MISSION HUGIN & MUNIN
TEAM RED – HUMAN ASPECTS

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***Abstract*—This paper aims to outline the aspects that have to be considered for a human mission to Mars. It describes which dangers humans face in deep space and which countermeasures have to be taken. As the mission is to be designed as minimal, the masses are minimised as much as possible while ensuring the safety of the astronauts, which is one of the biggest challenges the team faced. Optimistic assumptions were made regarding the availability of technology by the start of the mission. The aspects and requirements for the mission have been split into primary – definitely and immediately life-threatening – and secondary – possibly life-threatening long-term. The primary aspects and requirements divide into LSS, radiation control, environmental control and safety and emergency. The varying radiation exposures and the affects on humans have been studied and shielding for sufficient radiation control have been selected. Several emergency situations have been taken into account, and safety systems and equipment have been provided. The secondary aspects and requirements are made up of psychological, physical and medical aspects, hygiene and training. These aspects have been investigated and requirements have been set.**

***Index Terms*—Mars, Human Spaceflight, Pythom Space, Human Aspects**

NOMENCLATURE

ADES	Attitude Disturbance Estimation System
BMD	Bone Mineral Density
BNNT	Boron Nitride Nanotubes
BT	Body Temperature
CDRA	Carbon Dioxide Removal Assembly
CRS	Carbon Dioxide Reduction System
EVA	Extravehicular Activity
ECLSS	Environmental Control and LSS
GCR	Galactic Cosmic Rays
HEPA	High-Efficiency Particulate Air
ISRU	In Situ Resource Utilisation
ISS	International Space Station
LMS	Leak Monitoring System
LSS	Life Support System
MAV	Mars Ascent Vehicle
MDV	Mars Descent Vehicle
MLI	Multi-Layer Insulation
MOXIE	Mars Oxygen ISRU Experiment
NASA	National Aeronautics and Space Administration
NHV	Net Habitable Volume
OGS	Oxygen Generation System
PBA	Portable Breathing Apparatus
PFE	Portable Fire Extinguisher
PPE	Personal Protective Equipment
RAD	Radiation Assessment Detector
SPE	Solar Particle Event
SOI	Sphere of Influence
THC	Temperature and Humidity Control
T&T	Tom and Tina Sjögren
TV	Transfer Vehicle
WHO	World Health Organisation
WRS	Water Recovery System

I. INTRODUCTION

THE Hugin & Munin Mission seeks to send two people – Tom and Tina Sjögren – to Mars in a minimal way. This is a big challenge, especially for Human Aspects, as keeping the crew alive is crucial for mission success, but at the same time, space is hostile to human life. The Human Aspects group accepted the challenge and looked into the environments and setting needed, and decided on systems to implement them. For this, several assumptions were made, already available solutions were extrapolated regarding efficiency and new solutions were added. The aspects necessary for this mission were divided into primary and secondary requirements: definitely and immediately life-threatening and possibly life-threatening long-term.

For a more detailed overview of the mission, see the reports of the other groups in *Team Red* [1][2][3][4][5].

II. Primary Requirements

A. Life support systems

To ensure survival in the harsh environments of deep space and Mars surface, a Life Support System (LSS) is needed. These primarily include air, water and food supplies but also pressure and temperature regulation and waste disposal systems. In order to optimise the performance and ensure the safety of the crew, there should be much thought in what the supplies should contain, as well as the quantity of it. However, beyond safety there are additional constraints to consider, e.g. mass and volume costs concerning the whole mission. For a shorter mission an open loop system might be optimal, but for a Mars mission a partially closed loop system may be the most feasible and favourable way to go. Without a reliable LSS the whole mission would fail, as it would jeopardise the lives and health of the crew. Temperature and humidity control is another important aspect that directly affects human health, but also important for keeping equipment at its best condition which otherwise may lead to mission failure.

1) Water and Air: In order for the crew to survive, there must be systems available which provide breathable air and potable water. The atmosphere on Earth consists of 78.1% nitrogen, 20.9% oxygen, 0.93% argon, and several trace gases including carbon dioxide and water vapor [6]. On Earth, this happens naturally with i.a. photosynthesis, but in space it must be artificially imitated by various recycling and supply systems. The conditions found on Earth are, however, not completely set in stone but can be adjusted as long as some basic conditions are met. If the air pressure and temperature are not controlled, the bodily fluids may evaporate in an unwanted manner. The partial pressure of O_2 must be at a suitable level for metabolic use, while being low enough to prevent oxygen toxicity. If the pressure in the cabin becomes too low for a longer period of time, crew members can develop atelectasis – a condition in which the lungs collapse. To prevent the risk of this happening, there should be some physiologically inert gases available. And finally, the explosive hazards of the atmospheric gases must be as low as possible.

Beyond the supply of the input, the removal of the CO_2 and other toxic by-products is also important to acknowledge. Depending on the duration of the mission the acceptable CO_2 limits allowed on-board varies. The National Aeronautics and Space Administration (NASA) has stipulated an acceptable level of maximum 0.5% CO_2 for mission duration of about 1000 days as astronauts on-board the International Space Station (ISS) showed changed behaviour above this level [7]. For journeys in deep space this is not acceptable.

Using LiOH to absorb CO_2 is an effective and common technique [8]. It is an exothermic method which uses LiOH as a sorbent to recover the CO_2 and produces Li_2CO_3 and water, as seen in Equation 1. This chemical reaction is not reversible so the Li_2CO_3 must be discarded and the LiOH refilled, once it is used up.

$$2\,\mathrm{LiOH} + \mathrm{CO_2} \longrightarrow \mathrm{Li_2CO_3} + \mathrm{H_2O} \tag{1}$$

Regarding water in human spaceflight, it has a variety of purposes to support the lives of the crew. It is used for drinking, food preparation and personal hygiene. Furthermore, water also functions as coolant for systems, flush water and can even be used to extract oxygen.

There are many ways to provide functioning supply systems, and beyond safety and robustness there are other constraints to take into consideration, such as mass and volume restrictions. There are three conceptual methods of providing these resources; an open loop in which the water and air is brought as a complete storage, a closed loop where recycling is at full capacity, or a hybrid version of these approaches. This decision heavily relies on the technology available, duration of the mission and the crew size in a way that investigates mass savings: At what point do the masses of the water, air and carbon dioxide exceed the masses of their recycling systems?

Initially, it is useful to study the masses of the daily requirements and how much is produced. About $0.84\,\mathrm{kg}$ of O_2 is needed for metabolic use per crew member and day [9]. $1\,\mathrm{kg}$ of CO_2 and $0.35\,\mathrm{kg}$ of metabolic water is produced per crew member and day. The total water required per crew member and day is $5.67\,\mathrm{kg}$. A more detailed water mass balance is seen in the Appendix, Table 1.

On-board the ISS is the Environmental Control and LSS (ECLSS) which includes the Oxygen Generation System (OGS), Carbon Dioxide Removal Assembly (CDRA), Carbon Dioxide Reduction System (CRS) and Water Recovery System (WRS). The ECLSS is robust and has a low probability of failing, but despite that there are always one or two spares available. The purpose of the spares is not to decrease the probability of failure further but as insurance. As the mission duration increases, so do the risks. Beyond that, the great distance from Earth eliminates the conveniences of help, live communication and restocking. Because of this, additional spares of systems and margins are needed. Jones [9] calculated the amount of system spares in three different approaches and came to similar conclusions; three spares is satisfactory for a Mars mission. He then compared the different subsystems for air and water recycling available on the ECLSS, in order to determine the mass costs by using them on a Mars mission, or if it would be advantageous to open the loop and only bring storage. By examining the breakeven days – the amount of days it takes for the mass of the daily use of the resources of the crew to weigh out the total mass of the system – it is possible to determine which option is best. Table I presents the masses of each system with three spares, their mass breakeven days and payback ratios when considering a transfer duration of 960 days and a crew of two people. In this context, the system masses have been reduced to half compared to the systems on the ISS as it was designed for four people and technical advances are assumed to have been made for the mission.

Table I: Masses of subsystems of ECLSS with spares and breakeven days.

System	Mass of system and three spares [kg]	Mass breakeven days	Mass payback ratio
OGS	936	557	1.72
CDRA	332	95	9.08
CRS	493	301	3.19
WRS	1770	190	5.04
ECLSS	3531	219	4.38

The transfer segments of this mission use a version of the ECLSS, as the payback ratio is greater than 1 and therefore mass cost-effective. This system closes the air and water loops to some extent, meaning storage is also used due to recycling not being able to reach a full loop. However, all breakeven days are greater than the duration of the stay on Mars surface, 20 days, which is why additional LSS is not brought on the Mars Descent Vehicle (MDV), but a complete storage is used. Table II shows the masses and volumes of what will be included to be brought to Mars. Because of the open loop approach, a waste tank is also to be included, as seen in the table.

Table II: Masses and volumes of what will be brought to Mars surface.

	Mass [kg]	Volume [m^3]
Water	227	-
Water tank	5.58	0.23
Nitrogen	11.1	-
Nitrogen tank	10	0.30
Waste tank	5.9	0.30

The daily water use for Mars is reduced, compared to that of the transfer due to clothes not being washed and having disposable clothes instead. This solution reduces the total mass as a washing machine out-weighs 20 days of clothing. Oxygen, however, will be recycled with the Mars Oxygen ISRU Experiment (MOXIE), added by the *Mars Operations* group [4]. MOXIE utilises the CO_2 produced by the humans to generate O_2. Once this CO_2 is used up, the MOXIE continues to consume it from the CO_2 rich atmosphere of Mars. The purpose of the nitrogen is to pressurise the atmosphere of the Mars base, also taking leakage losses into account. The mass allowance, as prompted by the *Transfer Vehicle* group [5], for the Mars Ascent Vehicle (MAV) is close to zero and therefore everything is left behind on the Mars surface. The tanks in which the leavings are stored will be completely sealed as to ensure there is no contamination by the crew on Mars.

