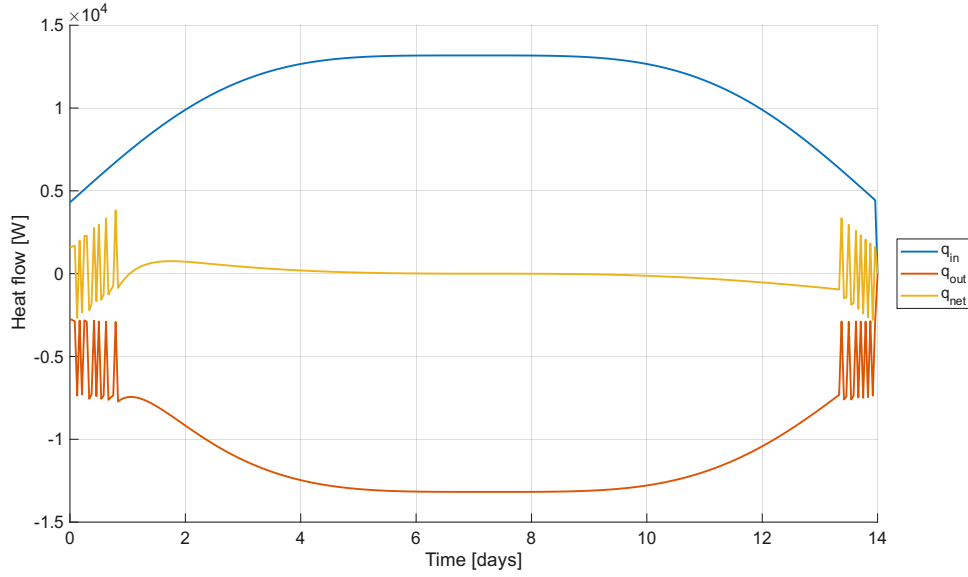


Figure 4.16: Net heat flow evolution with radiators and 20 MLI layers during the lunar daytime

The net heat flow evolution confirms the previous observations. During the initial and final portions of the lunar day, the alternating radiator operation produces fluctuations in the net heat balance as the system repeatedly compensates for the external heat inputs. In the central portion of the illuminated phase, the radiator remains continuously active, but the incoming thermal power exceeds the rejection capability, resulting in a persistent positive net heat flow and a continuous increase in cabin temperature.

Overall, the results demonstrate that the radiator model correctly reproduces the expected dynamic behavior of an active thermal control system. The analysis highlights the importance of radiator sizing and control strategy optimization, showing that the selected configuration can regulate the cabin temperature under moderate daytime conditions but requires further improvements to withstand the maximum lunar daytime thermal loads.

4.2 Environmental Control and Life Support System (ECLSS) Results

The Environmental Control and Life Support System (ECLSS) performance is evaluated by analyzing the evolution of consumable resources, the water management strategy, and the overall subsystem mass under different operational conditions. The analysis is organized according to four different scenarios, which allow the evaluation of the nominal system behavior, the benefits of regenerative technologies, and the response of the subsystem under degraded operating conditions.

The considered scenarios are:

- **Nominal regenerative architecture:** reference configuration with active water recovery processes and no emergency constraints.

- **Non-regenerative architecture:** configuration without water recovery capability, used to evaluate the impact of regenerative technologies on resource consumption and overall ECLSS mass.
- **WRS failure scenario:** emergency condition in which the Water Recovery System fails during the mission, resulting in the loss of the regenerative water management capability.
- **Shelter mode scenario:** emergency operating condition characterized by reduced crew resource consumption to extend the mission survivability after a critical event.

The results are presented by first analyzing the nominal regenerative architecture, which represents the baseline configuration for the rover mission. Subsequently, the effect of removing the water recovery capability is investigated, followed by the evaluation of the two emergency scenarios.

4.2.1 Nominal Regenerative Architecture

The nominal configuration assumes a regenerative ECLSS architecture operating under standard mission conditions, with active recovery processes for the water management subsystem and no emergency constraints. The consumable tanks are sized according to the mission duration, with the objective of minimizing the residual resources at the end of the mission while ensuring continuous operation throughout the complete mission profile.

Consumables Mass Evolution

The evolution of the main consumable resources is shown in Figure 4.17.

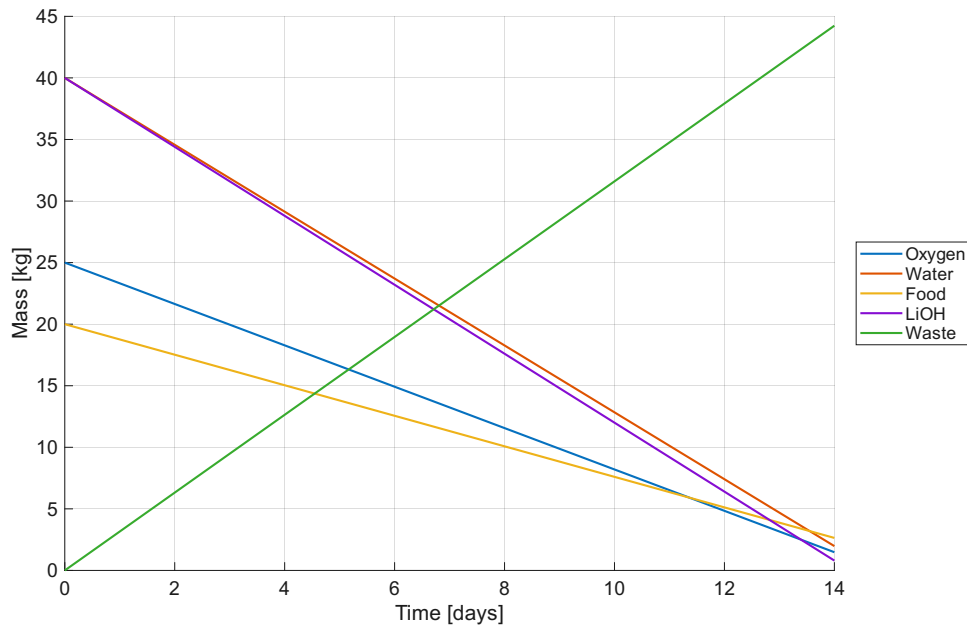


Figure 4.17: Consumables mass evolution for the nominal regenerative ECLSS architecture

The consumable evolution follows the expected behavior for a regenerative life support system. Oxygen, food, and other non-regenerative resources are progressively depleted according to the crew metabolic requirements, while no critical depletion occurs within the considered mission duration. The selected tank capacities are therefore sufficient to guarantee continuous operation until the end of the mission, with only limited residual quantities remaining at completion.

The waste mass shows an increasing trend throughout the mission as a consequence of the accumulation of non-recycled crew-generated products, reaching a final value of approximately 45 kg. This contribution represents a significant fraction of the final consumable mass and must be considered in the overall rover mass budget.

Water Management Performance

The water management subsystem behavior is analyzed by separating the main consumption and recovery contributions, as shown in Figure 4.18.

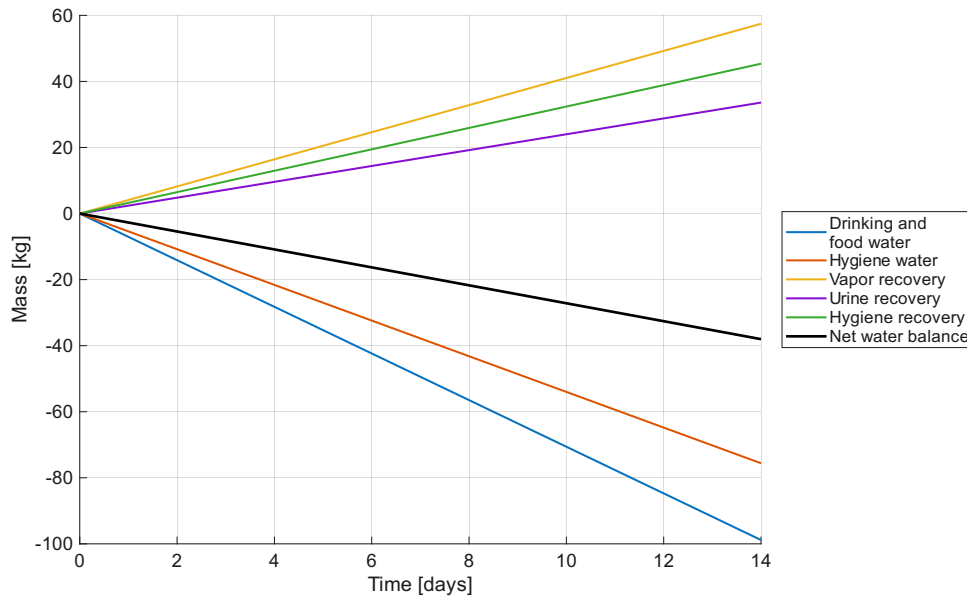


Figure 4.18: Water management breakdown for the nominal regenerative ECLSS architecture

The water balance highlights the interaction between the main crew water demands and the recovery processes implemented in the system. The total water losses are significantly reduced by the recovery of generated wastewater streams, including humidity condensation, urine treatment, and hygiene water recycling.

The resulting net water balance represents the amount of water that must be supplied by the initial storage tanks throughout the mission. For the nominal regenerative architecture, the cumulative net water consumption remains below 40 kg over the entire mission duration, demonstrating the effectiveness of the implemented recovery processes in reducing the required initial water storage.

Total ECLSS Mass Evolution

The resulting evolution of the total ECLSS mass is presented in Figure 4.19.

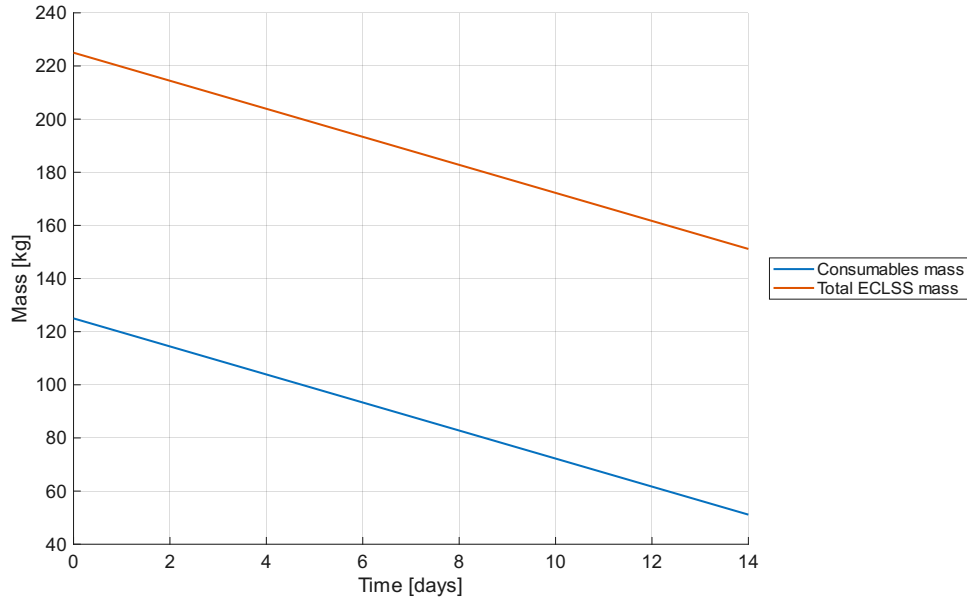


Figure 4.19: Total ECLSS mass evolution for the nominal regenerative architecture

The total ECLSS mass decreases throughout the mission as consumable resources are progressively consumed, while the hardware contribution remains constant. For the nominal regenerative configuration, the initial total ECLSS mass is 225.00 kg, decreasing to a final value of 151.14 kg, corresponding to a total mass variation of 73.86 kg.

The absence of critical resource depletion confirms that the selected consumable sizing is adequate for the considered mission duration. The obtained mass evolution represents the baseline reference for evaluating the benefits of water recovery and the impact of degraded and emergency operating conditions in the following sections.

4.2.2 Effect of Water Recovery System

The impact of the water recovery capability is evaluated by comparing the nominal regenerative architecture with a non-regenerative configuration in which the Water Recovery System (WRS) is removed. In this analysis, the crew metabolic loads and the consumption rates of non-regenerative resources are kept unchanged, allowing the effect of the water recovery technology to be isolated.

Consumables Mass Evolution without Water Recovery

The evolution of the main consumable resources for the non-regenerative configuration is shown in Figure 4.20.

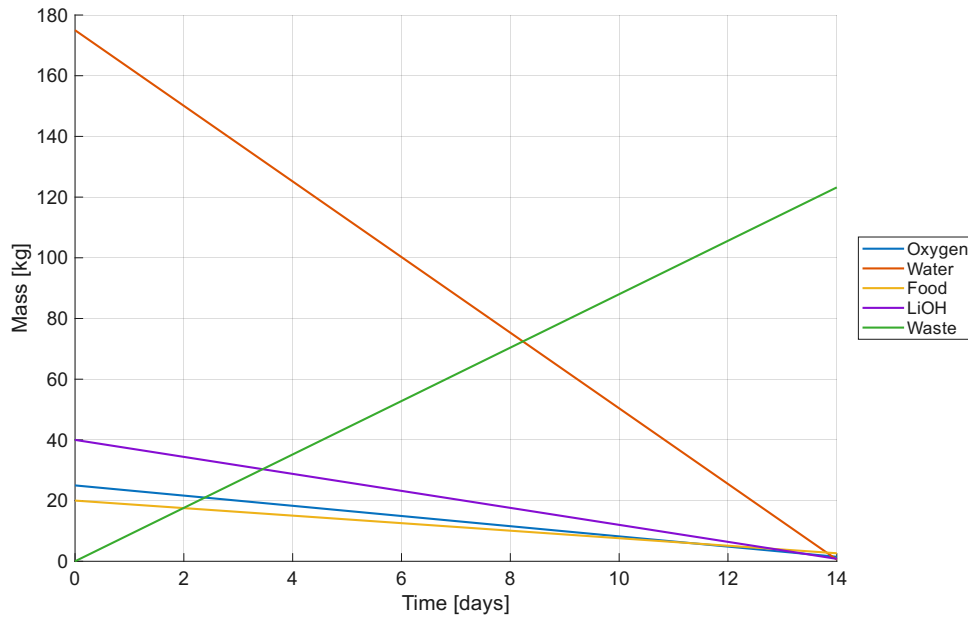


Figure 4.20: Consumables mass evolution for the non-regenerative ECLSS architecture

The removal of the water recovery capability does not affect the evolution of consumables directly related to crew metabolic requirements. Therefore, oxygen, food, LiOH, and waste follow the same trends observed for the nominal regenerative configuration.

