Transport System between Deep Space Gateway and Lunar Surface

Olivier Destrian, Giada Staniscia, Akane Wada, Brendan Wilhelm
Team Red - Human Spaceflight SD2905 - March 2018

Abstract—This paper proposes a solution for the transport system between the Deep Space Gateway (DSG) and the Lunar surface. The DSG is placed near the rectilinear Halo Orbit. After a first phase where the DSG is launched and assembled, and a Lunar base is built, four crew members are sent to the DSG and later on the Moon (phase two). The purpose of the mission, along with several scientific operations, is to prepare with the final goal in mind to eventually reach Mars. To achieve its objectives, a concrete design of the transport vehicle is described.

CONTENTS

1 INTRODUCTION

Firstly, the transfer maneuvers are described. The total Δv from the DSG to the Lunar surface is 2.44 km/s and the duration of the one-way trip is 2 hours and 38 minutes. The vehicle travels with a 4300 kg payload using liquid oxygen (LOX) and liquid hydrogen (LH2) as propellant. 34.8 tonnes of LOX and 8.7 tonnes of LH2 are needed, corresponding to 30.5 m^3 and 122.9 m^3, respectively. For the safety and health of the astronauts, the transport system uses Environmental Control and Life Support System (ECLSS), the same as the Space Shuttle. Power will be stored with Flywheel Energy Storage System (FESS) and fuel cells for emergency situations. The structure is made of aluminum-lithium alloy stiffened shells.

2 Transfer Maneuvers

The first maneuver to be performed is a Hohmann transfer orbit from the Deep Space Gateway perilune at 3233 km down to 15 km. The target perilune altitude is normally chosen between 10 and 15 km in order to safely avoid all lunar mountains [1]. The Hohmann transfer is the most fuel efficient choice [2] and is described by Fig. 1.

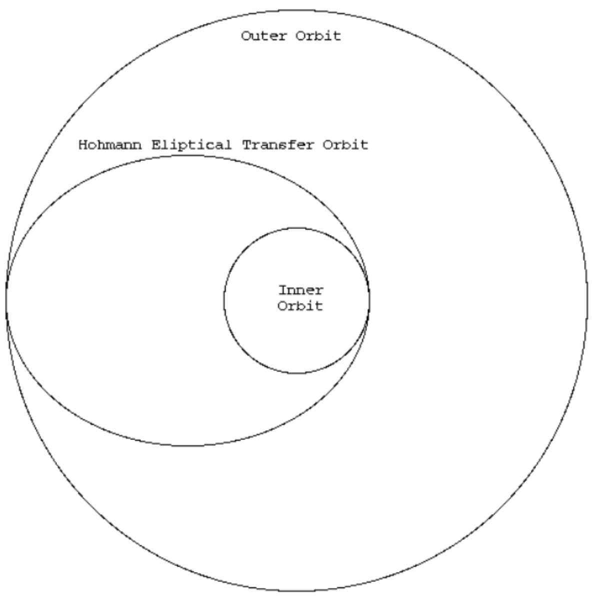

Fig. 1. Hohmann Transfer Orbit [3]

Two Δv are needed, one to start the elliptical transfer (Δv_1) and one to stay in the inner circular orbit (Δv_2):

$$\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 1\right) = 0.3614 \ \ km/s$$

$$\Delta v_2 = \sqrt{\frac{\mu}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1+r_2}}\right) = 0.2761 \ \ km/s$$

where the standard gravitational parameter for the Moon is $\mu = 4902.8 \ \ km^3/s^2$ and the radius of the Moon is 1737 km, therefore $r_1 = 1737 + 3233 = 4970$ km and $r_2 = 1737 + 15 = 1752$ km.

$$\Delta v_{total} = \Delta v_1 + \Delta v_2 = 0.6375 \ \ km/s$$

A Hohmann transfer is a relatively slow process. The amount of time it takes is:

$$t_H = \pi\sqrt{\frac{(r_1+r_2)^3}{8\mu}} = 8742 \ \ s = 2 \ \ h \ \ 26 \ \ min$$

At 15 km altitude, a powered descent is performed until 300 m, where the landing site becomes visible. Finally, the last phase is a terminal landing until touchdown (Fig. 2).