2) Food: A tremendous challenge is to develop a food system which combats the threats the deep space environment poses to humans while maintaining food palatability and minimising the volume and mass of it.

Astronauts on the ISS today receive a varied menu of food: they are provided with three meals a day, as well as snacks making sure they receive at least 2500 kcal daily [10]. Generally, a man needs 2500 kcal and a woman 2000 kcal, so by implementing a similar food system to T&T their calorie intake requirements are fulfilled. There must also be an addition of 200 kcal per Extravehicular Activity (EVA) hour, as it increases the metabolic rate [6]. However, a Mars mission cannot restock the storage every two months, like the ISS, which is one of the reasons the food planning needs more consideration. This also means the crew is only able to consume fresh vegetables and fruit in the first few days of the mission, which will have a toll on both their physiological and psychological health, as fresh food has been reported to boost morale [11]. Another big difference is that the products' shelf life must last longer for a Mars mission. Agriculture could be a solution for the future: NASA has been successful in growing edible plants on the ISS in their *Veggie* plant growth system [12]. The experiment –

called *Veg-01* – proved that safe foods can be harvested in a space environment. NASA has also attempted to produce Mars soil simulants for the purpose of one day growing food on Mars [13]. However, due to high uncertainties, agriculture will not be an option for T&T which is why they will be fed prepacked foods.

The food system needs to meet the following criteria [11]:

- **Safety**. Food risks associated with the health of the crew must be minimised to avoid contamination and sickness, such as food poisoning.
- **Stability**. The food system for a Mars mission must obtain stability for a minimum of 5 years, which unfortunately has not yet been developed. This can be challenging for numerous reasons, i.a. mass and volume restrictions of freezers as well as being stored in the hostile environment of space.
- **Palatability**. If the crew is not willing to prepare and consume the food, no other criteria matters. With longer missions this becomes more paramount, as the motivation to eat the food would decrease if it was unpalatable.
- **Nutrition**. Adequate nutrition intake is crucial for the health and performance of the crew and needs to be optimised and taken into serious account. Numerous exploration missions on Earth have failed due to lack and misuse of proper nutrition.
- **Resource minimalisation**. Beyond the criteria relevant for the acceptability and safety of the food, there must be consideration for the bigger picture of the mission concerning mass, volume and other constraints put by the vehicle to improve feasibility.
- **Variety**. Variety is connected to palatability in a way that it builds up motivation to consume the food and prevents menu fatigue. Variation includes assortment, consistency and flavor.
- **Reliability**. The food system must be robust and cannot risk failing, as it would lead to fatal consequences. Margins must be included and the system must be tested extensively in similar environments.
- **Usability**. The production and preparation of the food on-board must be easy and fast, especially when the purpose for the mission is exploration rather than colonisation. There should not be unnecessary time and focus spent in the kitchen.
- **Space ready appliances**. It is important to consider safety and space environment convenience for food preparation. Adding hot water and/or heat is a method used today on the ISS and is suitable for this mission as well.

The astronauts on ISS receive $0.83\,\mathrm{kg}$, of which $0.12\,\mathrm{kg}$ is packaging, per meal [14]. For two people on a 980 day journey while receiving three meals a day, and with a 5% margin, this results in $5124\,\mathrm{kg}$ of food, including packaging. The food would take up a volume of $2.18\,\mathrm{m}^3$ [15].

3) Temperature: The average temperature of empty space is $2.73\,\mathrm{K}$ which is the Cosmic Microwave Background (CMB) radiation [16]. Depending on the distance from stars and whether you are in the shade, determines the average temperature of specific points in space. In general, the further you are away from the Sun the colder the temperature is. The average temperature on Mars is $-63\,°\mathrm{C}$ which can range from $-140\,°\mathrm{C}$ to $30\,°\mathrm{C}$, depending on the time through the day and season [17]. The normal Body Temperature (BT) in general – regardless of an activity, age, gender, etc. – ranges from $36.4\,°\mathrm{C}$ to $37.2\,°\mathrm{C}$, [18]. In space, other than the extremely cold temperature, weightless condition is another factor that can affect BT. After monitoring astronauts on the ISS for 2.5 months, researchers have found that the astronauts' Core Body Temperature (CBT) increased up to approximately $38\,°\mathrm{C}$. Especially during exercise, astronauts easily get overheated, even exceeding $40\,°\mathrm{C}$ in some individuals [19]. Therefore, it is very important to keep optimal temperature levels inside the cabin, in order to avoid any possible health risks such as hyperthermia (BT $> 40\,°\mathrm{C}$) and hypothermia (BT $< 35\,°\mathrm{C}$).

The World Health Organisation (WHO) suggests 18 to $26\,°\mathrm{C}$ to be a safe and well-balanced indoor temperature for the general population's health. The lower limit was set for the countries with colder climates[20]. Considering the extreme cold conditions that T&T will experience during the Mars mission, lower and upper limit of the cabin is set at 18 and $26\,°\mathrm{C}$ respectively to minimise health risks.

Another way to protect a human from extreme temperature condition is a spacesuit. According to the research done at UC Berkeley, feet, lower legs, and upper chest are much less sensitive than average, while cheeks, back of the neck, and lower torso to thigh area (seat area) are 2-3 times more sensitive to cooling and warming. Also, every body part is more sensitive to cooling than warming [21]. When designing a spacesuit to protect astronauts from extreme conditions on Mars and in space, targeting more thermal sensitive body part can be more efficient to keep astronauts warm.

4) Humidity: On a spacecraft, the great change in humidity mostly comes from astronauts' activity including breathing and sweating [22]. Therefore, it is important to maintain the optimal humidity level inside the cabin for both astronauts' health and electronics. In high relative humidity, sweat evaporates slowly and the body can heat up, which can cause hyperthermia in high temperature. Also, humid air can worsen asthma as it is hard to breathe. In contrast, dry air takes moisture away from the skin and can lower the body temperature. Both low and high humidity condition can worsen allergies. Especially in high humidity condition, there is a high chance of microorganism growth which can cause illness [23]. Humidity level can also affect electronics. High condensation can cause corrosion of metals or damage printed circuit boards. On the contrary, low relative humidity can generate electrostatics, static damage, static susceptibility or discharge spark, [24].

According to building system standards, 30-70% is the recommended comfort relative humidity at ambient temperature (20-30 °C) [21]. The relative humidity levels on Columbus on the other hand, range from 25 to 75% – ISS keeps relative humidity around 60%. The upper limit is set to avoid condensation, while the lower limit is set to avoid electrostatic charge [25]. As temperature and humidity are closely related to each other, the strategy to decide the optimal relative humidity level inside the cabin is to adjust the humidity level according to the temperature or vise versa in order to fall into the comfortable zone (see Appendix, Figure 1) while avoiding condensation. Since the temperature is set at 18-26 °C, the relative humidity level in cabin is set at 30-70%.

5) Temperature and Humidity Control: Thermal control system can be divided into two categories: passive and active thermal control systems. Multi-Layer Insulation (MLI) blanket is widely used for passive thermal control which is consisted of multiple layers of thin sheets of metal coated plastic films and spacers with low conductivity in between. According to the experiment done by William L. Johnson, a professor at California Institute of Technology, MLI is most effective in high vacuum and when located closest to the cold boundary of 80 K [26]. Aerogel is another good material for insulation. Aerogel is the lightest solid material that is in a gel form of a polymer that has liquid replaced with air. Compared to MLI, Aerogel is the best in ambient pressure environment [26]. To increase the robustness covering variety of ranges of pressure and vacuum conditions with increased durability, MLI-Aerogel blanket is chosen as a passive thermal control system.

Most of the temperature and humidity control systems used for unmanned missions and short-term manned missions are not suitable for long-term manned missions. For example, the dehumidifier used for Crew Dragon would be impractical for long duration ECLSS application, as it vents water to space [27]. Therefore, taking the compatibility with ECLSS into account, Temperature and Humidity Control (THC) [28] is chosen as the active thermal control system.

B. Radiation

Radiation can be categorised into two types: ionising and non-ionising radiation. The former can remove electrons from atoms and molecules traveling through materials like water, air, and human tissue. Contrariwise, non-ionising radiation does not have sufficient energy to ionise atoms, but it can cause thermal damage [29]. In this section, the focus is ionising radiation – Solar Particle Event (SPE) and Galactic Cosmic Rays (GCR) – which is more detrimental to the spacecraft and crew members.

Before estimating how much radiation shielding is required for the mission, radiation effects on humans and multiple space agencies' suggested radiation exposure limits are discussed. According to the German Federal Office for Radiation Protection, acute exposure of deterministic radiation (damage in tissue caused by ionising radiation) over 1 000mSv can cause headache, nausea, vomiting, etc., over 2 000mSv can cause reddening of skin, and anything above 3 000mSv can cause death. Low-level radiation may not cause immediate health effect, but can increase the risk of cancer over time [30].

Multiple space agencies have their own radiation exposure career limits based on a 3% maximum lifetime cancer morality. Canadian, European, and Russian space agencies have 1 000mSv as their career limit regardless of sex and age, while NASA and JAXA (Japan Aerospace Exploration Agency) have their career limit based on sex and age. In this report, the career limit of NASA is used and it is shown in Figure I.