The main difference is observed in the water resource, which requires a larger initial storage capacity due to the absence of internal recovery processes. To account for the missing regeneration capability, an additional water storage mass of 135 kg is introduced, while the WRS hardware mass contribution is removed from the system. As a result, the water evolution represents the dominant variation between the two architectures, while the remaining consumables remain unchanged.

Water Management Performance without Recovery

The water management behavior for the non-regenerative architecture is shown in Figure 4.21.

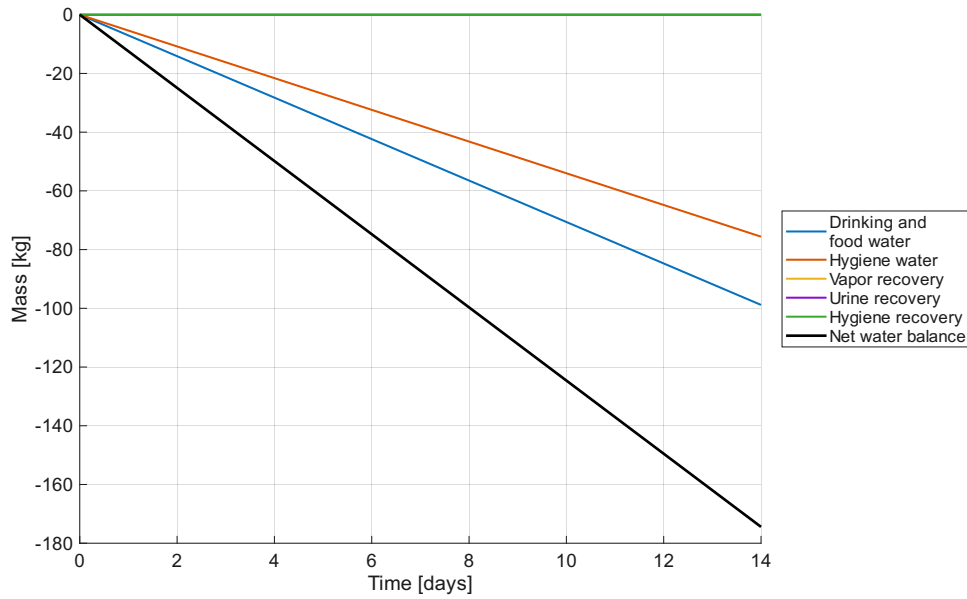


Figure 4.21: Water management breakdown for the non-regenerative ECLSS architecture

Compared with the nominal regenerative configuration, the water management breakdown shows the complete absence of recovery contributions. The condensation recovery, urine recovery, and hygiene water recovery terms are removed, leaving only the water consumption contributions associated with crew activities.

As a consequence, the cumulative net water consumption increases significantly compared with the regenerative case. While the nominal architecture requires less than 40 kg of net water consumption over the mission duration, the non-regenerative configuration requires almost 180 kg of stored water to compensate for the absence of recovery processes. This result highlights the dominant role of water recycling in reducing the consumable mass of long-duration surface missions.

Total ECLSS Mass Comparison

The resulting total ECLSS mass evolution is presented in Figure 4.22.

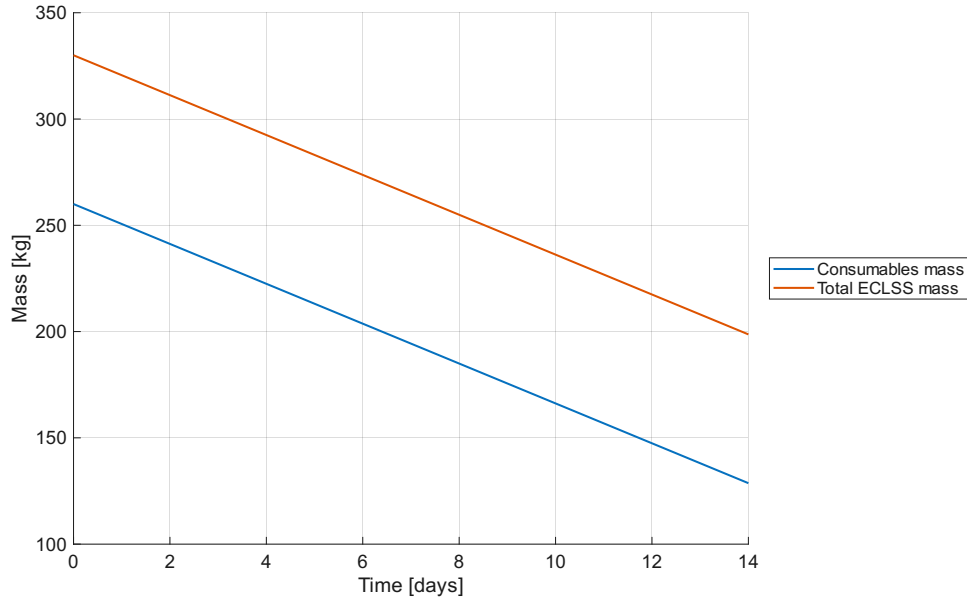


Figure 4.22: Total ECLSS mass comparison between regenerative and non-regenerative architectures

The comparison between the two architectures highlights the mass advantage provided by the water recovery system. The nominal regenerative configuration has an initial total ECLSS mass of 225.00 kg, while the non-regenerative architecture requires an initial mass of 330.00 kg. The resulting initial difference of 105.00 kg is directly related to the additional stored water required by the non-regenerative configuration (+135 kg), partially compensated by the removal of the WRS hardware contribution (−30 kg). This corresponds to an initial mass reduction of approximately 31.8% with respect to the non-regenerative architecture.

During the mission, both architectures show a similar reduction trend because the metabolic consumption rates of oxygen, food, and waste generation remain unchanged. However, the non-regenerative configuration maintains a higher total mass throughout the mission due to the larger initial water storage requirement.

At the end of the mission, the regenerative architecture reaches a final total ECLSS mass of 151.14 kg, while the non-regenerative case reaches 198.68 kg. The final difference is therefore 47.54 kg, corresponding to a mass reduction of approximately 23.9% with respect to the non-regenerative configuration.

These results demonstrate that the main benefit of the WRS is not a reduction of crew resource consumption, which remains unchanged, but rather the reduction of the initial consumable storage required to support the mission. This advantage becomes increasingly important as mission duration increases, where the mass penalty associated with non-regenerative architectures becomes progressively more significant.

4.2.3 Emergency Scenario: WRS Failure

The WRS failure scenario considers the loss of the water recovery capability during the mission. The failure is introduced at a predefined emergency activation time,

after which all water regeneration processes are disabled. The objective of this scenario is not only to evaluate the reduction of mission duration caused by the loss of the WRS, but also to assess the effectiveness of the implemented emergency management logic.

The emergency sequence is controlled through a set of configurable parameters, including the emergency activation time, the water critical threshold, and the allowed survival time after water depletion. For the considered case, the WRS failure is activated after 7 days, the water critical threshold is set to 5 kg, and the post-depletion survival allowance is set to 1 day.

Consumables Mass Evolution

The evolution of the main consumable resources during the WRS failure scenario is shown in Figure 4.23.

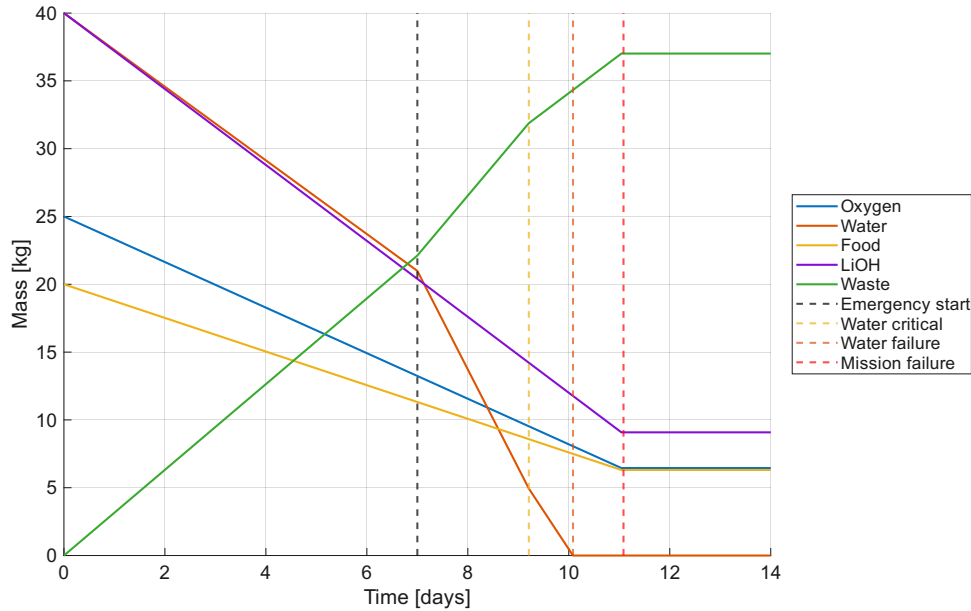


Figure 4.23: Consumables mass evolution during the WRS failure scenario

The consumable evolution highlights the different phases of the emergency scenario through the transition points indicated in the figure. Before the emergency activation, the system operates according to the nominal regenerative configuration. At $t = 7$ days, the WRS failure is introduced and the recovery processes are disabled, causing a faster depletion of the available water resource.

The loss of water regeneration mainly affects the water inventory and the waste generation, while oxygen, food, and LiOH continue to evolve according to the nominal crew consumption rates. The waste contribution is affected by the modified water management strategy, since the reduction of hygiene water availability changes the amount of generated waste streams.

When the available water reaches the critical threshold of 5 kg, the system enters a water conservation mode in which hygiene water consumption is removed and the remaining water is reserved for essential crew needs. This transition modifies the

water consumption trend and extends the available operational time before complete depletion.

Water Management Performance

The water management behavior during the WRS failure scenario is shown in Figure 4.24.

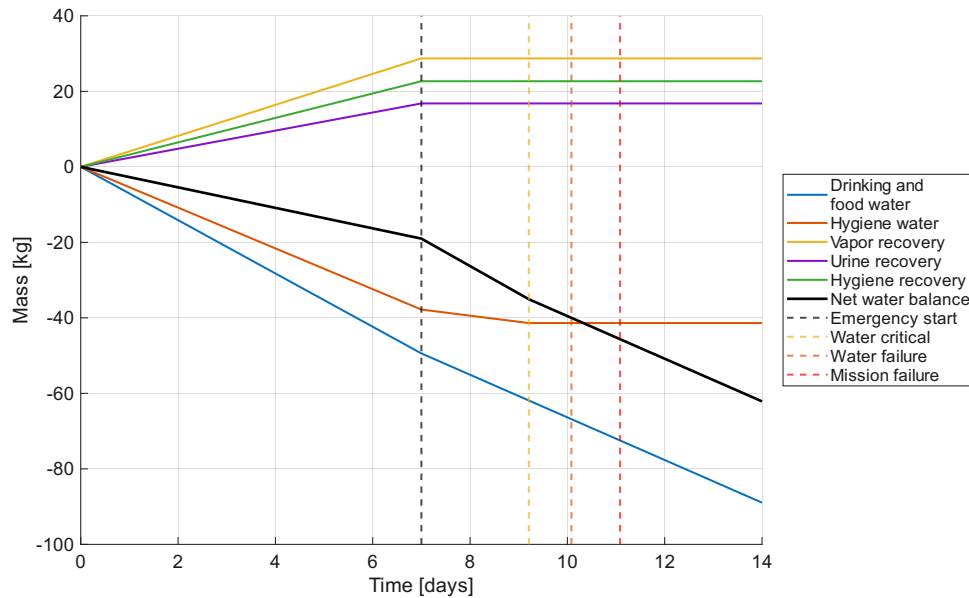


Figure 4.24: Water management breakdown during the WRS failure scenario

The water management breakdown clearly shows the sequence of events triggered by the WRS failure. During the initial mission phase, the water consumption is partially compensated by the recovery processes. After the emergency activation at 7 days, the recovery contributions become unavailable and the water balance is driven only by crew consumption.

The increase in the net water loss leads to the progressive reduction of the stored water inventory. When the water critical threshold is reached slightly after 9 days, the model activates the conservation strategy by eliminating hygiene water consumption and allocating the remaining available water exclusively to essential crew requirements. This change is visible as a modification of the water consumption trend.

The complete depletion of the available water occurs after approximately 10 days, after which the crew is assumed to maintain operations for one additional day according to the implemented survival allowance. The final mission failure condition is therefore reached after approximately 11 days, with water identified as the limiting resource.

Total ECLSS Mass Evolution

The total ECLSS mass evolution during the WRS failure scenario is shown in Figure 4.25.

