Human service-repair mission to GEO satellites Project

Human Aspects - Blue Team

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Stockholm March 16$^{\mathrm{th}}$ 2019

SD2905 Human Spaceflight
Aerospace Engineering
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1 Introduction

This report is a preliminary analysis on the human aspects of a manned service mission to geostationary orbit (GEO). It is part of a larger project where 5 smaller groups have cooperated, each with their respective area of focus: overall coordination, logistics, space vehicle design, services and human aspects. The goal of the mission is to extend the life of existing satellites in GEO by servicing them. Examples of this are refuelling, repairing damaged components and upgrading old components. A space station will serve as the main hub from which these services are performed. Unmanned drones will ferry the satellites to the station where humans can perform the servicing during extravehicular activities (EVAs). It is, therefore, crucial that the station is able to support humans living there during the servicing operations. This report will analyze the different systems required to achieve this goal and give preliminary values for the mass, volume, power consumption and costs of these systems. It is divided into 7 parts: radiation, atmosphere, water, food, waste, mass study and cost estimation.

1.1 Assumptions

- A mission lasts 60 days.
- The crew is composed of 4 people.
- Life support to and from the station will be handled by the Orion crew capsule.
- We service no more than 5 satellites in a mission.
- 30 EVAs are performed in a mission.
- The first launch is in 2030.
- Backup systems can make the crew survive for 20 days.

1.2 Background

During the first space missions, all human needs were provided by carrying the resources on board, and no regeneration was considered in this process. This practice, open-loop systems, certainly tends to be simple and highly reliable. However, it is important to consider that life-support resources increase linearly with the duration of the mission, as shown in Figure 1 [1]. As a result, resource regeneration techniques are suitable for long-duration space missions. The initial supply might be higher than that required for open-loop systems but the resource recovery will be more efficient over the duration of the mission.

There are two partially closed technology options for regeneration: physico-chemical and bio-regenerative. The former uses fans, filters, physical or chemical separation, and concentration processes. The latter uses living organisms to recover useful resources. A system including both technologies can be referred to as a hybrid system [1]. In order to satisfy the requirements of this mission, it is convenient to utilize physico-chemical systems because they are relatively compact, easy to maintain, and well known.

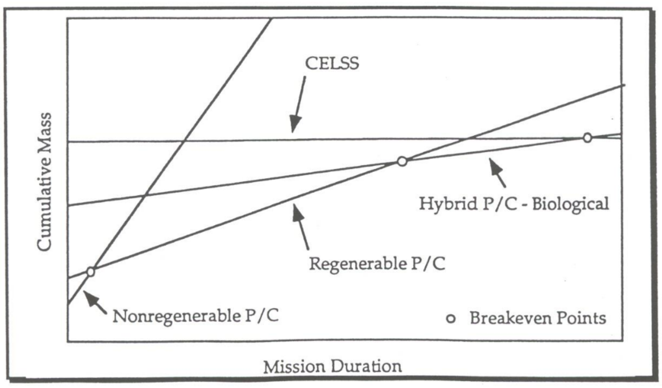

Figure 1: Reliability of Life Support Technology in terms of mission duration.

Finally, to meet the human spaceflight requirements, a life support system must regulate the main four functional areas: atmosphere, water, food and waste. The implementation of a partially closed life support system will clearly satisfy all functional areas. Figure 2 shows how material flows between the major life support functions.

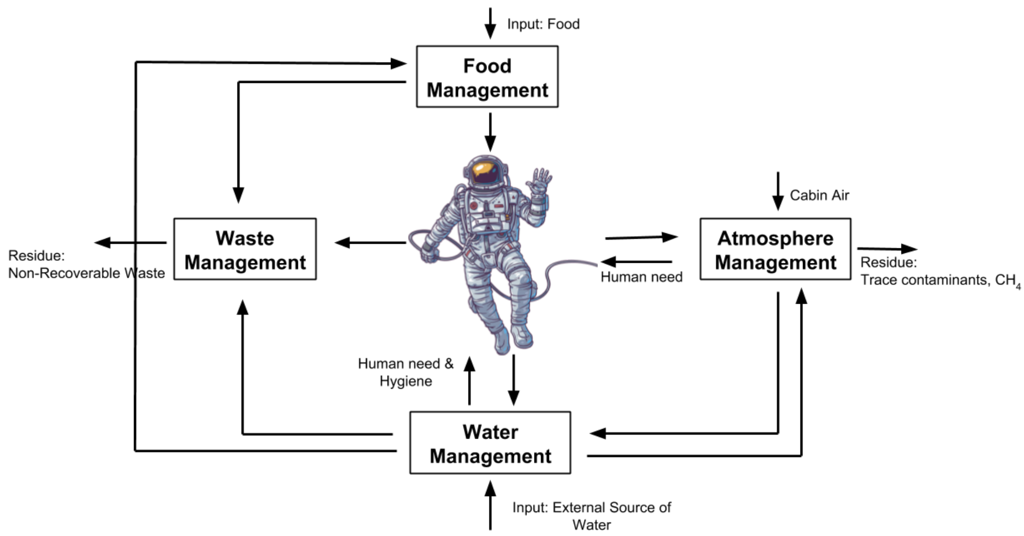

Figure 2: Partially closed regenerative life support systems and relationships.