	E(mSv) for 3% REID (Ave. Life Loss per Death, yr)	
Age, yr	Males	Females
25	520 (15.7)	370 (15.9)
30	620 (15.4)	470 (15.7)
35	720 (15.0)	550 (15.3)
40	800 (14.2)	620 (14.7)
45	950 (13.5)	750 (14.0)
50	1,150 (12.5)	920 (13.2)
55	1,470 (11.5)	1,120 (12.2)

Figure I: Career effective dose limit [mSv] and years of life lost [yr] [31].

Considering T&T's age, gender, duration of the mission, and the safety margin in case of solar flare etc., 1 500mSv is set as the radiation exposure limit.

Prior to the estimation of the amount of shielding needed for the mission, the mission is assumed to be done during solar maximum, as solar magnetic activity is more active during the solar maximum lowering the GCR intensity by deflection [32]. Also, to increase the accuracy of the estimation, the radiation dose measured by the Radiation Assessment Detector (RAD) during the NASA's Mars Science Laboratory mission was used: $1.7\,\mathrm{mSv}$ during cruise from Earth to Mars, $0.52\,\mathrm{mSv}$ on Mars during solar maximum and $0.75\,\mathrm{mSv}$ on Mars during solar minimum [33].

As Human Aspects focus only on the radiation protection during the cruise, the goal was set to reduce daily radiation effective dose from 1.7 to $1.55\,\mathrm{mSv/d}$ (see Appendix, Table 2).

In order to find the most effective radiation shielding in terms of weight and effective dose, aluminum, Boron Nitride Nanotubes (BNNT), liquid hydrogen, and polyethylene were discussed and they are shown in Figure II.

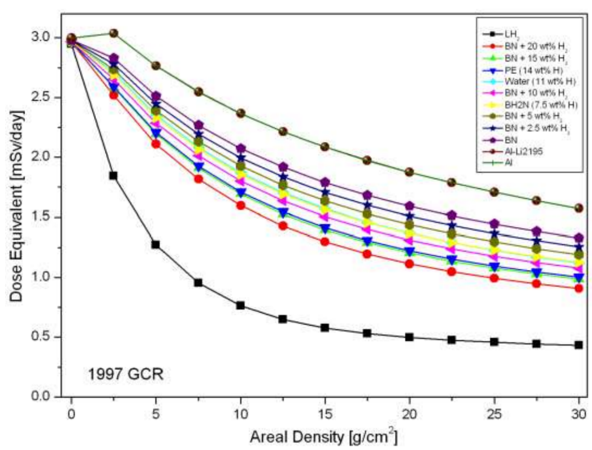

Figure II: Comparisons of multiple radiation shielding materials' equivalent dose as a function of areal density $[\mathrm{g/cm^2}]$ of GCR during solar minimum (1997) [33].

It is clear that BNNT, liquid hydrogen, and polyethylene are a lot more effective than aluminium – which is commonly used in spacecrafts – in shielding radiation and by increasing the hydrogen content, BNNT outperforms polyethylene. Although liquid hydrogen has the best effectiveness as it does not easily form secondary radiation compared to other materials, it cannot be used as structural material. Similarly, polyethylene is not suitable as a structural material, and it is also very flammable. In contrast, BNNT is stable at $700\,^{\circ}\mathrm{C}$ in air and small nanotubes can survive up to $900\,^{\circ}\mathrm{C}$. Furthermore, its elastic modulus and tensile strength are reported to be $1.3\,\mathrm{TPa}$ and $33\,\mathrm{GPa}$ respectively [34]. Therefore, BNNT is chosen as the radiation shielding material of the pressurised module.

Finding the right areal density of BNNT, is done simply by finding the corresponding equivalent does of $1.55\,\mathrm{mSv}$. As it can be seen in Figure II, the equivalent doses without shielding during solar minimum is around $3\,\mathrm{mSv}$ which is clearly greater than the RAD measurement $1.7\,\mathrm{mSv}$ which was taken during solar maximum. Therefore, $1.3\,\mathrm{mSv}$ was subtracted from each data point to match the RAD measurement. To shield $1.55\,\mathrm{mSv}$, roughly $1.25\,\mathrm{g/cm^2}$ of BNNT is required. And to cover the whole surface area of the pressurised module ($118.2\,\mathrm{m^2}$, right circular cylinder with diameter of $3.5\,\mathrm{m}$ and length of $9\,\mathrm{m}$), $1.48\,\mathrm{t}$ of BNNT is required.

Another possible material that can be used for the shielding is the BNNT reinforced aluminium composite – Al-BNNT composites. What makes the Al-BNNT composites stand out from other materials like aluminium alloy, polyethylene, and BNNT is its structural application. Instead of adding extra layer on the surface of the structure for radiation shielding, Al-BNNT composites can be used for building the pressurised module. By adding $0.045\,\mathrm{wt\%}$ BNNT, the nano-hardness, elastic modulus and tensile strength can be improved by 52, 17, and 13% [35] respectively. Also, Al-BNNT composites are lighter than Aluminium Alloy 2195 (Al2195) (commonly used on spacecraft structure), which makes them more fuel efficient. However, it is not certain whether Al-BNNT composites can provide the same effectiveness for radiation protection with such small content and how increasing BNNT or hydrogen content will affect the composites in terms of strength and radiation protection. Therefore, further research is needed.

C. Safety and Emergency

Situations which can be life-threatening to the astronauts should be avoided or averted quickly. That is why extensive testing of materials and systems in extreme conditions before the start of the mission is a very high priority. Nevertheless, emergency situations can happen on long missions, which can be seen on the ISS [36] [37]. Thus, the crew has to be able to overcome threats with systems and equipment on board. Additionally, the crew members have to be prepared for several emergency situations and have to have completed extensive training – see Section III-D.

General equipment on board includes the Personal Protective Equipment (PPE), for instance [6]. It consists of goggles, masks, gloves and the Portable Breathing Apparatus (PBA) [38]. Also, there must be emergency power supplies available, like emergency lighting, torches and batteries, and it must be possible for the crew to manually switch off systems, e.g. the power or the O_2-flow in specific areas.

1) Leakages: In the case of leakage the spacecraft can be exposed to different threats. Substances can escape or (toxic) substances enter the atmosphere within the spacecraft. For dealing with leakages three steps are important: monitoring of the spacecraft for leakage detection, searching for leaks, and sealing of leaks. For the detection a Leak Monitoring System (LMS) is set up. Supported by the LSS, it continuously monitors pressure and temperature of any substances present in the spacecraft, e.g. O_2, ammonia. In the case of any changes the crew is alerted [39]. The crew is informed about the leaking substance and the leakage rate. This helps the crew evaluating the risk of the leakage, searching and sealing the leak. Additionally, it informs them whether wearing PPE is advised.

If the leak is located in the habitable area of the spacecraft, the Attitude Disturbance Estimation System (ADES), presented by [40] is used for accurate localisation of the leak – the system is assumed to be fully functional. ADES "uses the attitude response [...] caused by the leak reaction force of the air flowing through a perforated hole. The vent thrust can yield a strong reaction torque depending on the size and location of the leak" [40].

The sealing is done with chemical sealing agent, e.g. resin, in combination with sealing material [41][42].

In the case of an external leak, meaning that a substance that is not part of the pressurised module leaves the spacecraft, e.g. ammonia, the crew is also notified through the LMS. In this case ADES does not strike alarm. Thus, the crew knows the leakage is external. The leak then has to be located and sealed during an EVA.

2) Fire Prevention, Detection and Suppression: Another threat during spaceflight is fire. To prevent harming or killing the astronauts several measures regarding prevention, detection and suppression of fire have to be taken. The oxygen level should be below 23% and its partial pressure below 30% of the total pressure of the atmosphere to avoid accelerated combustion – the values for this mission are 20.9% for oxygen level and 21% for oxygen pressure. Also, the materials used in the spacecrafts should have slow combustion rates, high ignition temperatures and low potential for exploding [6].

The detection of smoke and fire relies on proper convection by the ECLSS in the spacecraft, such that the smoke detectors can fulfill their function. The smoke detectors are mounted in equipment modules, pressurised areas and close to ventilation return ducts, to cover all inflammable areas of the spacecraft. In the case of an alarm, the crew is informed about which smoke sensor went off for localising the fire. To ensure that the fire-warning system always works – even in the case of failure of power or of an associated system – it has to operate independently. In the case of failure of the fire-warning system, the crew has to be immediately informed [6]. Following the example on the ISS, a combination of different Portable Fire Extinguishers (PFE) is used – water and CO_2-based. CO_2-based PFE ejects CO_2 and is mainly used for fires that are hard to reach or cannot be localised. The second set of PFE on board contains foaming agent and distilled water – they are used in the Russian part of the ISS and are called OKP-1. It is used for localised fire. The extinguishing agents in both PFE are nontoxic and do not chemically react with the materials in the spacecraft [6]. Additionally, the PFE must be accessible at all times and the extinguishing itself has to be easy.

After the fire is extinguished, the ECLSS restores the balance in the environment of the spacecraft and filters left contaminants.

3) Contamination: Contamination is split into three different aspects: toxic, biological, and particulate-based contamination.

Toxic contamination is treated like a toxic leakage in Section II-C1.

Biological contamination poses a danger to the astronauts, because it could compromise their health. Fighting it is more complicated than on Earth, as aerosols stay in the air due to lacking gravity. The solution is to have proper ventilation by ECLSS, filtration with High-Efficiency Particulate Air (HEPA) filters and monitoring [6].

