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Risk Assessment of a Mars Colony Utilizing a Mars-Svalbard Training Analog

Derrick Barger

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Faculty of Engineering Science and Technology
Department of Technology and Safety

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Abstract

As the space industry is rapidly privatized and countries once again have their eyes set on the moon and beyond, humanity is getting closer and closer to the days where a colony on Mars is a reality. During the preliminary planning phase of a mission to Mars, a large scale, top-down overview is essential. This report applies a risk and safety engineering approach to identify each of the core hazards, such as environmental hazards, infrastructural and logistical hazards, and psychological hazards, that a Martian colony would face. These hazards are then quantified using their probabilities to identify the risk severity of the hazards. To address and attempt to mitigate some of these risks a Mars-Earth Analog was developed by comparing the hazards faced on Mars to lose faced on a theoretical training location in the Arctic. The goal here was to propose a method of hands on, Arctic isolation training that future Mars astronauts could undertake in an environment that mirrors that of Mars as closely as possible. After outlining the shared hazards faced on both Mars and an Arctic training location, site analysis was conducted for both Mars and Svalbard, an island north of Norway. Three separate colony locations were identified at each location that balance the needs of astronauts and minimize the natural hazards those involved would face. These locations mirror each other as closely as possible and provide the basis for future astronaut training missions.

Table of Contents

List of Tables

List of Figures

Introduction

While it may seem to be an idea from science fiction, humanity is quickly approaching the days when a base or colony on Mars is a reality. However, concealed within this grand vision are multifaceted challenges that question the feasibility and sustainability of such a monumental endeavor; between the countless risks associated with such a harsh environment, establishing a foothold on Mars will be one of the most challenging goals that our species has ever undertaken. At the core of this endeavor lies the pressing need to identify, analyze, and effectively mitigate the extensive array of hazards inherent in this venture.

The allure of Mars as a potential second home for humanity is undeniable, yet the harsh realities of this desolate planet pose significant impediments. The challenges span the realms of technological limitations, environmental hostility, physiological adaptation, and logistical complexities. Each aspect increases risks that threaten not just the success but the very viability of a sustained human presence on Mars.

The lack of a breathable atmosphere, extreme temperatures, cosmic radiation, and the absence of readily available resources pose existential threats that demand meticulous consideration. Furthermore, the isolation and psychological strain resulting from the vast interplanetary distances amplify the complexity of human adaptation to a Martian habitat. However, before each of these individual hazards can be tackled, understanding the relationship between them is essential. Furthermore, it is vital to establish a structured way to organize and implement risk mitigation strategies after the identification of hazards. This thesis will examine these challenges, aiming not only to delineate the risks but to underscore their gravity and interdependencies. By doing so, one can identify the critical hurdles that must be overcome to transform the dream of a Martian colony into a tangible reality.

When undertaking a project as ambitious as colonizing a distant planet, simply identifying the hazards or remotely observing from afar is not sufficient. While there is obviously no 1:1 analog for Mars on Earth, one does observe parallels between Mars and the poles of our planet: isolation, extreme weather, desolate environment, and a lack of resources and infrastructure. While lab built, simulated Martian environments are possible, there is an undeniable benefit and realism to personnel training in real life environments. It is likely, if a sufficiently similar training location is identified and practical, it could better prepare future astronauts for the conditions they may face on Mars. This thesis will identify these shared traits and identify a potential training location to develop a system to prepare astronauts for both long- and short-term Mars missions.

Aim and Objective

The aim of this project is to conduct a comprehensive hazard overview of the global Martian conditions, perform a similar hazard investigation to the conditions found on Svalbard, an island near the North Pole, and lastly identify a location on Svalbard that best mimics Martian conditions and is possible to build a mock Maritain habitat to train astronauts. By synthesizing existing research, empirical evidence, and expert insights, a strategic framework and mitigation strategy can be developed. These measures are integral in decreasing the risks of a Martian colony. More specifically, the objectives of this research are to:

1. Conduct a global Martian engineering hazard identification
2. Identify hazard and risk similarities between Mars and Svalbard
3. Propose a Svalbard-Mars training location and identify strengths and weaknesses

Objective 1: Conduct a global Martian engineering hazard identification

The first step in any risk and hazard analysis is identifying the threats that are faced. While Mars is a very geographically varied planet, there are some hazards that are seen planetwide. Some of these challenges include harsh environmental conditions, life support and habitability, resource limitations, transport and logistics, isolation and psychological impact on astronauts. To begin the hazard and risk analysis, each of these global hazards will be identified, explained, and related to one another. The identification and explanation of these hazards will be based primarily on data gathered from NASA satellites and the complete data gathering process is outlined within the methodology section. After identifying the global hazards, different regional strengths and weaknesses should be classified. While no location on Mars is particularly hospitable, the surface conditions across Mars encompass a wide range of increased and decreased hazards. Whether it be varied radiation levels, temperature fluctuations, or access to subsurface ice, it is inaccurate to only identify global hazards when conducting a hazard analysis on Mars. Furthermore, the different risks associated with the most promising colony locations will be investigated. Some of these locations include the equatorial zone, Arcadia Planitia, Valles Marineries, Utopia Planitia, Hellas Basin, and the poles. Some of these areas cover vast swathes of land and encompass multiple distinct regions. The surface conditions, temperature, and elevation, also vary significantly across the Red Planet and each offers unique benefits and hazards that colonists would inevitably face. The aim of these sections is not to propose solutions, but to outline the core hazards faced.

Objective 2: Identify hazard and risk similarities between Mars and Svalbard

Following the risk and hazard assessment of Mars, a similar identification study will be conducted with Svalbard. This section aims to address the same categories posing an issue to Mars, and both quantitatively and qualitatively compare the conditions in both locations. While the Martian study will focus primarily on the global conditions and highlight some regional differences, the Earth-based hazard study is contained to the Svalbard archipelago, an area roughly the size of Denmark, and will highlight the regional differences at different locations and islands. This smaller-scale study is conducted to maintain the best chances of recreated Martian conditions.

Objective 3: Proposal of Svalbard-Mars training location and identify strengths and weaknesses

Following the hazard and risk study for both Mars and Svalbard, a set of locations will be determined that best balance the “ideal” Martian conditions and feasibility of base establishment. Simulated base locations will be identified using both satellite imagery and firsthand documentation.

Scope and Limitations

This project is not focused on the astronautical engineering challenges associated with getting to Mars or proposing the advanced technology and life support required to solve or mitigate the highlighted risks. Each of the mitigation strategies proposed would require vast amounts of research and experimentation to optimize and implement, and the challenges that some of the briefly mentioned risk reduction strategies pose should not be understated. Each the different hazards identified also warrant extensive research to fully gain a comprehensive overview. This project only seeks to apply a risk and reliability assessment approach to classify and organize the different challenges that will be faced. It should also be noted that this project does not concern itself deeply with a comprehensive training plan, simply the identification of a location where training could be performed and the benefits that could come with it. This report does not concern itself with what this theoretical Mars-Svalbard base will look or function like. Whether the base is a 1:1 recreation of a Mars base or simply a training center for the Svalbard mission, is not important within the scope of this project.

Furthermore, it is important to address the time constraints of this project. As a 1 semester master thesis, there is limited time for fieldwork and on-site analysis. For example, the third objective of this thesis aims to identify three different potential Mars-Svalbard analog training locations. Ideally, one would be able to visit each of these locations during a variety of seasons to assess them quantitatively and qualitatively. Due to time restraints, this was not able to be conducted. A similar approach should be taken with the Martian base locations utilizing landers and rovers, but this is obviously far beyond the expected scope.

Research Approach and Methodology

Research Approach

Establishing the frame within which this research takes place is an important tool and different terms such as induction, deduction, abduction, qualitative studies, and quantitative studies help to outline the approach and goal of this research project.

Induction involves deriving general principles or theories from specific observations or data [1]. This approach begins by gathering empirical evidence and identifying patterns or regularities within the data. The goal of induction is to formulate hypotheses or generalizations that explain the observed phenomena. However, induction does not provide certainty; rather, it aims for probability or likelihood based on the available evidence. Deduction, on the other hand, moves from general principles or theories to specific conclusions [1]. It begins with established theories or premises and uses logical inference to derive specific predictions or conclusions. Deductive reasoning aims for certainty: if the premises are true and the logic is valid, then the conclusion must also be true. Abduction involves reasoning to the best explanation for a set of observations or data. Unlike deduction, which moves from general principles to specific conclusions, abduction starts with observations and seeks the simplest and most plausible explanation [1]. Abductive reasoning is often used in situations where there are multiple possible explanations, and the goal is to select the one that best fits the evidence.

Due to the highly observational approach of this thesis, the results are very dependent on abduction reasoning. This project does not aim to develop new overall theories or to define strict likelihoods or probabilities. Abduction based reasoning allows one to observe the conditions on both Mars and Svalbard and develop conclusions based on the observations.

Furthermore, research styles can be separated into quantitative and qualitative research styles. Quantitative research collects and analyzes numerical data. It focuses on quantifying relationships, patterns, and phenomena. Quantitative research often employs statistical techniques to analyze data and draw conclusions. This approach is characterized by structured data collection methods, such as surveys, experiments, or structured observations. The aim of quantitative research is to produce numerical data that can be analyzed objectively to test hypotheses, identify patterns, or make predictions [2]. In contrast, qualitative research collects and analyzes non-numerical data. It focuses on understanding the complexities, meanings, and nuances of human behavior, experiences, and social phenomena. This approach emphasizes in-depth exploration, interpretation, and understanding of social phenomena within their natural context [2].

This project utilizes a fusion of these two styles. While primarily focusing on technical, non-personal matters, there is little focus or necessity for strict numerical data. Furthermore, there is no need for a statistical approach to process this data. Therefore, a qualitative research approach can be used to place non-technical emphasis and meaning on complicated topics, such as environmental conditions and habitability. For this broad, top-down approach it is well suited to develop an initial hazard identification and risk assessment strategy.

Data Collection and Analysis

The data collected for the Martian hazard study in this report is largely based on publicly available data provided from NASA's Mars orbiters. This data takes the form of radiation charts, elevation maps, sub surface icing maps, and surface temperature gradients provided by the *Mars Odyssey*, *Maven*, *Viking 1*, *Viking 2*, and *Mars Reconnaissance* orbiters. In addition to Mars orbiters, data collected from Mars rovers, such as *Curiosity* and *Perseverance*, is utilized. The rovers have provided invaluable data on Martian surface conditions and have conducted numerous experiments to test technology and atmospheric conditions on Mars.

The use of NASA content, including images, audio, video, and related media, for educational or informational purposes, is typically not restricted by copyright. This includes various materials used in the creation 3D models, such as texture maps. One is also permitted to utilize this material for educational or informational use. This permission also applies to the use of NASA content on personal web pages.

While NASA has gathered a large amount of planetary data on Mars such as temperatures, radiation levels, wind patterns, and unique geographical features, it is far more challenging to gather site specific data. The *Curiosity* and *Perseverance* rovers have done a fantastic job demonstrating the ground-based survey abilities, and this would undeniably be required prior to the landing of astronauts or pre-astronaut base construction. However, this data does not exist for this project, so the hazard identification and risk analysis will be limited to larger and more general features of Mars, rather than very localized risks associated with landing and the construction of the base, such as localized concentrations of sand, small craters, individual boulders, or other small scale surface features.

The satellite imagery and topographic maps of Svalbard are sourced from TopoSvalbard, a collection of topographic, satellite, and 3D maps organized by the Norwegian Polar Institute.

State of the Art

It is vitally important to look into current research within this field. Firstly, it establishes the context for the research, and highlights the current state of the field. After introducing and analyzing current research, gaps and unanswered questions will be identified, which justifies the significance of the proposed research. Furthermore, this literature review helps to prevent duplication by outlining the current progress made with existing studies. This is a crucial component that informs and contextualizes this thesis within the existing body of knowledge.

Risk Assessment and Hazard Identification

First and foremost, it is important to establish this project in the scope of risk and safety engineering, rather than mechanical, aerospace, or electrical engineering. Risk and safety engineering is a branch of engineering that focuses on the identification, assessment, and mitigation of risks and hazards in various systems, processes, and environments to ensure the safety and well-being of individuals, property, and the environment [3]. It involves applying scientific and engineering principles to analyze and manage risks associated with complex systems, technologies, and activities. Rather than developing new technologies to solve the problems, risk and safety engineering is more focused on the implementation, safety barriers, and safety culture surrounding a project [4]. This project will use a variety of concepts that are integral to risk and safety engineering such as risk assessment, hazard identification and management, and risk mitigation strategies.

Risk assessment is a crucial component of risk and safety engineering. It involves the systematic process of identifying, evaluating, and analyzing potential risks and their associated impacts to determine their likelihood and severity [5]. The goal of risk assessment is to provide a comprehensive understanding of potential hazards, enabling informed decision-making for risk management and mitigation strategies. This proactive approach to risk assessment is essential in ensuring the safety and reliability of complex systems across various industries.

Hazard identification and management plays a critical role in designing a safe and successful colony on Mars. This involves a systematic process of recognizing, documenting, and addressing potential sources of harm or danger within a system, environment, or process [6]. The objective is to proactively identify hazards and implement effective management strategies to prevent accidents, injuries, or adverse impacts.

Hazard identification and management typically includes the following steps: identification, risk analysis, control measure implementation, monitoring, review, documentation, and communication. While each of these components are essential, this project will be focused only on identification, risk analysis, and a hypothetical implementation of control measures, due to the theoretical basis of the project. By systematically identifying and managing potential hazards, risk engineers can create a safer working environment, minimize the likelihood of accidents and injuries, and ensure the protection of assets and the environment. This proactive approach to hazard management is essential for maintaining operational integrity and preventing potential risks in various industrial sectors, especially high stakes environments such as a Martian colony [5].

Risk mitigation strategies are essential components of risk and safety engineering, focusing on the development and implementation of measures to minimize or eliminate potential risks and their adverse consequences. These strategies aim to reduce the probability of risk occurrence and mitigate the impact of any potential incidents. Effective risk mitigation strategies often involve a combination of proactive planning, risk control measures, and contingency plans. Some key aspects of risk mitigation strategies include preventative measures, risk transfer, diversification, emergency response planning, and regular monitoring and review [7].

Lastly, a common misconception is the difference between a “hazard” and a “risk”. In the world of risk and safety engineering, “hazards” refer to potential sources of harm or adverse effects that can cause injury, damage, or negative impacts [8]. Broadly speaking, hazards can be either natural, such as earthquakes, floods, or fires, or they can be human made, such as toxic chemicals, machinery malfunctions, or unsafe working conditions. Identifying hazards is the first step in risk management, as it allows for the implementation of measures to eliminate or mitigate their potential negative consequences. Some hazards faced on Mars include radiation exposure, dust storms, and exposure to Mars’s limited atmosphere.

Risks, on the other hand, are the likelihood or probability that a particular hazard will cause harm or damage [8]. In other words, risks indicate the potential for loss or negative impact resulting from exposure to a hazard. Risks are often expressed in terms of the probability of an event occurring and the potential severity of its consequences. Managing risks involves not only identifying hazards but also assessing the probability of their occurrence and implementing strategies to reduce or control the likelihood and impact of these events.

Current Research Within this Field

Mental health of Astronauts

The study titled "The Burden of Space Exploration on the Mental Health of Astronauts: A Narrative Review" [9] aims to investigate the psychological and psychiatric impact of space exploration on astronauts. The researchers conducted a narrative review, summarizing existing literature on the topic. The study emphasizes the potential dangers of space missions, with a focus on physical and mental health implications. This study is important to include within a literature review to highlight the current, known hazards associated with space travel. While these hazards are primarily referring to zero gravity environments, there is still direct relevance to a colony on Mars.

Over the course of their narrative review, they found that microgravity and radiation are identified as major space perils affecting astronauts' health. The study outlines various health effects such as changes in cell structure, bone loss, altered immune response, cardiovascular dysfunction, cognitive dysfunction, and visual disturbances associated with these factors. The review also highlights emotional and interpersonal issues, including mood disorders, anxiety, reduced resilience, and interpersonal conflicts among space crew members. Prolonged isolation, routine disruption, and living in a confined environment contribute to psychological stress during space missions.

The study also discusses reported cognitive problems associated with space travel including the impact of space radiation on cognitive functions, including neurocognitive complications, memory impairment, and alterations in brain structure. It also touches on cognitive deficits associated with microgravity, though there are conflicting findings on whether it improves or impairs cognitive functions. It was reported that the cognitive disturbances increased the challenges of achieving quality sleep during space missions due to factors like discomfort, noise, and altered sleep-wake dynamics. Sleep alterations may lead to tiredness, reduced focus, and potential errors, emphasizing the importance of maintaining good sleep patterns for astronaut performance. Visual disturbances, potentially caused by radiation exposure and intracerebral pressure changes, are addressed.

Crew Health and Performance Exploration Analog

Although no completed studies have finished, NASA’s Crew Health and Performance Analog (CHAPEA) is a cutting-edge study intended to simulate year-long stays on the surface of Mars [10]. The three separate training exercises will consist of four crew members coming from a technical background, and they will be living in an isolated, 3D printed habitat of roughly 160 m^2. Throughout this mission, the crew will be conducting “spacewalks” and report back a plethora of factors on their physical and mental wellbeing.