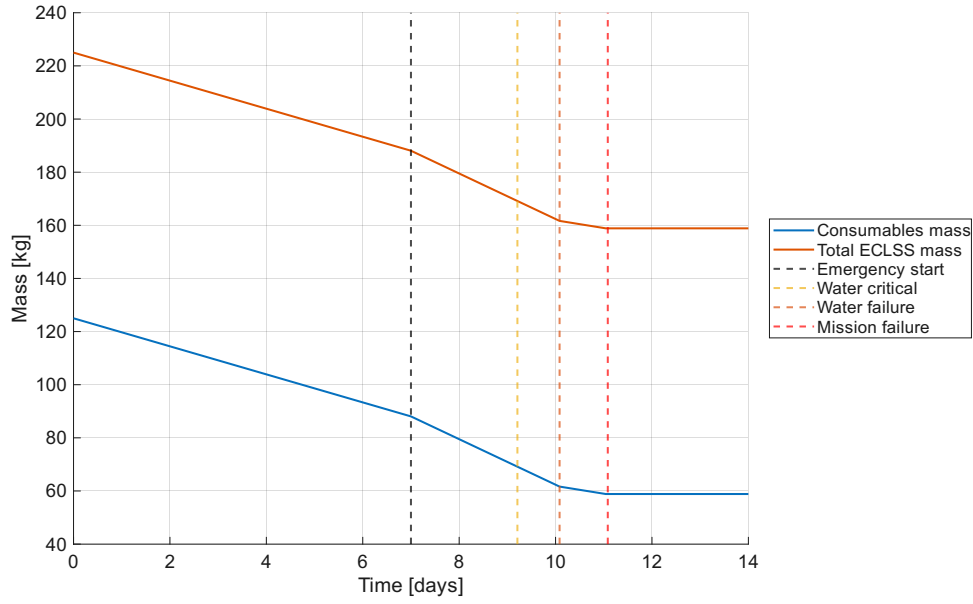


Figure 4.25: Total ECLSS mass evolution during the WRS failure scenario

The total ECLSS mass evolution reflects the different operational phases of the emergency scenario. The initial total mass is 225 kg, composed of approximately 125 kg of consumables and the remaining hardware contribution. Before the WRS failure, the system follows the nominal mass evolution, while after the loss of recovery capability the increased water consumption accelerates the reduction of the consumable inventory.

At the end of the emergency scenario, immediately before mission failure, the total ECLSS mass decreases to slightly below 160 kg, with the consumable contribution reduced to approximately 60 kg. The remaining mass corresponds mainly to the subsystem hardware, which remains unchanged throughout the scenario.

The results demonstrate that the implemented emergency logic correctly reproduces the progressive degradation of the life support system after a critical subsystem failure. The WRS failure does not immediately terminate the mission, but progressively reduces the operational margin through a sequence of controlled responses until water availability becomes the limiting factor.

4.2.4 Emergency Scenario: Shelter Mode

The shelter mode scenario represents an emergency operating condition in which the rover must support an increased crew population while reducing non-essential consumable usage to extend mission survivability. In this configuration, the number of crew members is increased from 2 to 4 after the emergency activation time, while food, drinking water, and hygiene water consumption are reduced according to the predefined emergency rationing strategy.

The objective of this scenario is to evaluate the capability of the ECLSS to adapt to an increased crew demand through emergency resource management and to identify the limiting resource under these degraded operating conditions. For the considered case, the shelter mode is activated after 7 days.

Consumables Mass Evolution

The evolution of the main consumable resources during the shelter mode scenario is shown in Figure 4.26.

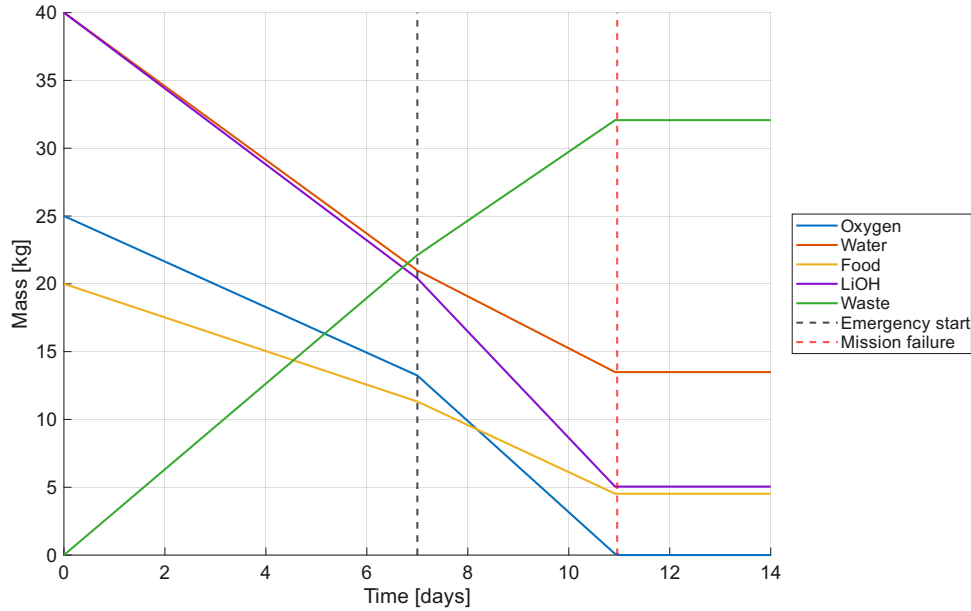


Figure 4.26: Consumables mass evolution during the shelter mode scenario

The consumable evolution highlights the effect of the emergency crew management strategy. At the emergency activation time, the crew population increases from 2 to 4 members, causing an immediate increase in metabolic-related consumables, particularly oxygen demand and carbon dioxide generation.

Unlike oxygen, the food and water resources are managed through emergency rationing, which reduces their consumption rates and prevents their rapid depletion. As a consequence, these resources remain available throughout most of the emergency period, while oxygen becomes the critical consumable governing the mission duration.

The waste evolution is also affected by the increased crew presence and the modified consumption strategy, resulting in a different trend compared with the nominal configuration. However, the waste generation does not represent a limiting factor within the considered mission duration.

Water Management Performance

The water management behavior during the shelter mode scenario is shown in Figure 4.27.

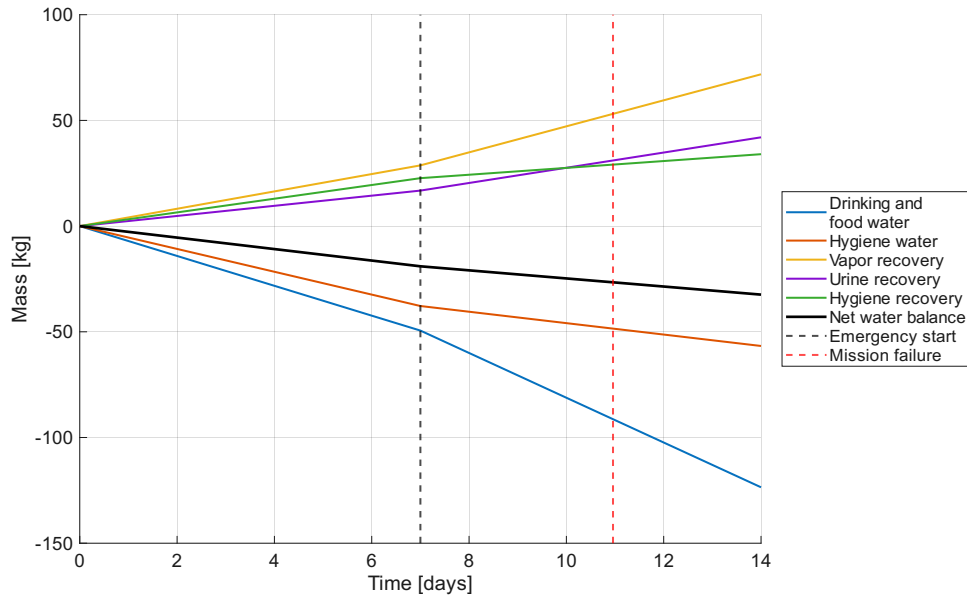


Figure 4.27: Water management breakdown during the shelter mode scenario

The water management behavior shows the effect of the emergency rationing strategy after shelter mode activation. Although the crew population is doubled, the water consumption increase is limited by reducing non-essential water uses, particularly hygiene water demand.

The recovery processes remain active, allowing the water balance to remain controlled during the emergency phase. As a result, water availability is maintained and does not become the limiting resource for mission survival.

This behavior demonstrates the importance of emergency operational modes in redistributing resource usage and preserving critical consumables when the nominal mission conditions can no longer be maintained.

Total ECLSS Mass Evolution

The total ECLSS mass evolution during the shelter mode scenario is shown in Figure 4.28.

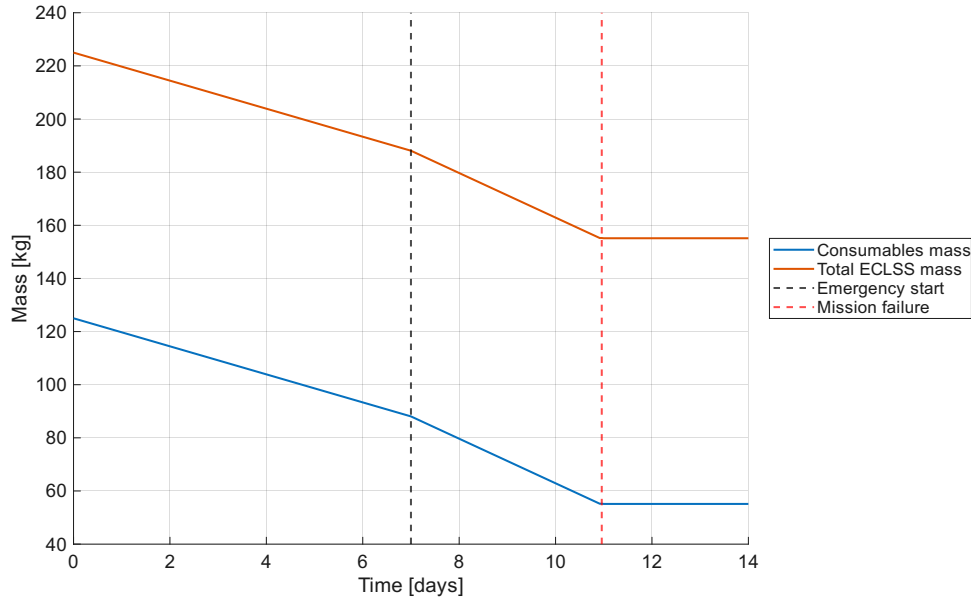


Figure 4.28: Total ECLSS mass evolution during the shelter mode scenario

The total ECLSS mass evolution reflects the combined effect of the increased crew demand and the emergency consumption reduction strategy. The initial total mass is 225 kg, including approximately 125 kg of consumables. Before the emergency activation, the system follows the nominal mission evolution.

After 7 days, the shelter mode is activated and the increased crew population leads to a higher oxygen consumption rate. At the same time, the rationing strategy limits the depletion of food and water resources, reducing the impact of the emergency condition on the overall consumable mass.

The mission failure condition is reached shortly before 11 days due to the complete depletion of the available oxygen resource, which represents an immediate failure condition in the model. At this point, the total ECLSS mass decreases to approximately 155 kg, with the consumable contribution reduced to approximately 55 kg. The results show that the shelter mode effectively extends the operational capability of the rover by preserving water and food resources, but the increased crew metabolic demand makes oxygen availability the dominant constraint. This confirms the importance of considering different emergency management strategies and failure mechanisms when evaluating long-duration exploration missions.

4.3 Summary of Results

This chapter presented the results obtained from the developed TCS and ECLSS models. The analyses demonstrated the capability of the models to reproduce the main physical phenomena governing the rover thermal and life support behavior under representative lunar environmental conditions.

The TCS analysis highlighted the fundamental role of passive and active thermal control strategies in limiting temperature excursions throughout the lunar day-night cycle. The MLI system proved effective in reducing radiative heat losses during the lunar night, while heaters and radiators provided additional control capability under

extreme thermal conditions.

The ECLSS analysis demonstrated the importance of regenerative technologies for reducing consumable mass and extending mission duration. The water recovery capability provided a significant mass advantage, while the emergency scenarios highlighted the critical resources and the capability of the system to adapt to degraded operational conditions.

The results obtained in this chapter establish the reference performance of the rover subsystems and provide the basis for the sensitivity analyzes and system-level trade-offs presented in the following chapter.

Chapter 5

Sensitivity Analysis and System Trade-Offs

The objective of this chapter is to investigate the influence of the main design parameters on the performance of the rover subsystems and to identify the most critical variables affecting the overall system behavior. Following the baseline configuration assessment presented in Chapter 4, a sensitivity analysis is performed to evaluate the impact of the main design choices on the TCS and ECLSS performance.

The sensitivity analysis is carried out by independently varying selected parameters within representative ranges while maintaining all the other model inputs equal to the baseline configuration. This one-parameter-at-a-time approach allows the identification of the variables producing the largest variations in the system response and provides a quantitative evaluation of the influence of the main design assumptions. For the TCS, the analysis focuses on the parameters affecting the thermal balance of the pressurized rover throughout the lunar day-night cycle. The investigated variables include the external surface optical properties, radiator sizing, heater capability, internal heat generation, thermal inertia, environmental radiative exchange, and MLI characteristics. Their influence is assessed in terms of cabin temperature evolution, minimum and maximum operating temperatures, and required active thermal control.

The selected parameters affect different aspects of the thermal behavior. Radiator area and surface absorptivity mainly influence the heat rejection capability during illuminated periods, while insulation effectiveness and heater power become critical during the lunar night. Internal heat generation represents one of the main contributors to the thermal balance, whereas thermal capacitance affects the transient response and the temperature variation rate. Finally, the MLI parameters modify the effective emissivity of the insulation system, directly affecting the radiative heat losses through the rover external surfaces.

