Human Aspects

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***Abstract*—Manned spaceflight plays a major role in space exploration especially due to the mobility of human beings and their capability to perform complex tasks in a new and complex environment. This paper will study the feasibility of a manned mission to an asteroid to mine precious minerals. This part will only focus on the design of a life support system to keep humans alive during this journey, such as supplying oxygen, water and food. Secondary human needs such as medical aspects, radiations, living space and more will also be taken into account. Performing a manned spaceflight requires that possible risks of failure are reduced as low as possible. This is especially important for long mission such as this one, where it is impossible to quickly abort the mission or sending an emergency resupply ship. Then an analysis and discussion about the level of redundancy required to keep a low risk while minimizing the mass of the system will be performed. Finally, the total mass of the life support systems will be estimated, with addition to volume and power budget which will constitute the results of the work, and be used in some other concept studies performed.**

I. INTRODUCTION

A. Background

To design a new life support system, it's appropriate to first look at some already existing systems in order to have an idea of how a life support system (LSS) works. What are the properties of an LSS, what exists today and what can be achieved in 10 years? There are different classifications of LSS, namely, open-, closed- and partially closed loops. These are all ways of treating and supplying the basic human needs, such as air, water and food in order to keep humans alive [1]. At the start of the project, the mission duration was not known. Thus, three types of life support system were taken into account and compared (see fig 1).

- The first loop is the open loop where nothing is recycled. Therefore, all necessities have to be brought, all the water, all the air and all the oxygen.
- The second one, is the partially closed loop, which means that most of the water and air are recycled , but food is not created/grown and solid waste is not reused.
- The last one, is the Controlled Ecological Life Support System. It is a complete closed system. It means that one recycle the air and water as in the previous loop, but also that it is done by natural processes using plants or algae. In that way one can produce food, air and water on site.

After comparing these three loops and assuming the mission duration around 300 days, it was determined that the best one for the intended mission would be partially closed loop, which is also used on the ISS (see fig 2.). This simplifies the work because data, information and inspiration can be taken from the ISS to design a life support system. The Tranquility module on the ISS is extra interesting since it contains most of the necessary components for a full LSS.

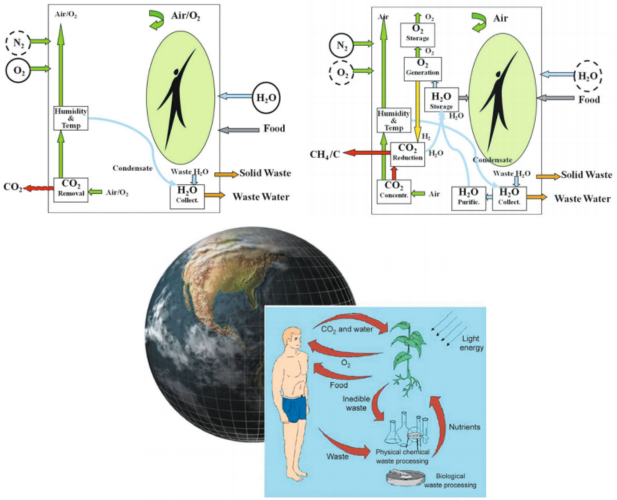


Fig. 1. Open loop, partially closed loop and CLESS [1]

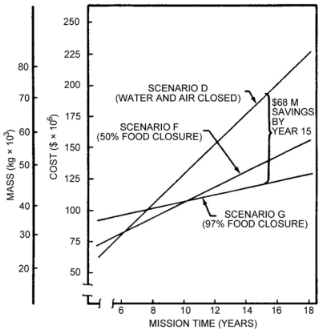


Fig. 2. Comparaison between open, partially closed loop and CLESS

B. Objectives

Based on the trajectory analysis performed by the *Space Vehicle* team, the total mission duration, including the staying time on the asteroid, is 304 days. The crew is composed of 3 astronauts, so 2 of them can perform an Extra Vehicular Activity (EVA) which is the minimum requirement in terms of safety, and the other one can stay in the spacecraft to manage this activity and help them in their tasks. Thus the main objective is to design a life support system capable of meeting basic human needs for a crew of 3 and a mission duration of 304 days. Furthermore, some ”secondary” human needs have to be taken into account to ensure the well-being and health of the crew and enable them to perform their assigned tasks, which is the second objective. The third one is to keep the risk level as low as possible by using redundant systems, while minimizing the mass and volume of the whole system.

II. BASIC HUMAN NEEDS

The major aspect of a manned mission is to design a life support system capable of meeting the basic human needs which represent a mass of approximately 5 kg/day/person of consumables. These physiological needs are: a breathable atmosphere, water consumption and food consumption. More information can be found in Figure 3.