Floating particulates in the spacecraft irritate the eyes and respiratory system [6]. This problem arises due to dust in the spacecraft and especially when T&T return to the TV after staying on Mars surface. This issue is also solved by ventilation and HEPA filtration. For the removal of bigger particles – and also for regular cleaning of the spacecraft, see Section III-C – a vacuum cleaner can be used [43]. It consists of a hose with different top pieces that can be attached to an air convection system. Considering enough redundancy for every hardware and system – e.g. 3 PPEs, 11 smoke detectors, 4 CO_2- and 4 water-based PFE – the total mass, volume and power needed for Safety and Emergency is estimated to $122.3\,\mathrm{kg}$, $0.221\,\mathrm{m}^3$ and $36.5\,\mathrm{W}$ [6][44][45]. In the Appendix in Table 3 the amounts are shown in detail.

III. Secondary Requirements

A. Medical and Physical Aspects

For the crew to complete the mission and return to Earth safely, the effects of long-term space travel on the human body must be considered. The longest time spent in space was by Valeri Polyakov in 1994-1995 where he spent 437.7 days aboard Mir [46]. Spending 980 days in microgravity has not been done before, so extrapolation from previous missions to space and current research on Earth was made.

1) Medical Aspects: Effects of space on the human body can be broken down into three stages: early response (first 3 weeks), intermediate (3 weeks to 6 months), and long term (over 6 months). Early responses to space travel are far more researched and include space sickness, sleep disturbances, and poor proprioception, where the awareness of the body's sense of movement and location is decreased. The most notable intermediate responses are bone resorption, muscle atrophy, and radiation exposure. Long term effects are less conclusive and include the worsening of bone and muscle loss, declining immunity, and cardiovascular deconditioning [47]. Bone loss has no documented "end point", so it is crucial to perform countermeasures to retain strength and prevent irreversible skeletal damage, especially on load-bearing areas such as the legs, spine, and pelvis [48].

There are several studies using bed rest as a simulation for microgravity, however these studies only last around 70 days so the results of these studies are not relevant for a Mars mission. Much of the relevant research on the effects space has on the human body has come from the ISS and previous spaceflights. A person's legs become thinner as there is no gravity to circulate the fluids in the body. Additionally, the heart will become smaller since it is doing less work than it normally would on Earth and there is less blood to pump [8]. Roscosmos found that after long duration space flights, the brain changes shape and fluids shift due to the lack of gravity [49]. These results came after only 170 days in space, so the effects would significantly worsen from a 980 day mission to Mars.

After spending 330 days in transit to Mars, the crew will have to decelerate through the Martian atmosphere and land on Mars. This will be similar to landing back on Earth after a long-duration spaceflight in which the side effects have been previously researched. However, they will then have to relaunch back into microgravity after only spending 20 days on the Martian surface. During launch, astronauts experience around 3 Gs, and 7 Gs on a ballistic landing [50][51]. The Pythom Space crew will experience G forces higher than 3 Gs for 21 seconds with a maximum of 3.6 Gs during ascent, and G forces higher than 3 Gs for 14 seconds when landing with a maximum of 6.7 Gs during descent, as calculated in *Transfer Vehicle* [5]. On the way to Mars, the crew will lose around 12% of their Bone Mineral Density (BMD), and by the time T&T arrive back on Earth, models predict they will have lost around one third of their BMD and be at severe risk for developing osteoporosis [52]. This does not take into account that postmenopausal women lose BMD at an increased rate [53].

There have been no studies on the effects of the human body experiencing several Gs after long periods of being in microgravity. Since there will be significant bone and muscle loss, the force of launching back into space may have detrimental effects on the body that are not yet known. Countermeasures must be taken so that T&T's bodies will be able to get through the Mars launch and landing.

Medical equipment will be brought on the mission including an ultrasound machine, defibrillators, and physician and dental equipment, along with several diagnostic, treatment, and supply packs. These medical packs will resemble those that currently exist on the ISS. Regular checkups will be performed weekly to monitor the physical state of the crew and see if any preventative measures are needed. These checkups will be supported by an Artificial Intelligence (AI) health professional.

2) Exercise: Astronauts on the ISS exercise roughly 2 hours per day, however on a long duration space mission, the crew must exercise more to prevent bone and muscle loss. To counteract the effects of microgravity, an average of 3 hours of exercise must be integrated into the crews' daily schedule. On a long-term space mission, there will be a significant loss in leg strength despite exercising regularly [54]. A strict exercise routine is designed to maintain muscle mass and bone density as the physical demands change throughout the mission.

A treadmill similar to COLBERT on the ISS will be brought on the mission, as well as two flywheel exercise resistance machines. The flywheel machine can be used to perform a variety of exercises that will target various muscle groups, specifically those in the legs [55].

The exercise routine will involve a combination of time on the treadmill and using the flywheel, with roughly 2-2.5 hours per day spent strengthening the leg muscles. A high intensity/low volume exercise program is suggested because although there is no significant improvement in muscle and bone loss, it will reduce the time the crew must spend exercising and can be used for maintenance or other tasks instead [56]. The overall time spent exercising will need to increase leading up to the arrival on Mars and Earth to make sure the bones and muscles are strong enough to support the crew when they are exposed to gravity.

B. Psychological Aspects

A mission to Mars far surpasses any current research or simulations on long term isolation. Existing studies on the psychological effects of long term space travel are nowhere near the length of an actual Mars mission. The longest isolation study was conducted by Russia, ESA, and China called MARS-500 was a study where the final stage simulated a 520-day mission to Mars [57].

As time passed, the overall MARS-500 crew activity level decreased significantly because of sleep deprivation and other side effects of long term isolation, and they spent 700 more hours in bed on the return journey than the outboard journey. Different crew members were assigned different sleep schedules and day lengths, which caused poor team performance and increased risk of accidents [57]. Separate sleep schedules were considered for T&T to have one person awake at all times in case of emergency, but this was found to have detrimental psychological effects.

The MARS-500 crew had roughly six times more NHV per person in their facility compared to the allocated living space for T&T in the TV, and the NHV in the Mars landing simulator module from the MARS-500 study was 35 times bigger [58], as shown from the volumes given in the *Transfer Vehicle* [5] and *Mars Operation* [4] reports. As such, the psychological effects studied from long term space travel such as boredom and isolation within the crew may worsen quicker [59].

The Pythom Space crew will need to adjust to the approximately 40 minutes longer Martian day, or "sol", since during their time on the Martian surface, they will be spending half of their time on the surface performing EVAs, as mentioned in *Mars Operations* [4]. Since the journey to Mars for this mission will take 330 days and the change in day length is 40 minutes longer, the crew will increase their day length by 10 minutes every 82 days, and by the time they reach Mars, they will be accustomed to using sols instead of Earth days. On the journey back to Earth, the crew will revert to using a 24-hour day immediately to reduce any unforced errors that may be a result of the longer day length.

The psychological effects of the isolation due to the recent COVID-19 pandemic are comparable to the long journey to Mars. It was found that during the isolating periods of the COVID-19 pandemic, couples' relationship satisfaction declined and experienced poorer cohesion [60]. On the other hand, conquering a difficult feat together, such as this mission, may in fact strengthen the couples' relationship. Crew dynamics and roles within the team do not need to be considered, since the crew is already chosen and has been on several expeditions together. However, since this mission is longer than previous expeditions T&T have been on, the crew may experience boredom, stress, claustrophobia, and increased irritability [61] – common side effects of long term space travel [62].

Crew morale will change throughout the 980 day period [63]. During the journey to Mars, common psychological effects long term space travel mentioned previously will arise. As time moves forward, harsh realisations will become more apparent, such as the limitation of resources or the realisation that if something were to go wrong, there is no chance for immediate help, escape, or rescue. Additionally, spending over 2.5 years traveling to and from Mars only to be able to spend 20 days on the Martian surface will have to be accepted by the crew. As T&T approach the Mars Sphere of Influence (SOI), they may feel the increased pressure to ensure the mission is successful. After leaving Mars SOI and the crew's time on the Martian surface is over, they may feel low-spirited having to orbit around the Red Planet for up to 310 days without being able to return. On the journey back to Earth, excitement to return to Earth and sadness of leaving Mars may result in conflicted feelings.

Other perhaps less critical psychological factors to consider are the Earth-out-of-view phenomenon and constant noise in the TV. Astronauts have always been able to look out a window and see Earth, so the psychological effects of the planet slowly shrinking away into the darkness is unknown, and different people may react differently. The constant mechanical humming of the TV can cause increased stress and irritability [64].

It is crucial to minimise the negative psychological effects of long term space flight, so T&T will remain focused on the task at hand while also being able to enjoy the journey. Anything that may lead to a strike or mutiny similar to what happened in SkyLab 4 should be avoided [65]. The Pythom Space crew should be as comfortable as possible while also keeping a strict but varying schedule. Each crew member will have an allowance of 3 kg for any personal belongings they wish to bring on the mission. Additional techniques to mitigate negative psychological effects include distinct areas on the TV for different activities, areas that can be used to spend time individually, keeping the crew entertained throughout the mission, and tracking mood and performance to spot any potential risks to the crew and the mission. Crew members should have their own personal goals to challenge themselves to learn new skills and spend time away from doing busy work [59].

C. Hygiene

Personal hygiene eliminates microorganisms and prevents the spread of disease. From a psychological point of view it has a considerable impact on morale of the crew and finally on productivity. Next to individual needs, waste management and housekeeping are in the scope of this report.