For the ECLSS, the sensitivity analysis evaluates the impact of mission-level and system-level parameters on consumables mass evolution and mission sustainability. The main investigated variables include crew size, mission duration, water recovery efficiency, and different operational scenarios. The analysis aims at quantifying the benefits of regenerative technologies and identifying the conditions under which the additional system complexity is justified by the reduction of consumables and the

increase in mission autonomy.

The results of the sensitivity analyzes are then used to perform a trade-off evaluation between alternative subsystem configurations. This analysis provides insights into the main design drivers and highlights the most effective strategies to improve rover performance while maintaining an acceptable balance between mass, complexity, and operational capability.

5.1 Thermal Control System Sensitivity Analysis

The objective of this section is to identify the parameters that have the largest influence on the rover thermal behavior and to quantify their impact on the internal temperature evolution. The analysis provides a design-oriented evaluation of the TCS by highlighting the main thermal drivers and the parameters that should be prioritized during the configuration optimization phase.

The sensitivity analysis is performed by varying the main thermal design parameters within the defined ranges while maintaining the remaining model inputs equal to the baseline configuration. The effect of each parameter is evaluated by analyzing the resulting temperature variation throughout the lunar day-night cycle and by comparing the achieved thermal margins with respect to the operational temperature limits.

5.1.1 Radiator Area Sensitivity

The radiator area represents one of the most influential parameters in the thermal control design since it directly determines the available heat rejection capability towards deep space. Increasing the radiator surface enhances the radiative heat transfer capability, allowing a larger amount of thermal energy to be rejected during high temperature conditions.

Figure 5.1 shows the internal temperature evolution obtained by varying the radiator area. As expected, increasing the radiator size reduces the maximum internal temperature reached during the illuminated period. The larger radiative surface improves the rejection of the heat generated by the external environment and by the internal rover systems, limiting the temperature increase during the lunar day. For smaller radiator areas, the system operates with a reduced thermal margin because the available heat rejection capability becomes limited during the warmest phases of the mission. Conversely, larger radiator configurations provide improved thermal performance by maintaining lower internal temperatures and increasing the margin with respect to the maximum allowable temperature. However, the improvement obtained by further increasing the radiator area becomes progressively smaller, indicating a diminishing return effect.

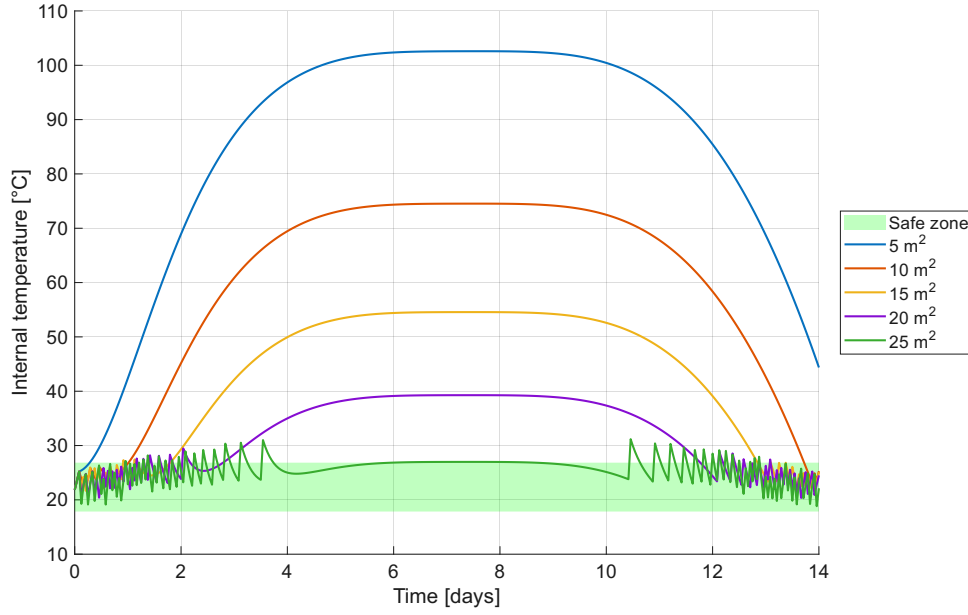


Figure 5.1: Internal temperature evolution for different radiator areas.

This behavior highlights the importance of an adequate radiator sizing strategy. An undersized radiator may lead to excessive daytime temperatures and require additional active thermal control, whereas an oversized radiator introduces unnecessary mass, volume, and integration constraints. Therefore, the radiator area should be optimized to achieve a suitable compromise between heat rejection capability and overall rover system resources.

5.1.2 Heater Power Sensitivity

The maximum heater power represents the active thermal control capability available during cold operating conditions, particularly during the lunar night. Unlike radiators, which provide a continuous heat rejection capability, heaters are activated only when the internal temperature approaches the lower operational limit and additional thermal energy is required to maintain the cabin within the acceptable range. Figure 5.2 presents the internal temperature evolution obtained by varying the maximum heater power. Increasing the available heater capacity mainly affects the minimum temperature reached during the cold phase of the mission. A higher heater power allows the TCS to compensate for the increased heat losses towards the external environment, limiting the temperature decrease and improving the thermal margin during the lunar night.

The influence of heater power during the illuminated period is limited since the heaters remain mostly inactive when the absorbed external radiation and internal heat dissipation are sufficient to maintain the required temperature range. Consequently, the temperature profiles associated with different heater capacities tend to overlap during daytime operations, highlighting the dominant role of passive thermal control mechanisms in these conditions.

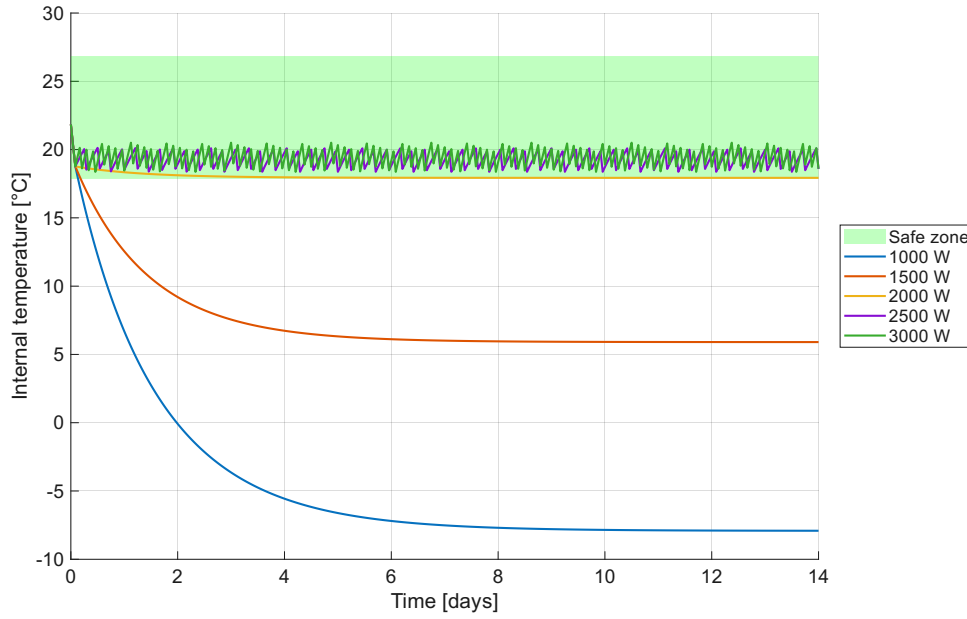


Figure 5.2: Internal temperature evolution for different maximum heater powers.

The results show that heater sizing is mainly driven by the worst-case cold scenario rather than nominal operating conditions. An excessive heater capacity increases the power subsystem requirements and the overall system complexity without providing significant thermal benefits, whereas an insufficient value may prevent the rover from maintaining acceptable temperatures during the lunar night. Therefore, the heater power should be selected to guarantee the required thermal margin under extreme cold conditions while avoiding unnecessary power oversizing.

5.1.3 Surface Absorptivity Sensitivity

The external surface absorptivity α determines the fraction of incident solar radiation absorbed by the rover external surfaces. Due to the absence of an atmosphere and the high solar flux characterizing the lunar environment, this parameter represents one of the main drivers of the external radiative heat input and directly affects the daytime thermal balance.

Figure 5.3 shows the influence of different absorptivity values on the internal temperature evolution. Increasing α results in a larger fraction of absorbed solar radiation and consequently leads to higher internal temperatures during the illuminated phase. The effect is particularly evident around the daytime temperature peak, where the contribution of solar radiation represents one of the dominant external thermal inputs.

Lower absorptivity values reduce the absorbed solar energy and improve the thermal conditions during lunar daytime operations by limiting the temperature increase. However, a reduction of α also decreases the capability of the external surfaces to exchange radiative energy with the surrounding environment, which may affect the thermal balance during cold operating conditions and increase the contribution required from active thermal control.

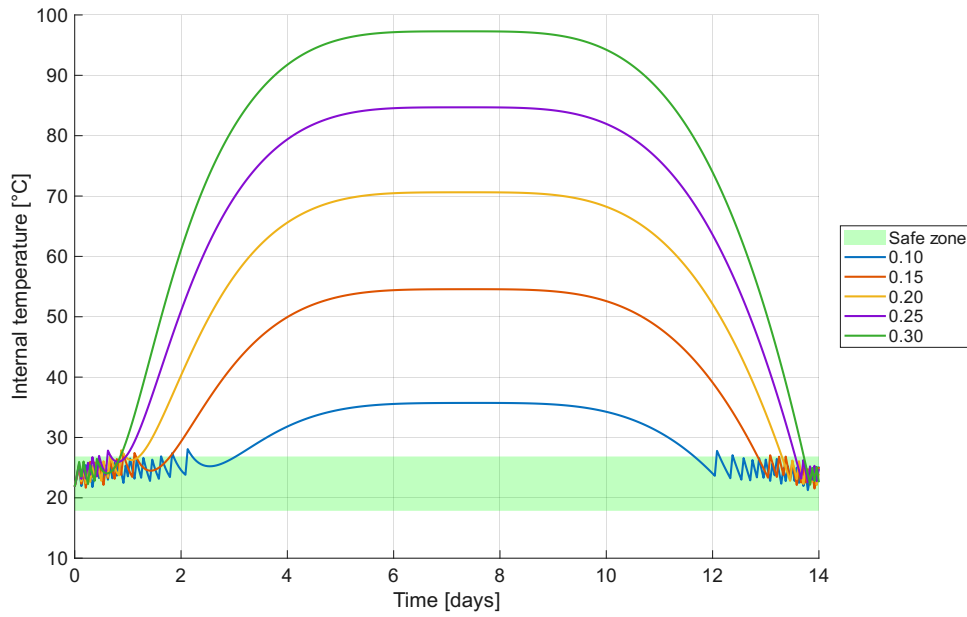


Figure 5.3: Internal temperature evolution for different surface absorptivities.

The results confirm that external optical properties represent an important passive thermal control parameter. The selection of the surface coating must therefore achieve a suitable compromise between reducing excessive solar heating during illuminated periods and maintaining adequate radiative exchange capability throughout the complete lunar day-night cycle.

5.1.4 Internal Heat Generation Sensitivity

Internal heat generation represents one of the most important parameters affecting the rover thermal balance since it directly accounts for the thermal contribution produced by the crew, electronics, and onboard equipment. Unlike external environmental loads, internal dissipation is continuously present throughout all operational phases and directly influences the amount of heat that must be rejected or retained by the thermal control system.

Figure 5.4 illustrates the effect of varying the internal heat load on the rover thermal response. As expected, increasing the internal power dissipation results in higher internal temperatures throughout the mission. The effect is particularly evident during periods with limited external heat rejection capability, where the additional thermal load increases the energy that must be managed by the TCS.

Higher internal heat generation values reduce the available thermal margin and increase the heat rejection requirements during illuminated conditions. Conversely, lower internal loads lead to colder operating conditions and may increase the contribution required from active heating systems during the lunar night.

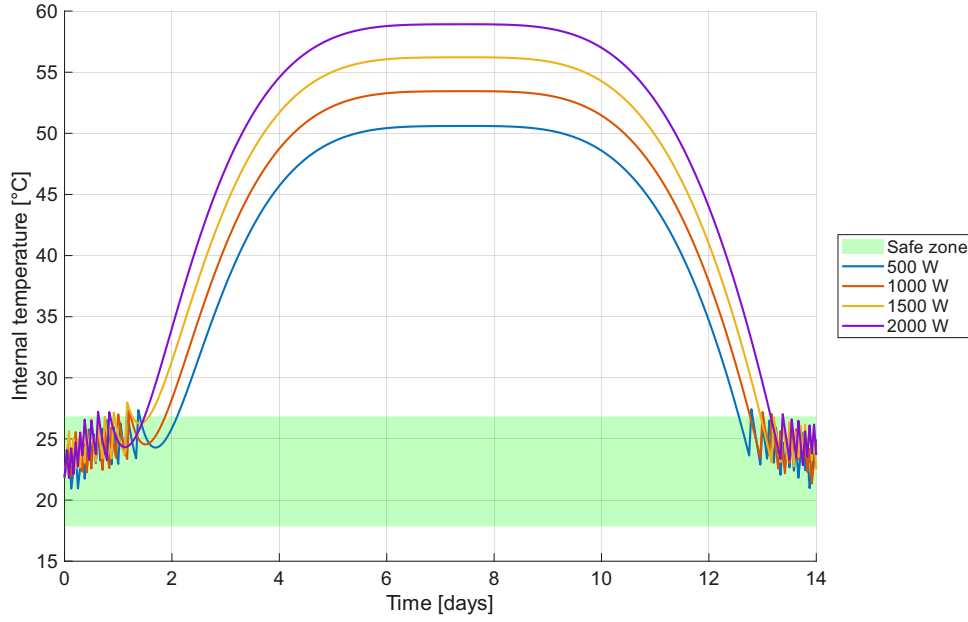


Figure 5.4: Internal temperature evolution for different internal heat generations.