2 Radiation

2.1 The Environment

The geostationary orbit environment poses multiple threats to humans in terms of radiation. The main ones are the trapped particles in the outer Van Allen belt, galactic cosmic rays and solar particle events. Out of these three sources, most of the radiation intensity in GEO is going to come from the outer Van Allen belt and the electrons located there. Even though other particles such as protons also reside there, the quantity is low enough for them to be negligible. With no shielding the equivalent radiation dose per hour is approximately 116 sievert according to the ESA-developed Space Environment Information System (SPENVIS) tool, which is extremely high. This can be compared to the worst case equivalent yearly GCR radiation dose of about 1.5 sievert without shielding [2]. The radiation from solar particles is usually low, but during temporary solar particle events the dose can get as high as 0.2 sievert per hour for astronauts wearing space suits with current radiation shielding technology [3].

2.2 Human Radiation Dose

To minimize biological effects such as an increased risk of cancer from long-term radiation exposure, limits are set by space agencies. These limits determine how much radiation a human is allowed to receive within a certain time interval. The boundaries set by NASA can be seen in Table 1. The reason for the wide range of the career limit is that it is affected by factors such as age and sex. Important to note it also that NASA implements the principle *As Low As Reasonably Achievable* (ALARA) to make sure that the astronauts stay well within the limits [4]. Calculations using the SPENVIS tool show that with a decently shielded space station astronauts can stay in GEO for extended periods of time. The main issue arises when astronauts need to leave the space station to perform an EVA. The radiation shielding of currently existing space suits mean that the monthly allowed radiation limit of 0.25 Sv would reached in about 54 minutes. With this result one can conclude that space missions involving EVAs in GEO are not feasible with current technology. Methods to resolve this issue are discussed in the following section.

Table 1: Monthly, yearly and career radiation exposure limits for NASA astronauts.

Exposure interval	Dosage limit (Sv)
Month	0.25
Year	0.50
Career	1.0 - 4.0

2.3 Mitigation Strategies

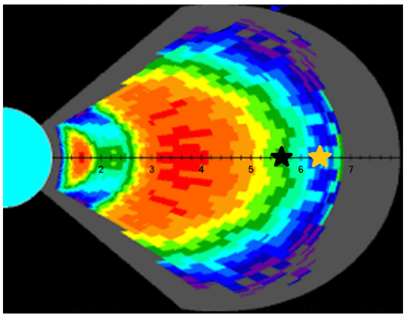

Figure 3: The distribution of trapped particles in the Van Allen belts. The black star shows the location of GEO while the yellow star shows the altitude 5000 km above GEO. The x-axis is the distance from Earth's center in units of Earth radii.

2.3.1 Orbital Change

The first attempt to deal with the high radiation intensity was to move the space station. Figure 3 shows the relative radiation in the Van Allen belts for different orbit altitudes, where red and purple correspond to the highest and lowest radiation intensities respectively. One can therefore see that moving the space station closer to the Earth would not be helpful, as the outer Van Allen belt has an intensity peak at about 3.5 Earth radii from the Earth's center. After discussions with the Logistics group the decision was eventually made to let the space station orbit at an altitude 5000 km outside of GEO. This lead to clear improvements in terms of radiation dose received by astronauts performing EVAs, but still only allowed for a total EVA duration of 2.5 hours before reaching 0.25 Sv.

2.3.2 Space Suits

The next aspect to consider was possible improvements of the space suit radiation shielding. According to [1], current space suits offer a shielding which is equivalent to about 1.9 mm of aluminum. Furthermore, future space suits currently in development seem to allow for much more efficient shielding equivalent to 5.9 mm of aluminum. The exponential nature of radiation penetration in materials means that this threefold increase in equivalent thickness results in a significant increase in maximum EVA duration. With some safety factors added and also considering the radiation dose astronauts would receive when inside of the space station, this would enable astronauts to execute 66 consecutive days of EVAs. In this case the radiation intensity is low enough for the yearly radiation limit of 0.5 Sv to be used instead of the monthly one. With plans to have the first mission around 2030 it seems reasonable to assume that the improved space suits will have moved from prototypes to finished products by then.