1) Personal hygiene: Personal hygiene covers body washing, oral hygiene, and grooming. The development of a crewed space mission should take into account the hereinafter explained influences. Experiences from previous missions show that adequate body cleansing improves the self-image of the crew and is therefore high on the list of priorities. Restrictions to hygiene practice due to limitations in water supply should be minimised. On short-duration missions partial-body cleaning using disposable wipes might be sufficient, whereas for long stays in microgravity reusable towels soaked with water are used for whole-body cleansing [6]. Aimed at the evaluation of a new concept, a shower was designed for Skylab and used on all three missions [66]. $2.8\,\mathrm{L}$ of preheated water were filled in a portable bottle which was attached to a flexible hose and a hand-held shower head [67][68]. To prevent water floating through Skylab a foldable fireproof curtain in cylindrical shape was attached to floor and ceiling. Excess water was vacuumed by using another hand-held flexible hose [69]. A major disadvantage of this concept is that whole-body cleansing requires about one hour [6]. As the duration of the mission discussed in this work exceeds previous ones by far, it is assumed that more crew time can be provided for personal hygiene aiming on optimised crew comfort. Given that wash water can be recovered up to 99% if a shampoo compatible with the ECLSS is provided, water limitations can be undermined [9]. For the analysis of the water supply – see Section II-A1 – it is assumed that $10\,\mathrm{L}$ of water is needed for a shower which is based on water restrictions on Mir [6]. Each crew member is allowed to shower twice a week. On Mars, disposable wipes and soaked towels are used for body cleansing to minimise the down mass. A concluding element of personal hygiene is feedback to the crew which can be provided in the form of whole-body mirrors.

2) Body waste management: Several influences should be considered for the design of a body-waste management facility in microgravity. The overall design goal is to enable body-waste management activities similar to conditions on Earth with aim at ease of use and the amount of time needed. Psychologically or physiologically unacceptable circumstances can lead the crew to modify their diet and eventually to nutritional deficiencies. As well as donning, doffing, and body cleansing, body-waste management activities require visual, auditory and olfactory privacy. An airstream is used to prevent unpleasant odors and assists the removal of feces in microgravity. Emergency use of the facility in case of vomiting or diarrhea also needs to be taken into account. Other than urine, feces are kept in a tank throughout the mission. For the sizing two defecations per crew member (CM) and day are assumed with a volume of $0.15\,\mathrm{L}$ each. Note that $1/3$ of the volume is water which is not carried back to the ECLSS. The waste water tank furthermore contains solids from urine which is $0.066\,\mathrm{L/CM/d}$ and tissues for cleansing [6]. Based on these assumptions a total volume of $0.97\,\mathrm{m}^3$ is required on the TV. Its mass of $14.7\,\mathrm{kg}$ is estimated assuming a cylindrical tank $1\,\mathrm{m}$ in diameter of $1\,\mathrm{mm}$ aluminium sheets. The body-waste facility for the Mars habitat can be designed in a similar way. With respect to gravity on Mars no restraints are needed to fasten the user to the facility. As an open water loop is provided in the habitat and no waste shall be dumped on Mars, the waste tank is dimensioned to contain all the water needed, $2/3$ of feces (as $1/3$ is considered to be water) and tissues. Based on these assumptions, the waste water tank has a volume of $1.174\,\mathrm{m}^3$ and a mass of $20.19\,\mathrm{kg}$ for a diameter of $0.7\,\mathrm{m}$.

3) Laundry facility: Objectionable odors can lead to interpersonal conflicts and are avoided by body cleansing but also by changing or washing clothes. Antimicrobial clothing (advanced clothing) partially consists of silver threads or merino wool which allow an extended usage rate before washing is necessary. While $0.2058\,\mathrm{kg/CM/d}$ of conventional clothing is required, advanced clothing reduces this number to $0.1576\,\mathrm{kg/CM/d}$. For a detailed overview of different items and its usage rates see [70]. The same study also states that the best clothing system depends on the mission and assumptions, but it is estimated that reusing clothes by washing them starts to pay off as a mission endures about one year or longer. Next to clothing items, also non-clothing items need to be taken into account, such as towels or sleeping bag liners, with a mass of $0.182\,\mathrm{kg/CM/d}$. Using disposable advanced clothing for this mission would thus require a mass of $680\,\mathrm{kg}$. Different solutions for washing or sanitising clothes in space are also evaluated based on [70]. It is assumed that clothes can be sanitised with steam, ozone or in a vacuum chamber up to 5 times while washing in a water based facility also enables the reuse of non-clothing items and is possible up to 100 times. It is expected that sanitising might eliminate microbes but does not remove dirt or grease. Thus, it is decided to use the water based simple microgravity laundry device. Considering the maximum load of $1.5\,\mathrm{kg/cycle}$, three cycles are needed per week. Each requires $0.003\,\mathrm{kg}$ of detergent and 11 L of water assuming the water consumption of the device presented in [71] scaled to a load of $1.5\,\mathrm{kg/cycle}$. After washing, the laundry needs to be spread out in the spacecraft to dry. Rounding the number of clothing and non-clothing items required to reasonable integers, the total mass for these is $172\,\mathrm{kg}$. It is assumed that $99\,\%$ of the wash water can be recovered [9]. Considering masses of clothing and non-clothing items, the laundry facility and water requirements, the breakeven time for this system compared to disposable clothing is 297 days. For the comparatively short time the crew spends on Mars, disposable advanced clothes are recommended with a total mass of $13.6\,\mathrm{kg}$.

4) Housekeeping: As well as personal hygiene, housekeeping plays an important role for the health of the crew and is a crucial part of habitability. Sources of microbes are, for example, hair, dead skin particles, clothing lints or food spills. NASA's experiences from Skylab show that the surfaces need to be smooth and illuminated to allow easy cleaning. Crevices or cracks accumulate dirt while mildew occurs in wet and poorly ventilated areas. An aromatic biocide sprayed with an aerosol is a practical way to clean the habitat and removes odor of urine spills and trash receptacles effectively. On Skylab and Space Shuttle vacuum cleaners showed to be effective for removing debris and liquids. They are also used to clean filters of the air revitalisation system. Furthermore wet wipes can be used for every kind of cleaning, also for hand washing [72].

D. Training

Throughout the whole mission, practical and theoretical know-how is inevitable for the crew to unharmfully operate the spacecraft and its subsystems as well as to safely accomplish planned and off-nominal tasks. All necessary competencies are provided by training before and during the mission. The overall approach is based on ESA's astronaut training which is partially adapted to focus on the most essential content. The aim is to prepare the crew for this particular mission rather than training them to qualifying as professional astronauts.

1) Basic Training: The basic training – usually provided by ISS partners – introduces the crew to global space activities and imparts fundamental knowledge of sciences related to human spaceflight. These include aerospace, electrical and computer engineering, as well as life, material, fluid, earth and space science [8]. It is intended to relate the content to applications that are part of this mission. While knowledge related to orbital mechanics, for example, is considered to be crucial for understanding the overall mission design and evaluating possible minor adjustments to it, the crew is not expected to comprehend the engineering background of subsystems. Next to classroom based education, it is suggested to schedule training of various practical skills. As critical maneuvers are supposed to be executed automatically (see *Transfer Vehicle* [5]), flight training might be omitted in order to save costs and time. Other than that, diverse EVAs are likely to be required for maintaining the TV and exploring Mars. After an introduction to procedures during an EVA, SCUBA diving prepares for activities in microgravity. Seven weeks of training might be considered for EVA training [73]. Parabola flights can help the crew to get used to microgravity and practice living on-board TV. On Mars, the crew will be confronted with numerous challenges related to communication and navigation during EVAs, space suit mobility and protection against dust and radiation. It is estimated that facilities like the Flashline Mars Arctic Research Station and Mars Desert Research Station can prepare the crew to overcome these challenges [74]. As the majority of classroom based training might be neglected, the basic training is assumed to last six months.

2) Advanced training: Similar to ESA's assigned crew training, the advanced training is expected to be tailored to each crew member. It aims to provide knowledge for nominal and off-nominal operations such as maintenance or reparation tasks on TV and MAV/MDV and handling of emergencies. Due to high latency and black-outs in the communication to Earth (see *Logistics* [2]), the crew cannot rely on immediate assistance from ground. For critical on-board systems such as the ECLSS, both crew members are supposed to be on qualification level "specialist", so that either of them can operate and analyse failures. For uncritical systems, e.g. experiments, it may be sufficient that only one crew member has in-depth system knowledge and the other only acts on the qualification level "user" or "operator". An estimation of effort considers that the crew of Inspiration4 has undergone a training of roughly six month including medical test, G-force training and instructions to operate Crew Dragon in the event of taking control [75]. The advanced training for Hugin & Munin lasts for ten months.

3) On-board training: During the mission, on-board training is required to keep proficiency for critical operations such as procedures in case of fire, rapid depressurisation or toxic spills. Unplanned maintenance and reparation tasks have to be prepared and can be assisted by virtual reality devices [73].

E. Environmental Aspects

When designing the human aspects of the Hugin & Munin Mission, environmental aspects were considered. The waste that is produced during the mission is kept to a minimum, as many resources as possible are recycled and the general volume, mass and power that is needed for the crew is minimised.

IV. Off-Nominal Scenarios

The off-nominal scenario the Human Aspects group considered is the failure of the WRS. That means the grey water cannot be recycled, but fresh water can still be extracted and used water can be pumped into the grey or the black water tank; see also in Figure III.

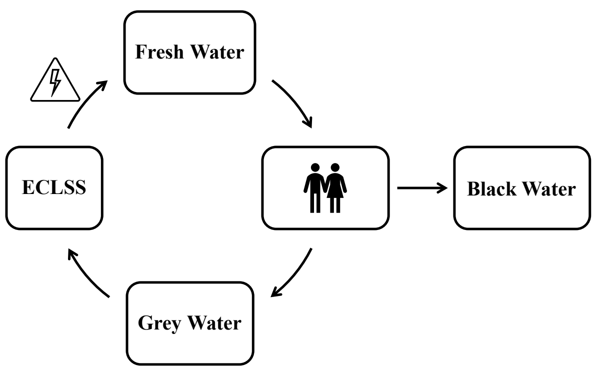

Figure III: Schematic representation of WRS failure.