The habitat will comprise individual living spaces for the crew, a kitchen, and designated zones for medical, recreational, fitness, work, and agricultural activities. Additionally, there will be a technical workspace and two bathrooms. Upcoming space exploration habitats could leverage 3D printing using additive construction technology, eliminating the necessity to transport substantial amounts of building materials through multiple flights.

Figure 1: Construction of CHAPEA [10]

To acquire the most precise data in the analog scenario, the analog mission will closely mimic Mars conditions, potentially incorporating stressors like limited resources, isolation, equipment malfunctions, and substantial workloads. Key crew activities during the analog may involve simulated spacewalks with virtual reality, communication tasks, crop cultivation, meal preparation and consumption, exercise, hygiene routines, maintenance work, personal time, scientific tasks, and sleep. The findings from CHAPEA and insights gained from the analog missions will enable NASA to assess the risk associated with the proposed exploration food system design concerning crew health and performance. This information will further guide NASA standards, vehicle mass and volume requirements, and resource-risk trade-offs for extended exploration missions.

Mars Desert Research Station

The paper titled "Human Factor Studies on a Mars Analogue During Crew 100b International Lunar Exploration Working Group EuroMoonMars Crew: Proposed New Approaches for Future Human Space and Interplanetary Missions" [11] explores the use of analogue research as a low-risk tool for understanding the challenges associated with human missions to Mars. This study was conducted at the Mars Desert Research Station (MDRS).

MDRS is a simulated Mars habitat and research facility located in the Utah, USA. It is operated by the Mars Society, a non-profit organization focused on human exploration and the settlement of Mars. Constructed in accordance with Mars Reference Mission guidelines [12], the MDRS consists of a habitat with an upper deck containing private staterooms, a galley area, workstations, and a meeting/eating area. The lower deck includes a laboratory, toilet, shower, and extravehicular activity (EVA) preparation rooms. The MDRS is utilized for short-duration analog studies, typically ranging from one to two weeks, providing a controlled environment for researchers to explore challenges associated with living and working on Mars. It offers a unique setting for conducting experiments related to psychology, physiology, performance, human-computer interaction, and other factors crucial for successful interplanetary missions. Crews at the MDRS engage in activities that mimic those expected during future missions to Mars, helping scientists and engineers better understand the complexities and requirements of human space exploration.

Figure 2: Mars Desert Research Sation overview [13]

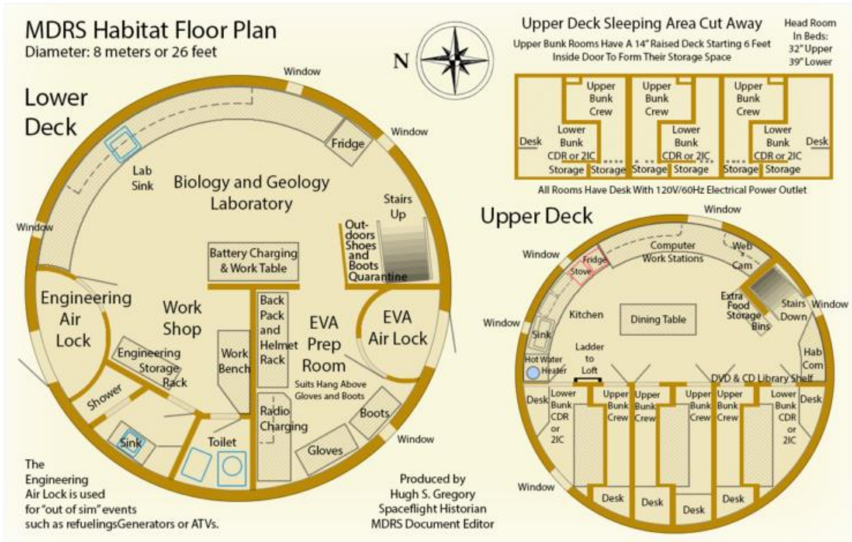

Figure 3: Mars Desert Research Station floor plan [13]

This study was conducted over 15 days and evaluated 15 human factors through subjective and objective means. These different human factors were quite varied and aimed to investigate team effectiveness, personal feelings, and the psychological effects of isolation. The 6 participants came from varied backgrounds and personalities. A breakdown of the mission profile is shown below.

Variables	Simulating habitat on surface of Mars
Number of crew members	Six
Crew gender and age	3:3; M:F (19–26 years)
Crew structure	Commander (cognitive, biomedical scientist, and emergency physician); health and safety officer; crew biologist (oral and medical physician); rover engineer (engineer); chief scientist (astrophysics); executive officer (engineer); Hab engineer (mechanical engineer)
Duration	Two weeks
Types of accommodations	Staterooms with work areas
International participation	2 Indians, 3 French, and 1 American
Maintenance	Power, electric, human waste, water
Tasking, scheduling, and control	All planning by crew members under the supervision of commander; mission supports logistics assistance; individual tasks, chores, and sleeping time open to individuals
Communications	Daily commander check-in report, commander report, chef report, science report, engineering report, journalist report. Also, posted with photos on public website
Mission timeline	General planning in 2 weeks preceding; crew did not meet prior; crew member replaced in final 2 weeks
Crew safety	Focus on fire and medical emergencies; flight surgeon on call
Habitat construction	Prefab panels assembled on site, ready for crew occupation

Figure 4: MDRS mission profile [11]

Following the 15 days of isolation, their findings were quantitative summarized into the following 12 points:

1. Sustaining genuine motivation or acting convincingly is beyond the capabilities of any crew over an extended period.

2. Crews recognize the significance of human factor research and are willing to invest substantial time if the study is perceived to yield meaningful results. The crew's Commander must provide a thorough overview of all experiments.
3. Crew members should not be compelled to participate in an experiment if they are unwilling to do so.
4. Remote imposition of experiments on crew members against their preferences should be avoided.
5. The potential for significant communication issues exists between crew members and the Mission Support team.
6. Communication latency poses a substantial obstacle to effective remote collaboration.
7. Specific crews may exhibit distinct strengths and weaknesses, providing an opportunity to suggest and test countermeasures for performance improvement.
8. Sharing meals and listening to music collectively enhances strength, motivation, and quality of teamwork, serving as countermeasures against work-related stress.
9. Due to limited medical training, biomarker analyses should be straightforward, utilizing easily accessible materials such as salivary biosensors and uncomplicated software.
10. Consideration should be given not only to the medical health but also to the oral health of crew members.
11. Planning human factor experiments requiring regular crew participation must account for the potential negative impact of a high workload, ensuring that the daily schedule is structured accordingly to prevent incomplete tasks.
12. Crew selection is a focal point in achieving a well-rounded set of skills and experience, prioritizing practical abilities, a strong work ethic, general professional skills, and interpersonal compatibility.

These lessons learned can be applied to both future analog experiments, like the one proposed in this report, and true long duration space missions. However, the fact that this study only spans 15 days could only be considered borderline “long duration”. This report, and the subsequent studies investigated, take some of the core principles learned from MDRS and increase the duration.

LUNARK

In a study titled “Social isolation in space: An investigation of LUNARK, the first human mission in an Arctic Moon analog habitat” [14], This study explores the social-psychological effects of social isolation and confinement in extreme environments, focusing on the experiences of two architects during a 61-day mission in Northern Greenland as part of the LUNARK project. The project aimed to simulate human life conditions in the first Moon analog habitat. The study aimed to explore the individuals' psychological experiences during prolonged isolation, particularly in the context of a simulated space expedition. This investigation is unique as previous research has predominantly focused on laboratory studies and relatively mild, short-lived forms of social isolation.

Figure 5: LUNARK Habitat [15]

The two male volunteers, who had previously participated in a 14-day stay in the Wadi-Rum desert as part of their training, were aged 23 and 25, both Danish. The LUNARK mission, which commenced on October 1, 2020, and concluded on November 30, 2020, involved various activities such as collecting ice, filming documentaries, conducting studies and experiments, and socializing within the habitat. The participants filled out a daily paper-and-pencil questionnaire for 47 of the 61 days, taking approximately 20 minutes each day.

The daily survey covered various behavioral and psychological variables, including emotions, need-threat, desire for social contact, loneliness, resignation, time perception, and daily activities. Desire for social contact was measured using a bipolar ad hoc scale. A separate scale was used to assess loneliness, but it was excluded due to low internal consistency. Resignation was measured using a scale adapted from previous research, and time perception was assessed using the Time Perception subscale of the Multidimensional State Boredom Scale [16].

Participants reported daily activities, and composite scores were calculated for specific constructs. Despite challenges like the harsh Arctic environment and the absence of internet access, the study aimed to provide fine-grained insights into the consequences of long-term social isolation and the coping strategies developed over time. The methodology allowed for a dynamic analysis of changes in participants' mental states and coping strategies throughout the mission. The study contributes valuable empirical data to the growing literature on the psychological effects of long-term isolation in extreme simulated environments, particularly those relevant to future space missions.

This study marked the first examination of a simulated human Moon expedition within an Arctic analog habitat. Upon analyzing their responses while in the habitat, connections were identified between daily activities and psychological factors associated with the extended social isolation typical of space missions. Specifically, engaging in discussions about personal matters was linked to lower levels of psychological resignation. Moreover, conversing about personal topics and engaging in physical exercise were associated with a heightened desire for social interaction, contrasting with tendencies towards social withdrawal. While a direct linear relationship wasn't found between increased isolation days and escalating negative emotions or psychological resignation, there was an observed increase in the desire for social contact over time. These findings could be valuable for shaping future training strategies and planning daily activities during extreme environment expeditions. Notably, activities such as discussing personal matters, leisure time, and physical exercise, although not directly work-related, could be emphasized as crucial elements in safeguarding individuals' psychological well-being against the detrimental impacts of prolonged social isolation.

The LUNARK project yield valuable data for multiple different studies. A separate study titled “Team effectiveness and person-environment adaptation in an analog lunar habitat” [17] was more focused on the relationship between the subjects, rather than the individual level. It concluded that maintaining healthy psychological relationships among team members working in an cramped and isolated environments for an extended period is a significant challenge, especially in the context of long-duration missions to the Moon and beyond. Using the psychological assessments conducted at various stages of the mission revealed substantial differences among team members in personality traits, personal values, and stress-coping factors. Notable variations were observed in NEO-PI-3 agreeableness and extraversion traits, as well as portrait values questionnaire stimulation, power, and achievement values.

The NEO-PI-3, or the NEO Personality Inventory-3, serves as a psychological assessment tool designed to evaluate personality traits. This inventory measures individuals across five key dimensions.

“Neuroticism” assesses emotional stability, impulse control, and anxiety, while “extraversion” gauges sociability, assertiveness, and activity levels. “Openness to experience” explores traits related to creativity, curiosity, and receptivity to new ideas. “Agreeableness” focuses on interpersonal relations, including cooperation, empathy, and altruism, while “conscientiousness” assesses characteristics such as organization, dependability, and goal-directed behavior. The NEO-PI-3 is often used in psychological research and workplace assessments to provide an insight into an individual's personality profile and exploring variations in tendencies and behaviors across these five fundamental dimensions [18].

Figure 6: LUNARK test subjects with habitat [15]

The questionnaire used in the study indicated consistency in high ratings for “passion” and “commitment” and “purpose and goals” scales, with low ratings on the “roles” scale. The study highlighted the leveling impact of decision authority, noting its detrimental effects on interpersonal interactions and work performance. Additionally, the interior design, featuring Earth-like materials, and the circadian lighting system were associated with improved work performance and relaxation. The study provided insight into how incompatibilities in personality traits and values can affect team performance, the challenges associated with decision authority in long-term relationships, and the human factors in habitat design that contribute to effective individual and team functioning.

While the LUNARK project yielded valuable results and was one of the first field-based isolation studies of its kind, it had notable differences from the Mars-Svalbard training base proposed in this report. First and foremost, these studies were more focused on the psychological impacts of a base of this nature. The test subjects were architects with no affiliation with any national space administration. While these studies aimed to research and document the subjects' experiences, the proposed project aims to train and prepare future astronauts for a mission. Furthermore, this experiment utilized a habitat specifically designed for the moon analog experiment. The Svalbard-Mars training exercise would take a Martian habitat that, as close as safely possible, mimics the actual base that will be used on Mars. Also, rather than use test subjects, the participants would ideally be astronauts that will soon be embarking on a true long duration mission. Although 61 days is a substantial time to be isolated in the Arctic, this project investigates the benefits of a multi-seasonal isolation training mission. This fundamental change in priorities shifts the focus from data gathering, but more practical training information. However, the different psychological questioners administered on the LUNARK subjects is an effective way to monitor the psychological conditions of the astronauts and ensure that they are an effective team.

Results and Discussion

The areas of discussion are centered on the stated research objectives.

Objective 1: Martian Engineering Hazard Identification

In order to first approach this problem, a broad overview of the Martian environmental and situational conditions must be analyzed. By treating Mars as a generalized engineering system with different hazards to mitigate, rather than an insurmountable planet, one can objectively identify the different areas that must be focused on to engineer a safe system. Considering this analysis is coming from the perspective to maximize human safety, psychological stresses and strains on the colonists are prioritized on equal footing with physical hazards. The hazards on Mars are divided into the following three categories:

- Environmental hazards
- Logistical and infrastructural hazards
- Psychological hazards

Martian Environmental Hazards

A core and unavoidable challenge associated with building a colony on Mars are the very harsh environmental conditions. The following hazards all link back to the ambient conditions on the planet.

Thin Atmosphere

Mars has an atmosphere that is about 100 times thinner than Earth's. This thin atmosphere primarily consists of carbon dioxide (95.1%), while also containing nitrogen (2.59%), argon (1.94%), oxygen (.16%), and carbon monoxide (.06%). This atmospheric pressure makes it inhospitable to humans without specialized life support systems. At this pressure, water boils at temperatures significantly lower than on Earth, rendering open-air breathing impossible and the chances of finding liquid water on the surface impossible. Furthermore, the low air pressure results in quite different wind speeds. Although average wind speeds have been recorded from 2-10 m/s during normal conditions and up to 30 m/s in dust storms, even the greatest wind speeds recorded would only exert the same pressure as a gentle breeze on earth, due to the atmosphere being 1% of Earth's [19].

The decreased wind pressure does not imply that Martian storms are not a serious hazard to infrastructure and safety. Due to the lack of natural wind blockers, such as trees or buildings, or Earth's atmospheric protection against strong winds, large dust storms can become an issue. Scientists have observed "planet-encircling" dust storms composed of tiny dust particles that have prompted them to suspend rover operations in the past. Martian dust storms are quite common, particularly in the southern hemisphere spring and summer. This seasonal warming generates increased winds that help to stir up the tiny surface particles. Typically, these dust storms stay isolated in a local area, but sometimes they propagate into worldwide events. Unlike Earthly dust storms, Mars's thin atmosphere and decreased gravity, permits these particles to stay airborne much longer. Resulting in decreased sun exposure and abrasive, low pressure winds [20].

A much less visible, but a potentially far deadlier hazard is the radiation exposure one would experience on Mars. Mars's thin atmosphere provides minimal shielding against cosmic and solar radiation. This exposes Martian scientists or colonists to elevated levels of radiation, which can be harmful to human health and a long-term colony would need to employ effective countermeasures. An instrument on NASA's Curiosity Mars rover monitors the radiation environment on the Martian surface and is designed to detect both cosmic and solar radiation sources. The following figure shows the first 10 months of radiation detection after its initial landing near Gale Crater.

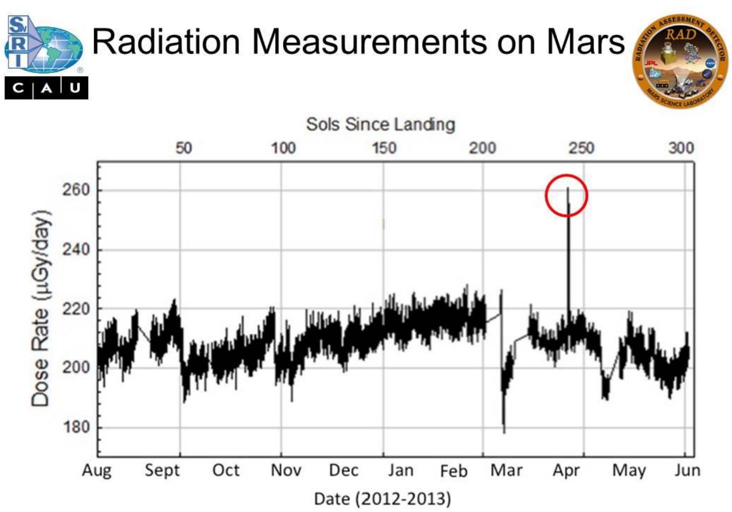

Figure 7: Daily radiation dosage on Mars [21]

The average surface radiation during this 10-month period was approximately 200-220 micrograys/day. In contrast, the average micrograys/day on earth is between 2.4-4.8 micrograys/day. It is difficult to estimate an average exposure level for Earth as a whole, due to your radiation exposure being highly dependent on elevation, location, and environmental conditions, but this suggests radiation exposure on Mars is between 40-80 times higher than that on Earth [21].

Using an instrument on NASA's Mars 2000 Odyssey spacecraft and Mars's surface elevation from NASA's Mars Global Surveyor, a global radiation map was estimated. There is a strong correlation between elevation and radiation levels because low elevation locations have more atmosphere above them to block some of the radiation [23]. This global map is shown below.