2.3.3 Solar Particle Events

One final thing to consider is that the astronauts will also need to avoid the harmful radiation emitted during solar particle events. There are three main levels of precautions that could be implemented here. The primary one that should be done no matter the magnitude of the solar particle event is to bring all astronauts currently performing an EVA to the inside of the space station as soon as possible. If the solar particle event is of a more severe kind the astronauts could seek shelter in a specially designed radiation shelter section of the space station, where they could stay until the situation has stabilized. Finally, in the worst case scenario, the astronauts would don their space suits while still staying inside of the radiation shelter.

3 Atmosphere

The atmosphere management for a space habitation requires a complex integration of many different systems, which have different functions, but that are often dependent on each other. The atmosphere management system of our station is mainly based on the system of the International Space Station (ISS) and enriched with information presented in [5] and [1]. This complex integration between the different systems involved in the atmosphere management is shown in Figure 4.

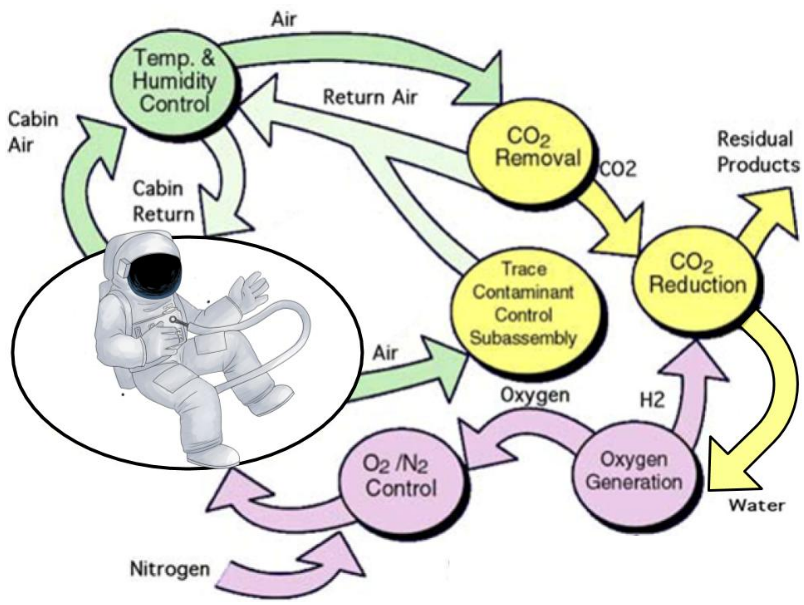

Figure 4: Systems involved in the atmosphere management.

The atmosphere management systems can be open loop or partially closed loop. In open loop systems, all the consumables are provided by on-board storage. However, because of the duration of the mission (60 days), open loop systems cannot be implemented, because they will have an extremely high mass. To reduce mass penalties and, therefore, decrease the costs, partially closed systems must be implemented.

3.1 Basic Functions and Requirements

One of the main functions of the atmosphere management is to provide a suitable and breathable atmosphere, with a sufficient quantity of oxygen. The Apollo 1 deadly accident in 1967, which was due to pure oxygen in the cabin and an electrical spark, showed the importance of also keeping a sufficient quantity of nitrogen in the atmosphere to suppress the reactive nature of pure oxygen. Additionally, it is essential to remove the atmospheric waste products of the human metabolism (mainly carbon dioxide, but also other trace contaminants), because an increase in the carbon dioxide concentration is toxic or, for higher concentrations, even lethal.

In Figure 5 basic requirements for the air revitalization are shown. Consisting in 0.83 kg of oxygen required per person per day and 1 kg of carbon dioxide produced per person per day.

Managing the atmosphere also means monitoring and maintaining the adequate pressure, temperature and humidity, as well as providing a proper air circulation through ventilation.

3.2 Pressure, Temperature, Humidity and Ventilation Control

The current standard for long-term habitation aims to reflect as much as possible the Earth's atmospheric characteristics, specifically the sea-level condition that humans are well adapted to. The values for these parameters are based on the ISS ones and they are shown in Table 2.