The crew will at any point in the mission have access to at least three days worth of fresh water, which gives T&T enough time for identifying the issue, finding an appropriate solution and repairing the WRS. If the problem cannot be found during that time until the spare fresh water is used up, the crew will have the possibility to access the water meant for Mars surface. This water would get T&T through another three weeks which would give them more time to find and fix the issue. After repairing the WRS, fresh water tanks of MDV/MAV are refilled with excess water from TV. Additionally, the grey water tank is big enough to store the used water, even though the recycling process is not working.
As the crew needs to be trained extensively – see Section III-D – they will be able to understand and fix hardware and systems on board. Also, there will be three spares in the TV for the reparation of the WRS – see Section II-A1 – which makes complete WRS failure during the mission almost impossible [9].
Further off-nominal scenarios that are kept in mind are other failures of the ECLSS – e.g. OGS, MOXIE, CDRA, THC – damage of the radiation shielding, rapid depressurisation, serious illness, injury or death of the crew amongst many others.

V. Conclusion

It can be said that Hugin & Munin Mission is extremely challenging: even with several assumptions made it will take about three years to then have 20 days on the Mars surface. In addition, several risks and unknowns have to be taken into account, like the radiation exposure, physical changes and extreme isolation.
But then again, someone always has to make the first (big) step to allow progress of any kind. Lots of systems and hardware are already available; they only should be further improved to make a mission to Mars possible.
The Human Aspects group wishes T&T good luck.

VI. Workload Breakdown

A. Jeongmyeong Bae

Jeongmyeong worked on the Radiation II-B, Temperature II-A3, Humidity II-A4, and Temperature and Humidity Control II-A5.

B. Josephine Gurman

Josephine worked on the Safety and Emergency II-C and the Off-Nominal Scenarios IV. Additionally, she wrote the abstract, introduction I and conclusion V. She acted as the Humans Aspects' team leader and stayed in close contact with the other groups of *Team Red*.

C. Henri Kammler

Henri worked on the Sections Hygiene III-C and Training III-D. He also assisted Tara with calculations on subsystems of ECLSS. Furthermore, he organised the references.

D. Tara Mohammed-Amin

Tara worked on the Life Support System II-A, specifically for Water and Air II-A1 and Food II-A2.

E. Laura Yang

Laura worked on the Medical III-A, Physical III-A2, and Psychological Aspects III-B. She also assisted Tara with the Food Section II-A2, specifically the calculations related to the mass, volume and power requirements.

REFERENCES

[1] Magkos, M. et al. *Report Coordination Group*. Human Spaceflight KTH Stockholm, 2022.

[2] Martín-Fuertes, J. et al. *Report: Logistics Group*. Human Spaceflight KTH Stockholm, 2022.

[3] Mirzaeedodangeh, O. et al. *Report: Mission Design Group*. Human Spaceflight KTH Stockholm, 2022.

[4] Lindstein, C. et al. *Report: Mars Operations Group*. Human Spaceflight KTH Stockholm, 2022.

[5] Pilar Alliri, M. et al. *Report: Transfer Vehicle Group*. Human Spaceflight KTH Stockholm, 2022.

[6] Liskowsky, D.R., Seitz, W.W. *Human Integration Design Handbook (HIDH)*. Washington DC, June 5, 2014.

[7] James J.T. *Carbon Dioxide-Our Common "Enemy"*. 2009.

[8] Norberg, C. *Human Spaceflight and Exploration*. Springer Praxis Books. Springer Berlin Heidelberg, 2013. ISBN: 9783642237256.

[9] Jones, H., ed. *Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?* 2017.

[10] Royal Museums Greenwich. *What do astronauts eat in space?* [Online accessed: March 8, 2022]. 8.03.2022. URL: https://www.rmg.co.uk/stories/topics/what-do-astronauts-eat-space.

[11] Douglas, G.L. et al. "Space Food for Thought: Challenges and Considerations for Food and Nutrition on Exploration Missions". In: *The Journal of Nutrition* 150.9 (2020), pp. 2242–2244. ISSN: 0022-3166. DOI: 10.1093/jn/nxaa188.

[12] Rainey, K. "Crew Members Sample Leafy Greens Grown on Space Station". In: *NASA* (7.08.2015). URL: https://www.nasa.gov/mission_pages/station/research/news/meals_ready_to_eat.

[13] Gillis, K. "Solving Space: Growing greens". In: *Space Center Houston* (13.07.2021). URL: https://spacecenter.org/solving-space-growing-greens/.

[14] Larc, B.A. *NASA - Human Needs: Sustaining Life During Exploration*. 3.07.2013. URL: https://www.nasa.gov/vision/earth/everydaylife/jamestown-needs-fs.html.

[15] Manned Spaceflight Center, ed. *SPACE SHUTTLE/ FOOD SYSTEM STUDY*. Houston, Texas, 1975. URL: https://ntrs.nasa.gov/api/citations/19750008160/downloads/19750008160.pdf.

[16] ESA. *Planck and the cosmic microwave background*. [Online accessed: March 1, 2022]. URL: https://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_and_the_cosmic_microwave_background.

[17] NASA Science Mission Directorate. *Mars Facts | All About Mars – NASA's Mars Exploration Program*. [Online accessed: March 1, 2022]. URL: https://mars.nasa.gov/all-about-mars/facts/.

[18] Johns Hopkins Medicine. *Fever*. [Online accessed: March 1, 2022]. URL: https://www.hopkinsmedicine.org/health/conditions-and-diseases/fever.

[19] Stahn, A.C. et al. "Increased core body temperature in astronauts during long-duration space missions". In: *Scientific Reports* 7.1 (2017). DOI: 10.1038/s41598-017-15560-w. URL: https://www.nature.com/articles/s41598-017-15560-w.

[20] WHO. *Housing and Health Guidelines*. Geneva, Switzerland: World Health Organization, 2018. ISBN: 9789241550376.

[21] Luo, M. et al. "High-density thermal sensitivity maps of the human body". In: *Building and Environment* 167 (2020). DOI: 10.1016/j.buildenv.2019.106435.

[22] Let's Talk Science. *Humidity on Earth and on the Space Station*. [Online accessed: March 4, 2022]. URL: https://letstalkscience.ca/educational-resources/backgrounders/humidity-on-earth-and-on-space-station.

[23] PICKHVAC. *Ideal Indoor Humidity (with Chart): Ultimate Guide*. [Online accessed: February 28, 2022]. 20.05.2021. URL: https://www.pickhvac.com/ideal-indoor-humidity/.

[24] Uday, C. *Humidity, It's Effect On Electronic Industry And Solutions*. [Online accessed: February 28, 2022]. URL: https://www.bryair.com/wp-content/uploads/2017/05/uploads_artcale_ARTCALE_249041F5FF9D6D93electr_instry.pdf.

[25] Ley, W., Wittmann, K., Hallmann, W. *Handbook of Space Technology*. Aerospace Series. Wiley, 2009. ISBN: 9780470742419.

[26] Johnson, W.L., Demko, J.A., Fesmire, J.E. "Analysis and Testing of Multilayer and Aerogel Insulation Configurations". In: *AIP Conference Proceedings* 1218.1 (2010), pp. 780–787. ISSN: 0094-243X. DOI: 10.1063/1.3422431.

[27] Silverman, J., Irby, A., Agerton, T. *Development of the Crew Dragon ECLSS*. [Online accessed: February 25, 2022]. 2020 International Conference on Environmental Systems, 2020. URL: https://ttu-ir.tdl.org/handle/2346/86364.

[28] ERASMUS Centre - Directorate of Human Spaceflight and Operation. *Environment Control and Life Support System (ECLSS)*. [Online accessed: March 13, 2022]. URL: http://wsn.spaceflight.esa.int/docs/Factsheets/30%20ECLSS%20LR.pdf.

[29] Djezzar, B. *Ionizing Radiation Effects and Applications*. IntechOpen, 2018. ISBN: 9789535139539. URL: https://books.google.se/books?id=-WaQDwAAQBAJ.

[30] Federal Office for Radiation Protection. *Limit values in radiation protection*. [Online accessed: February 28, 2022]. URL: https://www.bfs.de/EN/topics/ion/radiation-protection/limit-values/limit-values_node.html.

[31] Cucinotta, F.A., Durante, M. *Risk of Radiation Carcinogenesis*. 2009.

[32] Rahmanifard, F. et al. "Evidence From Galactic Cosmic Rays That the Sun Has Likely Entered a Secular Minimum in Solar Activity". In: *Space Weather* 20.2 (2022). DOI: 10.1029/2021SW002796.

[33] Simonsen, L.C., Zeitlin C. *Mars Radiation Environment – what have we learned? Briefing to NAC HEO/SMD Joint Committee Meeting*. [Online accessed: February 25, 2022]. URL: https://www.nasa.gov/sites/default/files/atoms/files/mars_radiation_environment_nac_july_2017_final.pdf.

[34] Singh, K. "Review of Boron Nitride Nanotubes for Space Radiation Shielding". PhD thesis. Georgia Institute of Technology. URL: https://smartech.gatech.edu/handle/1853/66179.

[35] Antillon, M. et al. "Strengthening in Boron Nitride Nanotube Reinforced Aluminum Composites Prepared by Roll Bonding". In: *Advanced Engineering Materials* 20.8 (2018). DOI: 10.1002/adem.201800122.

[36] Malik, T. "Repaired Oxygen Generator Fails Again Aboard ISS". In: *Space* (5.01.2005). URL: https://www.space.com/641-repaired-oxygen-generator-fails-aboard-iss.html.