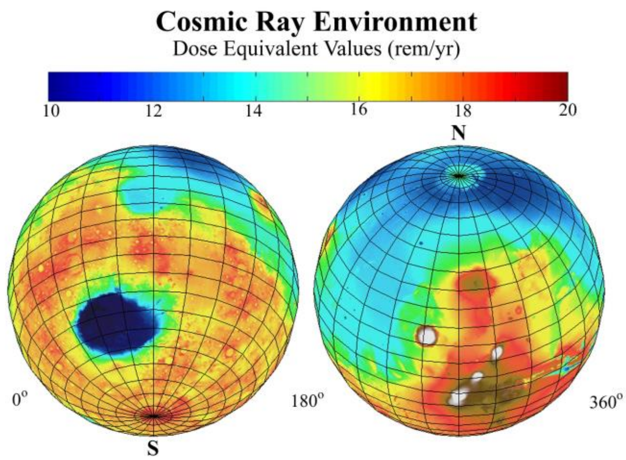

Figure 8: Global Mars Radiation Map [23]

The preceding figures describe radiation in different ways, with the Curiosity rover measuring radiation absorption (the radiation traveling through someone) and the planetary map utilizing dose equivalence (combining the radiation absorption and the medical effects of that type of radiation).

The average dose equivalence on Mars is generally between 10-20 rems. This falls well beyond the average experience on Earth, which is only .62 rem [22]. It should also be noted that the value experienced on Earth also includes manmade sources of radiation, including medical, commercial, and industrial systems. Thus, even after including manmade sources, the average dose equivalence is between 16-32 times greater on Mars.

Extreme Temperatures

A Martian colony will also experience extreme temperature fluctuations due to its thin atmosphere, lack of greenhouse gasses, and axial tilt. These factors cause exceptionally low temperatures on the surface, particularly during the long Martian winter. At its coldest, temperatures can plummet to -195C at the poles. At temperatures this low, vital life support systems are in danger of freezing and damage, even with external sources of heating. The Martian atmosphere is also largely incapable of retaining heat, so the surface temperature is dependent on its sun exposure. The following figures demonstrate the extreme temperature fluctuations seen between day and night.

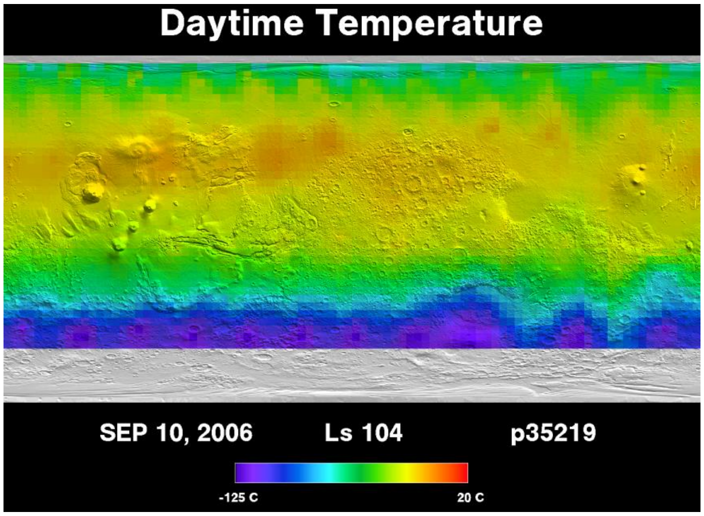

Figure 10: Daytime temperatures on Mars [24]

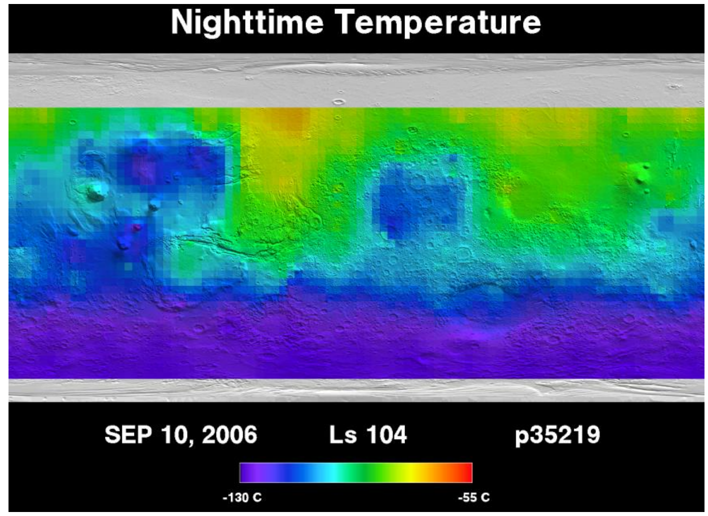

Figure 9: Nighttime Temperatures on Mars [24]

Even along the equator, there are substantial temperature swings, changing by nearly 100C in the span of a few hours. This daily temperature fluctuation will cause increased stress on materials and energy systems.

Life Support and Habitability

The goal of establishing a colony on Mars, presents a multitude of complex challenges. One of the core tasks is to ensure the survival and well-being of colonists in the face of Mars' harsh environmental conditions. Central to this endeavor are the twin challenges of life support and habitability.

The thin Martian atmosphere is composed primarily of carbon dioxide, with negligible levels of oxygen [19**Error! Reference source not found.**]. Consequently, colonists on Mars would be unable to breathe the Martian air, necessitating the development of advanced life support systems to provide a continuous supply of breathable air. These life support systems must achieve two primary goals: the removal of carbon dioxide exhaled by colonists and the generation of oxygen for their respiration. To achieve this, technologies for carbon dioxide removal and oxygen generation are essential components of Martian habitats. In the isolated environment of Mars, where resupply missions from Earth would be infrequent, these systems must be highly efficient, reliable, and designed for long-term sustainability.

Recent breakthroughs with in-situ resource utilization (ISRU) is one method to reduce the mass and cost of planetary missions. The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 rover *Perseverance* has produced breathable oxygen from atmospheric carbon dioxide via solid oxide electrolysis. The system used a high efficiency particulate air filter to filter Martian dust from the system. While a similar system designed to support a human would have to be around 100 times the size, demonstrating the ability to extract breathable air from the harsh Martian atmosphere was an important first step [25].

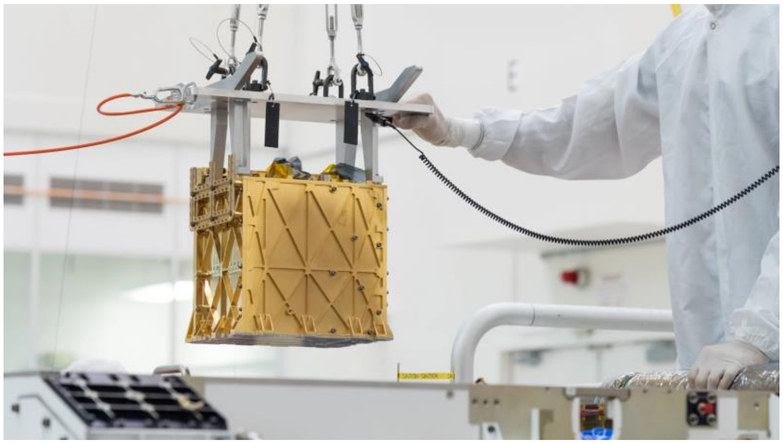

Figure 11: Mars Oxygen ISRU Experiment being loaded into Perseverance [25]

However, breathable air is only one facet of life support. Another significant challenge lies in maintaining a suitable atmospheric pressure within habitats. The atmospheric pressure on Mars is a mere 0.6% of Earth's, a level incapable of supporting human life. To prevent bodily fluids from boiling at these lower pressures, habitats must maintain higher internal pressure, a technical feat that poses additional challenges.

Moreover, Mars' thin atmosphere offers limited protection against the harmful radiation that pervades space. Cosmic and solar radiation, which can be detrimental to human health and equipment, must be effectively shielded against. Habitat design, therefore, requires integration of radiation shielding materials, such as regolith or specialized composites, to ensure the safety of colonists and critical equipment.

Temperature is another significant aspect of habitability on Mars. The planet experiences extreme temperature fluctuations due to its thin atmosphere and lack of greenhouse gasses. Frigid Martian nights can see temperatures plummet to -195°C (-319°F), while daytime highs only slightly exceed freezing. To create comfortable living conditions, habitats must incorporate efficient insulation to retain heat during cold nights and prevent overheating during the day. Climate control systems are vital for maintaining stable temperatures and humidity levels.

Resource constraints on Mars present yet another habitability hazard. The planet lacks readily available resources such as water. Colonies must either transport essential supplies from Earth or develop technologies for resource utilization, such as mining water ice from Martian soil. Achieving self-sufficiency in resource utilization is a key goal to reduce reliance on Earth for resupply. As the establishment of a Martian colony is envisioned as a long-term endeavor, the sustainability of life support systems over extended periods becomes paramount. The closed-loop systems that provide for human needs, including air, water, and food, must be robust and capable of continuous operation. Reliability, redundancy, and fail-safe mechanisms are non-negotiable requirements for the survival of colonists.

The challenges of life support and habitability when building a colony on Mars are complex and demanding. They require advanced engineering solutions, robust systems, and a comprehensive understanding of Martian environmental conditions. In addressing these challenges, the design and construction of Martian habitats become critical endeavors. Colonies on Mars may opt for various architectural strategies, including underground habitats or those with buried sections. These approaches offer added thermal stability and radiation protection, crucial for long-term human habitation.

Martian Logistical and Infrastructural Hazards

Resource Limitations

Two paramount hazards inherent to the vision of a sustainable Martian colony are resource limitations and the development of critical infrastructure. These two challenges often go hand in hand: infrastructure is required to acquire scarce resources and the scarce resources are required to build the infrastructure.

Mars lacks readily available water, fertile soil, and an abundance of natural resources. This resource deficit necessitates that future Martian colonists bring or generate these essentials locally to sustain human life and colony operations. Water is a prime example. While there is evidence of water ice on Mars, it is not easily accessible. Colonists will need to develop innovative techniques for mining and processing this ice for drinking, agriculture, and the production of oxygen and hydrogen. The location of subsurface ice has been studied by NASA’s SWIM project. This can be seen in Figure 12, and the location of the subsurface ice must be considered when determining a colony location. The varying depth of this ice has also been determined and is shown in 13. It goes without saying that near-surface ice is advantageous. Similarly, fertile soil for farming is in short supply and must be manufactured. Martian pioneers will need to devise strategies for cultivating crops in the Martian soil which lacks the nutrients found in Earth's soil, and access to water is one of the first steps in starting this process.

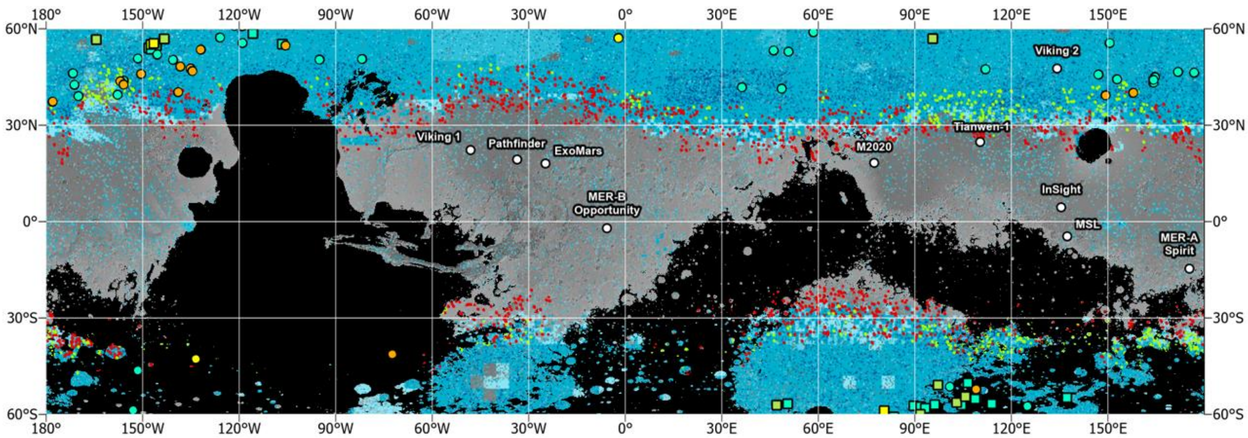

Figure 12: Mars SWIM Project Map of ice consistency across the study area; blue areas indicate presence of ice, red areas contain no ice [26]

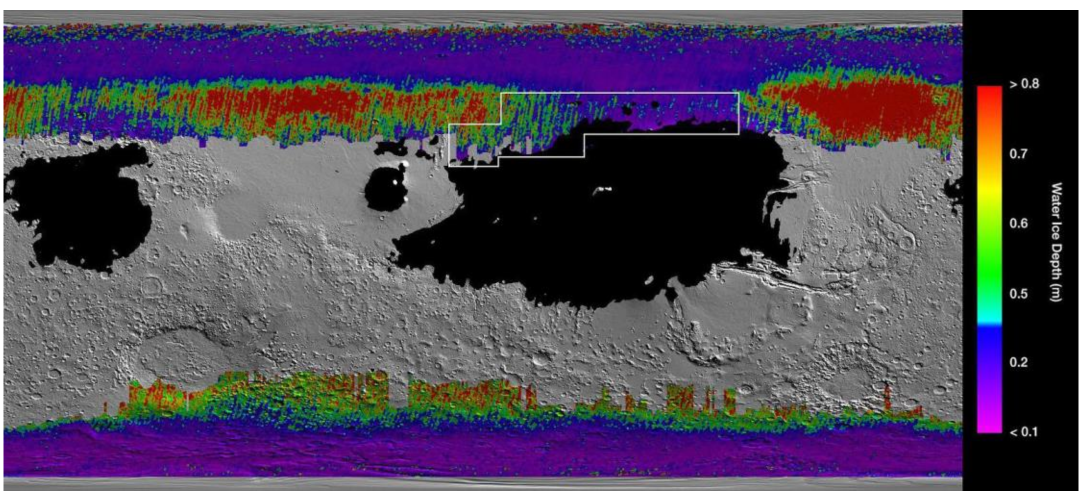

*Figure 13: Subsurface ice/water depth [27**Error! Reference source not found.**]*

Building Infrastructure

Infrastructure is the backbone of any society, and on Mars, its construction presents a unique set of challenges. The first challenge is the hostile Martian environment. Extreme temperature variations, thin and unbreathable air, and exposure to cosmic radiation make surface operations treacherous. Colonists must design and construct habitats that can withstand these harsh conditions. Innovative materials and building techniques are required to ensure structural integrity and radiation protection. The adaptation of

3D printing technology for construction purposes holds promise for on-site fabrication of habitats and infrastructure, reducing reliance on materials transported from Earth. Communication infrastructure must also be established to facilitate data transmission between the Martian colony and Earth. The inherent time delay in signal travel between the two planets requires the development of robust and reliable communication systems. To address these hazards collaboration between engineers, scientists, and researchers from various fields is essential.

Transportation

Transportation infrastructure is equally critical. Efficient transportation systems are needed for the movement of people, equipment, and resources across the Martian surface. Rovers and vehicles must be designed to operate in the low-gravity environment and navigate rugged Martian terrain.

The rugged Martian terrain poses a substantial risk to rovers and mobility equipment. Rovers must endure abrasion, mechanical stress, and punctures while traversing uneven surfaces. Furthermore, Mars is notorious for its planet-wide dust storms, which can obscure vision, erode equipment, and hinder navigation. Abrasive Martian dust can infiltrate machinery, leading to mechanical failures. Considering that a rover breakdown can quickly lead to a life-threatening situation, a colony would need to employ strict safety radius rules and ensure that multiple rovers can be in the field at all times.

Logistics

Mars's lack of essential resources, notably water and fertile soil, necessitates resource utilization systems. The failure of these systems could lead to critical shortages, endangering the colony's sustainability. To establish a permanent presence on Mars, a colony must be self-sustaining, or at least partially so. The road to Martian self-sustainability will be lengthy and challenging. Disruptions in the supply chain from Earth, be it due to mission failures or logistical mishaps, can leave the colony without vital resources. For the immediate future, stringent supply chain management is requisite. The logistics chain will be dependent on Earth for anything that cannot be produced on Mars. Assuming the technology is developed to produce food, oxygen, water, and fuel, all medical supplies, engineering components, construction material, and more will be dependent on Earth for a steady stream of resupply. In the status quo, this will be exorbitantly and prohibitively expensive. This also produces a very delicate and dangerous system. If contact is cut with Earth, the colonists on Mars will quickly run out of resources.

Energy Generation

Energy generation is a cornerstone of any human settlement, and a Martian colony is no exception. On the Red Planet, however, energy generation poses unique challenges that demand innovative solutions. While Mars is equipped with abundant sunlight due to its proximity to the sun, the thin atmosphere and frequent dust storms introduce substantial variability in solar energy availability. Dust storms can obscure sunlight for extended periods, reducing energy input and impacting power generation. The Martian surface is coated with fine dust particles that can settle on solar panels, diminishing their efficiency over time. The static charge on dust particles further complicates this issue, making them adhere to surfaces. To mitigate this challenge, Martian colonies must deploy efficient solar panel cleaning mechanisms and advanced tracking systems that optimize the collection of available sunlight and minimize the amount of unnecessary astronaut cleaning missions. Innovative materials that resist dust adhesion may also be employed to minimize the impact of dust accumulation. Energy storage solutions, such as high capacity batteries or regenerative fuel cells, are essential for storing surplus energy during periods of high solar input for use during storms or nighttime.