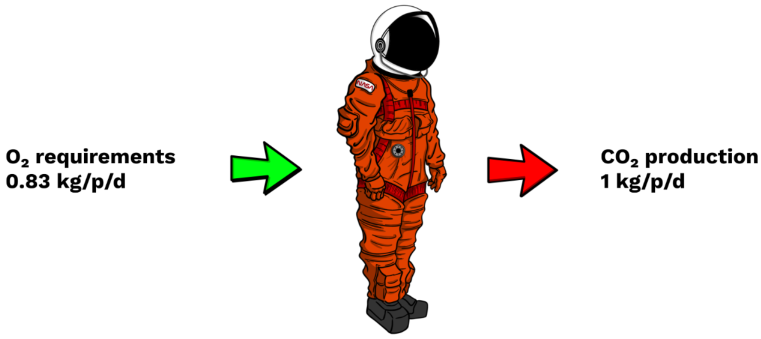

Figure 5: Input and output of the atmosphere management system.

Table 2: Atmospheric parameters, based on the ISS values in [5].

Parameters	Values
Total atmospheric pressure (kPa)	99.9 – 102.7
O_2 Partial pressure (kPa)	19.5 – 23.1
Temperature (°C)	18.35 – 29.45
Relative humidity (%)	25 – 70
Ventilation (m/s)	0.051 – 0.203

The pressure is controlled by pressure regulators and valves, which preserve an adequate atmosphere. They also monitor the total pressure of the cabin and the partial pressure of the most important components (oxygen, nitrogen and carbon dioxide).

Regarding temperature and humidity control, there is a tight relationship between these two parameters, which affects the crew's comfort. For higher temperatures, the relative humidity must be lower in order to intensify evaporative cooling, and vice versa. The temperature and humidity control is performed by using a condensate heat exchanger (provided with a hydrophilic coating) in combination with a rotating centrifugal water separator.

Ventilation is another important feature that needs to be considered, because an insufficient ventilation can induce several problems in microgravity. The main problem, caused by a poor ventilation, is the formation of carbon dioxide "bubbles" around the heads of the astronauts. In order to avoid this problem and provide an adequate air circulation, fans are placed in each module of the station. The fans also cycle the air through the different subsystems as shown in Figure 4, including the CO_2 removal devices, the trace gases removal devices and the temperature and humidity control unit [5].

During a preliminary analysis, the hardware of the aforementioned systems (pressure, temperature, humidity and ventilation control) can be neglected [5].

3.3 Trace Contaminants Removal

The most important air contaminant that the life support systems must remove from the habitat's atmosphere is the carbon dioxide produced by the astronauts. This process is explained in the Section 3.4.

However, there are other air contaminants that must be removed. These include trace contaminants produced by humans, equipment and materials inside the crew habitat. Trace contaminants of this kind are removed by a system composed by the combination of particulate filters, a catalytic burner and active charcoal. The latter one is separated from the other parts, and this allows regenerative operations by exposing the charcoal to vacuum [5].

3.4 CO_2 Removal

As mentioned, the most important air contaminant that must be removed is carbon dioxide in order to prevent the crew habitat from becoming toxic.

Because of the duration of the mission (60-days mission), we have chosen a regenerative method, that does not need a lot of resupply, to remove the carbon dioxide: the 4-bed molecular sieve (4-BMS). This system contains synthetic zeolites or alumino-silicate metal ions to collect the carbon dioxide. The advantage of this system is that the materials it uses can be regenerated and used again. The system consists of two adsorbing beds which work in parallel with two identical beds for desorption. The two adsorbing beds are one desiccant bed for the humidity control and one zeolite molecular sieve for the CO_2 trapping.

Therefore, the 4-BMS physically sieve and separate the CO_2 from the cabin air and, then, it feeds the CO_2 into the Sabatier reactor.

3.5 Off-Nominal Scenario: 4-BMS Stops Working

The 4-BMS is an essential part of the atmosphere management, because if it stops working the carbon dioxide concentration would continuously increase in the confined space habitat. If the CO_2 reaches a concentration of about the 8 %, it is lethal to humans.

Therefore, we need to design a backup system in order to make the mission more versatile. The selected backup system is a lithium hydroxide (LiOH) system. This is a non-regenerative method, that removes the CO_2 by using the following chemical process:

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

According to [5], 1 kg of LiOH is able to remove about 1 kg of CO_2. Moreover, according to [1], the mass of the LiOH system can be assumed to be 7 kg/4p/d, if we consider also the packaging (mass of the cartridge). Therefore, since the crew members are four and the backup system time span is assumed to be 20 days, the total mass for the LiOH system is 140 kg.

Thanks to this backup system the crew would be able to survive in emergency situations and they would have the time to repair the 4-BMS system or, in the case that it is not possible to repair it, they would have the time to arrange an emergency egress.