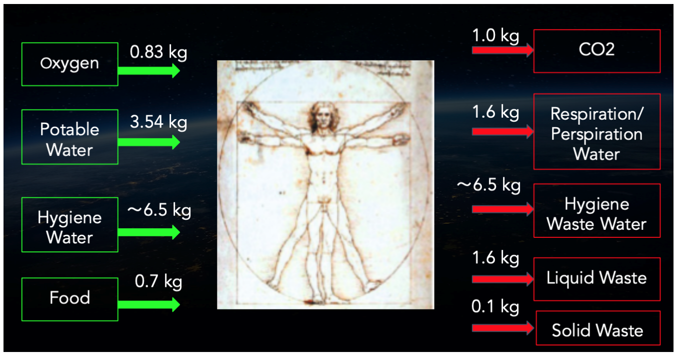


Fig. 3. Basic human needs [1]

A. Air Management System

One of the first basic human needs that the life support system has to ensure is to produce a breathable atmosphere. On the ISS, an atmosphere similar to the one on Earth is maintained, i.e. composed of approximately 21% of oxygen and 79% of nitrogen (in volume). The reason why the air on the ISS is composed of a large portion of nitrogen is to avoid intense fires, created by an oxygen rich atmosphere, which can be a real threat to the mission. However this leads to some constraints as the fact that astronauts have to purge their body of nitrogen for a long time before performing an EVA, because EVA suit is using pure oxygen. The air pressure is kept around 101.3 kPa (1 atm). This value might be carefully controlled because some systems are sensitive to pressure variations. This depends on what systems will be used on spacecraft. For example the pressure requirement on ISS is between 97.9 kPa and 102.7 kPa.

1) Oxygen Generation: As seen before, the human body needs around 0.83 kg of oxygen per day. If we don't produce oxygen in the crew spacecraft and only store it in tanks, then the minimum mass of oxygen to bring for a 304 journey with a crew of 3 people would be 757 kg which is quite heavy. Moreover, a big tank will be required to store all that oxygen which will add mass and in case of a leakage no oxygen can be produced which represent a huge risk. Thus, it was decided to use an oxygen generation system.
On the ISS, the CO_2 produced by a human is recycled into oxygen using a system composed of:

- a CO2 removal system
- a Sabatier reactor
- an electrolyser

The CO2 removal system aim is to catch the CO2 from the atmosphere and transfer it to the Sabatier reactor. More details about it will be given in the next part. The Sabatier reactor uses the eponymous chemical reaction to turn the CO2 combined with some hydrogen into water and methane. Then the water created is sent to an electrolyser where it's turned into hydrogen and oxygen. The oxygen is released into the cabin and the hydrogen is sent back to the Sabatier reactor to supply the reaction. The methane produced by this reaction can be discarded or stored. Moreover new rocket engines using methane as a propellant are in development so one can think to use this "waste" to power the engines (for example the SpaceX Raptor engine), but this study won't be focused on this particular aspect.

It's also important to notice that even if some hydrogen is recovered by the electrolysis, an extra amount of hydrogen is required to supply the Sabatier reaction. For 1 ton of hydrogen, the Sabatier reactor and the electrolyser produce together 2 tons of methane, 4 tons of oxygen and 0.5 tons of hydrogen [2]. For the total mass of oxygen to create (757 kg, and 833 kg with a safety margin of 10%), the total mass of hydrogen to bring is 104 kg with a safety margin of 10% ($\frac{(1000-500)\times 833}{4000} = 104kg$). In addition, if all this hydrogen is consumed, approximately 416 kg of methane will be produced and stored.

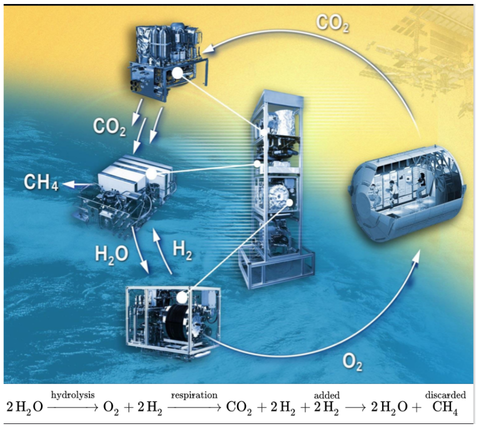


Fig. 4. Oxygen generation system

2) CO_2 removal: CO_2 is a natural byproduct of humans and is not dangerous when in low concentrations, but when its concentration in the atmosphere rises above 8% [1] it becomes dangerous and even lethal, since it blocks the income of oxygen. CO_2 will not disperse as fast in μG as on Earth. This means that as astronauts breath out, there's a risk of CO_2 accumulating in bubbles around the astronaut, which can be dangerous. That's why a proper air circulation is necessary and CO_2 needs to be removed from the atmosphere to keep its concentration bellow 8%, all to reduce the risk of it accumulating.

First method to remove CO_2 from atmosphere was by using a lithium hydroxide system, which was used in U.S. spacecraft and space suits. This method is non-regenerative and for our mission it would require large mass and volume.

A newer system in use is the molecular sieve. This system is regenerative, so it's favorable for longer missions. Currently used on ISS is a four-bed molecular sieve system (4BMS), which is more effective, so subsequently doesn't require a lot of mass. It consists of two adsorbing and two desorbing beds, which switch after some time (i.e. adsorbing become desorbing) and the system becomes regenerative. CO_2 is then stored in cartridges and part of it is processed in the Sabatier module. The rest of the air with water vapor is then blown back into the cabin.