[37] Dunbar, B. *NASA - Ammonia Leak Outside Station; Crew in No Danger*. 3.07.2013. URL: https://www.nasa.gov/mission_pages/station/expeditions/expedition35/e35_050913.html.

[38] Uhlig, T. et al. "ISS emergency scenarios and a virtual training simulator for Flight Controllers". In: *Acta astronautica* 128 (2016), pp. 513–520. ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2016.08.001.

[39] Hao, P., Jia, D.Y., Yin, Z. "Leak Detection and Location of Seals in Spacecraft Structures Based on a Multi-sensor Data Fusion Method". In: *Protection of Materials and Structures from the Space Environment*. Cham: Springer International Publishing, 2017, pp. 563–572. ISBN: 978-3-319-19309-0.

[40] Jong-Woo, K. et al. "International space station leak localization using attitude disturbance estimation". In: *2003 IEEE Aerospace Conference Proceedings (Cat. No.03TH8652)*. 2003, pp. 3475–3494. ISBN: 1095-323X. DOI: 10.1109/AERO.2003.1234191.

[41] Howell, E. "Cosmonauts seal air leak in Russian module of the International Space Station". In: *Space* (10.03.2021). URL: https://www.space.com/cosmonauts-seal-space-station-air-leak-cracks.

[42] Weitering, H. "Astronauts Work to Seal Air Leak on Space Station. Here's How". In: *Space* (30.08.2018). URL: https://

www.space.com/41685-space-station-astronauts-sealing-air-leak.html.

[43] McArthur, W. S. *Workplace Safety on ISS: Senior Leadership ViTS Meeting*. October 5, 2015. URL: https://sma.nasa.gov/docs/default-source/safety-messages/safetymessage-workplacesafetyoniss-2015-10-05.pdf?sfvrsn=44be5f8_2.

[44] Whitaker, A. *Overview of ISS US Fire Detection and Suppression System*. 2003.

[45] Urban, D. et al. *Particle and Smoke Detection on ISS for Next Generation Smoke Detectors*. 2013.

[46] Wall, M. "The Most Extreme Human Spaceflight Records". In: *Space* (23.04.2019). [Online accessed: March 13, 2022]. URL: https://www.space.com/11337-human-spaceflight-records-50th-anniversary.html.

[47] Byerly, D. *Human Space Travel: Medical Challenges Present and Future*. [Online accessed: February 25, 2022]. URL: https://www.lpi.usra.edu/education/explore/space_health/presentations/byerly.ppt.

[48] Smith, S.M. et al. "Benefits for bone from resistance exercise and nutrition in long-duration spaceflight: Evidence from biochemistry and densitometry". In: *Journal of Bone and Mineral Research* 27.9 (2012), pp. 1896–1906. ISSN: 1523-4681. DOI: 10.1002/jbmr.1647.

[49] Gohd, C. "Cosmonaut brains are 'rewired' by space missions, scientists find". In: *Space* (February 18, 2022). [Online accessed: March 1, 2022]. URL: https://www.space.com/cosmonaut-brains-rewired-by-spaceflight.

[50] Baily, Z. *What g-force do astronauts experience during a rocket launch?* [Online accessed: March 13, 2022]. 13.03.2022. URL: https://www.spaceanswers.com/space-exploration/what-g-force-do-astronauts-experience-during-a-rocket-launch/.

[51] Weitering, H. "Astronaut, Cosmonaut in 'Good Health' After Surviving Soyuz Rocket Launch Failure". In: *Space* (12.10.2018). [Online accessed: March 13, 2022]. URL: https://www.space.com/42109-soyuz-launch-failure-astronaut-crew-good-health.html.

[52] Collins, N. "Mars-bound astronauts likely to develop brittle bones, new study suggests". In: *Stanford University School of Medicine* (January 22, 2020). [Online accessed: March 7, 2022]. URL: https://scopeblog.stanford.edu/2020/01/22/mars-bound-astronauts-likely-to-develop-brittle-bones-new-study-suggests/.

[53] Dervay, J. et al. *Lost in Space: Bone Density: Exploring Space Through Math*. [Online accessed: March 15, 2022]. URL: https://www.nasa.gov/pdf/516064main_ALG_ED_BoneDensity%5C%2012-23-10.pdf.

[54] Gaffney, C.J. et al. "The effect of long-term confinement and the efficacy of exercise countermeasures on muscle strength during a simulated mission to Mars: data from the Mars500 study". In: *Sports Medicine - Open* 3.1 (2017), p. 40. ISSN: 2198-9761. DOI: 10.1186/s40798-017-0107-y.

[55] ESA. *Flywheel Exercise Device (FWED): Non-gravity dependent resistance exercise device on the International Space Station*. [Online accessed: February 20, 2022]. URL: http://www.capcomespace.net/dossiers/ISS/europe/columbus/Nouveau%5C%20dossier/fs044_10_fwed.pdf.

[56] English, K.L. et al. "High intensity training during spaceflight: results from the NASA Sprint Study". In: *npj Microgravity* 6.1 (2020), p. 21. ISSN: 2373-8065. DOI: 10.1038/s41526-020-00111-x.

[57] Sample, I. "Fake mission to Mars leaves astronauts spaced out". In: *The Guardian* (January 7, 2013). [Online accessed: February 27, 2022]. URL: https://www.theguardian.com/science/2013/jan/07/fake-mission-mars-astronauts-spaced-out.

[58] ESA ISS Utilisation Department. *Mars 500 Isolation Study: Information Kit*. Noordwijk, May, 2010.

[59] Heinicke, C. et al. "Crew self-organization and group-living habits during three autonomous, long-duration Mars analog missions". In: *Acta astronautica* 182 (2021), pp. 160–178. ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2021.01.049.

[60] Pietromonaco, P.R., Overall, N.C. "Implications of social isolation, separation, and loss during the COVID-19 pandemic for couples' relationships". In: *Current Opinion in Psychology* 43 (2022), pp. 189–194. ISSN: 2352-250X. DOI: 10.1016/j.copsyc.2021.07.014.

[61] Collins, D.L. "Psychological issues relevant to astronaut selection for long-duration space flight: a review of the literature". In: *Human performance in extreme environments : the journal of the Society for Human Performance in Extreme Environments* 7.1 (2003), pp. 43–67. ISSN: 1529-5168. DOI: 10.7771/2327-2937.1021.

[62] Kanas, N. et al. "Psychology and culture during long-duration space missions". In: *Acta astronautica* 64.7-8 (2009), pp. 659–677. ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2008.12.005.

[63] Kanas, N. "Socio-Cultural Issues During Long Duration Space Missions". In: *SAE Transactions* 100 (1991), pp. 2299–2304. ISSN: 0096736X.

[64] Marazziti, D. et al. "Space missions: psychological and psychopathological issues". In: *CNS Spectrums* (2021), pp. 1–5. ISSN: 2165-6509. DOI: 10.1017/S1092852921000535.

[65] Mars, K. "The Real Story of the Skylab 4 "Strike" in Space". In: *NASA* (16.11.2020). [Online accessed: March 7, 2022]. URL: https://www.nasa.gov/feature/the-real-story-of-the-skylab-4-strike-in-space.

[66] The NASA History Series, ed. *SP-4208 LIVING AND WORKING IN SPACE: A HISTORY OF SKYLAB, Chapter 7*. [Online accessed: February 27, 2022]. July 3, 2014. URL: https://history.nasa.gov/SP-4208/ch7.htm.

[67] The NASA History Series, ed. *SP-4208 LIVING AND WORKING IN SPACE: A HISTORY OF SKYLAB, Chapter 16*. [Online accessed: February 25, 2022]. July 3, 2014. URL: https://history.nasa.gov/SP-4208/ch16.htm#t7.

[68] The NASA History Series, ed. *SP-4208 LIVING AND WORKING IN SPACE: A HISTORY OF SKYLAB, Chapter 5*. [Online accessed: February 28, 2022]. July 3, 2014. URL: https://history.nasa.gov/SP-400/ch5.htm.

[69] Astronautix. *Skylab*. [Online accessed: February 28, 2022]. March 30, 2019. URL: http://www.astronautix.com/s/skylab.html.

[70] Ewert, M.K., Jeng, F.F., ed. *Will Astronauts Wash Clothes on the Way to Mars?* 45th International Conference on Environmental Systems, 2015.

[71] Michalek, W. et al. *Advanced Micrograviy Compatible Integrated Laundry System (AMCILS) Development*. 47th International Conference on Environmental Systems, 2017.

[72] NASA JSC. *Housekeeping*. [Online accessed: February 25, 2022]. August 29, 2020. URL: https://msis.jsc.nasa.gov/sections/section13.htm#_13.2_HOUSEKEEPING.

[73] Illmer, N. *ESA Astronaut Training*. Lecture at KTH, Stockholm, February 17, 2022.

[74] Carlsson, E. *On to Mars!* Lecture at KTH, Stockholm, January 27, 2022.

[75] Sesnic, T. "Inspiration4 launch nears as intense training schedule continues". In: *NASASpaceFlight.com* (August 23, 2021). [Online accessed: March 7, 2022]. URL: https://www.nasaspaceflight.com/2021/08/inspiration-4-update/.

[76] Wilson, P. *Temperature Relative Humidity and Dew Point in Air Conditioning*. [Online accessed: March 17, 2022]. January 12, 2022. URL: https://www.mrfixitbali.com/air-conditioning/temperature-humidity-dew-point-251.html.

Appendix

Table 1: Water mass balance per person and day.

Water input [kg/CM-d]		Water output [kg/CM-d]	
Drinking and food preparation water	2.38	Respiration and perspiration condensate	2.28
Wash water	1.29	Used wash water	1.29
Urine flush water	0.50	Urine and flush water	2.00
Water in food	1.15		
Metabolic water	0.35		
Total	**5.67**	**Total**	**5.57**

Table 2: Mission phase and accumulated effective dose.