The sensitivity of the system to Q_{int} highlights the importance of accurately estimating crew and equipment power dissipation during the mission definition phase. Since this parameter affects both daytime heat rejection requirements and nighttime heating needs, it represents one of the main drivers for the integrated thermal design and for the sizing of the active and passive TCS components.

5.1.5 Ground View Factor Sensitivity

The ground view factor F_{ground} represents the fraction of the rover external surface exchanging infrared radiation with the lunar terrain. Since the lunar surface can reach relatively high temperatures during the illuminated period, the radiative exchange between the rover and the ground contributes to the external thermal environment and affects the overall thermal balance.

Figure 5.5 shows the effect of varying the ground view factor on the internal temperature evolution. Increasing F_{ground} increases the amount of infrared radiation received from the lunar surface, resulting in a higher external radiative contribution and consequently in an increase of the internal temperature.

The effect is mainly observed during the illuminated phase, when the lunar surface temperature reaches its maximum value and the infrared contribution from the ground represents an additional heat input to the rover. During nighttime operations, the influence of this parameter becomes less significant because the lunar surface temperature decreases considerably and the dominant thermal exchange is associated with radiative heat losses towards deep space.

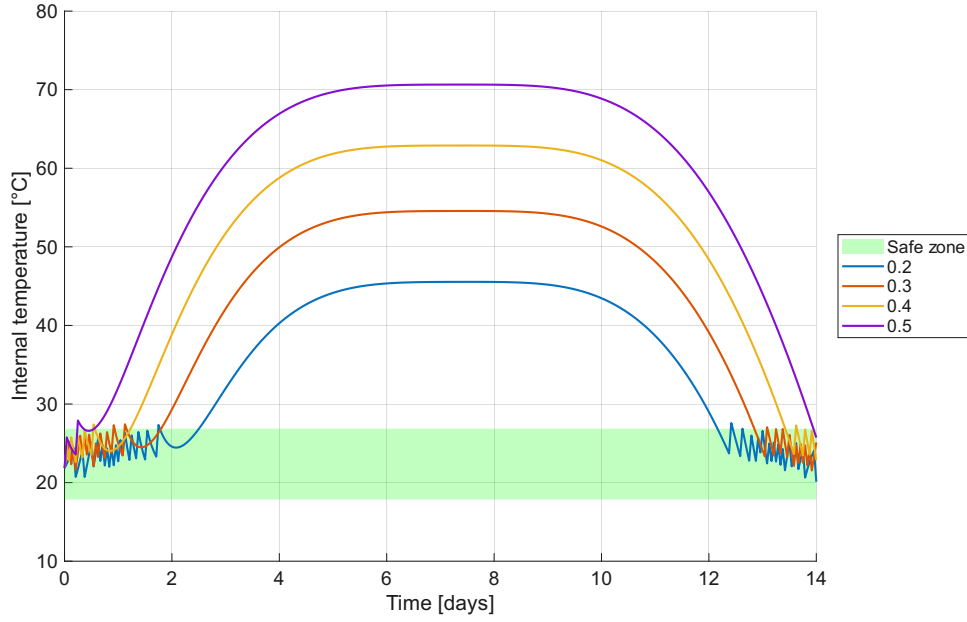


Figure 5.5: Internal temperature evolution for different ground view factors.

Although the impact of the ground view factor is lower compared with the main thermal design parameters, such as radiator area or internal heat generation, it represents an important environmental and geometrical parameter. The rover orientation, external configuration, and operational conditions can modify the exposed surface fraction and therefore influence the thermal environment experienced by the vehicle.

5.1.6 Thermal Capacitance Sensitivity

The thermal capacitance C_{th} represents the capability of the rover structure to store thermal energy and directly affects the transient response of the thermal model. Unlike parameters modifying the energy balance terms, thermal capacitance does not directly affect the equilibrium temperature of the system but influences the rate at which temperature variations occur throughout the lunar cycle.

Figure 5.6 presents the effect of different thermal capacitance values on the internal temperature evolution. Increasing C_{th} increases the thermal inertia of the rover, reducing the temperature variation rate during both heating and cooling phases. As a result, higher thermal capacitance values produce a smoother temperature evolution and reduce the amplitude of short-term thermal fluctuations.

During daytime operations, a larger thermal capacitance delays the temperature increase caused by solar radiation and internal heat dissipation. Similarly, during nighttime conditions, the increased thermal storage capability slows down the cooling process, reducing the temperature decrease rate and improving the transient thermal stability of the system.

Conversely, lower thermal capacitance values lead to a faster response of the system to external and internal heat inputs, resulting in larger temperature variations over the mission cycle. However, the maximum and minimum temperatures reached during the complete lunar cycle remain relatively similar, confirming that C_{th} mainly

affects the dynamic behavior rather than the final thermal equilibrium.

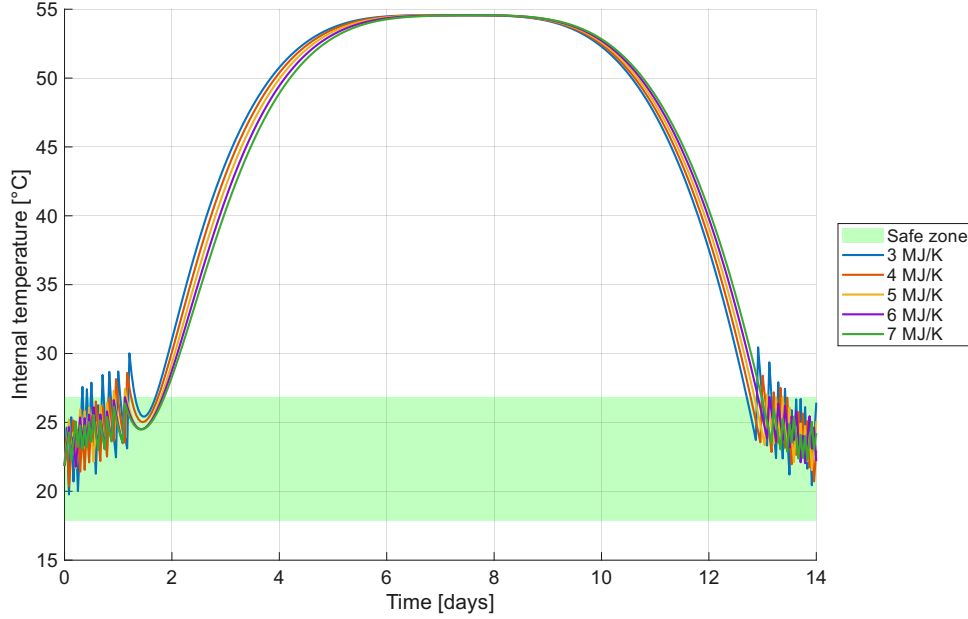


Figure 5.6: Internal temperature evolution for different thermal capacitances.

Therefore, thermal capacitance is an important parameter for accurately predicting transient conditions and temperature variation rates, but it has a lower impact on the overall thermal sizing compared with parameters directly affecting heat generation or rejection. Its main contribution is related to the dynamic response of the rover and to the capability of the system to withstand temporary variations in the external thermal environment.

5.1.7 Uninsulated Surface Emissivity Sensitivity

The emissivity of the uninsulated external surfaces ε_{unins} affects the radiative exchange between the rover and the surrounding environment. Higher emissivity values increase the capability of the external surfaces to exchange thermal radiation, modifying both the heat rejection capability during warm conditions and the radiative heat losses during cold conditions.

Figure 5.7 presents the sensitivity of the internal temperature to variations of ε_{unins} . Increasing the emissivity enhances the radiative coupling between the rover external surfaces and the surrounding environment. During illuminated conditions, this can improve the heat exchange capability, reducing the temperature increase caused by the combined contribution of external and internal thermal loads.

However, during nighttime conditions, the same increase in emissivity leads to higher radiative losses towards the cold lunar environment and deep space. Consequently, excessive emissivity values may reduce the thermal margin during the cold phase by increasing the amount of heat dissipated by the rover surfaces.

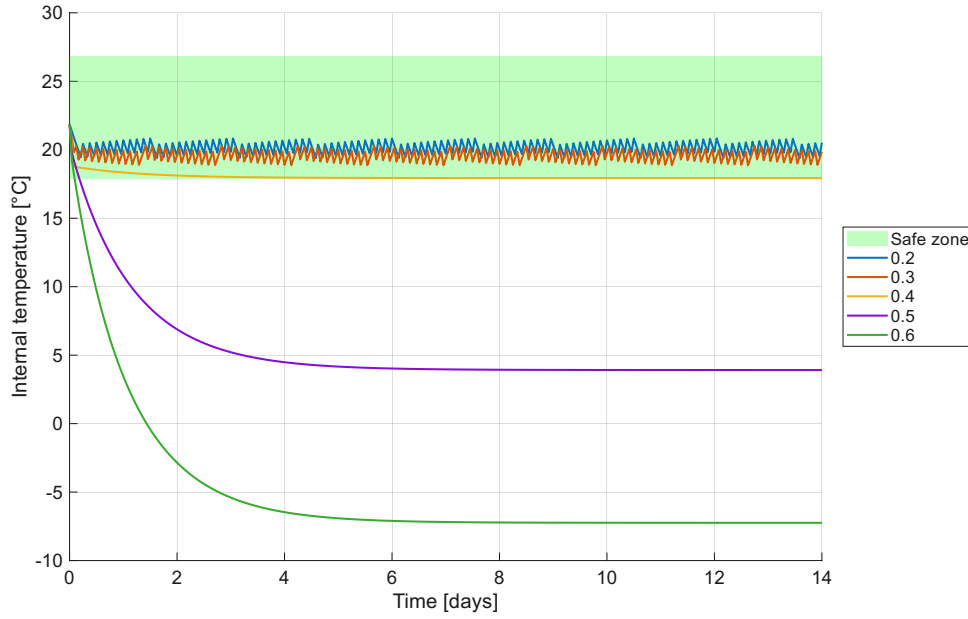


Figure 5.7: Internal temperature evolution for different uninsulated surface emissivities.

The influence of ε_{unins} is lower compared with the main thermal design parameters, such as radiator area or insulation effectiveness, since it affects only the uninsulated portion of the rover external surfaces. Nevertheless, this parameter contributes to the overall passive thermal control performance and must be evaluated together with absorptivity and MLI characteristics to achieve a balanced thermal design.

5.1.8 MLI Penetration Parameter Sensitivity

The MLI penetration parameter p describes the effect of imperfections and thermal leakage paths through the insulation system. In the MLI model, this parameter modifies the effective emissivity of the insulation layers, influencing the radiative heat exchange between the rover internal structure and the external environment. Figure 5.8 shows the influence of the MLI penetration parameter p on the internal temperature evolution. Increasing p leads to a degradation of the insulation performance by increasing the effective emissivity of the MLI system. As a consequence, the thermal coupling between the rover interior and the external environment becomes stronger, increasing the heat exchange through the insulated surfaces.

The influence of this parameter is mainly observed during the lunar night, when the external environment reaches extremely low temperatures and the primary objective of the insulation system is to minimize heat losses from the cabin towards space. Higher penetration levels increase the heat leakage through the insulation, resulting in lower internal temperatures and a higher requirement for active heating to maintain the required operational conditions.

During illuminated periods, the influence of the MLI penetration parameter is reduced because external heat inputs, mainly solar radiation and internal dissipation, dominate the thermal balance. Nevertheless, insulation performance remains a crit-

ical aspect for long-duration lunar missions since it directly affects the required heater power and the thermal stability during extended cold conditions.

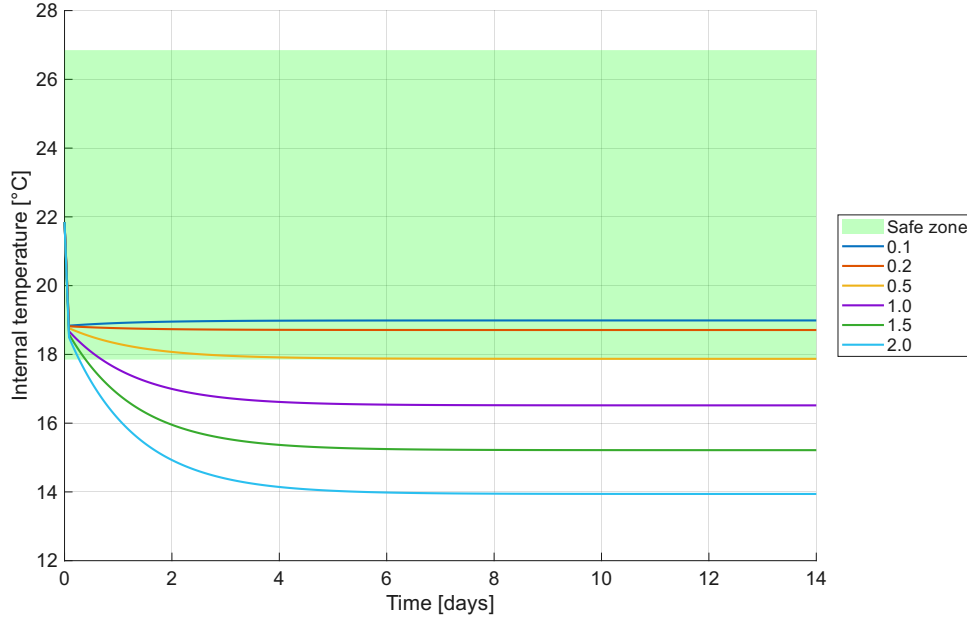


Figure 5.8: Internal temperature evolution for different MLI penetration levels p .