3) Contaminants removal: Because astronauts will live in a closed environment, it's required to control odor and remove contaminant gases that can accumulate. This function is handled by the Trace Contaminant Control System (TCCS). For short missions a combination of particulate filters and active charcoal is used, and for longer missions a catalytic burner is added. The active charcoal is either in a separate canister or integrated into the CO2 removal unit (e.g. the LiOH cartridge). The advantage of using a separate canister for long missions is that it enables regenerative operation by exposing the charcoal to vacuum.

4) Others systems: Other secondary systems are also put in place in order to ensure proper functioning of air management systems and air quality. First, air circulation is performed by fans which suck the air out of the cabin and then blow it into CO_2 removal devices. The cabin pressure is controlled by the pressure regulators and valves that monitor total cabin pressure and the partial pressures of oxygen, nitrogen, and CO_2. On ISS, the oxygen partial pressure is kept between 19.5 kPa and 23.1 kPa, and the CO_2 partial pressure is kept around 707 Pa on average [1].
Furthermore, an atmosphere monitoring and control system is needed in order to keep track of these parameters. It is composed of several active sensors such as:

- Transducers (pressure)
- Thermistors (temperature)
- Electrochemical or infrared sensors (CO_2)
- Electrochemical sensors or fiber optics (O_2)
- Mass spectrometer and gas chromatograph (trace gases)

Finally, humidity and temperature control is managed by a condensing heat exchanger in combination with a water separator.

5) Leakage: No spacecraft can be perfectly air-tight. Thus, it's important to think about air leaks, especially for long-term missions like this one. First, there are kinds of *constant* leaks due to the design of the systems. For example on the ISS, the leak rate has increased from ≈ 0.064 kg/day air in 2004 to ≈ 0.227 kg/day air in 2011, which is assumed to be due to additional modules that have been added to ISS [3]. Since our concept of a crew spacecraft will not be as large as the ISS, let's assume that the air leaks in it are the same as on ISS in 2004 (which might be overestimated). Then, for a mission of 304 days, the amount of air lost will be approximately 19.5 kg. The oxygen (which represent $\approx 23\%$ of the air in terms of mass) is generated by the Oxygen Generation System, so the oxygen lost due to leaks can easily be recovered (≈ 4.5 kg in 304 days). However, no system enable to create nitrogen, so nitrogen needs to be stored before launch to account for these leaks. The air is composed of $\approx 77\%$ of nitrogen in terms of mass, therefore ≈ 15 kg of nitrogen will be lost in 304 days. If a 10% safety margin is taken into account (30 extra days), then the total lost mass will be ≈ 17 kg.

In addition, more concerning are leaks occurring during an EVA. Indeed, astronauts have to move through an airlock which will be the main cause of these leaks. On ISS, around 1.4 kg of air is lost per EVA on the US side (Quest airlock) [3], which represents ≈ 1.1 kg of nitrogen per EVA. During this mission, around 25 EVA are planned (see *Workload* part). This represents a total loss of ≈ 28 kg of nitrogen.

Finally, an off-nominal case was taken into account in which an important air leak will occur. For example a little hole in the structure or depressurization to contain and extinguish fire. Let's say that it's needed enough nitrogen to fill the whole spacecraft pressurized volume ($V \approx 75m^3$, see *Habitable Volume*). At a pressure of 102.7 kPa and a temperature of $25C$, the air density ρ is $\approx 1.2\ kg/m^3$. Then the mass of nitrogen required to fill the whole pressurized volume is $0.77\rho V \approx 70$ kg.

With all of these considerations, the total mass of nitrogen to bring is $m_{N2} \approx 115$ kg including margins.

B. Water Management

Clean water is an absolute necessity to sustain life. Bringing all water needed for a 304 day mission is not feasible, and therefore all of the water should ideally be recycled.
A frugal human consumes roughly 10 kg of water per day. Whereas 3.5 kg is consumed directly as potable water. Roughly two thirds of the potable water is consumed by adding it to the dry food while one third is consumed directly. The remaining 6.5 kg is used as hygiene water. This means that a crew of 3, during a 304 day mission would need roughly 9 tons of water. Bringing over 9 tons of water is not feasible, therefore an open-loop system is not possible, but a fully closed loop is not possible either, due to limits in the water reclamation technology efficiency.
There are three sources of contaminated water. These have to be treated and reclaimed differently depending on how dirty the water is.

- Grey water: Grey water is a lightly contaminated water that mainly stems from hygiene water and atmosphere condensate. It is therefore quite easy to purify using a multi-filtration system in addition with an ambient temperature catalyst process. This process almost has an 100% reclamation rate.

- Yellow water: Yellow water stems from urine waste and is not as easy to reclaim. Vapor Compression Distillation (VCD) can be used to reclaim the majority. This water can there after be added either to the grey water loop, or be used in the oxygen generation system. There is also the byproduct problem of highly concentrated ammonia, which is extremely hazardous, and must be handled with care.
- Black water: Water in fecal matter is called black water, and is hard to reclaim, although the quantity of black water is not that large in comparison with the other two water waste sources.

Black and yellow water also has an ethical/psychological problem to them, drinking water reclaimed from urine and fecal matter is not a pleasant thought.