The risks associated with a colony-wide loss of power are substantial. Unlike Earth, a loss of power could quickly cause one to freeze to death or run out of oxygen. While proper safety measures to track sunlight and minimize dust buildup will be taken, long term energy storage and redundancy are critical. Energy storage solutions must be robust enough to supply power during extended periods of darkness or dust storms, while redundancy is essential to ensure uninterrupted energy supply. Martian colonies should deploy redundant energy generation systems, such as backup solar arrays or even nuclear power sources, to maintain a stable power supply. Advanced energy storage technologies like high-capacity batteries or regenerative fuel cells should be incorporated into the energy infrastructure to store excess energy and provide backup power during energy shortfalls.

A Martian colony must aim for long-term sustainability. Therefore, energy generation systems must operate efficiently and durably over extended periods to support colony growth and self-sufficiency. Thus, incorporating advanced, durable materials and components into energy generation infrastructure is key to ensuring long-term sustainability. Overcoming these hazards is vital for the colony's energy security, sustainability, and overall success in the harsh Martian environment.

Martian Psychological Hazards

Establishing a self-sustaining colony on Mars comes with the intricate challenge of managing the psychological well-being of the colonists, given the extreme isolation and confinement they will experience. Communication is the lifeline of any human settlement, but the vast distance between Mars and Earth introduces communication delays that can impact every aspect of life on the Red Planet. This discussion explores the multifaceted challenges associated with isolation and the psychological impact on a theoretical Martian colony.

First and foremost, Martian colonists will experience unprecedented isolation, cut off from the rest of humanity for extended periods. The remoteness of Mars means that communication with Earth will have substantial time delays, potentially causing feelings of isolation and loneliness. Mars and Earth are separated by varying distances, depending on their positions in their respective orbits. Consequently, communication signals can take between 4 and 24 minutes (one-way) to travel, leading to significant delays in real-time communication. This delay can hamper everything from scientific research to emergency responses. To address this challenge, colonies must develop robust communication infrastructure. Regular video messages and data exchange with Earth can help bridge the emotional distance. Additionally, establishing strong interpersonal relationships within the colony can provide emotional support.

Strong relationships between the initial colonists are essential, considering the Martian habitat's inherently limited living space. The confined environment can lead to feelings of claustrophobia and a lack of personal privacy, potentially contributing to stress and interpersonal conflicts. Therefore, habitat design should prioritize comfort and personal space to the extent possible. Rotating work and living areas, incorporating recreational spaces, and providing private quarters can help alleviate the psychological impact of confinement.

Considering the small living environment, life on Mars will likely be characterized by routine and monotony. The repetition of tasks and the absence of diverse experiences could lead to boredom and disengagement. Therefore, it is essential that colonies should invest in providing a variety of recreational activities and hobbies to keep colonists engaged and mentally stimulated. Scheduled breaks, cultural events, and creative outlets can add diversity to daily life.

The psychological impact of communication delays cannot be overstated. These different factors could all contribute to stress, anxiety, and other mental health issues. Martian colonists may experience mental health challenges such as depression, anxiety, and interpersonal conflicts due to isolation and confinement. Access to mental health professionals and adequate healthcare facilities is crucial.

Furthermore, mental health team should be an integral part of the colony's staff. Telemedicine services can offer psychological support and consultations with Earth-based mental health experts, but the communication lag can hinder real-time diagnosis and treatment. Medical emergencies require swift decisions and actions, which may be impeded by communication delays. Therefore, a local medical team trained in emergency procedures should be able to act promptly in critical situations, with remote assistance from Earth-based medical experts. Regular psychological and physiological check-ups can also help identify and address issues proactively.

The psychological challenges of isolation and confinement in a theoretical Martian colony are intricate and must be addressed proactively. Through thoughtful planning, robust support systems, and interdisciplinary cooperation, Martian colonies can create an environment that prioritizes the psychological well-being of colonists, ensuring that they thrive emotionally and mentally. The success and safety of the colony depend on advanced planning, resilient infrastructure, clear protocols, and the development of innovative technologies that enable effective communication despite the vast interplanetary distances. Martian colonies must navigate these challenges to thrive and ensure the viability of human exploration beyond our home planet.

Mars Risk Impact Study

While a Martian colony is still fully theoretical, the risks that it will face are very real. The field of safety engineering has many different models and approaches to quantify the severity of risks and outline mitigation strategies. A typical way to perform risk assessment is by developing a matrix for each category bordered by severity and frequency [28]. The risk evaluation will be performed by comparing the results of the risk analysis with risk acceptance criteria to determine whether the risk is acceptable or not. The categories are split into three regions: the unacceptable region, tolerable region, and acceptable region. The unacceptable region (high risk) encompasses risks that fall above acceptance criterion. Risk reducing measures must be implemented at this level. Next, the tolerable or as low as reasonably possible region (medium risk) are risks that fall between the acceptance criterion and the goal. Risk reducing measures should be implemented as long as they are practicable, and the associated costs are reasonable. Lastly, the broadly acceptable region (low risk) are risks that are accepted in this context. Risk reducing measures are not required at this point. Considering the consequences of this investigation, the risk tolerance is very conservative. This risk assessment will investigate the risk to infrastructure and human life based on the following criteria.

Table 1: Hazard classification

Nr	Severity	Consequnces for humans	Consequnces for infrastructure/technology
E	Very High	Physical or psychological injury with permanent damage or potentially deadily outcome/many serious or very serious outcome	Irrepairible damage to habitat, transportation, or equipment that renders it useless
D	High	Physical or psychological injury with potential of permanent damage that needs to be treated by perfessionals	Irrepairible damage to habitat, transportation, or equipment that severely limits its useablilty
C	Medium	Physical or psychological injury that needs treatmeant by professionals, or many less serious injuries	Repairible damage to habitat, transportation, or equipment that requires immediate repairs to restore functionality. Can lead very serious consequnces if left untreated
B	Low	Small local injury with no permanent damage that could be treated locally	Minor, repairible damage to habitat, transportation, or equipment that has a limited impact on immediate useage. Can lead to serious issues if left unrepaired for for an extended perioud
A	Insignificant	Minor superficial injury that causes discomfort but does not need to be treated	Minor superficial damage. Does not impact immediate funcionality, but should be repaired when time allows

After characterizing the consequences of the different hazards, the assessment is then broken into different categories based on its likelihood. This is shown in Table 2.

Table 2: Hazard and probability relationship

Very likely	5					
Likely	4					
Possible	3					
Unlikely	2					
Near impossible	1					
		A	B	C	D	E
		Insignificant	Low	Medium	High	Very High

After defining the different categories for the risk mitigation table, they can be implemented. This risk mitigation system works by identifying the hazard and the effects of the hazards, and then observing how the risk is decreased after a mitigation measure is implemented. An example of this risk mitigation system applied to the environmental hazards, logistical and infrastructural hazards, and psychological hazards is seen below.

Table 3: Risk Matrix for Martian Environmental Conditions

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Enviormental Conditions	Radiation Exposure	Crew health: Radiation sickness/cancer	Lack of Martian atmosphere provides minimal protection to cosmic and solar rdiation	Advanced Radiation Shielding/underground habitat design	E4
		Habitat Health: Damage to electronics	Increased risk of damage to electronics in the case of heightened solar activity	Advanced Radiation Shielding/underground habitat design	B3
	Extreme Temperatures	Crew health: hypothermia	Extreme temperatures that will quickly cause hypothermia and death in the event of loss of heating	Highly redundant heating systems and habitat with advanced insulation properties	D3
		Habitat Health: Extreme temperature swings (+/- 50C/day) causing increased mechanical strain on system	Highly fluctuating temperatures can cause increased mechanical strain on system	Habitat design must be capable of functioning in extreme low temperature	C2
	Lack of breathable air	Crew Health: suffocation	Lack of breathable air on Mars	Highly redundant/reliable oxygen processing systems	E3
	Dust storms	Crew Health: Loss of power due to solar panel coverage	Dust buildup on solar panels can reduce or eliminate energy generation. Sky can also become obstructed for extended periods of time	Redundant power/backup battery systems and self cleaning features for the solar panels to reduce unneccessary EVA missions	D2
		Habitat Health: Abrasion and dust buildup	Abrasion to habitat due to combined sustained loading of wind and dust particles. Dust acumulation can damage electronics	Routine inspections on all critical components, replacement parts for critical components, and abrasion resistant materials	B2

Table 4: Risk Matrix for Martian Logistical and Infrastructural Hazards

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Logistical and Infrastructural Hazards	Resource Limitations	Lack of water	A lack of liquid surface water dictates landing site selection and increased reliance on water processing technology and an increased risk in the face of technical failure	Habitat location should be chosen based on proximity and accessibility of subsurface, ice water, habitat should have advanced water recycling systems	D3
		Lack of building materials and natural resources	Dependancy on resupply from Earth and inability to replace and repair the habitat during emergency situations	Multiple supply/delivery missions prior to human arrival and advanced in-situ processing technology	B3
		Lack of fertile soil	Substantial habitat enviorment committed to food production, risk of food shortage and starvation, lack of healthy or varied diet, psychological strain due to lack of varied diet	Large supplys of emergency, freeze dried food transported from Earth, streamlined and systematic growing system, transported vitamens and occassional specialty food	C4
		Lack of food	Risk of starvation if lack of supplies from Earth, inability to produce sufficient food, or spoilage of food supplies	Large emergency supplys of food from Earth, advanced and efficient year round farming methods, foolproof food sotrage methods	D4
		Lack of oxygen	Risk of suffocation in the case of technical failure, inability to produce fuel for equipment or spacecraft	Highly redundant oxygen producing system with backup supplies, location selection near subsurface ice water for processing	E4
	Transportation Issues	Dependancy on rovers to traverse Martian surface	Life threatening situation if rover stuck, runs out of power, breaks, etc	Multiple rovers in service, routine maintenance inspections, strict maximum safety radius	C2
	Energy Generation	Energy and life support issues with Habitat	Risk of hypothermia, lack of comunication with Earth, suffocation, and loss of life support during loss of power event	Independent and redundant energy generation systems utilizing mulitple methods to generate energy and backup battery supplies in the case of generation failure	D2
	Earth Dependency	Dependancy on Earth resupply	Risk of supply shortage, dependancy on continued Earth funding	Substantial reserve supplies stored and consistent resupply missions	D3

Table 5: Risk Matrix for Martian Psychological Hazards

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Psychological	Personal Issues	Feelings of Isolation	Increased risk of depression, decreased productivity, isolation from crewmates, detachment from Earth	Regular video/audio messages to family, strong bonds between crew prior to departure, experience and training to identify onset	C3
		Depression/Anxiety	Decreased emergency prepardness/response, suicide risk, increased stress	Access to Earth-based telemedicine, quaiified thereapists/health professionals as part of crew	D4
		Boredom/disengagment	High levels of monotony, adherence to routine, lack of variation in environment, lack of variety in food, confined environment	Scheduled breaks, cultural events, creative outlets, recreational activites, ability to pursue hobbies, scheduled days to stay busy, testing various personal interests	B3
		Issues Sleeping	Tiredness, irritability, increased risk of accident, decreased response time	Adapt to Martian day/night cycle, access to sun lamps, sleeping aides, medication	B3
	Group Issues	Team conflict	Frustration among team members, ineffective communication, poor teamwork, physical altercation, lack of personal space, irritability	Confirmation of team performance in isolation, field experience as a team, conflict deescalation skills, testing different leadership structures prior to departure	B2

This risk mitigation model could be greatly improved after gathering data to base the probability and consequence ratings from. While its inclusion within this study is to demonstrate its usage and practicality when organizing risk mitigation strategies and the hazards and mitigation measures are very real, the calculation of the risk is unfortunately based on semi-arbitrary assumptions.

Objective 2: Svalbard Hazard Identification and Comparison to Mars

Following hazard identification on Mars, a similar process will now be conducted on Svalbard to compare the hazards faced by these two desolate colonies.

Svalbard is an archipelago located in the Arctic Ocean, situated about midway between mainland Norway and the North Pole. It is a territory of Norway, although there are certain international treaties governing its status. Situated at high latitudes in the Arctic region, the archipelago spans a range of latitudes, but the main islands, including Spitsbergen, where the largest settlement Longyearbyen is located, are roughly between approximately 74° to 81° North latitude. Longyearbyen is at a latitude of around 78° North. This high latitude means that Svalbard experiences extreme Arctic conditions, including long polar nights in winter and midnight sun during the summer. The variation in daylight is a result of the Earth's axial tilt and its orbit around the sun, creating these unique patterns of sunlight and darkness at high latitudes.

The Svalbard archipelago consists of several islands, the largest of which are Spitsbergen, Nordaustlandet, Edgeøya, and Barentsøya. Svalbard has a polar climate, characterized by extremely cold temperatures and long, harsh winters. Even during the summer months, temperatures can remain quite low. A topographic overview of Svalbard is seen below in Figure 15.

In addition to the temperature and isolation, Svalbard is defined by its extensive ice cover and unique geography. The archipelago is known for its rugged and glaciated terrain, with fjords, mountains, and glaciers dominating the landscape. Notable features include the Austfonna, the largest ice cap in the Eurasian Arctic, and various glaciers on Spitsbergen, including the Hornbreen and Von Postbreen. These glaciers flow from the central mountainous areas, shaping the rugged terrain and contributing to the archipelago's icy character. The presence of ice fields adds to the overall frozen expanse, creating a challenging environment covered by permafrost. Sea ice is a significant component, covering the surrounding waters, influencing maritime activities, and impacting the movements of marine life. Icebergs, breaking off from glaciers or ice shelves, can be observed in the Arctic waters around Svalbard.

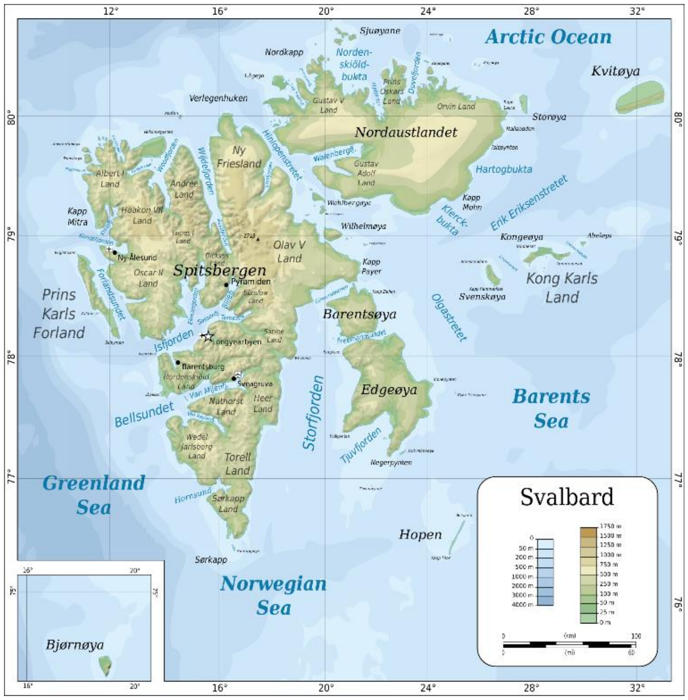

Figure 14: Map of Svalbard [29]

Svalbard Environmental Hazards

Svalbard presents harsh environmental conditions characterized by extreme cold temperatures, long polar nights, rugged terrain dominated by glaciers and ice caps, and isolation. The archipelago experiences frigid winters with temperatures often dropping well below freezing, creating challenging conditions for both wildlife and human inhabitants. Long polar nights during winter and continuous daylight in summer contribute to the extreme variations in sunlight. Additionally, the presence of permafrost, sea ice, and icebergs further shapes the challenging Arctic landscape. These conditions are exacerbated by the remote and isolated nature of Svalbard. When comparing these harsh conditions to Mars, similarities can be drawn in terms of extreme cold temperatures, isolation, and challenging terrain. Both environments require adaptations for survival, making Svalbard's extreme conditions a terrestrial analogue for studying the challenges that may be encountered in future Mars exploration and colonization efforts.

Thin Atmosphere and Radiation

Radiation exposure is generally greater at the Earth's poles compared to other latitudes. This increased radiation is primarily due to the configuration of the Earth's magnetic field.

The Earth's magnetic field helps protect the planet from the solar wind. Near the equator, the magnetic field lines are more parallel to the Earth's surface, providing a more effective barrier against these charged particles. However, near the poles, the magnetic field lines are more perpendicular to the Earth's surface, allowing more solar particles to penetrate the atmosphere. This phenomenon results in an increased likelihood of charged particles interacting with the Earth's atmosphere near the poles. This means that the polar regions experience higher levels of radiation compared to other latitudes [30].

While the radiation levels at the Earth's poles are higher than at the equator, they are still far lower than the radiation levels on celestial bodies like Mars, which lacks a strong magnetic field and thick atmosphere to provide substantial protection from solar and cosmic radiation. Due to this reason, radiation exposure and atmosphere composition will not be considered when determining a location for the Mars-Svalbard training location. Furthermore, intentionally exposing trainees to increased levels of radiation is counterproductive to the mission and unnecessarily dangerous, regardless of if a Mars-Earth analog was possible.