3.6 CO_2 Reduction

The CO_2 trapped from the 4-BMS is, then, transferred into the CO_2 reduction unit. Nowadays, the most advanced system for CO_2 reduction is the Sabatier process, which uses the the following exothermic reaction to convert CO_2 and hydrogen into water and methane:

$$\mathrm{CO_2 + 4H_2 \longrightarrow 2H_2O + CH_4}$$

We assume that this reaction will be 100 % efficient. This may seem unreasonable, however, NASA experiments have shown efficiencies of up to 95 % [6]. With such high efficiency the mass of the lost CO_2 will be in the order of 10 kg for the whole mission and can be neglected. The methane is either vented overboard or, if we want to recover the hydrogen, the Sabatier process can be combined with the carbon formation reactor (CFR). The hydrogen produced by the CFR is then fed back to the Sabatier machine [5].

3.7 Air Supply

Nitrogen, which is the main component of the crew habitat atmosphere, is stored in tanks on-board. Nitrogen must be replaced regularly because of losses due to leakages and airlock operations.

The oxygen is produced on board. This is done by the Oxygen Generation Assembly (OGA), which produces oxygen by electrolysis of water. The water produced by the Sabatier process (or hygiene water if required) is fed into the OGA, which breaks the water molecules, according to the following electrolysis process:

$$\mathrm{2H_2O \longrightarrow 2H_2 + O_2}$$

The oxygen produced is then vented into the cabin, while the hydrogen is fed back to the Sabatier reactor. Ideally, CFR and OGA should recover all the hydrogen used in the Sabatier process. However, in reality, there are some losses due to leakages and, therefore, some hydrogen (or water) must be brought regularly to the station.

3.8 Off-Nominal Scenario: OGA Stops Working

As in the previous off-nominal scenario, we have designed a backup system in the eventuality that the OGA stops working. Backup oxygen tanks will be stored on the space station and provide enough oxygen to the crew of four for 20 days in case of OGA failure. This should give the crew members enough time to repair it or in worst case perform an emergency evacuation.

4 Water

4.1 Metabolism of Water

Besides a suitable atmosphere, water is a crucial element to keep the crew alive. Each astronaut demands water for drinking and food preparation, but also for hygiene purposes such as shower, hand washing and ordinary cleaning.

In Figure 6 basic requirements for potable and hygiene water are shown. Considering a metabolic balance, 3 kg of water for drinking and food generates 1.5 kg of urine and 1.5 kg of sweating and water found in respiration. On the other hand, it can be assumed that the total amount of hygiene water can be recovered after use.

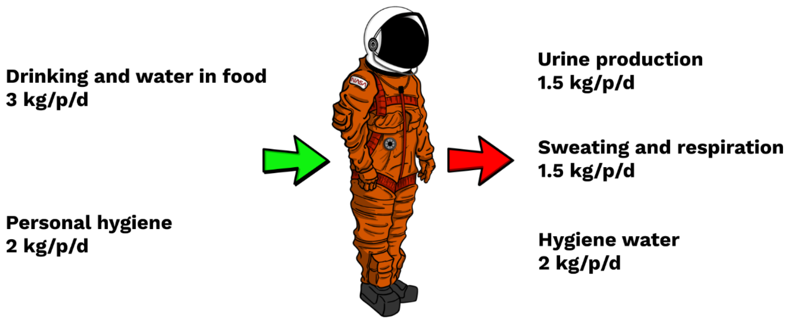

Figure 6: Input and output of water management system.

4.2 Water Reclamation System

The 60-day mission would need to carry 1200 kg of water to satisfy the requirements of 4 crew members if an open loop system was implemented. However, transporting this amount of water from Earth is very expensive so the implementation of a water recovery systems is necessary to reduce the cargo mass per mission.

The space station will include two different technologies to recover water from the outputs of the human metabolism. Since urine has high salt content and urea, it is first treated separately in a system called vapor compression distillation (VCD) [1]. In this process, urine is heated to evaporate water from the waste and then condensed to form distillate. Then, this treated water joins with grey-water recovered from hygiene processes, sweating and respiration. Once all the waste water is finally collected, it is sent through a multi-filtration unit (MF) for final processing (Figure 7) [5].

However, this technology is not completely effective so it is assumed that both systems have an efficiency of 85 % which is a bit lower than that of the current ISS water system, allowing us to consider the worst case scenario for the mission [1]. Thus, we can calculate the amount of potable water per person per day that is recycled after the cleaning process as

$$\text{Recovered potable water} = 85\ \% \times (85\ \% \times \text{Urine water} + \text{Hygiene water} + \text{Sweating and respiration}).$$

Therefore,

$$\text{Recovered potable water} = 4\ \text{kg/p/day}$$

It means that every day only 4 kg of water can be recycled as there is a loss of 1 kg per person per day. In order to compensate for this loss of water, we need to bring extra resources in tanks to the station.

$$\text{Supply potable water} = 1 \text{ kg/p/day} \times 4 \text{ p} \times 60 \text{ days} = 240 \text{ kg}$$

This supply will be carried each 60-day mission and kept in a storage tank. As a result, the cargo per mission would transport 245 kg, including potable water and the mass of the tank where it is contained, which is around 2 % of the reserve potable water mass [1].