Before consumption the water has to go through quality control to make sure it is safe to drink. Standard procedure to purify the water is to add iodine (U.S.) or silver ions (Russia) and to heat sterilize it afterwards [1]. There are several ways to monitor the water quality. The main measured parameters are pH-value which should be between 6.5 and 7.5, measuring the conductivity, measuring free gases and finally through microbial counting.

Today on the ISS, around 85% of all water is recovered. As mentioned, close to a 100% of the grey water, around 65-70% of the yellow water and none of the black water is recycled.

With some technological advances in the decade to come, a research paper estimated a hygiene and urine water reclamation efficiency of 98% and black water of 50% to 90% [4]. So a total recycling efficiency of 95% was assumed. This would mean that out of the 30 kg of water used by the crew everyday, 28.5 kg can be recycled, while 1.5 kg goes to waste. This also assumes humans are comfortable drinking reclaimed water from all sources.

For the intended mission a grand total of 456 kg of water would go to waste, which is what needs to be brought. With a safety margin of 10%, or 1 month of extra water this number rises to 502 kg of stored water needed for the mission.

After purification, the water will be distilled and lack necessary minerals. Drinking large quantities of distilled water is dangerous. This can be mended by adding some sodium, calcium and other minerals after distillation.

C. Food

As mentioned in the background part, food will not be grown on the spacecraft because it is not worth it for a mission of 304 days. Using a 50% closed loop becomes beneficial only after 8 years. All food and packaging required will be brought and stored for mission, i.e. an open-loop food system. Of course it is different from a meal on a shuttle or from the ISS where they can have fresh food because of the food supplies brought from Earth. This mission will only include dry food because it is easy to preserve and it is lighter than other means of preservation, because of the lack of water. A normal sized man needs around 2500 kcal/day. To calculate the mass for required calories per day, the figure from the book [5] was used and subsequently showed that 0.7 kg of dry food mixed with water can provide all the energy and nutriments required per day.

The three crew members will therefore need $0.7[kg] * 3[crew - m] * 304[days] = 640kg$ of dry food for whole mission. With a 10% margin this gets to a total of 702 kg of dry food. The packaging of the food also adds up to a considerable amount, each daily portion requires 0.6 kg of packaging [4]. For the full mission this comes to $0.6[kg] * 3[crew - m] * 304[days] * 1.1[margin] = 602\ kg$ of food packaging.

III. SECONDARY HUMANS NEEDS

Beyond basic human needs, it's very important to keep the crew safe, healthy and comfortable throughout the whole mission to enable them to perform their assigned tasks. This is also important from a psychological point of view, while being in isolation in a small area for a long time. This will be covered in the following section.

A. Medical

Keeping the astronauts healthy is of paramount importance. Not much is known about how the human body behaves over a long term mission and how it reacts to serious injuries in space. Clear work procedures would have to be defined as to lower the risk of accidents and injuries as much as possible. The mission can not include a full medical facility with all necessary equipment because of mass restrictions. But some small medical packets with the bare essentials should be brought.

Some studies [1] have been conducted in regards to the negative effects of the space environment on the human body and its systems [6].

Two of the greatest concerns is bone atrophy and muscle deterioration in space (i.e loss of bone and muscle mass). It is caused by the microgravity environment, because no reaction forces are acting on the body like by standing on Earth. This can be somewhat negated by exercising regularly by imitating these reaction forces, but the problem still persists over long term making the body generally more fragile. It is not known how bones heal in space, if they heal at all.

The second concern is the cardiovascular system, which also seems to deteriorate over long periods in micro gravity. The total amount of blood volume and red blood cells is reduced. Blood vessels dilate and contract slower. All of this makes the bodies natural response to open wounds worse, and small injuries could prove fatal due to blood loss. Precaution to not get hurt has to be taken.

Lastly, the immune system also turns out to worsen in the space environment, mostly because of isolation in closed space, while bacteria, viruses and fungi could get worse and also from psychic ”load” by being in contact with only two other people. This implies that a clean environment should be kept, with a properly designed trace contaminant filtration system. Also psychological countermeasures should be done, for example architecture of habitat or reduced noise and vibrations. Astronauts should also make sure not to bring any diseases from Earth.

B. Exercise

As mentioned in the medical chapter, exercise is of extreme importance to retain bone and muscle mass, in addition to its positive effects on the cardiovascular system as well as psychological health and general well being. Astronauts on the ISS exercise for 2 hours per day on average. Although exercising in space is not as easy as on Earth. The training equipment on the ISS is too heavy and bulky to use on this mission. Therefore the versatile Yoyo flywheel[7], see figure 5 is being used instead, which has a mass of 65kg and a power draw of merely 55W. In the case of one breaking, one extra is brought for the redundancy.

Fig. 5. The Yoyo flywheel

C. Clothes

One of the first things one think about when travelling somewhere is clothes. Of course, an astronaut needs to bring clothes to space in order to live ”comfortably” and preserve their intimacy. In order not to waste water by washing their clothes, we have considered that an astronaut will bring ”disposable” clothes. The weight is estimated with average around 0.34 kg per person per day [4] which gives around 310 kg for three astronauts and the whole journey. The reason why disposable, single use, clothes have to be used is mainly because of hygiene. The astronauts have to exercise at least a couple of hours per day, and it is unhealthy and can become disgusting in a closed environment to reuse sweaty clothes. This is paramount when considering hygiene, comfort and even medical aspects.