Extreme Temperatures

Svalbard grapples with extreme temperatures during its prolonged winter months. Average temperatures can plummet well below freezing, ranging from -15C to -25C, with a record temperature as low as -50C. The polar nights exacerbate these harsh conditions, contributing to an environment where the combination of low temperatures and biting Arctic winds can lead to dangerous wind chill factors. The heightened risk of frostbite becomes a significant concern, as exposed skin can freeze quickly in such severe cold. Annual temperature averages and winter temperature averages for Svalbard can be found below in Figure 15 and Figure 16. However, it should be noted that the Arctic is one of the areas on Earth most influenced by climate change and these temperatures are now warmer and will continue to increase.

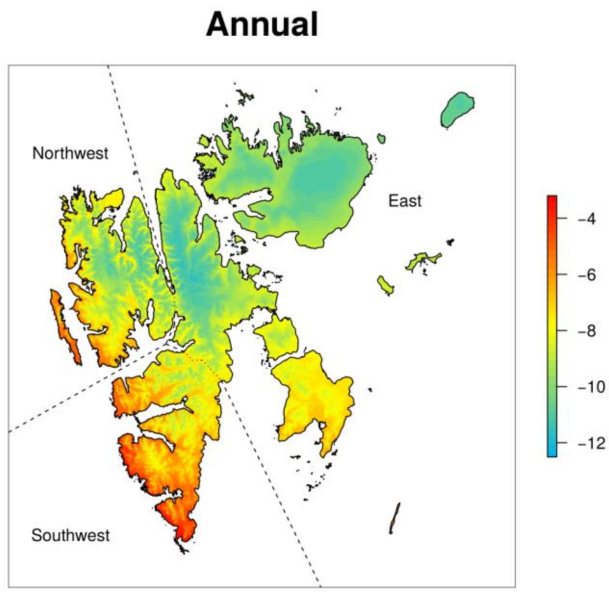

Figure 15: Annual temperatures averages on Svalbard (1971-2000) [31]

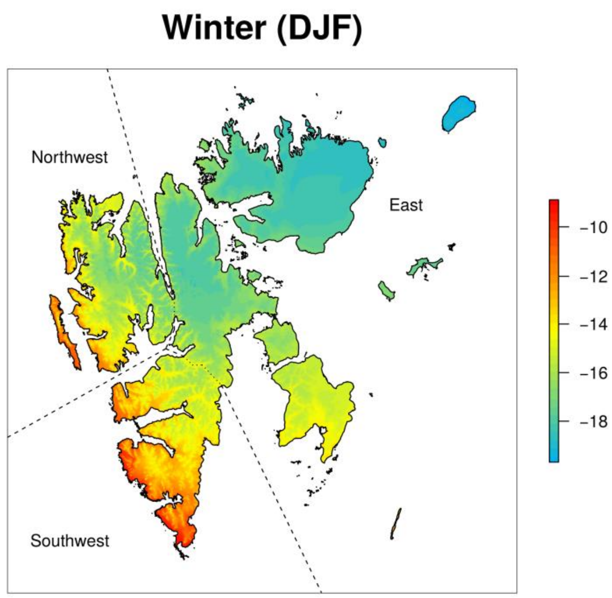

Figure 16: Winter temperature averages on Svalbard (1971-2000) [31]

In comparison, Mars maintains an overall colder climate, with average surface temperatures around -62C The thin atmosphere on Mars, mainly composed of carbon dioxide, results in rapid temperature fluctuations between day and night. While wind chill is not a factor on Mars due to its thin atmosphere, the persistent cold presents continuous challenges for any potential human exploration. The thin atmosphere also contributes to the lack of an atmospheric buffer against solar and cosmic radiation.

The key distinction between Svalbard and Mars lies not only in their temperature extremes but also in the atmospheric conditions. Svalbard's thicker atmosphere, while contributing to wind chill concerns, allows for more moderate day-night temperature changes. Despite the dangers of extreme cold and frostbite on Svalbard, the thin atmosphere of Mars creates a more hostile environment with pronounced temperature variations and constant exposure to frigid conditions. Both locations pose challenges with extreme temperatures, but the inclusion of frostbite risks on Svalbard emphasizes the critical need for protective measures in the Arctic environment. Mars, with its thin atmosphere, presents unique challenges that extend beyond temperature extremes, most notably being unbreathable air.

In addition to the cold temperatures, Svalbard is known for high wind speed due to the gulfstream currents, lack of vegetation, and open sea surrounding the islands. The cold temperatures on Svalbard quickly become more dangerous when wind chill is factored into the equation. Based on estimates from NOAA, the adjusted temperature can be found below.

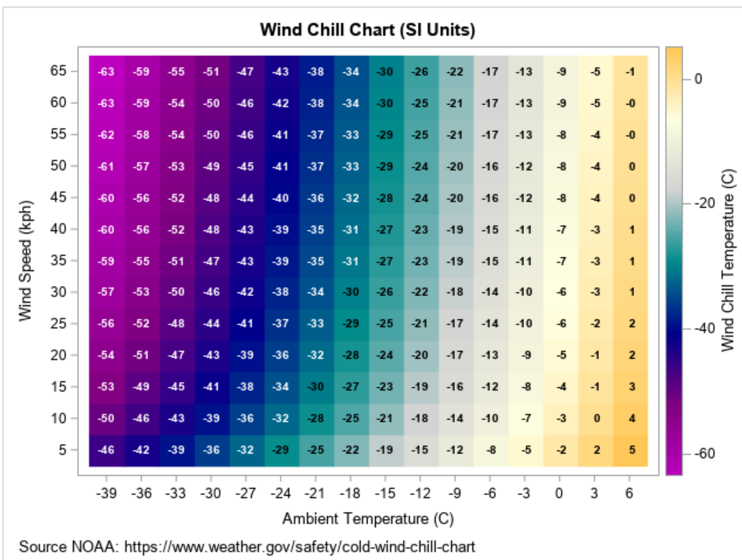

Figure 17: Wind chill chart [32]

At these temperatures, frostbite on exposed skin will occur within minutes. Therefore, while one may not have to don a space suit to exit a habitat in an isolated habitat on Svalbard, leaving warm shelter without the proper winter gear and protection can quickly lead to serious injury or death. This necessity of winter equipment and the danger of prolonged exposure to the elements is one of the most compelling analogs between Svalbard and Mars.

Life Support and Habitability

Svalbard and Mars present distinct challenges related to life support and habitability, rooted in their differing atmospheric conditions, climates, and planetary characteristics. Svalbard obviously does not parallel Mars in all aspects, such as the radiation dangers or lack of breathable air. However, its extreme Arctic climate, with frigid temperatures and long polar nights, poses unique challenges for maintaining habitable conditions.

On the other hand, Mars, with its thin atmosphere primarily composed of carbon dioxide, lacks the atmospheric density necessary to support human life. The absence of a breathable atmosphere and the extreme cold temperatures present significant hurdles for habitation. Life support systems on Mars must address not only the provision of oxygen but also the challenges associated with temperature regulation, radiation exposure, and the need for sustainable resources.

Svalbard's challenges are more centered around adapting to the existing Arctic environment, while Mars demands the creation of life support systems capable of overcoming the inhospitable conditions inherent to the planet. Both environments require advanced technologies and comprehensive life support strategies to enable sustained, isolated, and independent human presence. To best replicate a Martian scenario, a mock-Mars habitat could be delivered to the desired training location by helicopter.

Svalbard Logistical and Infrastructural Hazards

Resource Limitations and Building Infrastructure

Resource limitations and building infrastructure present distinct challenges on Mars and Svalbard, stemming from the unique characteristics of each environment. On Svalbard, the challenges lie in harnessing and managing available resources in the remote Arctic setting. The archipelago faces limitations in terms of fertile land, liquid freshwater sources, and the availability of certain materials essential for construction. All building supplies must be delivered to Svalbard from mainland Norway, only highly specialized animals are capable of survival, and all crops must be grown inside greenhouses. The only resource relevant to this mission that Svalbard has in abundance is water, and this is frozen for most of the year. The need to carefully manage these resources is crucial for sustaining the small human population and supporting scientific research activities.

Mars presents an even more extreme scenario, characterized by a scarcity of resources essential for human survival. The thin Martian atmosphere lacks the necessary oxygen, and the planet's surface is devoid of liquid water. Choosing a landing site with access to ice water is essential. Building infrastructure on Mars involves addressing the challenge of resource extraction and utilization, including sourcing materials for construction, generating oxygen, and developing sustainable water sources. Martian habitats would need to rely on advanced technologies for recycling and repurposing limited resources, as transportation from Earth is both logistically complex and resource intensive. In order to best replicate the Martian scenario in a training exercise, it is important to adhere to the same conditions one would face on Mars, namely, self-sufficiency and infrequent resupply.

The construction of infrastructure on Svalbard focuses on adapting to the Arctic conditions, with considerations for energy-efficient buildings, permafrost-resistant foundations, and sustainable practices. In contrast, on Mars, building infrastructure requires innovative engineering solutions to contend with the thin atmosphere, extreme temperature variations, and the absence of readily available materials. Structures on Mars would likely need to incorporate radiation shielding and temperature control systems to ensure habitability. While both locations demand careful resource management and strategic infrastructure planning, the challenges on Mars are more pronounced due to the planet's hostile conditions and the necessity of creating a habitable environment from essentially barren surroundings. However, due to the similarities the two locations, an ideal training scenario, would simply utilize a near identical Martian habitat on Svalbard. Between the necessity of harvesting surface/subsurface ice and the frigid temperatures, a Martian base should be applicable to the conditions faced on Svalbard.

Transportation

Transportation in isolated Svalbard is characterized by the archipelago's challenging Arctic conditions and remote location. The limited infrastructure and vast, rugged landscapes necessitate a variety of transportation modes tailored to the unique environment.

One primary mode of transportation is by snowmobile, which is widely used during the long winter months when the archipelago is covered in snow and ice. Snowmobiles provide a practical means of navigating the snowy terrain, connecting settlements, and facilitating transportation across the archipelago. Boats and ships are crucial for transportation between the islands during the ice-free summer months and year-round on the generally ice-free western coast. They are essential for carrying supplies, facilitating trade, and connecting the various settlements scattered across the archipelago's coastline.

Furthermore, air travel is vital for connecting Svalbard to mainland Norway and other international destinations.

Martian geography is primarily characterized by dust and rocks. While not particularly dusty, Svalbard's barren topography has been shaped by glacial activity so when not covered by snow, fields of rocks stretch for kilometers. Perhaps these rock fields could be used with a Martian rover, but the arrival of snow, and therefore terrain that a Martian rover would be wholly unsuited for, suggests that it would be better to not attempt direct Martian transportation recreation and accept that simulated Martian transport will not be possible on a Mars-Svalbard training mission.

Logistics

Establishing a base on Svalbard presents challenges similar to what will be faced on Mars, but of a much smaller scope. On Svalbard, the difficulties primarily revolve around adapting to the harsh Arctic conditions. Logistical challenges include the need for specialized construction to withstand extreme temperatures, permafrost, and delivery of supplies and construction materials. The remote location of Svalbard requires careful planning for the transportation of supplies, given the limited infrastructure and reliance on seasonal modes of transport such as ships and planes. In contrast, establishing a base on Mars introduces a set of complexities unparalleled on Earth. The logistics of sending materials, equipment, and personnel to Mars involve overcoming the vast distances, limited launch windows, and the substantial cost and resources associated with space travel. The thin atmosphere, lack of resources, and the absence of any pre-existing infrastructure on Mars demand innovative solutions for constructing habitats, creating sustainable life support systems, and ensuring the availability of essential resources. The logistical difficulties extend to the need for advanced technologies capable of withstanding the planet's extreme temperatures, radiation, and dust storms.

While Svalbard's challenges are rooted in adapting to and managing existing conditions on Earth, the logistical difficulties of a Mars base are intricately tied to the need for establishing a habitable environment in an alien and inhospitable planetary setting. Both scenarios demand meticulous planning, resource management, and the development of specialized technologies, but the nature and scale of the challenges differ significantly due to the unique characteristics of each location. A simulated mission would best be performed by adhering to the same delivery and resupply schedules that would be inevitable on Mars, rather than taking advantage of frequent helicopter resupply drops.

Energy Generation

Off-the-grid energy generation on Svalbard involves developing sustainable and independent power sources to cater to the energy needs of isolated buildings or communities without relying on traditional power grids. Svalbard's remote location and challenging Arctic conditions necessitate resilient and environmentally friendly energy solutions.

One crucial aspect of off-the-grid energy generation at Svalbard training location is the utilization of renewable energy sources. Solar power plays a significant role, leveraging the extended daylight hours during the Arctic summer to capture sunlight through solar panels. Despite the long polar nights in winter, solar energy remains viable during the sunlit months. However, the sustained months of darkness necessitate an additional source of power to maintain consistent energy throughout the polar night. Furthermore, while not at risk of dust coverage, snow and ice storms can cover the solar panels and reduce or halt the panels' energy generation.

Wind power is another key component of off-the-grid energy solutions on Svalbard. Wind power is a promising secondary power source in the sunny months and could be the primary energy source in the winter. The region experiences strong Arctic winds, especially in the winter, and wind turbines can be strategically placed to harness this renewable energy source. Wind power complements solar energy, helping to ensure a more consistent and reliable power supply throughout the year. However, wind turbines are also susceptible to ice loading that can damage the structure.

In addition to harnessing renewable energy, off-the-grid systems on Svalbard must incorporate energy storage solutions. Battery systems can be employed to store excess energy generated during periods of sunlight or strong winds. These stored reserves can then be tapped into during periods of low renewable energy production, such as during the dark winter months. However, the extreme cold temperatures can be damaging to batteries and a method to keep them warm is a must.

Considering the intermittent sun, likelihood of solar panel coverage, required battery warming, and dependency on renewable energy, an isolated community on Svalbard and a Martian habitat share clear similarities. Because the difficulties faced are so close, the Mars-Svalbard analog is similar enough for the training center to simply build and design its energy generation array based on its operating conditions on Svalbard. Furthermore, forcing the isolated habitat on Svalbard to utilize an energy generation system designed for Mars puts the trainees in unnecessary danger.

Svalbard Psychological Hazards

Living in a highly isolated colony on Svalbard comes with a multitude of psychological hazards stemming from the extreme environment and isolation factors. These hazards mirror those found on Mars, just to a slightly less extreme. The relentless cold, long dark winters, and the phenomenon of polar night can induce feelings of confinement and hopelessness among residents. The absence of sunlight during the polar night can disrupt circadian rhythms, leading to mood disturbances like depression and anxiety [33].

Social isolation presents another significant challenge. With a small population and remote location, a long duration training mission on Svalbard may leave individuals feeling profoundly disconnected. Limited social interactions and a lack of community support systems exacerbate feelings of loneliness and alienation. Being confined indoors due to harsh weather conditions could add to the psychological strain, causing feelings of restlessness, irritability, and boredom can intensify, leading to tension and conflicts within the community. This can create a sense of suffocation and exacerbate existing mental health issues.

The high stress levels associated with living in such an environment cannot be overlooked. Coping with limited resources, unpredictable weather, and the constant need for self-reliance can take a toll on mental health. Trainees may find themselves struggling to manage the challenges, leading to heightened stress and anxiety. Trainees may find it difficult to access professional help or support services for their psychological well-being, leaving many mental health issues untreated.

The combination of these factors increases the risk of mental health crises such as suicidal ideation or self-harm. Without adequate support systems in place, trainees may find themselves overwhelmed by despair and hopelessness. Addressing these psychological hazards requires proactive measures to ensure the mental well-being of individuals living in a highly isolated colony on Svalbard. While sounding quite harsh, the conditions on Svalbard will pale in comparison to what astronauts would face on Mars and coming to understand and deal with these feelings is one of the core objectives of a mission such as this.

Svalbard Risk Impact Study

In order to analyze the risks associated with each of the hazards facing a training exercise on Svalbard, one can utilize the same risk matrix applied to the hazards on Mars in Objective 1. The Svalbard risk impact study assessment parameters are the same as those outlined in Table 2. The corresponding risk matrices are shown below.