The results confirm that MLI optimization must be considered together with active thermal control elements. Improved insulation performance reduces the nighttime thermal losses, decreasing the heater requirements and improving the overall energy efficiency of the rover.

The sensitivity analysis performed on the TCS parameters highlights the different roles played by active and passive thermal control elements. Radiator area, internal heat generation, and surface optical properties represent the main parameters affecting the daytime thermal behavior, whereas heater power and MLI performance are primarily responsible for maintaining acceptable temperatures during the lunar night.

The obtained results provide a quantitative basis for the evaluation of alternative TCS configurations. In the following sections, the most influential parameters will be considered in the overall system trade-off analysis in order to identify the solution providing the best compromise between thermal performance, mass, and power requirements.

5.2 Environmental Control and Life Support System Sensitivity Analysis

The sensitivity analysis of the ECLSS is aimed at evaluating the impact of mission duration and emergency scenarios on the system autonomy and consumables sizing. While the variation of mission duration mainly affects the total amount of consumables required, emergency scenarios provide more relevant information about the

robustness of the selected architecture and the critical resources limiting mission survival.

5.2.1 Mission Duration Sensitivity

The first sensitivity case considers an increase of the nominal mission duration from 14 to 28 days. As expected, the consumable mass increases approximately proportionally with the mission duration, since oxygen, food, and waste generation are directly related to crew-days. Conversely, the total ECLSS mass does not double, as it also includes fixed contributions associated with the hardware subsystems, which are independent from the mission duration.

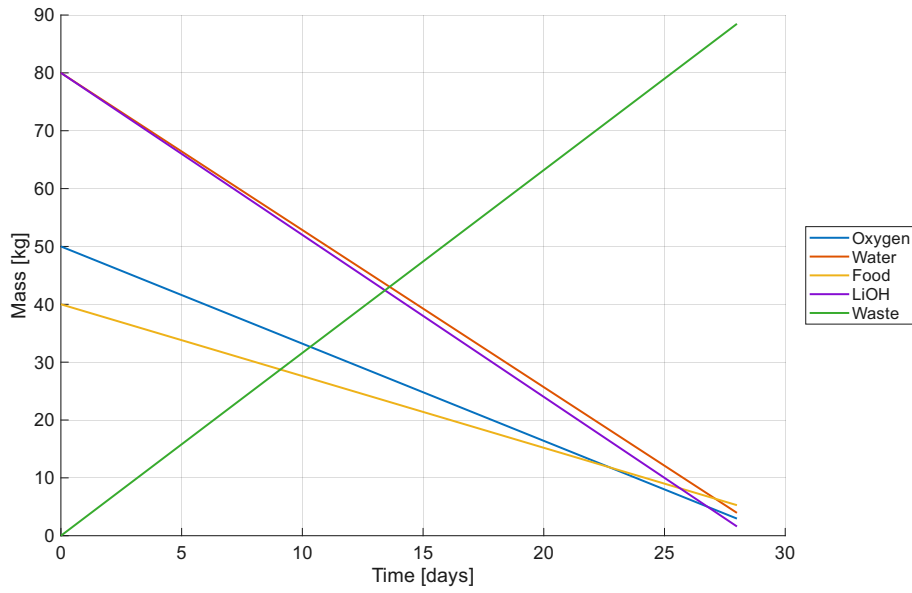


Figure 5.9: Consumables mass evolution for 28 days mission durations.

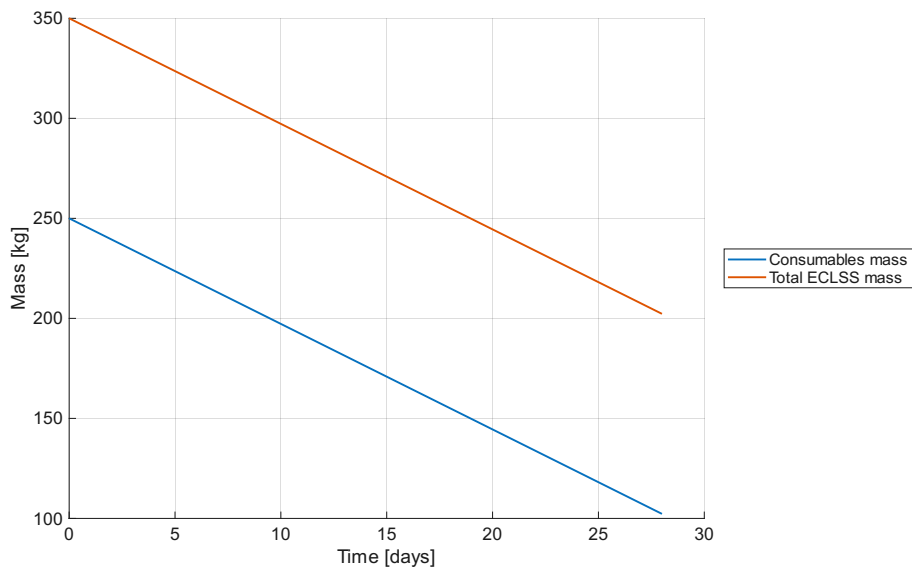


Figure 5.10: Total ECLSS mass variation for 28 days mission durations.

The previous analysis highlights that mission duration mainly affects the consumables sizing, while the emergency scenarios represent the actual driver for the system design robustness. Therefore, two emergency conditions are investigated: WRS failure and shelter emergency operation.

5.2.2 Water Recovery System Failure Scenario

The first scenario assumes a failure of the regenerative water recovery capability after a selected time from mission start. The loss of water recovery rapidly increases the water consumption rate, making water availability the main limiting factor. Two activation times are considered in order to evaluate the influence of the remaining nominal operation period before failure.

For an early failure activation after 3 days, the mission failure occurs at approximately 8.6 days due to water depletion. When the failure is delayed to 10 days, the remaining nominal operation before the emergency condition significantly extends the achievable mission duration, leading to failure at approximately 13 days.

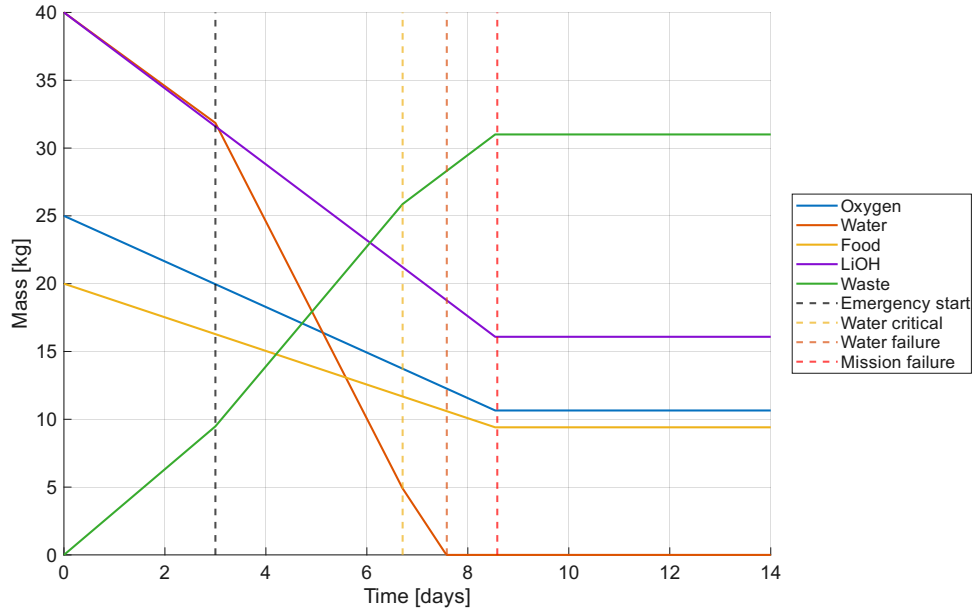


Figure 5.11: Consumables mass evolution during WRS failure emergency scenario activated after 3 days.

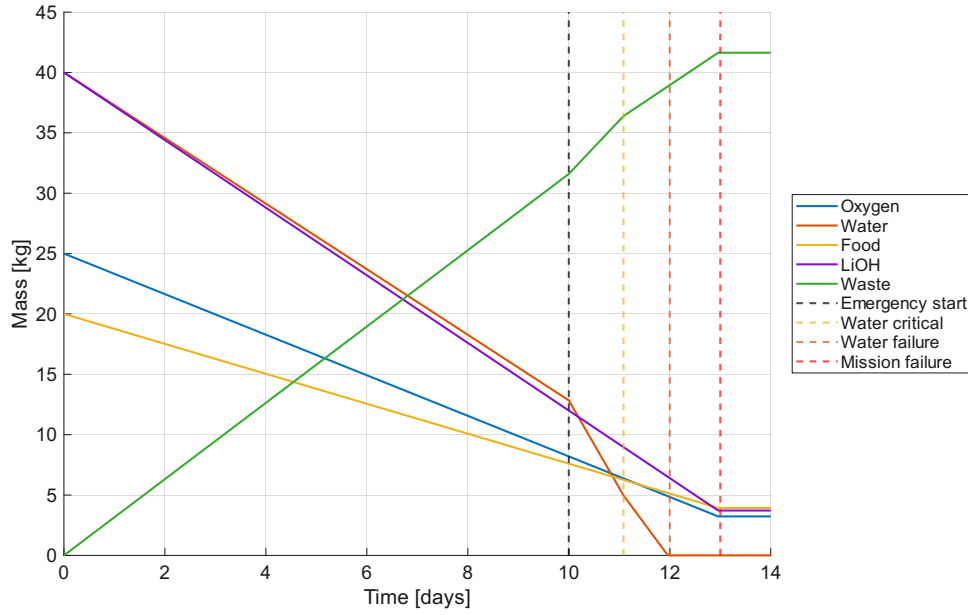


Figure 5.12: Consumables mass evolution during WRS failure emergency scenario activated after 10 days.

5.2.3 Shelter Emergency Scenario

A second emergency condition is represented by the shelter mode, where crew activity is reduced and consumable usage is modified according to emergency operational constraints. The scenario is evaluated with the same two activation times.

For an activation after 3 days, the reduced consumption rates partially extend the operational capability compared with the WRS failure case; however, the mission eventually fails after approximately 9 days due to oxygen depletion. With a delayed activation after 10 days, the available resources are sufficient for a longer operation, but oxygen remains the limiting consumable, leading to failure after approximately 12.5 days.

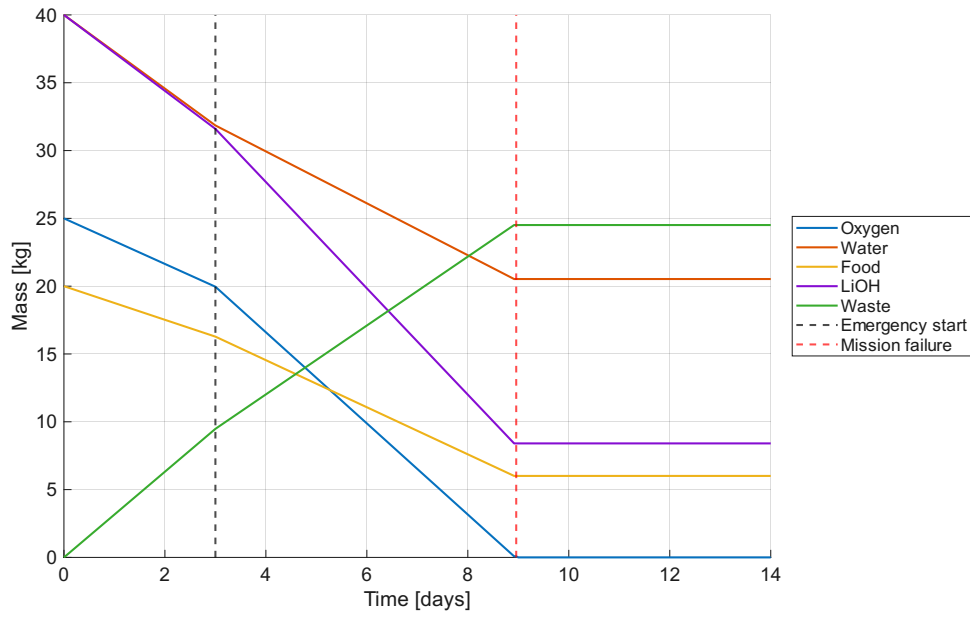


Figure 5.13: Consumables mass evolution during shelter emergency scenario activated after 3 days.

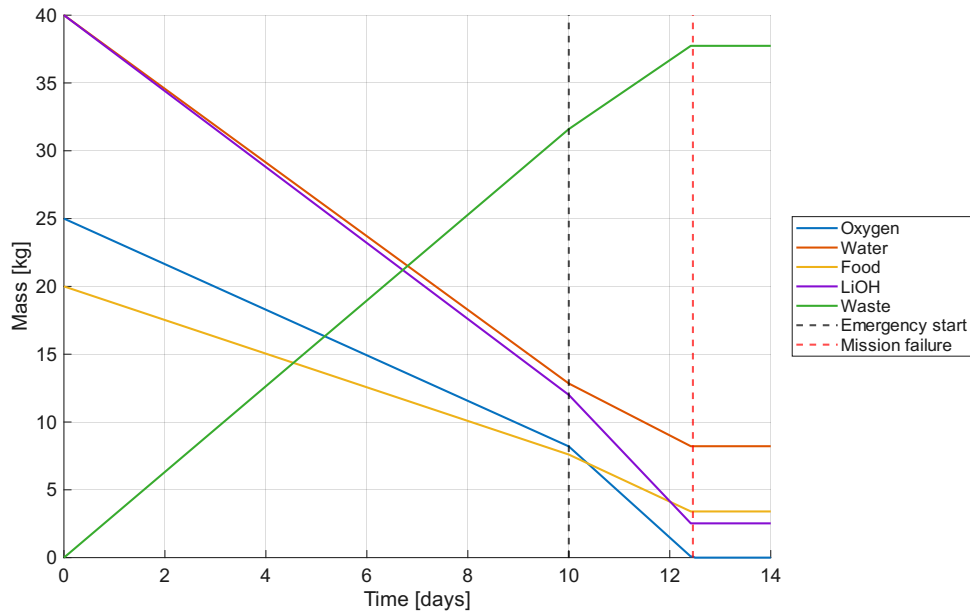


Figure 5.14: Consumables mass evolution during shelter emergency scenario activated after 10 days.