In addition, the aim of the humans for this mission is to set up the mining equipment. That means that they will have to perform EVA (Extravehicular activities). It was decided to use the space suit which is currently used by astronauts on the ISS, the EMU (Extravehicular mobility unit) (see fig 6). They have a bare bones mass of 55.3 kg and 145 kg with all the equipment. With that suit, an astronaut can perform an EVA for 8 hours and has a backup life support system for 30 min.

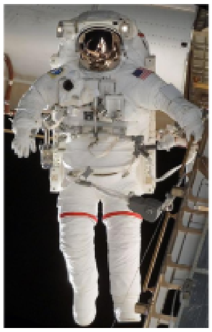


Fig. 6. Picture of an EMU

D. Workload

It has been estimated (with the logistic team) that the total number of EVA hours that have to be performed is around 350 hours to set up the mining equipment. Due to security measures, an EVA always has to be performed with two astronauts at the same time and one inside in order to guide them and help in case of problems arising. In order to take some safety margin, it was estimated that an astronaut can actually perform only 7 hours of work during an EVA (not 8 hours). This means that there are 25 EVAs needed to perform all the work. Considering that an astronaut can perform an EVA every 3 days (one to prepare, one to perform the EVA and one to rest) it will take 75 days to perform all the tasks. They will stay 112 days on the asteroid, thus they will have some margins to perform their work in case of problems arising.

E. Radiation

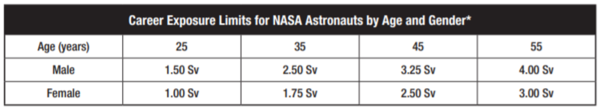
Radiation is of great concern and one of the limiting factors for the amount of time an astronaut can stay in space. There are three major sources for radiation in space. The first one is the Sun, its radiation will increase and decrease with solar activity and random events such as solar storms. On Earth we are protected from the most dangerous radiation and charged particles thanks to Earths magnetic field.

The second source is Galactic Cosmic Rays, or GCRs for short. They originate from outside of the solar system, (from high energy events such as supernova) and consist mainly of heavy charged particles. The amount of GCRs will vary with the expansion and contraction of the suns magnetic field, being most dangerous at solar minimum.

The third source are all of the trapped charged particles in Earths magnetic field.
The posed asteroid mission will be outside of Earths magnetic field protection, meaning that accurate estimates are hard

to make. In a NASA paper [8] the radiation exposure for a fictional 6 month transit mission to Mars was estimated to a 300[mSv] radiation dose, which is a comparable radiation environment, outside of earths magnetic field, to that of the asteroid mission.

The second concern is the radiation the astronauts will be exposed to when doing an EVA. Another paper [9] studied the increased radiation exposure of astronauts on an EVA on the ISS. The paper concluded that the radiation dose roughly doubled outside of the ISS protection. By using this data for a 304 day mission with 25 EVA missions, with a duration of 7 hours each a total mission radiation estimate was reached. The astronauts would be exposed to a 0.525[Sv] radiation dose, which can be compared to the NASA career exposure limits in the table below (see fig. 7).



Career Exposure Limits for NASA Astronauts by Age and Gender*				
Age (years)	25	35	45	55
Male	1.50 Sv	2.50 Sv	3.25 Sv	4.00 Sv
Female	1.00 Sv	1.75 Sv	2.50 Sv	3.00 Sv

Fig. 7. NASA career radiation exposure limits

The radiation dose estimated for this mission is high, and would not allow an astronaut to make a life long career out of this. These radiation dose limits are calculated to not exceed a 3% risk of dying prematurely, meaning that if the crew member could accept a higher risk the amount of possible missions would be extended.

In this regard, it appears that a radiation protection is required to protect the crew from radiation, especially during Solar Particle Event (SPE) (radiation protection are inefficient to protect astronauts from Galactic Cosmic Rays). For example, the Zvezda module on ISS uses TeSS Polyethylene for radiation shielding. A system using a water wall around the module can also be considered but might add a huge extra mass of water. In addition, the potable water can't be used for the shielding because it can be contaminated by such radiations and present a risk for the crew, and this quantity will decrease during the journey.

F. Safety systems

There are three critical emergencies that have to be countered in some way. Fire, depressurization and toxic atmosphere. Fire can be detected through a multitude of sensors, thermistors, photo-electrical sensors, optical sensors and of course the sense of smell. Putting out a fire in space is tricky, one way would be to evacuate the module where the fire is, and depressurizing it, another way would be to use a foam-based hand held extinguisher.

In case of depressurization the crew immediately has to evacuate to an adjacent module and put on their space suits. If the atmosphere suddenly turns toxic, maybe because of a fault in the CO_2 removal system, the crew must put on their oxygen masks. CO_2 levels are measured in the oxygen generation system, but multiple CO_2 sensors should be placed around the spacecraft as a redundancy.