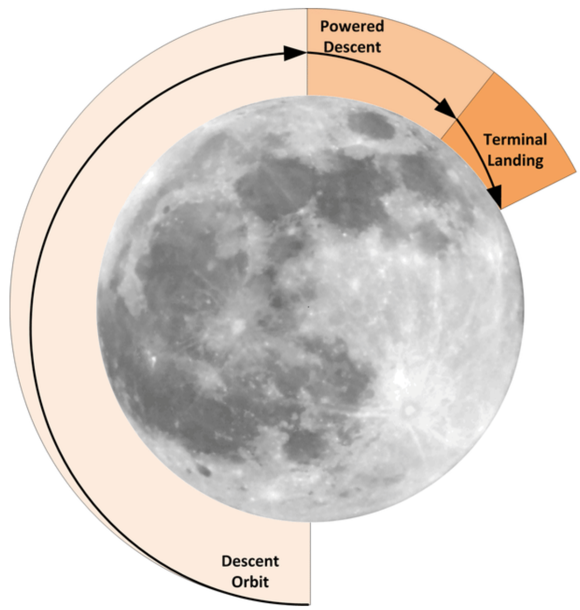

Fig. 2. Lunar Landing Phases [4]

In order to estimate the Δv, the fuel consumption and the time budgets of the landing phases, some assumptions were taken from the Apollo missions data, such as those in Fig. 3. Fuel consumption is discussed in the next section.

For the landing phase we have that:

$$\Delta v = 1.8 \ \ km/s$$
$$t = 12 \ \ minutes$$

Summing the two contributions, we have the total Δv and time budgets of the entire transfer from the DSG to the Lunar surface:

$$\Delta v = 2.44 \ \ km/s$$
$$t = 2 \ \ h \ \ 38 \ \ min$$

As we can see from Fig. 3, the main difference between descent and ascent is not in the the Δv, but rather in the fuel consumption:

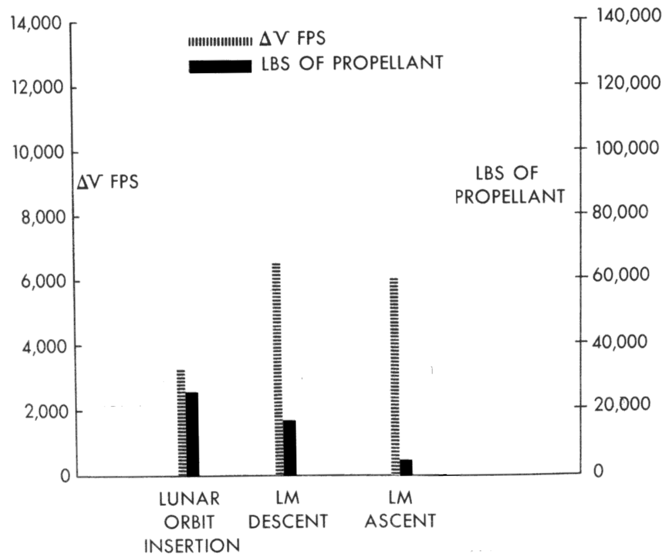

Fig. 3. Apollo Missions Energy Requirements [5]

about three to four times more is needed during descent due to the retroactive braking to soft land. Thus, another assumption made was to consider the same Δv for both ascent and descent. As for the time, ascent takes about 4 minutes less than descent.

3 Fuel Consumption

A Liquid Oxygen (LOX) and Liquid Hydrogen (LH2) mixture was chosen as propellant for two reasons: the high specific impulse ($I_{sp} = 450\ s$) and because one of the objectives of the mission to the Moon is to mine this fuel from the Lunar surface. A disadvantage is the very low density of the hydrogen. In fact, we will see that quite large fuel tanks are needed.

Mass calculations were based on the Tsiolkovsky rocket equation:

$$\Delta v = v_e\ ln\ \frac{m_0}{m_f}$$

where v_e is the exhaust velocity:

$$v_e = I_{sp} \cdot g_0 = \\ = 450\ s \cdot (9.81/1000)\ km/s^2 = 4.42\ km/s.$$

Δv is the one calculated in the previous section (2.44 km/s), m_0 and m_f are the initial and final mass respectively and can be written as following:

$$m_0 = m_f + m_p$$
$$m_f = m_s + m_l$$

where m_p is the propellant mass, m_s the structural mass, and m_l the payload mass.