To further investigate the failure mechanisms, an additional shelter scenario is analyzed by reducing the initial food inventory. This allows the identification of the food resource as an additional possible mission constraint and verifies the correct implementation of the failure logic.

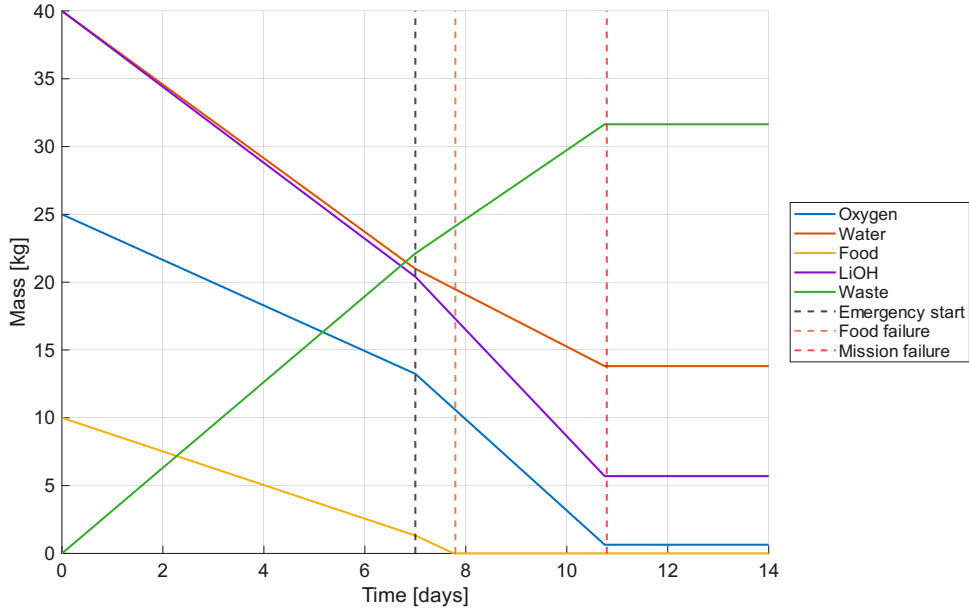


Figure 5.15: Food mass evolution during shelter emergency scenario with reduced initial food inventory.

5.3 Trade-off Analysis

The sensitivity analyses performed for both the TCS and the ECLSS allow the identification of the main design drivers affecting rover survivability. Based on these results, a final configuration refinement is performed by modifying the most influential parameters and evaluating whether the system can satisfy the required operational constraints.

5.3.1 Thermal Control System Optimization

The TCS optimization is performed by modifying the parameters identified as critical during the sensitivity analysis. The objective is to maintain the internal cabin temperature within the acceptable range during both lunar daytime and nighttime operations.

The selected modifications are summarized in Table 5.1.

Table 5.1: TCS optimized configuration parameters.

Parameter	Initial value	Optimized value
Ground view factor (F_{ground})	0.30	0.25
Solar absorptivity (α)	0.15	0.10
Maximum heater power ($Q_{heater,max}$)	2000 W	2500 W
Radiator area (A_{rad})	15 m ²	20 m ²

The combined effect of these modifications improves both the heat rejection capability during lunar daytime and the heat retention capability during lunar nighttime.

The resulting configuration maintains the internal temperature inside the required operational limits throughout the mission.

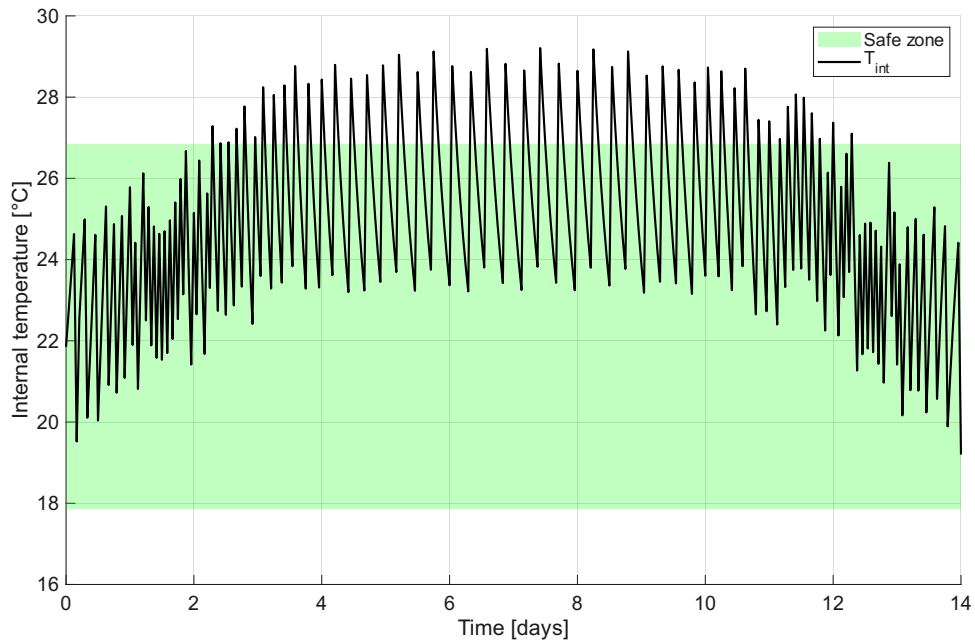


Figure 5.16: Internal cabin temperature evolution during optimized lunar daytime operations.

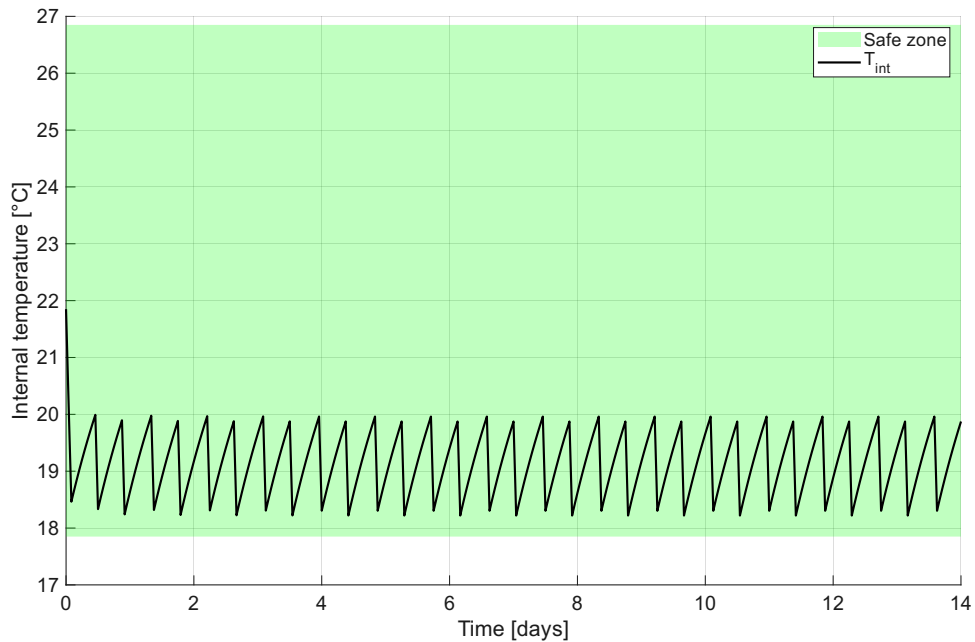


Figure 5.17: Internal cabin temperature evolution during optimized lunar night-time operations.

5.3.2 Environmental Control and Life Support System Optimization

The ECLSS optimization focuses on the emergency scenarios identified as critical during the sensitivity analysis. The WRS failure and shelter emergency cases activated after 10 days are selected as representative worst-case scenarios.

The analysis shows that the main limiting resources are water, oxygen, and LiOH. Therefore, the consumables inventory is increased while maintaining the same system architecture. The updated configuration is summarized in Table 5.2.

Table 5.2: ECLSS optimized consumables inventory.

Consumable	Initial value	Optimized value
Water	40 kg	55 kg
Oxygen	25 kg	35 kg
LiOH	40 kg	45 kg

The increased consumables margin removes the previously identified failure conditions and allows the rover to successfully complete the analyzed emergency scenarios. The resulting behavior for the WRS failure and shelter emergency cases is shown in the following figures.

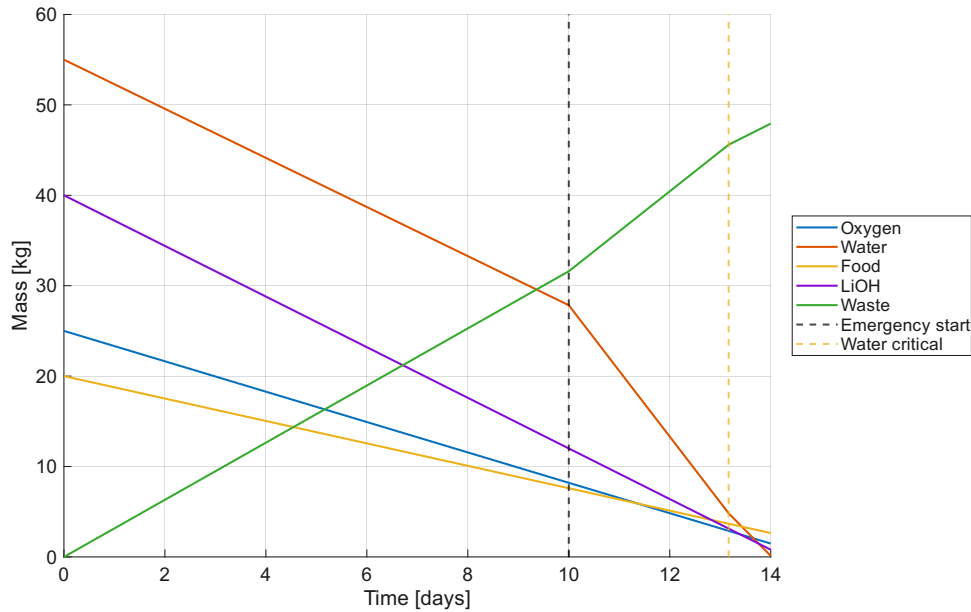


Figure 5.18: Optimized ECLSS configuration response during WRS failure emergency scenario activated after 10 days.

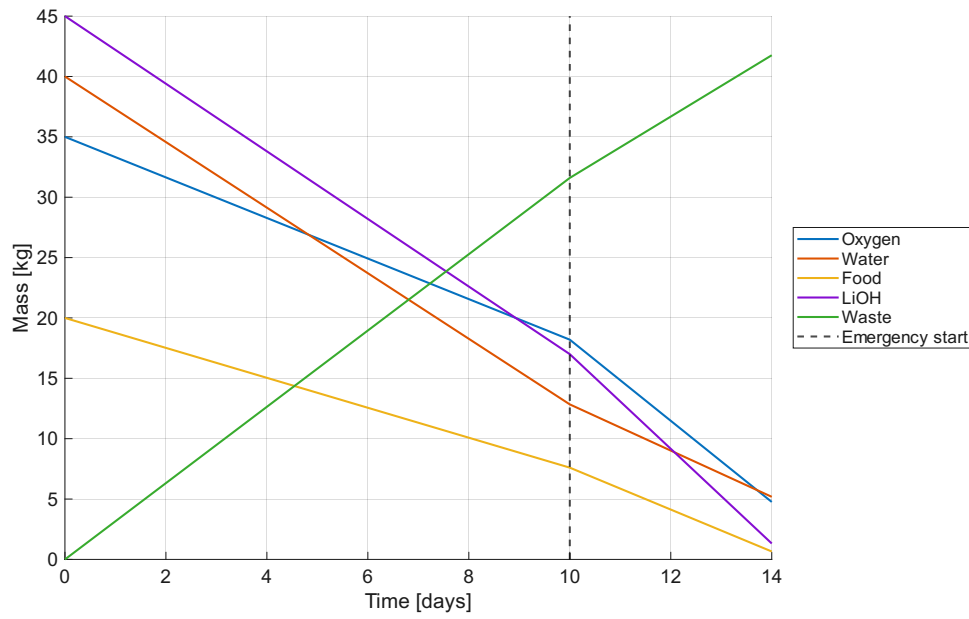


Figure 5.19: Optimized ECLSS configuration response during shelter emergency scenario activated after 10 days.

Chapter 6

Conclusions and Future Work

6.1 Summary of Results

This thesis presented the development of parametric models for the analysis and preliminary sizing of the TCS and ECLSS of a lunar pressurized rover. The main objective was to develop a system-level framework capable of evaluating the influence of mission parameters, subsystem design choices, and operational scenarios on rover performance during the preliminary design phase.

A modular MATLAB-based modeling approach was developed, allowing the independent analysis of the two subsystems while maintaining the possibility of future integrated system evaluations. The TCS model combined a passive thermal control analysis based on MLI sizing with a dynamic lumped-parameter thermal model. The model considered the main heat transfer mechanisms affecting a lunar surface vehicle, including solar radiation, lunar infrared radiation, internal heat dissipation, radiator heat rejection, and heater operation.