Table 6: Risk Matrix for Svalbard Environmental Hazards

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Enviormental Conditions	Avalanche and landslides	Crew health: suffocation and burial	Winter avalanches and spring, summer, and fall land slides can happen very suddenly and trap the trainees under snow and Earth. Self rescue is very unlikely, and without immediate outside help, death is likely	Avoidance of dangerous terrain, avalanche terrain training, self rescue training, required avalanche beacons when outside/in terrain, rapid notification of air rescue services	E3
		Habitat health: structural damage	Avalanches and landslides can hit structures with very high force and rip them off of their foundations or crush them	Careful consideration of habitat location to avoid avalanche and land slide terrain	B2
	Extreme temperatures	Crew health: hypothermia/frostbite	Extreme temperatures that will quickly cause hypothermia and death in the event of loss of heating	Highly redundant heating systems, clothing, and habitat with advanced insulation properties	E4
		Habitat Health: Extreme temperatures can cause increased mechanical strain on system	Extreme and fluctuating temperatures can cause increased mechanical strain on system	Habitat design must be capable of functioning in extreme low temperature	B2
	Snow storms	Crew Health: Loss of power due to solar panel coverage	Snow buildup on solar panels can reduce or eliminate energy generation. Sky can also become obstructed for extended periods of time	Redundant power/backup battery systems and self cleaning features for the solar panels to reduce unneccessary service	C3
		Habitat Health: Wind damage and precipitation buildup	Damage to habitat due to combined sustained loading of wind and snow/ice buildup. Snow/ice buildup acumulation can damage electronics and structure	Routine inspections on all critical components, replacement parts for critical components, built to extreme tolerance to withstand ice loading	D3
	Polar night	Crew health: psychological challenges	Lack of consistent day/night cycles can cause serious mental challenges	Strict routines to follow can reduce to the physical confusion of constant or lack of sunlight. Sleep aides can help maintain normal sleep cycles	B3
		Habitat health: lack of solar energy	For almost half of the year, there will be minimal or no sunlight. Solar panels will be completely useless	Alternative energy sources to solar energy is essential	E4

Table 7: Risk Matrix for Svalbard Logistical and Infrastructural Hazards

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Logistical and infrastructural	Resource limitations	Lack of water	Water is frozen for most of the year	Habitat must have the means to unthaw water sources	B1
		Lack of building materials and natural resources	Dependancy on resupply from outside settlements and inability to replace and repair the habitat during emergency situations	Multiple supply/delivery missions prior to the start of training	B5
		Lack of fertile soil	Substantial habitat enviorment committed to food production, risk of food shortage and starvation, lack of healthy or varied diet, psychological strain due to lack of varied diet	Large supplys of emergency, freeze dried food transported from settlements, streamlined and systematic growing system, transported vitamens and occassional specialty food	C2
		Lack of food	Risk of starvation if lack of supplies from settlements, inability to produce sufficient food, or spoilage of food supplies	Large emergency supplys of food from settlements, advanced and efficient year round farming methods, foolproof food storage methods, hunting	C3
	Transportation issues	Dependancy on snowmobiles or ATVs to traverse the area	Life threatening situation if snowmobile stuck, runs out of power, breaks, etc	Multiple vehicles in service, routine maintenance inspections, strict maximum safety radius	B3
	Energy generation	Energy and life support issues with Habitat	Risk of hypothermia, lack of comunication with settlements, and loss of life support during loss of power event	Independent and redundant energy generation systems utilizing mulitple methods to generate energy and backup battery supplies in the case of generation failure	C2
	Outside dependency	Dependancy on outside resupply	Risk of supply shortage, depandancy on continued mission funding	Substantial reserve supplies stored and consistent resupply missions	B3

Table 8: Risk Matrix for Svalbard Psychological Hazards

Hazard Category	Hazard Description	Effects on the system	Mechanism	Measures and Recommendations	Position in Risk Matrix
Psychological	Personal Issues	Feelings of Isolation	Increased risk of depression, decreased productivity, isolation from crewmates, detachment from society	Regular video/audio messages to family, strong bonds between crew prior to departure, experience and training to identify onset	C3
		Depression/Anxiety	Decreased emergency prepardness/response, suicide risk, increased stress	Access to telemedicine, qualified thereapists/health professionals as part of crew	C3
		Boredom/disengagment	High levels of monotony, adherence to routine, lack of variation in environment, lack of variety in food, confined environment	Scheduled breaks, cultural events, creative outlets, recreational activites, ability to pursue hobbies, scheduled days to stay busy, testing various personal interests	B3
		Issues Sleeping	Tiredness, irritability, increased risk of accident, decreased response time	Attmept to maintrain day/night cycle, access to sun lamps, sleeping aides, medication	B5
	Group Issues	Team conflict	Frustration among team members, ineffective communication, poor teamwork, physical altercation, lack of personal space, irritability	Confirmation of team performance in isolation, field experience as a team, conflict deescalation skills, testing different leadership structures prior to departure	B2

Objective 3: Svalbard-Mars Training Center Location Identification

After determining the risks and hazards faced on Mars and Svalbard, one can organize these hazards into three categories: natural hazards, simulated hazards, and unrelated hazards. The natural hazards represent hazards that a base on Mars and Svalbard naturally share, such as extreme cold, lack of resources, and challenges with energy generation. Simulated hazards represent conditions that are found on Mars, but not Svalbard that can be implemented into an exercise by simulating conditions. Examples of this include resupply intervals and communication delay. Lastly, unrelated hazards represent hazards that are either too different to simulate or too dangerous to simulate. This category includes hazards such as radiation exposure, wildlife danger, and avalanche risk. These hazards can be seen in the following table below.

Table 9: Mars-Svalbard Hazard Classification

Mars-Svalbard Training Exercise Hazard Classification		
Natural Hazards	**Simulated Hazards**	**Unrelated Hazards**
Extreme cold	Resupply intervals	Dangerous wildlife
Energy generation	Communication delay	Avalanche danger
Resource limitation	Transportation methods	Radiation exposure
Isolation	Habitat construction	Lack of oxygen
Accessing frozen water		Landslides
Warming batteries		
Inconsistent lighting		

Considering the location selection on Mars is considerably more complicated due to scarcity of ice deposits, increased landing hazards, and atmospheric challenges, the location on Mars will be determined first and a corresponding location on Svalbard will be identified afterwards. With these hazards in mind, one can begin the selection of the base location on Svalbard and Mars.

Much like Earth, Mars has several planetary regions that can be characterized by different geographical and climate conditions. These different regions each offer benefits and challenges. The following map shows the generally accepted regions: polar, transitional, and equatorial [34]. These regions do not necessarily have a strict east to west dividing line, nor are the conditions between the north and south pole identical, but by dividing the planet in this way, one can find broad similarities between the regions. It should also be noted that Mars's topography is incredibly diverse and changing, much like Earth's. There will always be localized changes, and this report is more focused on the large-scale trends, rather than the small-scale terrain variation. A map of the Martian climate zones is seen below:

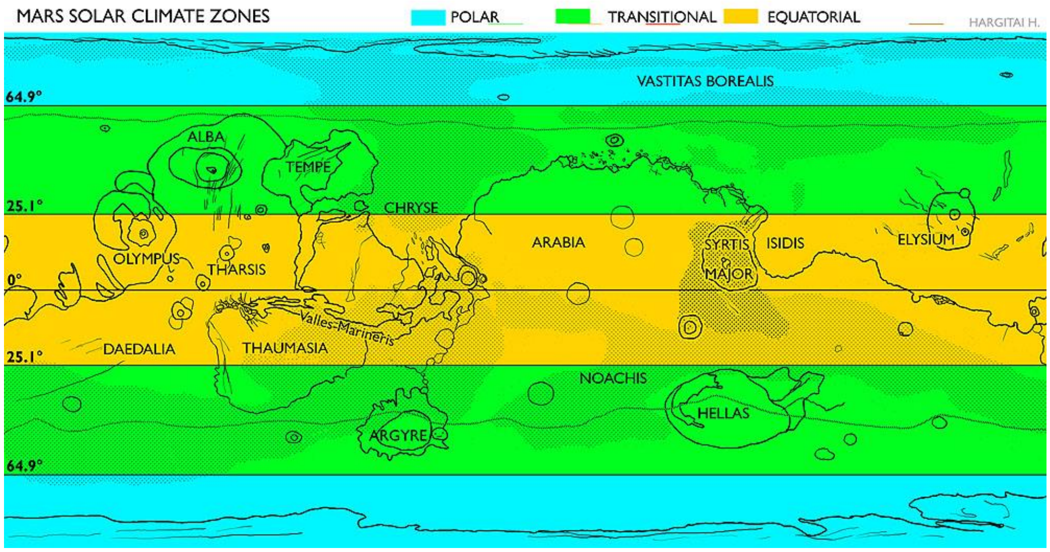

Figure 18: Mars solar climate zones [34]

Equatorial Zone Conditions

Establishing a Martian colony in the equatorial zone presents a distinct set of challenges and opportunities. This region, known for its relatively mild temperatures, by Martian standards, and favorable solar exposure, has both strengths and weakness for a landing site. This is the largest of the proposed landing sites. Thus, the equatorial zone is not necessarily a specific colony or landing site, but more of a general region that could be advantageous.

Despite the favorable solar exposure in the equatorial zone, the increased intensity of solar radiation poses a significant risk to human health and equipment. As seen in Figure 7 and Figure 8, the solar radiation in this region is the most extreme. While the increased temperature and solar energy does bring some benefits, prolonged exposure to unshielded radiation can lead to increased cancer risks and potential damage to sensitive electronics. A colony within the equatorial zone will need to pay special attention to the radiation risks.

The equatorial zone of Mars is characterized by a diverse and intriguing terrain shaped by ancient geological processes. This region is distinct from the polar regions of Mars and exhibits several prominent features that define its landscape. More so than other regions, the equatorial zone showcases a mix of both large and small impact craters, remnants of past asteroid and meteorite collisions. The variability of these craters can be seen in the following image:

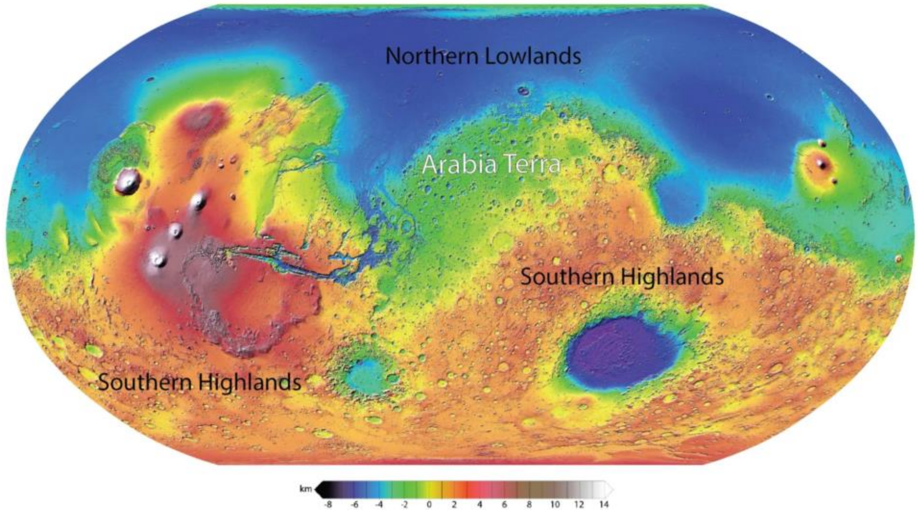

Figure 19: Planetary elevation map [35]

These craters could act as a good landing sight due to their low elevation and better access to subsurface water. There are also numerous valleys and channels, believed to be carved by ancient rivers and floods that can be found in the equatorial zone. This region also encompasses extensive volcanic plains, such as the Tharsis and Elysium volcanic regions, known for their vast shield volcanoes and lava flows [36]. These volcanic features contribute to the diverse topography of the equatorial zone, creating expansive plains and towering mountains that shape the landscape. The equatorial zone is also home to many Martian sand dunes, composed of fine-grained basaltic sand. These dunes create intricate patterns and formations across the Martian surface and make particularly poor landing sites due to the unstable surface, dust kick back during landing, and potential to damage instruments [36].

A Martian colony in the Equatorial Zone presents a mix of unique risks, hazards, and benefits. While the region offers relatively more favorable conditions for human habitation and resource utilization, challenges such as radiation exposure, increased prevalence of sand dunes, and the general resource limitations hinder a Mars mission. Furthermore, an understanding of the terrain of the equatorial zone of Mars is crucial for any prospective missions or colonization efforts in the region. A successful mission demands careful planning, robust infrastructure, and innovative solutions to ensure the safety, sustainability, and long-term success of the colony.

Polar Zone Conditions

Much like Earth, Mars's polar regions experience some of the most extreme cold temperatures on the planet, with frigid conditions that can plummet as low as -125°C (-193°F) [24]. Managing these temperature extremes is crucial for ensuring the functionality of infrastructure and maintaining the health and safety of colonists. Polar regions on Mars also receive limited sunlight for a significant part of the year, leading to challenges in energy generation and storage. Power generation systems, such as solar panels, may experience reduced efficiency and productivity, requiring innovative solutions for sustainable power supply. Mars also experiences the same sunlight extremes as Earth's poles [37]. These light extremes increase the psychological challenges the astronauts would face, in addition to providing inconsistent energy generation.

However, as seen in Figure 12 and Figure 13, Mars's polar regions are known to harbor substantial water ice deposits, representing a critical resource for sustaining life, supporting agriculture, fuel production, and facilitating various industrial processes within the colony. Access to this water resource is invaluable for long-term sustainability. These thick layers of ice and regolith can also serve as natural shielding against cosmic and solar radiation. The north pole is also approximately 500m lower in elevation than the south pole. Between the lowered elevation yielding increased atmospheric radiation shielding and ice shielding, Mars's north pole is one of the safest places on the planet when dealing with radiation [23].

The terrain of the Martian poles is characterized by a unique combination of surface features, including polar ice caps, layered deposits, and distinctive geological formations shaped by the planet's climate and geological history. Both the north and south poles of Mars are covered with polar ice caps primarily composed of water ice and carbon dioxide ice. These ice caps exhibit dynamic seasonal changes, with variations in size and composition during Martian summers and winters. The polar ice caps play a crucial role in shaping the landscape and influencing the planet's climate dynamics. It is also typical of this region to find craters that are partially or fully covered by ice. There are far fewer impact craters at the north pole than there are at the south pole. This can be seen in Figure 21.

While unconfirmed, research suggests that terrain may conceal subsurface features such as buried glaciers, subsurface water ice, and potential geothermal activity. Investigating these subsurface characteristics is crucial for understanding the availability of water resources and assessing the feasibility of establishing future habitats and infrastructure [38].

Martian Base Location Selection

Rather than scour the entire planet, it is helpful to first eliminate regions of Mars based on certain parameters. Two of the most essential parameters are elevation and ice deposits. A low elevation Martian habitat is helpful for two primary reasons: the thin atmosphere makes landing more challenging than Earth and high elevation locations are subject to considerably greater radiation exposure. While a paired system of parachutes and thrusters is essential, a landing location at an elevation greater than -2.5 km, has been the cutoff for safe landings on previous missions [39], and no mission has successfully landed above -1.4 km. While new technology may be developed in the future to allow high elevation landings, this safe window will be utilized throughout this investigation. Furthermore, the radiation, while still high, becomes more manageable at the lower elevations. The next essential parameter is the presence of surface or near subsurface ice, which is essential for sustaining the crew and its use in producing fuel or other chemical compounds.

Based on Figure 12, Figure 13, and Figure 21, the possible landing zone would be limited to 30°N-90°N due to the lower elevation of the Northern lowlands and the abundant, by Martian standards, presence of ice. While still an incredibly large area, these parameters reduce the potential search area by about 65%. However, these high latitudes can quickly become a problem due to the inconsistent lighting. While a mock base on Svalbard could potentially generate enough energy from the wind to survive the dark winters, the very thin Martian atmosphere means that the wind does not carry sufficient force to spin wind turbines, even if there are very high wind speeds. Furthermore, the high latitude locations are simply too cold to realistically keep a base warm enough. While Svalbard can be used as a training exercise due to its frigidity, the coldest temperatures ever record on Svalbard are some of the warmest temperatures on Mars. Considering this challenge, some of the best locations for a base on Mars would then need to fall between ~30°-45°N. This region is shown in Figure 22.

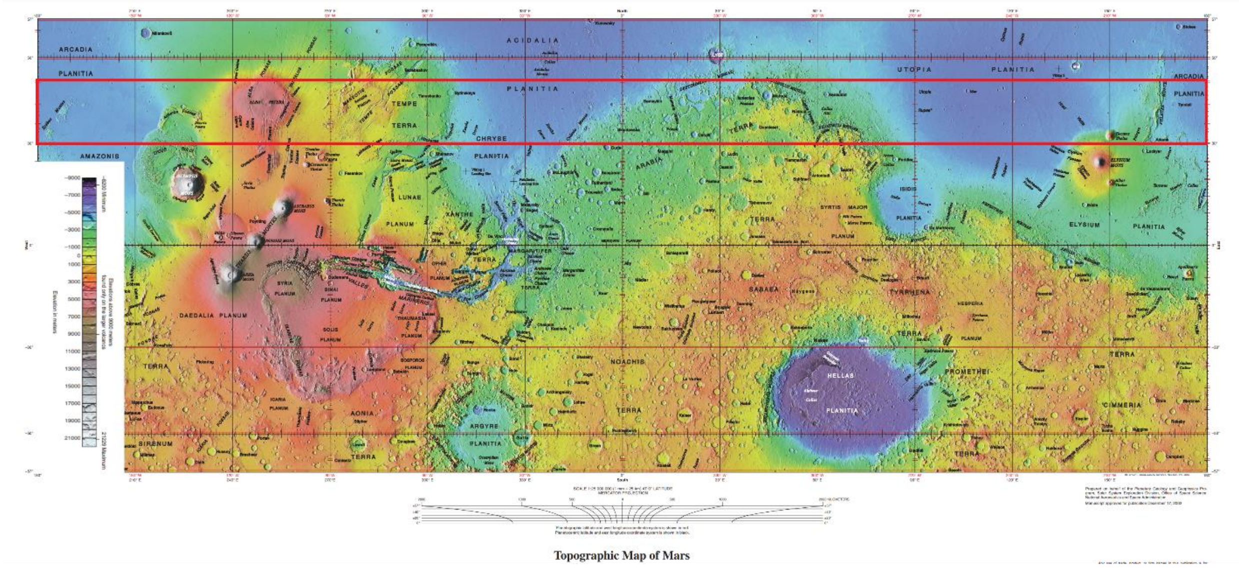

Figure 20: Potential landing region zone on Mars [40]

With this narrow band of low elevation, accessible ice, and consistent daylight established, one can begin to look closer to identify specific regions and areas to land. For site specific characteristics, flat, open terrain with no thick dust deposits or a large quantity of boulders is ideal. Previous studies searching for a landing site for the Mars Science Laboratory defined safe rock height and abundance as “less than 0.5% probability of at least one ≤ 0.55m high rock in 4 m^2 are, equivalent to rock abundance of <8%” [41]. Based on these requirements, Arcadia Planitia, Acidalia Planitia, and Utopia Planitia stand out as potential landing sites due to their low elevation, relatively flat terrain, and accessibility of near surface ice. For the scope of this report and the purpose of finding a similar location on Svalbard, narrowing the area on Mars to these three regions is sufficient.