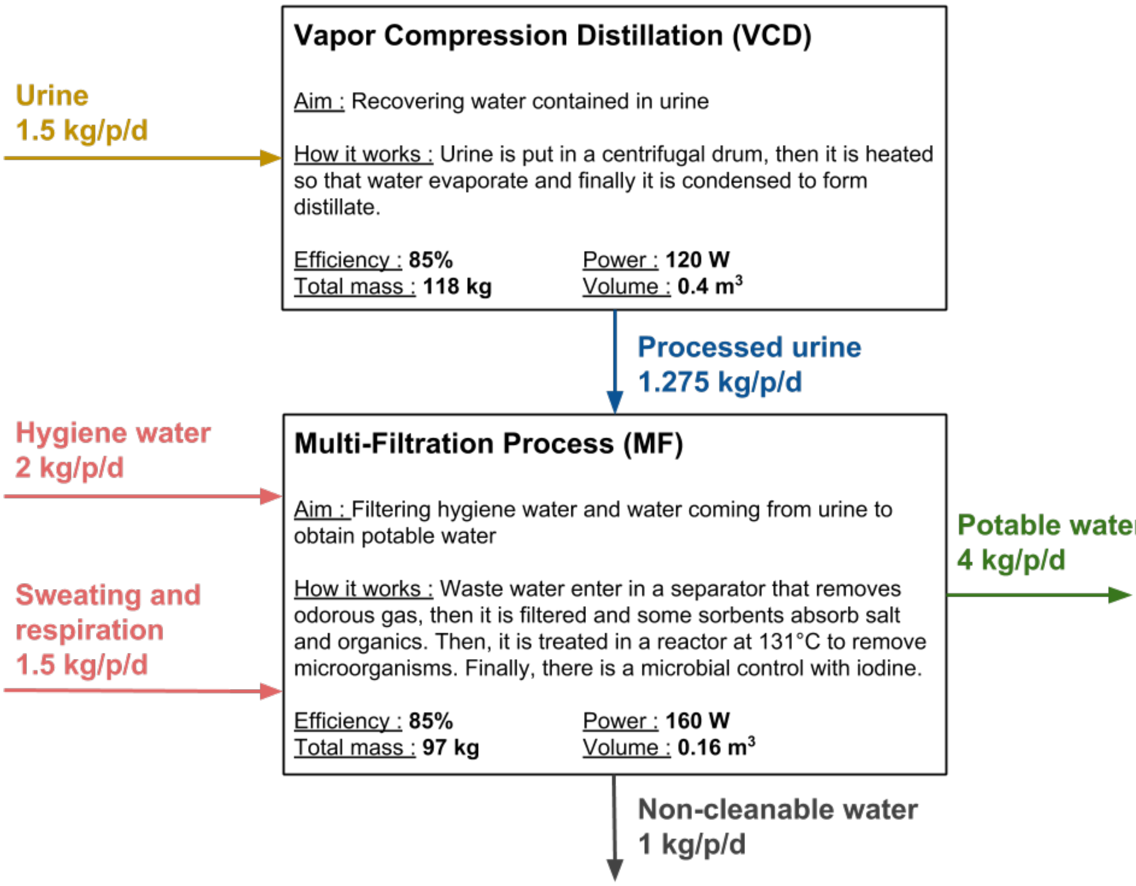

Figure 7: Water reclamation system.

4.3 Water Requirement for EVA

A space suit requires a cooling system to control body temperature and minimize perspiration. This system includes a sublimator which cools water flowing in the cooling ventilation garment. The sublimator works as a heat exchanger that rejects heat to space by subliming ice into the vacuum of space. About 7 kg of water is used to replenish the ice used for this process [1].

As a result, we need to supply this amount of water from Earth and it is independent of the water required in the reclamation system. The mission can service up to 5 satellites with 6 EVAs per satellite so 30 EVAs in total are scheduled for one mission. Including a safety margin, we bring the amount of water needed for 40 EVAs instead, in case something goes wrong and more EVAs are necessary. This yields the mass of required EVA water as

$$\text{Supply EVA water} = 7 \text{ kg/EVA} \times 40 \text{ EVAs} = 280 \text{ kg of water.}$$

Finally, considering the mass of the tank (2 % of the mass of water), the cargo per mission also needs to include around 285 kg of water resources for EVA operations. In the case when there is no EVA-related incident during the first mission, we will not need to bring the safety margin again. In this nominal case, water for EVA will represent about 214 kg for the second mission.