The ECLSS model was developed to estimate consumables requirements and system autonomy for different mission architectures. The model included crew metabolic loads, oxygen and water management, food consumption, waste generation, regenerative water recovery, and emergency operating modes. Different mission scenarios were analyzed, including nominal operation, recovery system failure, and shelter emergency conditions.

The developed models were evaluated through subsystem-level sensitivity analyses in order to identify the parameters with the highest impact on rover performance. The obtained results were then used to perform a system trade-off analysis aimed at identifying improved configurations capable of satisfying the operational constraints. For the TCS, the sensitivity analysis highlighted the importance of radiator sizing, heater availability, external optical properties, and environmental coupling parameters. The final configuration obtained by modifying the most influential parameters was able to maintain the internal cabin temperature within the required operational range during both lunar daytime and nighttime conditions.

For the ECLSS, the analysis demonstrated that consumable availability represents the main driver for long-duration autonomy and emergency survival capability. The emergency scenarios identified water, oxygen, and LiOH as the main limiting resources. Increasing the consumable margins allowed the system to successfully

withstand the investigated emergency conditions without requiring modifications to the overall architecture.

6.2 Key Findings

The main outcomes of this work can be summarized in the following key findings. The developed models demonstrated that a parametric approach can effectively support preliminary design activities for lunar rover subsystems. The possibility of rapidly modifying mission parameters and subsystem characteristics enables the evaluation of multiple configurations without requiring computationally expensive high-fidelity simulations.

For the TCS, the analysis showed that passive thermal control elements, particularly MLI performance and external surface properties, have a significant influence on nighttime thermal behavior. Conversely, during lunar daytime operations, heat rejection capability becomes the dominant design driver, requiring an appropriate balance between insulation performance, radiator sizing, and heater availability.

The results also highlighted the strong coupling between environmental conditions and subsystem sizing. Parameters such as the ground view factor and surface absorptivity significantly affect the external thermal loads, demonstrating the importance of considering rover geometry and operational environment during early design phases.

For the ECLSS, the analysis confirmed the advantages of regenerative architectures for extended lunar missions. In particular, water recovery significantly reduces the required consumable mass compared with a fully non-regenerative configuration, improving mission scalability and autonomy.

The emergency scenario analysis showed that the failure of regenerative systems can rapidly become a mission-limiting condition. The implemented failure logic allowed the identification of critical resources and demonstrated the importance of maintaining adequate consumable margins for contingency operations.

Overall, the integrated analysis highlighted the importance of combining subsystem-level sensitivity studies with system-level trade-offs. The final configurations obtained from the analysis provided increased robustness while requiring limited modifications to the original design assumptions.

6.3 Limitations

Although the developed models provide a useful framework for preliminary rover design assessment, several limitations must be considered.

The thermal model relies on a lumped-parameter approach, representing the rover cabin as a single thermal node. This assumption enables efficient parametric analyses but does not capture spatial temperature gradients, local thermal effects, or detailed heat transfer paths between different rover components.

The TCS analysis also relies on simplified environmental representations. Effects such as detailed rover orientation, terrain-dependent infrared radiation, shadowing phenomena, and transient illumination variations are not explicitly considered. Fur-

thermore, radiator performance is represented through simplified assumptions and does not include detailed geometry or operational constraints.

The ECLSS model is based on analytical crew consumption rates and average metabolic loads. A more detailed approach would require the inclusion of realistic crew activity profiles, variations in resource consumption, component degradation, maintenance operations, and detailed subsystem characteristics.

Moreover, additional rover subsystems, such as the EPS, communication systems, mobility systems, and structural aspects, were not directly included in the integrated analysis. Their interaction with TCS and ECLSS sizing represents an additional level of system complexity that was beyond the scope of this work.

6.4 Future Work

Several improvements can be considered for future developments of this work.

For the TCS, the model could be extended by introducing a multi-node thermal representation including the main rover components, such as cabin walls, equipment, batteries, and radiators. A higher-fidelity thermal model would allow the investigation of local thermal gradients and improve the accuracy of subsystem sizing.

The environmental model could also be enhanced by including detailed lunar terrain characteristics, rover orientation effects, and time-dependent illumination conditions. The integration of a more detailed radiator model would further improve the evaluation of heat rejection capability.

For the ECLSS, future work could focus on modelling individual components in greater detail, including their mass, power consumption, reliability, and degradation over time. Component-level models would enable a more accurate evaluation of regenerative and non-regenerative architectures and their impact on overall rover design.

A further development would involve the integration of the TCS, ECLSS, and EPS models into a complete system-level framework. This would enable the analysis of subsystem interactions and the evaluation of coupled effects between thermal loads, life support requirements, power availability, and total rover mass.

Finally, the developed parametric framework could be extended towards automated multidisciplinary optimization methods. While sensitivity analysis allows the identification of the main design drivers, optimization algorithms would enable the systematic search for optimal rover configurations considering multiple objectives, such as minimizing mass, maximizing mission duration, reducing power consumption, and increasing system robustness.

List of Figures

1.1	Concept of the JAXA Lunar Cruiser pressurized rover [1].	1
1.2	Photographs of the first lunar rovers used during the Apollo missions for surface exploration.	5
3.1	Interpolated layer correction factor f_N as a function of the number of MLI layers N	31
3.2	Interpolated penetration correction factor f_P as a function of the MLI penetration level p	31
3.3	Simplified architecture and resource flows of the Environmental Control and Life Support System (ECLSS)	34
4.1	Effective emissivity ϵ_{eff} of the MLI system for different layer numbers N and penetration levels p	42
4.2	Heat flux through the MLI system Q_{MLI} for different layer numbers N and penetration levels p	42
4.3	Specific thermal resistance R of the MLI system for different layer numbers N and penetration levels p	43
4.4	Cabin temperature evolution without MLI during the lunar night . .	44
4.5	Heat balance components without MLI during the lunar night	45
4.6	Net heat flow without MLI during the lunar night	45
4.7	Cabin temperature evolution without MLI during the lunar daytime .	46
4.8	Heat balance components without MLI during the lunar daytime . . .	46
4.9	Net heat flow without MLI during the lunar daytime	47
4.10	Cabin temperature evolution during the lunar night for different numbers of MLI layers	48
4.11	Heat balance components with 20 MLI layers during the lunar night .	49
4.12	Cabin temperature evolution with heater during the lunar night for different numbers of MLI layers	50
4.13	Heat balance components with heater and 20 MLI layers during the lunar night	51
4.14	Cabin temperature evolution with radiators during the lunar daytime for different numbers of MLI layers	52
4.15	Heat balance components with radiators and 20 MLI layers during the lunar daytime	53
4.16	Net heat flow evolution with radiators and 20 MLI layers during the lunar daytime	54
4.17	Consumables mass evolution for the nominal regenerative ECLSS architecture	55

4.18	Water management breakdown for the nominal regenerative ECLSS architecture	56
4.19	Total ECLSS mass evolution for the nominal regenerative architecture	57
4.20	Consumables mass evolution for the non-regenerative ECLSS architecture	58
4.21	Water management breakdown for the non-regenerative ECLSS architecture	59
4.22	Total ECLSS mass comparison between regenerative and non-regenerative architectures	60
4.23	Consumables mass evolution during the WRS failure scenario	61
4.24	Water management breakdown during the WRS failure scenario . . .	62
4.25	Total ECLSS mass evolution during the WRS failure scenario	63
4.26	Consumables mass evolution during the shelter mode scenario	64
4.27	Water management breakdown during the shelter mode scenario . . .	65
4.28	Total ECLSS mass evolution during the shelter mode scenario	66
5.1	Internal temperature evolution for different radiator areas.	70
5.2	Internal temperature evolution for different maximum heater powers.	71
5.3	Internal temperature evolution for different surface absorptivities. . .	72
5.4	Internal temperature evolution for different internal heat generations.	73
5.5	Internal temperature evolution for different ground view factors. . . .	74
5.6	Internal temperature evolution for different thermal capacitances. . .	75
5.7	Internal temperature evolution for different uninsulated surface emissivities.	76
5.8	Internal temperature evolution for different MLI penetration levels p .	77
5.9	Consumables mass evolution for 28 days mission durations.	78
5.10	Total ECLSS mass variation for 28 days mission durations.	78
5.11	Consumables mass evolution during WRS failure emergency scenario activated after 3 days.	79
5.12	Consumables mass evolution during WRS failure emergency scenario activated after 10 days.	80
5.13	Consumables mass evolution during shelter emergency scenario activated after 3 days.	81
5.14	Consumables mass evolution during shelter emergency scenario activated after 10 days.	81
5.15	Food mass evolution during shelter emergency scenario with reduced initial food inventory.	82
5.16	Internal cabin temperature evolution during optimized lunar daytime operations.	83
5.17	Internal cabin temperature evolution during optimized lunar nighttime operations.	83
5.18	Optimized ECLSS configuration response during WRS failure emergency scenario activated after 10 days.	84
5.19	Optimized ECLSS configuration response during shelter emergency scenario activated after 10 days.	85

List of Tables

1.1	Comparison of representative lunar and planetary rover concepts. . .	7
2.1	Performance requirements.	17
2.2	Operational requirements.	17
2.3	Environmental requirements.	18
2.4	Mission input parameters.	19
2.5	Environmental input parameters.	19
2.6	Qualitative influence of operational modes on subsystem loads.	21
3.1	Nominal daily allocation of operational modes	23
3.2	Environmental and radiative parameters adopted in the thermal model.	25
3.3	Baseline values and variation ranges of the thermal model parameters.	27
3.4	Baseline values adopted for the ECLSS model parameters.	28
3.5	Correction factor for number of MLI layers.	30
3.6	Penetration correction factor for MLI performance degradation (adapted from Gilmore).	30
5.1	TCS optimized configuration parameters.	82
5.2	ECLSS optimized consumables inventory.	84

Bibliography

- [1] Toyota Motor Corporation. *Lunar Cruiser*. Link (cit. on p. 1).
- [2] G. Heiken, D. Vaniman, and B. M. French. *Lunar Sourcebook: A User's Guide to the Moon*. Cambridge University Press, 1991 (cit. on pp. 2, 18, 25).
- [3] NASA. *Apollo 15 Image AS15-86-11603*. Link. 1971 (cit. on p. 5).
- [4] NASA. *Apollo 17 Image AS17-147-22526*. Link. 1972 (cit. on p. 5).
- [5] K. Creel, J. Frampton, D. Honaker, K. McClure, and M. Zeinali. *Pressurized Lunar Rover*. Senior Design Project. Virginia Polytechnic Institute, State University, Department of Aerospace, and Ocean Engineering, 1992 (cit. on pp. 5–7).
- [6] M. Bhardwaj, V. Bulsara, D. Kokan, S. Shariff, E. Svarverud, and R. Wirz. *Design of a Pressurized Lunar Rover*. Tech. rep. NASA-CR-192033. Virginia Polytechnic Institute, State University, Department of Aerospace, and Ocean Engineering, 1992 (cit. on pp. 5–7).
- [7] B. Romig, J. Kosmo, M. Gernhardt, and A. Abercromby. *Desert Research and Technology Studies 2008 Report*. SAE Technical Paper 2009-01-2563. NASA Johnson Space Center, 2009 (cit. on p. 5).
- [8] J. Zakrajsek et al. “Exploration Rover Concepts and Development Challenges”. In: *1st Space Exploration Conference: Continuing the Voyage of Discovery*. 2005 (cit. on p. 6).
- [9] B. Griffin, D. Thrasher, and B. Wallace. “A Pressurized Rover for Early Lunar Exploration”. In: *Space Programs and Technologies Conference*. 1992 (cit. on p. 7).
- [10] S. J. Hoffman and D. I. Kaplan. *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*. NASA-SP-6107. NASA, Lyndon B. Johnson Space Center, 1997 (cit. on p. 7).
- [11] National Aeronautics and Space Administration. *Space Exploration Vehicle (SEV) Concept Fact Sheet*. Tech. rep. NF-2010-06-499-HQ. NASA, 2010 (cit. on p. 7).
- [12] K. Liles and R. Amundsen. *NASA Passive Thermal Control Engineering Guidebook*. Tech. rep. NASA, 2023 (cit. on p. 12).
- [13] European Cooperation for Space Standardization. *ECSS-E-ST-10-06C: Technical Requirements Specification*. Tech. rep. ECSS, 2009 (cit. on p. 17).

- [14] National Aeronautics and Space Administration. *NASA Spaceflight Human-System Standard: Volume 2 – Human Factors, Habitability, and Environmental Health*. Tech. rep. NASA-STD-3001 Volume 2 Revision E. NASA Office of the Chief Health and Medical Officer, 2025 (cit. on p. 17).
- [15] National Aeronautics and Space Administration. *NASA Spaceflight Human-System Standard: Volume 1 – Crew Health*. Tech. rep. NASA-STD-3001 Volume 1 Revision C. NASA Office of the Chief Health and Medical Officer, 2023 (cit. on p. 23).
- [16] B. C. Di Maggio. “Multidisciplinary Design and Optimization of a Pressurized Rover for Lunar Surface Exploration”. MA thesis. Politecnico di Torino, 2026 (cit. on p. 24).
- [17] P. O. Wieland. *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems*. NASA Reference Publication 1324. NASA George C. Marshall Space Flight Center, 1994 (cit. on p. 27).
- [18] M. K. Ewert, T. T. Chen, and C. D. Powell. *Life Support Baseline Values and Assumptions Document*. Tech. rep. NASA/TP-2015-218570/REV2. NASA Lyndon B. Johnson Space Center, 2015 (cit. on p. 27).
- [19] D. Gilmore. *Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies*. The Aerospace Press, 2002 (cit. on p. 28).