Mission Phase	Duration [day]	Accumulated Effective Dose [mSv]
Cruise + Mars orbit	$(440 \cdot 2) + 80 = 960$	$1.7 \cdot 960 = 1\,632$
Mars	20	$0.52 \cdot 20 = 10.4$
Total Accumulated Effective Dose [mSv]	$1\,632 + 10.4 = 1\,642.4$	
Daily dose limit during cruise [mSv]	$\frac{1\,500 - 10.4}{960} = 1.55$	

Temperature, Relative Humidity and Dew Point

Temp. °C \ Relative Humidity %	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
46	-2.62	7.11	13.18	17.67	21.26	24.27	26.87	29.16	31.22	33.08	34.79	36.36	37.83	39.2	40.49	41.71	42.86	43.96	45	46
45	-3.32	6.36	12.4	16.86	20.43	23.42	26	28.27	30.31	32.17	33.86	35.43	36.89	38.25	39.53	40.74	41.88	42.97	44.01	45
44	-4.01	5.61	11.61	16.04	19.59	22.56	25.13	27.39	29.41	31.25	32.94	34.5	35.94	37.3	38.57	39.77	40.91	41.99	43.02	44
43	-4.7	4.86	10.82	15.23	18.75	21.7	24.25	26.5	28.51	30.34	32.01	33.56	35	36.34	37.61	38.8	39.93	41	42.02	43
42	-5.4	4.11	10.03	14.41	17.91	20.85	23.38	25.61	27.61	29.43	31.09	32.62	34.05	35.39	36.64	37.83	38.95	40.01	41.03	42
41	-6.09	3.36	9.25	13.6	17.08	19.99	22.5	24.72	26.71	28.51	30.16	31.69	33.11	34.43	35.68	36.86	37.97	39.03	40.04	41
40	-6.79	2.61	8.46	12.78	16.24	19.13	21.63	23.83	25.81	27.6	29.24	30.75	32.16	33.48	34.72	35.89	36.99	38.04	39.04	40
39	-7.49	1.85	7.67	11.96	15.4	18.27	20.76	22.94	24.91	26.68	28.31	29.82	31.22	32.53	33.75	34.91	36.01	37.06	38.05	39
38	-8.19	1.1	6.88	11.15	14.56	17.42	19.88	22.05	24	25.77	27.39	28.88	30.27	31.57	32.79	33.94	35.03	36.07	37.06	38
37	-8.88	0.34	6.09	10.33	13.72	16.56	19.01	21.17	23.1	24.85	26.46	27.95	29.33	30.62	31.83	32.97	34.05	35.08	36.06	37
36	-9.58	-0.41	5.29	9.51	12.88	15.7	18.13	20.27	22.2	23.94	25.54	27.01	28.38	29.66	30.86	32	33.08	34.1	35.07	36
35	-10.28	-1.17	4.5	8.69	12.04	14.84	17.25	19.38	21.29	23.02	24.61	26.07	27.43	28.71	29.9	31.03	32.1	33.11	34.08	35
34	-10.99	-1.93	3.71	7.87	11.19	13.98	16.38	18.49	20.39	22.11	23.68	25.14	26.49	27.75	28.94	30.06	31.12	32.12	33.08	34
33	-11.69	-2.68	2.91	7.05	10.35	13.12	15.5	17.6	19.48	21.19	22.75	24.2	25.54	26.79	27.97	29.08	30.14	31.14	32.09	33
32	-12.39	-3.44	2.12	6.23	9.51	12.25	14.62	16.71	18.58	20.27	21.83	23.26	24.59	25.84	27.01	28.11	29.16	30.15	31.1	32
31	-13.09	-4.2	1.33	5.41	8.66	11.39	13.74	15.82	17.67	19.36	20.9	22.32	23.65	24.88	26.05	27.14	28.18	29.16	30.1	31
30	-13.8	-4.96	0.53	4.58	7.82	10.53	12.87	14.93	16.77	18.44	19.97	21.39	22.7	23.93	25.08	26.17	27.2	28.18	29.11	30
29	-14.5	-5.72	-0.27	3.76	6.98	9.67	11.99	14.03	15.86	17.52	19.04	20.45	21.75	22.97	24.12	25.2	26.22	27.19	28.12	29
28	-15.21	-6.48	-1.06	2.94	6.13	8.8	11.11	13.14	14.96	16.61	18.12	19.51	20.8	22.01	23.15	24.22	25.24	26.2	27.12	28
27	-15.92	-7.25	-1.86	2.11	5.29	7.94	10.23	12.25	14.05	15.69	17.19	18.57	19.86	21.06	22.19	23.25	24.26	25.22	26.13	27
26	-16.63	-8.01	-2.66	1.29	4.44	7.08	9.35	11.35	13.14	14.77	16.26	17.63	18.91	20.1	21.22	22.28	23.28	24.23	25.14	26
25	-17.33	-8.77	-3.46	0.46	3.59	6.21	8.47	10.46	12.24	13.85	15.33	16.69	17.96	19.15	20.26	21.31	22.3	23.24	24.14	25
24	-18.04	-9.54	-4.26	-0.36	2.75	5.35	7.59	9.56	11.33	12.93	14.4	15.75	17.01	18.19	19.29	20.33	21.32	22.26	23.15	24
23	-18.75	-10.3	-5.06	-1.19	1.9	4.48	6.71	8.67	10.42	12.01	13.47	14.81	16.06	17.23	18.33	19.36	20.34	21.27	22.15	23
22	-19.47	-11.07	-5.86	-2.02	1.05	3.62	5.83	7.77	9.52	11.09	12.54	13.88	15.12	16.27	17.36	18.39	19.36	20.28	21.16	22
21	-20.18	-11.83	-6.66	-2.84	0.2	2.75	4.94	6.88	8.61	10.18	11.61	12.94	14.17	15.32	16.4	17.42	18.38	19.3	20.17	21
20	-20.89	-12.6	-7.46	-3.67	-0.65	1.88	4.06	5.98	7.7	9.26	10.68	12	13.22	14.36	15.43	16.44	17.4	18.31	19.17	20
19	-21.6	-13.37	-8.26	-4.5	-1.5	1.01	3.18	5.08	6.79	8.34	9.75	11.06	12.27	13.4	14.47	15.47	16.42	17.32	18.18	19
18	-22.32	-14.14	-9.07	-5.33	-2.35	0.15	2.3	4.19	5.88	7.41	8.82	10.11	11.32	12.44	13.5	14.5	15.44	16.33	17.19	18
17	-23.03	-14.91	-9.87	-6.16	-3.2	-0.72	1.41	3.29	4.97	6.49	7.89	9.17	10.37	11.49	12.53	13.52	14.46	15.35	16.19	17
16	-23.75	-15.68	-10.67	-6.99	-4.05	-1.59	0.53	2.39	4.06	5.57	6.96	8.23	9.42	10.53	11.57	12.55	13.48	14.36	15.2	16
15	-24.47	-16.45	-11.48	-7.82	-4.9	-2.46	-0.36	1.49	3.15	4.65	6.03	7.29	8.47	9.57	10.6	11.58	12.5	13.37	14.2	15
14	-25.19	-17.22	-12.28	-8.65	-5.75	-3.33	-1.24	0.6	2.24	3.73	5.09	6.35	7.52	8.61	9.64	10.6	11.52	12.38	13.21	14
13	-25.9	-17.99	-13.09	-9.48	-6.6	-4.2	-2.13	-0.3	1.33	2.81	4.16	5.41	6.57	7.65	8.67	9.63	10.54	11.4	12.22	13
12	-26.62	-18.77	-13.9	-10.31	-7.46	-5.07	-3.01	-1.2	0.42	1.89	3.23	4.47	5.62	6.69	7.7	8.65	9.55	10.41	11.22	12
11	-27.35	-19.54	-14.71	-11.15	-8.31	-5.94	-3.9	-2.1	-0.49	0.96	2.3	3.53	4.67	5.73	6.74	7.68	8.57	9.42	10.23	11
10	-28.07	-20.31	-15.51	-11.98	-9.16	-6.81	-4.78	-3	-1.4	0.04	1.36	2.58	3.72	4.78	5.77	6.71	7.59	8.43	9.24	10
5	-31.69	-24.2	-19.56	-16.16	-13.44	-11.17	-9.22	-7.5	-5.97	-4.58	-3.3	-2.13	-1.04	-0.02	0.93	1.83	2.69	3.5	4.27	5
0	-35.33	-28.1	-23.63	-20.35	-17.73	-15.55	-13.67	-12.02	-10.54	-9.2	-7.98	-6.85	-5.8	-4.82	-3.91	-3.04	-2.22	-1.45	-0.71	0

Dry · Comfortable · Alright · Uncomfortable · Very Uncomfortable

Figure 1: Temperature [°C], relative humidity [%], dew point [°C], and comfort [76].

Table 3: Masses, volumes and power needed for the Safety and Emergency equipment on board.

Equipment	Mass [kg]	Volume [m^3]	Power [W]
PPE	$3 \cdot 11 = 33$	$3 \cdot 0.008 = 0.024$	/
LMS	3	0.002	10
ADES	3	0.002	10
smoke detectors	$11 \cdot 0.3 = 3.3$	$11 \cdot 0.003 = 0.033$	$11 \cdot 1.5 = 16.5$
PFE (CO_2- & water-based)	$8 \cdot 10 = 80$	$8 \cdot 0.02 = 0.16$	/
TOTAL	122.3	0.221	36.5