4.4 Off-Nominal Scenario: MF Stops Working

Crew demands depend on the condition of the recovery systems. Therefore, it is necessary to consider an off-nominal scenario to make the mission more robust. In the case when one or both systems stop functioning properly, the crew demands will not be completely satisfied so water consumables will be stocked on the space station, ready to be used for these kind of situations.

The mission enters an emergency mode when following conditions occur:

- The multi-filtration system stops working properly, making further processing of potable water impossible.
- It takes several days to understand and fix the problem.

While systems are repaired, astronauts will have to rely on the stocked consumables. Our astronauts will have water supplies for 20 days, consuming the minimum level of water for drinking, food and hygiene. The extra water supply needed is therefore calculated through

$$\text{Water in stock} = 4 \text{ kg/p/day} \times 20 \text{ days} \times 4 \text{ p} = 320 \text{ kg of water.}$$

We obtain, therefore, about 325 kg (tank included) of water permanently stored on the space station.

5 Food

5.1 Nominal Case

Astronauts will of course need food for their mission. Today, on the ISS, food is an open-loop system: all food needs to be brought from Earth. There are research and projects (such as the Melissa project by ESA) to make food a more closed-loop system by considering growing plants in space such as wheat and potatoes which have a good ratio of nutritional composition per required area. However, these systems are very complex and not developed yet. We could choose to assume that they would be ready within 10 years, but since our mission is only 60 days long, we considered there was no need for such a complicated and probably expensive system. Therefore, we choose to bring all food from the Earth. We assumed that we need 0.7 kg of dry food per person per day [5], with water contained in food already taken into account in the water section of the report. It gives us 168 kg of food for 60 days and 4 crew members. Also, this food needs to be packaged and package implies additional mass. We assume the mass of packaging represents 30 % of the dry food. Thus, it gives 220 kg of food (including packaging) for the whole mission.

5.2 Off-Nominal Scenario

Let's assume that the last satellite to be serviced has a problem and needs more time than predicted to be repaired. It takes around 10 days to fully analyze the situation, come to an agreement with the satellite's company and plan the different EVAs that need to be performed. Then, the satellite is serviced during 5 days until it is repaired. In this case, extra food needs to be brought to the station. We considered that we needed to bring food for 20 extra days to be safe. It gives us 56 kg of food. We then add the 30 % of packaging, which results in around 80 kg of extra food (including packaging). This stock of food will be brought only once to the station, before the arrival of the astronauts, and will be kept there until it may become useful one day. There is very little risk of mold since this food is very well preserved.

6 Waste Collection System

The human metabolic waste can be divided into two main categories: liquid and solid. For this mission we have based the human waste management on the one used on the ISS. For the liquid part this means that recycling happens through use of the water management system as mentioned in previous sections. The liquid waste that is not cleaned properly due to process imperfections is stored in containers until they are disposed of. Without proper closed ecological life support systems in place the processing of solid metabolic waste is difficult, and is therefore not attempted for this mission [7]. Instead, the solid waste will be dewatered, hand-compressed and sealed with meltable plastics into inert disks in order to avoid odors and microbial pathogens to spread [8]. These disks are then placed in larger plastic bags which are sealed properly and placed together with the liquid waste containers while awaiting disposal. The metabolic waste is eventually brought down to Earth on the next crew or cargo mission .

7 The Mass Study

The mass study is divided into 3 parts. We calculated the mass we need to bring to the station before the arrival of the astronauts (mass permanently in the station), the mass that will be brought at each beginning of a 60-day mission (upmass) and the mass coming back to Earth after each 60-day mission (downmass).

7.1 Mass Permanently in the Station

In this part, we consider systems such as the air revitalization system, the water reclamation system, the waste collection system and the temperature and humidity control system that will always stay in the station. This also includes the water storage, food storage and air storage. We also need to consider all equipment needed in the station and equipment used by astronauts to live (to cook, exercise and perform other activities). The values provided for this equipment in Table 3 (and also values for Table 4 and 5) are inspired by [1]. The cabin air mass was calculated assuming air density of 1.225 kg/m^3 and a habitable volume of 74 m^3 similar to that of the NASA mission study [9]. It gives a total mass of approximately 3100 kg for the mass permanently in the station.