These three different areas can be seen in depth in the appendix.

Svalbard Base Location Selection

From this point, a location on Svalbard can be found that is sufficiently flat, distanced from mountains to ensure optimal sunlight and safety from avalanches, in the coldest regions of Svalbard, on stable terrain, isolated from outside contact, and adequately distanced from coastline. Following a similar approach to the Martian analysis, large swathes of Svalbard’s territory can be omitted to ensure the base is placed in the coldest regions. Because the coldest region of Svalbard generally lies in the North-Northwest region of the archipelago, this region will primarily be focused on throughout this analysis. The specified geographical region is shown below in Figure 23.

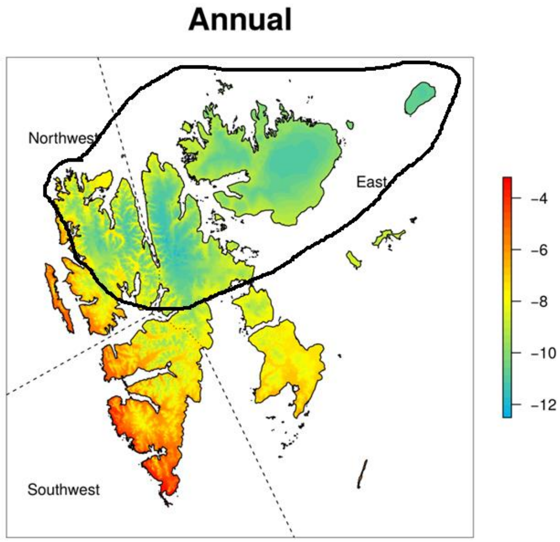

Figure 21: Mars-Svalbard training location preliminary region [31]

Due to Mars's thin atmosphere, the seasonal changes in temperature and surface conditions are not near as substantial as on Earth. In contrast, Svalbard is a much different place depending on the seasons. This is one of the few advantages Mars offers over Svalbard. One must consider not only the snow buildup in the winter, but also the snow melt in the warmer seasons. To highlight these differences, one can use TopoSvalbard to compare the summer and winter conditions. The drastic differences are seen in Figure 24 and Figure 25.

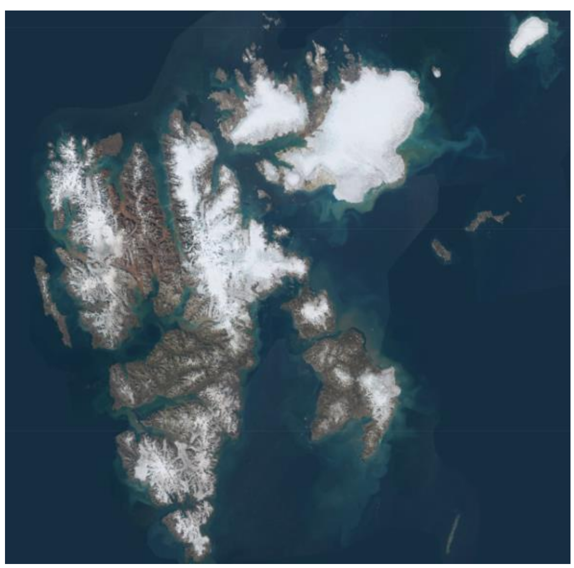

Figure 22: Summer Svalbard [42]

Figure 23: Winter Svalbard [42]

Thus, one must be careful when considering the seasonal changes in habitat selection because, assuming the training mission will span multiple seasons, a safe location in the winter far from mountain slopes could turn into a raging river in the summer. In addition to snow melt rivers, much of Svalbard's terrain can be quite unstable in the summer months to the water saturated active layer of the permafrost [43] and glacial moraine.

After considering these features, the challenges with analog base selection become obvious. Too close to mountain slopes puts the habitat in avalanche danger [44], too far in the valley and the habitat is likely in a spring/summertime river, too close to a glacier and the habitat is dealing with very challenging terrain, permafrost in the winter, and an unstable, water saturated, active layer in the warmer months. However, while also being covered in many sharp mountain peaks, Svalbard boasts many plateau mountains. These mountains are often covered by year-round glaciers and ice caps. Although it may seem counterintuitive, a Mars-Analog base location situated on one of these ice caps could be the most seasonally and structurally stable location to build a semi-permanent training base. With these criteria in mind, three very hypothetical training locations can be identified. Their general locations can be seen below.

Figure 24: Svalbard-Mars analog locations [42]

Location 1

Location 1 is centrally located on Austfonna, the largest ice cap on Svalbard. Its coordinates are 79.81966°N 24.22356°E and it lies at an elevation of 785 m. In addition to more consistent temperatures and landscape, the Autstfonna is very level and spans a large area, potentially adding to the feelings of isolation. This base would be entirely built and secured to an ice cap. However, doing so introduces complicated legal challenges that are discussed in a later chapter.

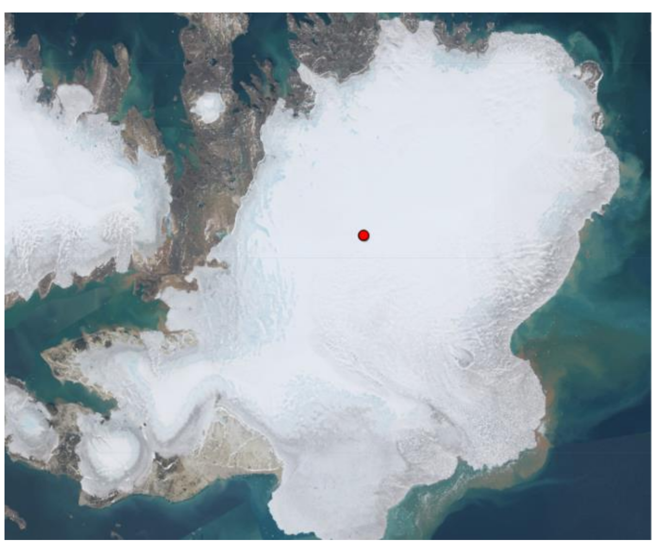

Figure 25: Location 1 in summer [42]

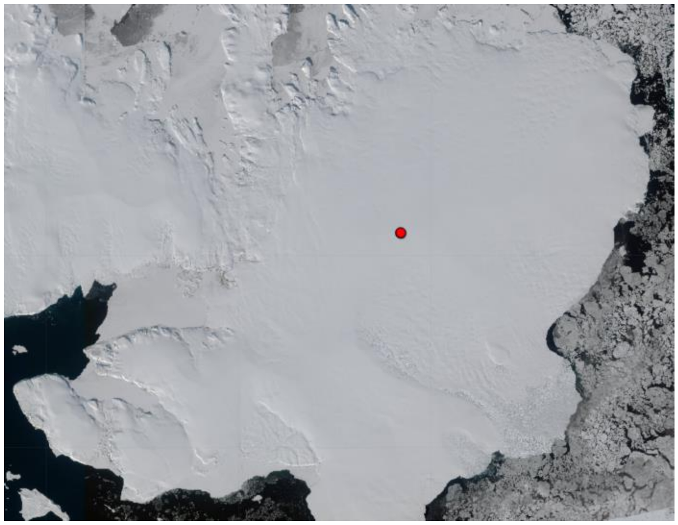

Figure 26: Location 1 in winter [42]

Figure 27: 3D visual of Location 1 [42]

Location 2

The second location lies atop a small mountain between the upper part of Moltkebreen and Hochstetterbreen. This potential location is in the northeast of Olav V Land at 78°56.443'N 19°43.603'E and 424 m in elevation. In contrast to Location 1, this location does experience full snow melt in the summer. This will result in increased seasonal variation and the structure will be secured to earth, rather than an ice cap.

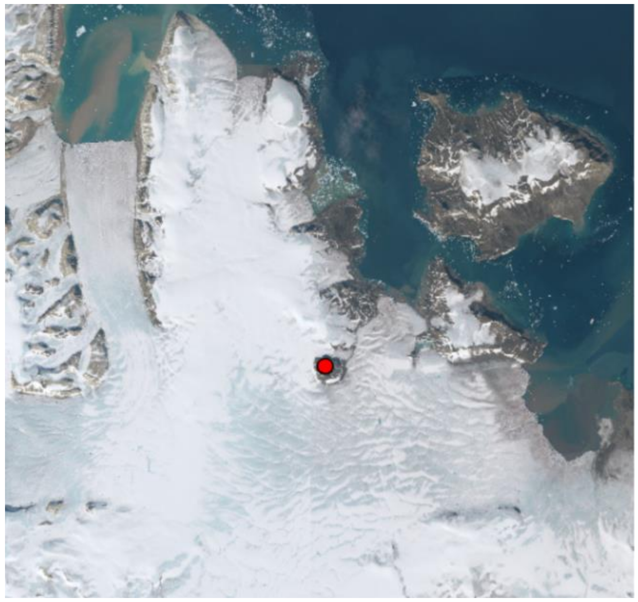

Figure 28: Location 2 in summer [42]

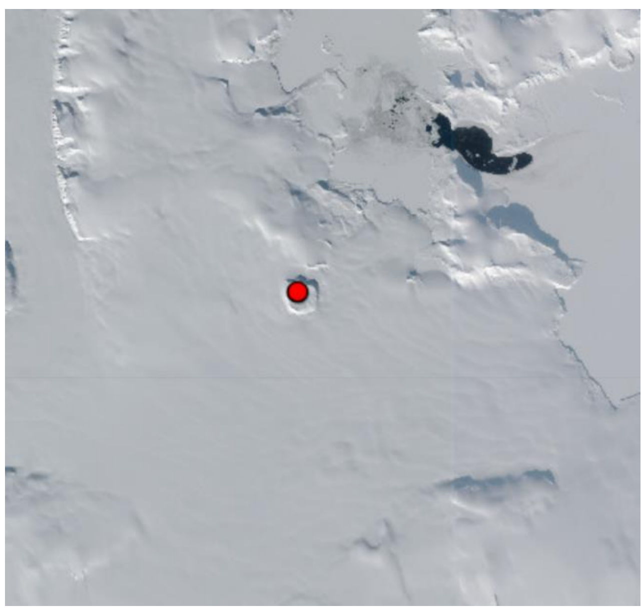

Figure 29: Location 2 in winter [42]

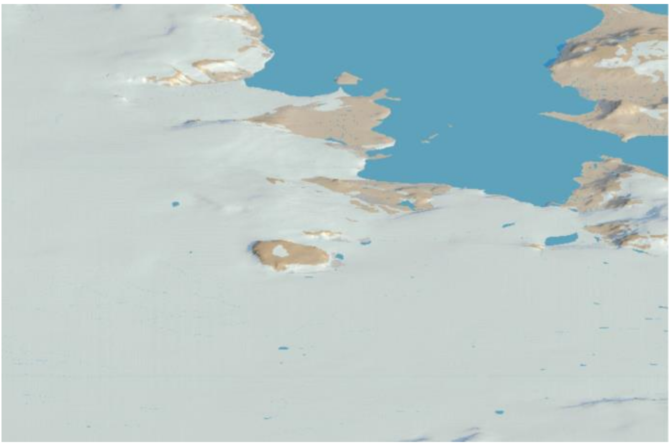

Figure 30: 3D visual of Location 2 [42]

Location 3

The third theoretical training location is in the southwestern region of the icecap Åsgardfonna and in the central part of Ny-Friesland. Location 3 is at 79°23.290'N 16°42.114'E and an elevation of 1164 m. Placement on this location is built upon an icecap, rather than solid ground.

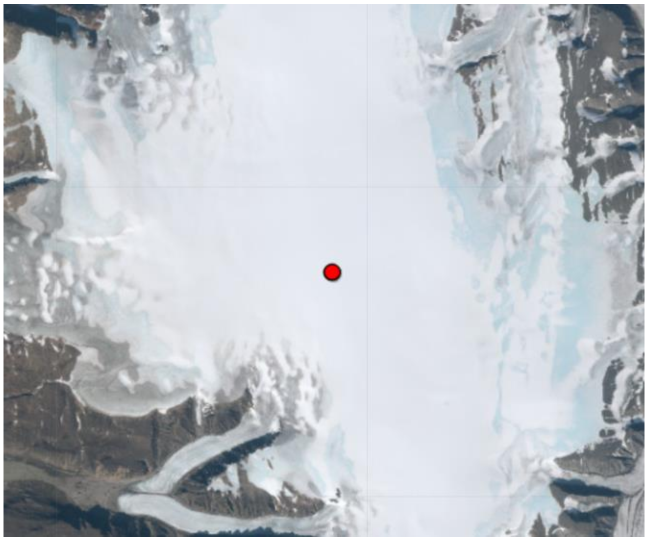

Figure 31: Location 3 in summer [42]

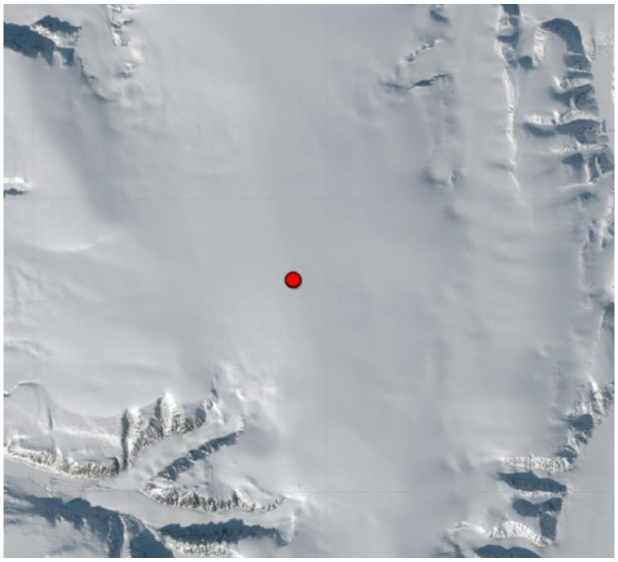

Figure 32: Location 3 in winter [42]

Figure 33: 3D visual of Location 3[42]

Svalbard-Mars Base Advantages

Isolation training

Providing astronauts with isolation training before a mission to Mars is crucial for various reasons. Isolation during long-duration space missions can significantly impact astronauts' mental and emotional well-being. Astronauts need to be mentally prepared to cope with the extended isolation of a Mars mission. The astronauts will be faced with unprecedented isolation both on Mars and during the journey there. Therefore, isolation training plays a key role in fostering effective team dynamics among the astronaut crew. Living and working together in a confined space for an extended period can lead to interpersonal challenges. Learning to navigate and resolve conflicts in a controlled environment is essential for maintaining a cohesive and functional team during the mission.

Effective communication becomes paramount during periods of isolation, where astronauts rely heavily on communication with mission control and fellow crew members. Training in isolation helps astronauts refine their communication skills, ensuring clarity and efficiency in conveying critical information [14].

Isolation training also provides astronauts with the opportunity to develop and practice coping strategies for the challenges they may face. This includes stress management techniques, leisure activities, and maintaining a healthy work-life balance in the confined space of a spacecraft. Astronauts who undergo isolation training are better equipped to handle the unique stressors associated with long-duration space missions [14]. This preparedness contributes to mission success by reducing the likelihood of psychological issues that could impact crew performance, decision-making, and overall mission objectives.

Realistic and high stakes environment

Training in a realistic, high-stakes environment offers several advantages over a controlled and safe setting. The authenticity of such scenarios provides a more genuine and practical experience, exposing individuals to real-world conditions and stressors. This exposure helps develop stress management, decision-making, and adaptability skills. While the Arctic is not a perfect training environment, the true isolation and environmental challenges will increase the stress and consequences for participants, compared to a fully controlled, internal simulation like NASA’s CHAPEA. High-stakes training promotes teamwork and collaboration, enhancing communication and coordination among individuals. The challenges encountered in these environments foster emotional intelligence, as individuals learn to understand and manage emotions both individually and within a team. Additionally, the hands-on experience allows for the practical application of skills, reinforcing learning and skill acquisition. The heightened sense of challenge and risk in high-stakes training leads to increased engagement, motivation, and improved retention of skills and knowledge. Overall, realistic, high stakes training better prepares individuals for the unpredictable nature of the real world.

Svalbard-Mars Base Disadvantages

Logistical and time constraints

One of the greatest strengths with the Mars-Svalbard training exercise, is also one of its greatest weaknesses. This training exercise hinges on training the potential astronauts in a highly isolated location for a long amount of time. However, the astronauts will have to prepare for far more than simply isolation before a mission to Mars. Requiring a full year isolation exercise prior to departure, while yielding valuable skills and lessons learned, could detract from additional essential training. Furthermore, true astronauts will already be required to leave their families for an extended period. The results are inconclusive if requiring them to be isolated from their families for an additional extended period to complete a mandatory training exercise will outweigh the additional emotional strain that is to be expected of them.