G. Redundancy

Redundancy of the life support system is a major point in order to ensure the smooth running of the mission. Indeed, if a non-nominal case occur (failure of the oxygen generation system, failure of water recovery system,etc...), another system have to take over to keep a livable environment. Since the crew can respond to failures, a crewed spacecraft can be designed as a repairable system. Then some full set of spares or hard redundancy (i.e. duplicate the system) can be used.

1) Two-fault tolerant life-critical system: Our analysis was based on a NASA study concerning a Mars mission [10], in which they consider an ECLSS system composed of 4 elements, a four bed molecular sieve (4BMS), a Trace Contaminant Control System (TCCS), an Oxygen Generation System (OGA) and a Vapor Compression Distillation unit (VCD). They assume that the probability that an ECLSS subsystem, such as the 4BMS, will fail on a 180 day transit is on the order of 0.1 (10%). In other words, this means that the failure rate is around $0.1/180$ days$= 5.5 \times 10^{-4}$ failure per day, or one failure in 1800 days ($= 4.9$ years). Thus, the probability that all three identical subsystems will fail would be $0.1^3 = 0.001$. Then triple redundancy is sufficient to keep the total probability failure of any one of the four ECLSS subsystems to 0.004, or 0.4%. In fact, the water recovery system (VCD) is more reliable than the other ones, so a double redundancy is enough.

If their values were adapted to our mission, using the same failure rate, then the estimated probability that an ECLSS subsystem would fail would be $5.5 \times 10^{-4} \times 304 = 0.167$. With three identical systems, the total probability failure would be $0.167^3 \times 4 \approx 0.019$ or 1.9%. This value seems a bit high, but it might be a good trade-off to ensure a certain level of safety with a minimised mass of the life support system. Moreover, ECLSS subsystems will probably be more reliable in 10 years.

In conclusion, our life support system will be triple redundant for the air management systems (4BMS, TCCS, OGA, and Sabatier module which will be taken into account in the mass budget), and double redundant for the water recovery system (VCD) which make it two-fault tolerant (except for water recovery).

2) Margin on consumables: A margin on consumables must be taken into account in case of something out of ordinary happens. To estimate this safety margin, the following off-nominal case was considered: if the crew vehicle misses the departure window from the asteroid, then they have to wait one more month for the next departure window. Then the safety margin on extra consumables required is 10 % of consumables needed for the nominal mission (304 days), which represents 30 extra days.

3) Off-nominal situation: Two off-nominal situations have also been considered. The first one is an air emergency situation, i.e. a situation in which the crew urgently need to breath oxygen. One solution is to use Chemical Oxygen Generator, also called *candles*. It's a thin-walled steel tube containing a mixture based on lithium perchlorate which produce oxygen once ignited. One of this device provides enough oxygen for one person during 24 hours. Some rescue suits can also be used in such a situation. They are attached to the spacecraft life support system by an umbilical and are supplied with oxygen and cooling for periods of up to several days. In the autonomous emergency mode (when the life support system doesn't work) the suit is only functional for some 30 minutes by means of an oxygen supply. Both of these systems can be used to give time for the crew to fix the problem and start a spare system.

The other off-nominal scenario is a power outage. Indeed, if for some reasons the power generation system doesn't work as expected, the spacecraft must have enough electrical energy to enable the main life support systems to work for several hours. Then the energy stored on the batteries should never go down under a certain level to allow the crew to survive for a 8-12 hours to mend the problem or conduct repairs. After consultation with the logistics group it was found that the batteries had more than sufficient storage capacity to keep the bare essential life support systems running for several times this period.

H. Waste Management

A lot of non-recyclable waste builds up during the span of the mission. This waste consists of human produced waste such as water reduced fecal- and urine waste. It also includes all of the food packaging, used and dirty clothes, CO_2 from the air-revitalization system and other non-reusable items or bi-products from the LSS and its redundancies.

There are some options in regards to waste disposal. The first is to just leave it at the asteroid, or maybe throw it out of the air-lock regularly to remove mass, although this might become a future debris problem. The second option could be to incinerate all of the waste that can be incinerated. Although this would require additional heavy machinery, equipment, and still produce waste that can't be used. Even though it might be able to produce some extra power.
The easiest option is to leave all of the waste at the mining station to be able to bring back more valuable minerals. Just the waste derived from consumables (food, packaging, waste water,clothes) adds up to a considerable mass of around 1.7tons for the whole mission. Meaning that hundreds of kilograms of extra material could be brought back.

I. Habitable Volume

Each person needs some amount of space to be able to comfortably live in. In order not to have pointlessly large spacecraft, it is necessary to estimate minimum acceptable net habitable volume per person (NHV). It is a volume left for the crew and it is for example volume of sleeping quarters, common area where astronauts eat, meet and socialise, exercise or work area.

In NASA study that was done for 2.5 year long mission and crew of 6 people, the NHV was estimated to 25 m^3 per person [11]. Also smaller volume might be possible, but this also covers psychological well-being of the crew. The study also assumes a microgravity environment that allows use of all of the volume, which is also assumed on our spacecraft. Since we have only 3 people it might be higher volume, since some areas like for example exercise area can be about the same volume, because it's assumed it's not occupied by everyone at the same time. But also our mission is much shorter, so again volume might be slightly reduced and then this value is being used also for our spacecraft, so the total habitable volume would be 75 m^3.