Table 3: Mass permanently in the station

Mass permanently in the station	kg
Life support system	
Air revitalization system	500
Backup air revitalization system	300
Temperature and humidity control system	180
Cabin air	90
Water reclamation system	220
Backup water	320
Waste collection system	500
Fire suppression	100
Emergency food stock	80
Other equipment	
Microwave oven	20
Cooking/Eating supplies	2
Restraints	83
Various equipment (video cameras, lenses, etc)	120
Sleep provisions (sleep restraints only)	36
Exercise equipment	145
Medical suite	250
Medical consumables	125
Total	3100

7.2 Upmass

This part (Table 4) contains the consumables that have to be resupplied such as water (to compensate the non-100% efficiency of the water reclamation system), food, hydrogen, EVA water and hygiene consumables. Also, we took into account the mass of the astronauts and their personal belongings. It gives a total of 1500 kg. The book *Human Spaceflight: Mission Analysis and Design* helped us to determine what astronauts would need in terms of hygiene consumables and personal belongings, but we modified some values that seemed unrealistic to us. For example, the book assumed the astronauts to use new clothes for only 1 day before discarding them. That way, the mass of the clothes, taking into account 4 people for 60 days, would be 140 kg.

However, we assumed that the astronauts can use the clothes for 2-3 days before discarding them, resulting in a mass of about 60 kg.

Table 4: Upmass

Upmass	kg
Consumables	
Potable water (tank included)	245
EVA water	285
Food (including packaging)	220
Hydrogen refill (for Sabatier reactor)	22
Kitchen cleaning supplies	15
WCS supplies	12
Fecal collection bags	55
Personal hygiene kit	7
Hygiene supplies (consumables)	18
Disposable wipes for cleaning	72
Trash bags	12
Operational supplies (ziplocks, tape, etc)	80
Astronauts and their belongings	
Mass of astronauts	320
Clothing	60
Personal stowage	100
Total	1500

7.3 Downmass

The downmass (Figure 5) is composed of waste and of the astronauts going back to Earth. The mass is about 1100 kg. We notice there is no balance between the upmass and the downmass, which is mainly due to the water for EVA that will be lost into space.

Table 5: Downmass

Downmass	kg
Waste	
Non-cleanable water	240
Trapped carbon	65
Solid waste	24
Packaging	30
Kitchen cleaning supplies	15
WCS supplies	12
Fecal collection bags	55
Personal hygiene kit	7
Hygiene supplies (consumables)	18
Disposable wipes for cleaning	72
Trash bags	12
Operational supplies (ziplocks, tape, etc)	80
Astronauts and their belongings	
Mass of astronauts	320
Clothing	60
Personal stowage	100
Total	1100

7.4 Discussion

We know that this study does not take into account all the masses related to human aspects, and that our analysis may lack a lot of aspects. As a comparison, we found a NASA document [9] also designing a mission for 60 days and 4 crew members. They estimated that the mass of the life support systems contained permanently in the station (the upper part of Figure 3, they call it "hardware") was about 4000 kg, whereas our numbers give about 2500 kg. It is the same order of magnitude but we see that our analysis is not completely exhaustive. Also worth noting is that the mass of the space suits has already been taken into account by the Services group.

Providing the required resources as well as setting the proper environment to keep humans alive in space is a complex and extensive task. In space, some life cycles need to be closed with physico-chemical or biological assistance. Certainly, life cannot be sustained in space as on Earth so the main principles of the implementation of life-support systems in space missions are to endure the activity of astronauts, secure their psychological well-being, and maintain their physical performance.

Finally, next major goal of life support systems is the development of highly efficient regenerative systems to support long duration human exploration in deep space. Efficiency rate must be improved so that astronauts can travel for long periods without expensive and risky supply missions from Earth.

8 Cost Estimation

With the masses of the various systems known, a first order cost estimation could be performed. For this estimation we assumed that the systems listed in Table 6 would correspond to a significant majority of the total cost and thus be a good approximation of the total cost.

According to [10], the total life cycle cost of ultra reliable life support systems is roughly \$814,000 per kilogram. However 10 % and 15 % of that corresponds to launch and operations costs respectively which will be covered by the Logistics and Overall-Coordination groups. The remaining 75 %, \$611,000 per kilogram, will include development and manufacturing costs of the systems. Using this value, the total cost and costs of each system have been computed and are displayed in Table 6.

Table 6: Systems with dominant cost.

System	Mass (kg)	Cost ($ million)
Air revitalization system	500	305
Water recycling system	220	134
Waste collection system	500	305
Temperature and humidity control system	180	110
Total	1400	855

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