Environmental differences

Mars and Svalbard present stark environmental disparities. Mars, a barren planet, lacks a breathable atmosphere and experiences extreme temperature fluctuations, with surface temperatures averaging around -60 degrees Celsius in the targeted landing region. Its thin atmosphere offers minimal protection from harmful radiation, and its landscape is characterized by desolate deserts and towering volcanoes. In contrast, Svalbard boasts a relatively hospitable climate despite its high latitude. With annual temperatures typically ranging near -10 degrees Celsius, Svalbard supports a variety of life forms, including polar bears, seals, and various bird species. Its icy landscapes are punctuated by glaciers, fjords, and tundra, contributing to its unique biodiversity. Considering this analog is proposed due to the similarities they share, and temperature is a primary selling point, an average temperature difference of 50 degrees is quite substantial. Although Svalbard and the Arctic may be one of the closest analogs to Mars, this does not mean they are all that similar. A training location on Svalbard will likely be on ice or surround by snow for large portions of the year, a stark contrast to the red deserts of Mars. Despite this, both environments share challenges related to isolation, making them compelling subjects for scientific study and exploration. A detailed cost benefit analysis is required to determine if the harsh environment, though not perfect, if adequate justification to conduct the exercise.

Changing Arctic environment

Svalbard has experienced a warming trend that is notably higher than the global average. Over the past few decades, temperatures in the region have risen at a rate more than twice as fast as the global average.

The exact extent of warming can vary across seasons and locations within Svalbard, but the overall trend underscores the vulnerability of Arctic environments to climate change. The warming trend in Svalbard is part of a broader pattern of climate change affecting the Arctic region. Data from meteorological stations on the archipelago reveal a clear trend of rising temperatures over the past few decades. While there can be year-to-year variability, the overall warming is evident in both the winter and summer months [45]

One key contributing factor to the accelerated warming in the Arctic is the phenomenon known as Arctic amplification [46]. This refers to the Arctic region warming at a faster rate than the global average. Reduced ice and snow cover in the Arctic lead to a decrease in the albedo effect, where ice reflects sunlight, and instead, more sunlight is absorbed by darker surfaces like open water or exposed ground. This increased absorption of solar energy contributes to higher temperatures, creating a feedback loop that further accelerates the melting of ice and snow. In Svalbard, the effects of warming are multifaceted. Glaciers are retreating, and the extent and thickness of sea ice are diminishing. Permafrost, which has traditionally been a stable feature of the landscape, is thawing, impacting the stability of the ground and influencing local hydrology. These changes have direct consequences for the region's ecosystems.

Considering this training exercise hinges on the harsh, frigid, and isolated landscape of current Svalbard, this project could quickly lose its relevancy if the rate of Arctic warming does not slow down. If this project aims to replicate the -60C averages on Mars, there is no reason to pursue such a costly training exercise if this “simulated Martian colony” is placed on a comfortable 20C mountaintop.

Legal Challenges

While it was previously suggested that the Mars-Svalbard training location could be placed on one of the northwestern ice caps, it is not near this simple. This region makes up the Nordaust-Svalbard Nature Reserve. This reserve was established to safeguard the unique Arctic flora and fauna and is managed by the Norwegian Polar Institute. Access restrictions are in place to minimize human impact on sensitive environments, especially during critical wildlife breeding seasons. Throughout all of Svalbard, there are quite strict environmental regulations. In the case of an advanced astronaut training mission on a self-sufficient Martian base, it is likely that exceptions to these restrictions could be made, but it is important to establish some of these restrictions.

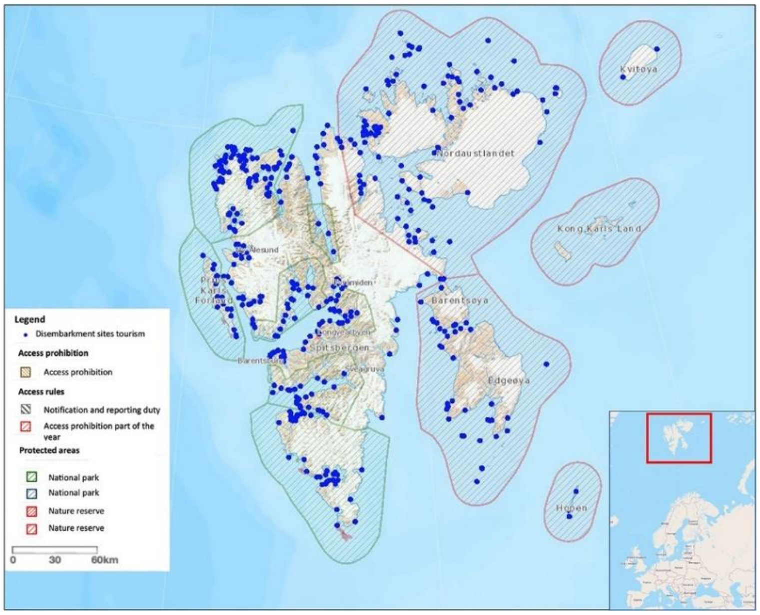

Figure 34: Svalbard legal distinctions [47]

Further Study

This project is both helped and hindered by its large scope. It is one thing to analyze and propose and another to implement and test. By using available literature and studies, it was possible to understand the surface conditions of both Mars and Svalbard and identify the benefits, but actually using this testing strategy on a large scale is a project that, in its idealized state, would require a near replica of an actual Martian habitat, a full staff of researchers and safety coordinators, and a full team of astronauts that would be using what is learned on a future mission. To achieve all these things would the support of numerous countries and an immense amount of money. Therefore, it may be a better to approach a Mars-Svalbard training mission more similar to LUNARK and CHAPEA, a Martian base replica with non-astronauts to gain data, than use true astronauts, due to their already incredibly tight and intense training regime.

Because of the highly theoretical nature of this project, there are many unanswered questions. While the hazard identification is well understood, the base location leaves some to be desired. Despite using the best available satellite imagery, locations cannot be fully cleared as a good landing site without on the ground observation, which in the case of Mars would be a massive Mars lander project costing 100s of millions of dollars, and for Svalbard, a weeklong expedition requiring an experienced team of Arctic nature field guides. Therefore, ground observations are far outside of the scope of this project. To identify the best Mars-Earth analog, ground observations are essential.

Conclusion

The colonization of Mars will be one of the most technically challenging things humanity has ever undertaken. The first step in tackling the engineering difficulties is to grasp the different areas that must be addressed after arrival to Mars. By first analyzing the state-of-the-art literature outlining the surface conditions on Mars from the perspective of engineering a human habitat, rather than basic scientific observation, one can begin to address the issues and propose solutions. This non-technical overview is essential to begin the engineering process and investigate how the different hazards interact with each other. Furthermore, by comparing these Martian hazards to those seen in the Arctic, a preliminary overview was be made that will help future training missions. In addition to outlining and addressing the various hazards faced, this report has used different safety and risk engineering strategies to propose methods of quantification and mitigation that can be used in an engineering management environment. While this risk assessment is fully theoretical, this model can be utilized in a real-world situation to minimize the risks of a future colony or other engineering system. Future use of this risk model could be improved by gathering experimental data on both the probability of failure to better quantify the risk and the true effectiveness of the mitigation solutions to observe for successful the solutions were in removing the risks.

Appendix

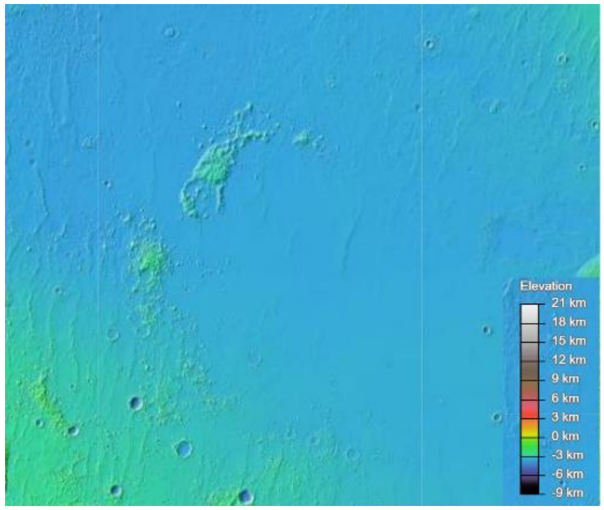

Figure 35: Arcadia Planitia-elevation [48]

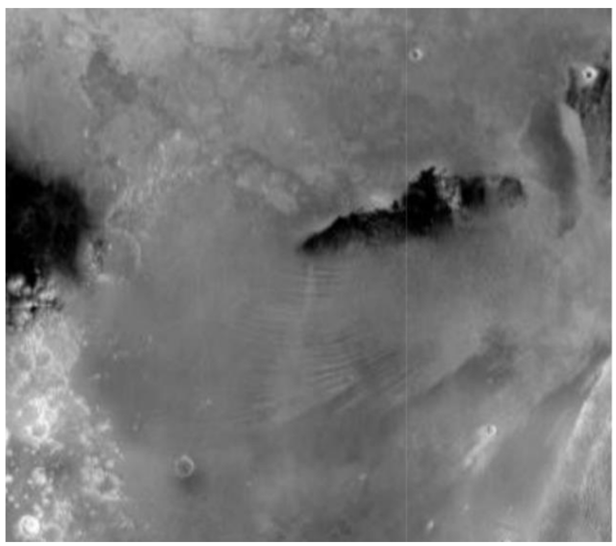

Figure 36: Arcadia Planitia-visible [48]

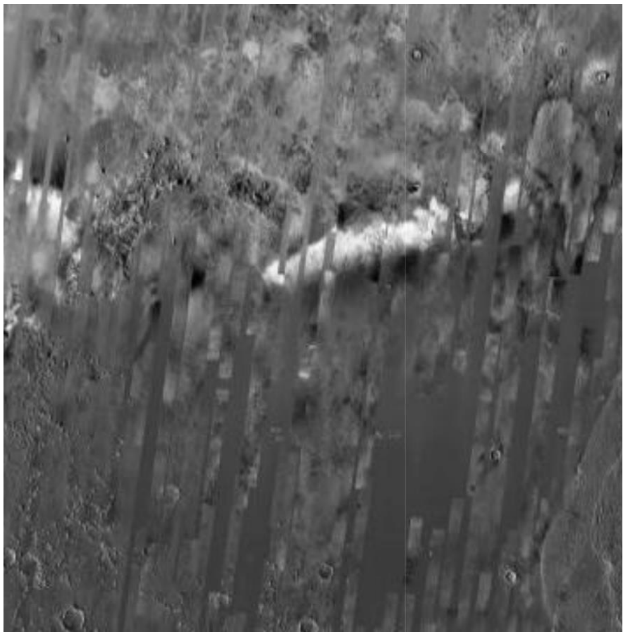

Figure 37: Arcadia Planitia-infrared [48]

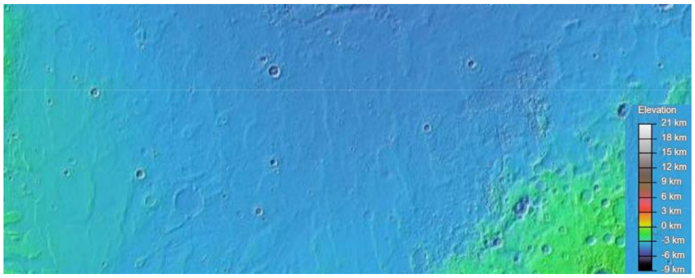

Figure 38: Acidalia Planitia-elevation [48]

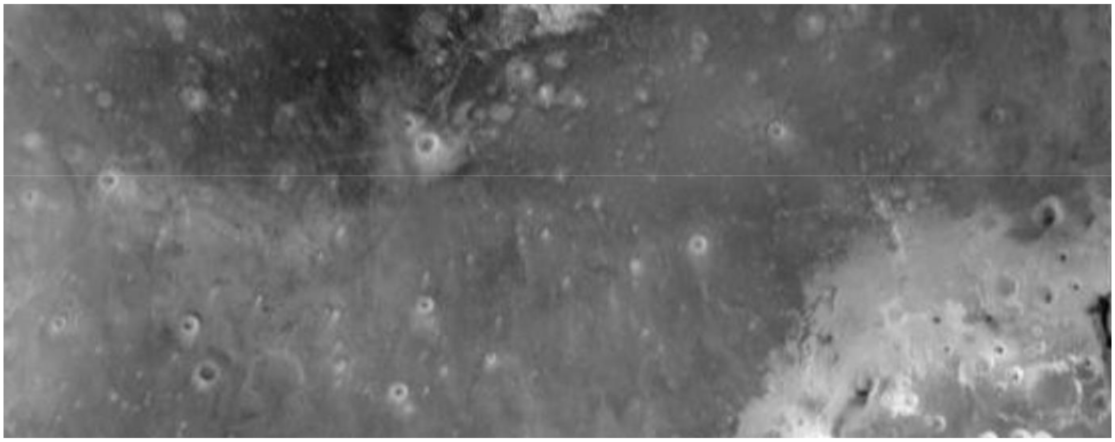

Figure 39: Acidalia Planitia-visible [48]

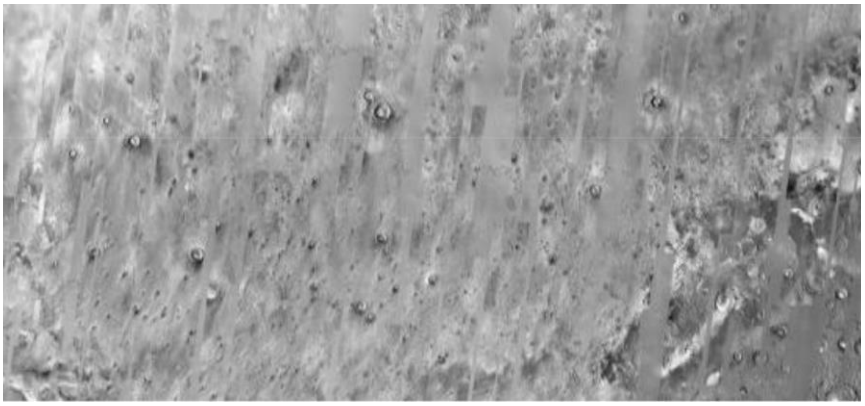

Figure 40: Acidalia Planitia-infrared [48]

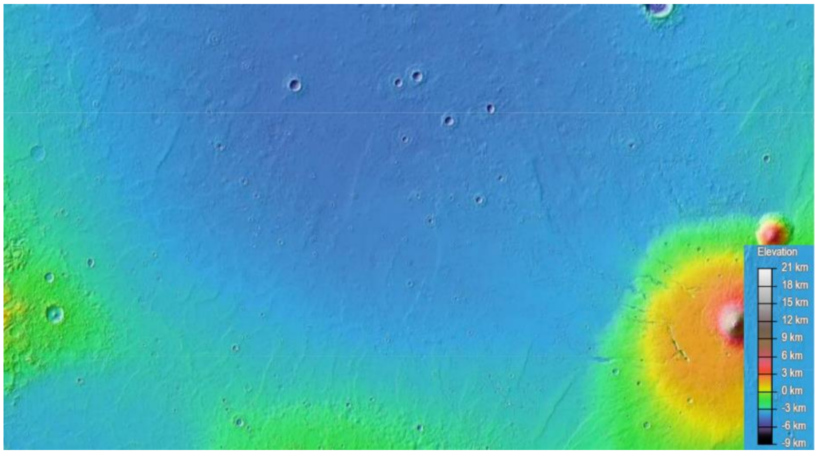

Figure 41: Utopia Planitia-Elevation [48]

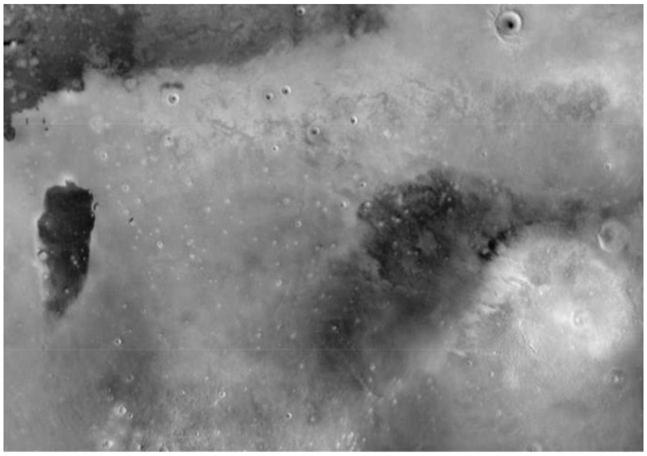

Figure 42: Utopia Planitia-visible [48]

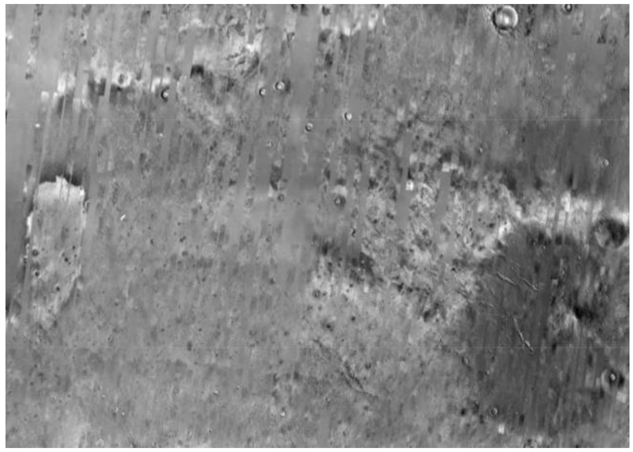

Figure 43: Utopia Planitia-infrared [48]

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