IV. PROJECT RESULTS

Now that the different elements of the life support system are defined, it's important to establish a budget in terms of mass, volume and power. Indeed, these parameters will strongly effects the design of the crew spacecraft and the mission.

A. Power budget

First let's try to assess the power required to run the main life support systems, namely the water recovery system, the CO_2 removal module, the Sabatier reactor and the oxygen generation system (electrolyser). The CO_2 removal system and the Sabatier reactor consumes respectively 800 W and 600 W (rough numbers). The power consumed by the electrolyser wasn't found, but it can be assumed it's in the same order of magnitude than the two other systems. Then, in rough estimation, the power required by the air management system is 2 kW. No data was found about the electric consumption of the water recovery system. However, this kind of system might consume quite a lot, because it usually heat the waste water to condensate it. Then, we can assume that its consumption is in the same order of magnitude as the air management system, so around 2-3 kW (again this number is a rough estimation). Finally, also all the other subsystems have to be taken into account, like sensors, pumps, etc... Because it's really difficult to have an estimation of this without exactly knowing the number and type of component in the real system, it was chosen to double the total power required to run the air management system and the water recovery system, which is totally arbitrary. However it seems quite reasonable because each of these subsystems won't consume a lot compare to the main life support systems. Then the total power it required is around 10 kW. In comparison, the Tranquility module on ISS, which contains the life support system for 6 crew members, can consume up to 23 kW (including all the other elements of the module like computers) [13]. It's important to notice that even the redundancy doesn't affect the power consumption. Indeed, only one set of ECLSS systems will be in operation while the redundant units are stored as backups in case of failure.

B. Mass and Volume budget

Again, it's quite difficult to evaluate the mass and volume of each subsystem. Indeed, it's first not that easy to find accurate data even for systems used on the ISS. In addition, when one want to resize a specific system he can't assume that the relation between the mass (or the volume) and the number of people the system is designed for is linear (for example to scale down a oxygen generation system which meet the requirement for 6 people to a system for only 3 people, it doesn't seem correct to just divide the mass of the real system by 2, because some components might remain unchanged in both cases). Then these budgets can be evaluated thanks to a NASA study about a Mars mission [10]. In this study, average masses and volumes per crew member (CM) were estimated for each main components (see Table I).

	Mass/CM [kg]	**Mass/CM with redundancy [kg]**	**Volume/CM $[m^3]$**	**Volume/CM with redundancy $[m^3]$**	**Redundancy**
4BMS	30	90	0.15	0.45	3
CCS	20	60	0.15	0.45	3
OGA	35	105	0.03	0.09	3
VCD	25	50	0.1	0.2	2
Total/CM	110	305	0.43	1.19	-
Total/CM with ISS factor $(\times 5)$	550	1 525	2.15	5.95	-
TOTAL	1 650	**4 575**	6.45	**17.85**	-

TABLE I
MASS AND VOLUME BUDGET OF LIFE SUPPORT SYSTEM WITH AND WITHOUT REDUNDANCY

Firstly, the redundancy of each subsystem (triple redundancy for 4BMS, TCCS and OGA, and double redundancy for VCD) has to be taken into account. Then masses and volumes per crew member of each system are added up, and then the result is multiplied by the number of crew. However, the life support system considered in this NASA study isn't the same as the one we consider. To include the ISS's Sabatier carbon dioxide reduction, multifiltration wastewater processing, and oxygen and water storage tanks, the mass and volume per crew member have to be multiply by a factor of five (which is called the *ISS factor in Table I*). So a pretty good estimate of the mass and volume of the life support system is given (4 575 kg). The same calculation is performed for volume, and ended up with a total volume of $17.85\ m^3$. It can be noticed that the redundancy has a huge impact on the mass and the volume of the system (almost triple).

After that, the mass of the non-consumable items have to be added to the previous estimation. EVA suits weight 145 kg each and 3 of them are brought (2 for normal EVAs and 1 for redundancy). The mass of the training device is 65 kg and because of its importance another one is taken for redundancy. The mass of the medical kit is just a guess since no information have been found, so we assume it weights 50 kg. So all of this represents an extra mass of 615 kg, which leads to a total mass of non consumable items of 5 190 kg including redundancy.

The mass of consumables to bring (clothes, food, water, gases) for a 304 days journey was calculated in the previous parts, and added up to a total of 2 089 kg. Taking a 10% of safety margin for each of them, and a bit more for nitrogen to take into account air leakage during EVA and a total depressurisation scenario, we end up with a total mass for consumables around 2 366 kg. Therefore, the total mass of the life support system for a mission duration of 304 days and a crew of 3 members is approximately **7.6 tons** including redundancy and safety margin (Table II).

	Estimated Mass [kg]	**Mass with redundancy [kg]**	**Redundancy**
Total for LSS	1 650	4 575	3x for Air system 2x for Water system
EVA suits	290	435	2+1
Training device	65	130	2
Medical kit	50	50	1
Total (Non consumables)	2 055	5 190	-
H2	95	104	10%
N2	43	115	10% for continuous leakage 70 kg to fill the pressurized volume
Water	456	502	10%
Food	638	702	10%
Food packaging	547	602	10%
Clothes	310	341	10%
Total of consumables	2 089	2 366	10%
Total (with consumables)	4 144	7 556	-

TABLE II
MASS BUDGET FOR HUMAN ASPECTS WITH AND WITHOUT REDUNDANCY

V. DISCUSSION

A. Crew

It was decided that a crew size of 3 astronauts was the most suitable. This decision was mainly due to safety reasons. But the composition of the crew is also important. Ideally all astronauts should be able to perform all necessary tasks related to piloting, engineering, assembly and of course have a basic medical understanding in case of emergency. This would mean that the crew can shift job assignments which might make the EVAs more frequent and efficient.

Although this might not be possible. In this case, as discussed in the Workload chapter, it might be best to have one mission commander responsible for overseeing the mission, piloting the s/c (docking, reentry, orbit maneuvers,etc...), directing and planning the EVAs, and handling communications. At least one of the astronauts should be a proficient mechanical engineer to be able to handle inconveniences with the equipment and machinery. And the last crew member should be a mining engineering also proficient in geology.

B. Existing Modules

The results of this study can be compared with some existing modules that contain a full life support system, as a reality check. On the ISS, the LSS is mainly divided into two modules :

- *Tranquility* (also called *Node-3*)
- *Zvezda Service Module* (also called *Salyut DOS-8*)

Both of them have life support systems able to keep up to 6 people alive, which provide some redundancies on the ISS (crew of 6 members on average). They also have the same pressurized volume which is equal to $75\ m^3$, even if the Zvezda Service Module is bigger (its length is 13.1m and its diameter is 4.2m whereas the Tranquility module has a length 6.71m of and a diameter of 4.48m) ([13] [14]). However the different systems take up some place, then on Zvezda, the habitable volume is only $47\ m^3$. This module contains living

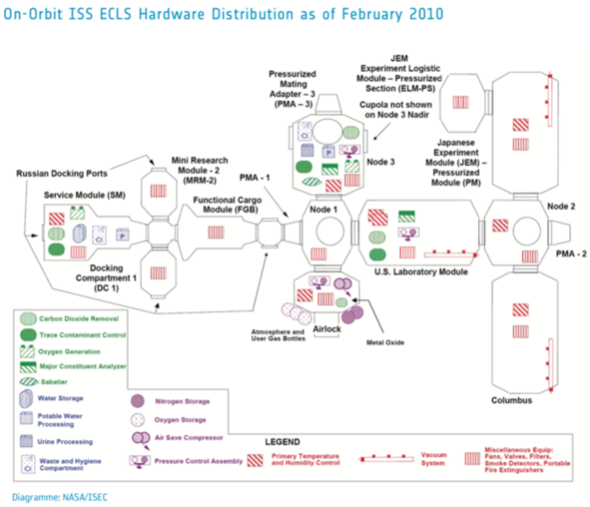


Diagramme: NASA/ISEC

Fig. 8. Overview of the life support systems on board of the ISS [12]

quarters for 2 crew members, so the habitable space per crew member is 23.5 m^3 which is very similar with the minimum habitable considered in this study (25 m^3).
In terms of mass, the Oxygen Generation System of ISS (probably the one of Tranquility since the Zvezda module is usually used as a backup) weights 680 kg and its Water Recovery System weighs 1500 kg, which represents a total mass of 2200 kg [1]. In this study, the Air Management system and the Water Recovery system weight is 1 650 kg (without redundancy), which represents 75% of the one of the ISS. It's important to keep in mind that the calculations were made based on a global study so it's hard to directly compare these two results since the assumptions and the crew size are quite different. However, the total mass found in this study seems coherent, since it's less than the mass of the ISS life support systems (designed for 6 people) and more than half of this value (because it doesn't seem correct to divide the mass of the system by 2 if the crew size is divided by two).

C. Assumptions on Future Technology

Since the aim of this project is to plan a mission toward an asteroid in 10 years, some assumptions can be made about the performance of future life support system technologies in 10 years. For example, the current water recovery system on ISS recycle around 85% of the waste water. However, it can be assumed that this rate will reach $\approx 95\%$ in the next decade, which will enable to significantly decrease the mass of water to bring. Therefore, the calculations concerning this part are only right under this assumption. It's possible that such a level of recovery isn't reached in 10 years, which will impact the mass budget of the mission.

The redundancy estimate was based on a NASA study for a Mars mission [10]. In this study, they assume a failing rate based on rough estimations, since it's very difficult to access this kind of data without performing a test on a real device. This rate is important to determine the level of redundancy to use in order to keep a low risk of failure. In addition, future technologies might be more reliable and significantly decrease this rate, or can also be less reliable if there were just designed and still have a low TRL level. However, even if this failure rate isn't so accurate and can change in a decade, the conclusion to use triple and double redundancies, respectively for air and water systems, seems coherent. Then the total mass of the life support system evaluated should not change a lot.

Finally, it's important to keep in mind that this study is a concept study and not a design one. Thus, all calculations are rough estimations based on specific hypothesises, that only give a general idea of the size, mass and power that a life support system designed for this specific mission would have.

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