To run a simulation, some assumptions had to be made:

$$m_s = 0.2 \cdot m_0$$
$$m_{0,return} = 0.75 \cdot m_0$$

the structural mass was assumed to be 20% of the total initial mass, and the initial mass of the return trip (from the Lunar surface to the DSG) was set to 75% of the initial mass from the DSG to the Moon.

The mission of the transport is to bring a 4300 kg payload to ensure the survival of a 4 person crew on the Moon for six months. The histogram of Fig. 4 was built to answer the optimization question of how often the Lunar surface should be resupplied from the DSG. On the y-axis we have the tonnes of mass of the total propellant needed (in blue), the propellant per two-way trip (in orange), the total initial mass of the vehicle leaving the DSG (in yellow), and the amount of payload that can be sent back to the DSG (in purple).

The more we want to travel back and forth, the more fuel is needed in total, even if the fuel per trip decreases since the total initial mass also decreases. The optimal choice was found to be two trips in six months, i.e., to resupply the Lunar surface every three months. Therefore, we have:

fuel consumption for every two-way trip:
$$m_p = 43.427\ tonnes$$

total initial mass of the vehicle:
$$m_0 = 56.971\ tonnes$$

payload mass from DSG to Lunar surface:
$$m_l = 4.3/2 = 2.15\ tonnes$$

payload mass from Lunar surface to DSG:

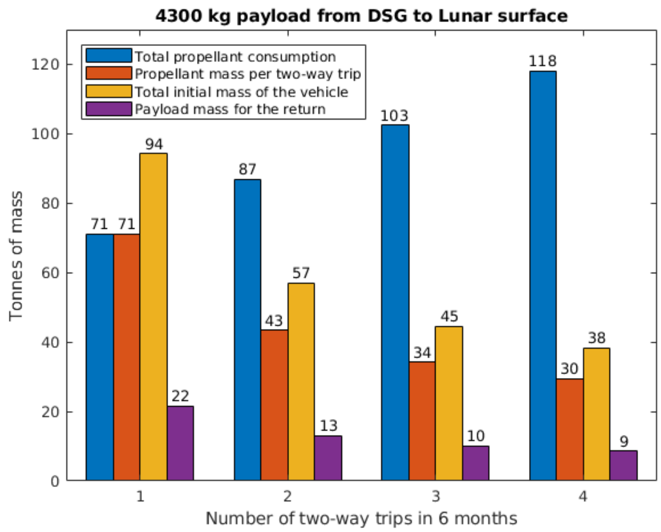

Fig. 4. Vehicle Mass Evaluation

$$m_{l,return} = 12.98\ tonnes.$$

Now that we have the propellant mass, its volume needs to be calculated. Since the stoichiometric mixture is not the most efficient one, an optimal 80% oxygen and 20% hydrogen mixture was chosen, as according to NASA [6]. Thus, of the 43.5 tonnes of fuel, we have 34.8 tonnes of LOX and 8.7 tonnes of LH2. The densities are $1141\ kg/m^3$ (LOX) and $70.8\ kg/m^3$ (LH2), therefore we have:

$$\text{LOX volume} = 30.5\ m^3$$

$$\text{LH2 volume} = 122.9\ m^3$$

$$\text{total propellant volume} = 153.4\ m^3.$$

4 Life Support System

A suitable life support system needs to be selected to ensure the astronauts well-being during the trip between the DSG and the Moon. The following table shows a comparison between the Space Shuttle and our vehicle.

Vehicle	Duration (one-way)	Crew
Space Shuttle	3 days [7]	7 people [8]
Transport system between DSG and the Lunar surface	2 hours and 38 minutes	4 people

TABLE 1
Comparison between Space Shuttle and our vehicle

As shown in Table 1, the Space Shuttle has a longer duration for a one-way trip and a higher crew capacity. This means that the functions of the life support system in the Space Shuttle is sufficient for the relatively short trip between the DSG and the Moon. Therefore, the same system is used for life support and it is described below.

4.1 ECLSS

ECLSS [9] stands for Environmental Control and Life Support System and it was used to keep the astronauts healthy on the Space Shuttle. Figure 5 illustrates how water, hydrogen, oxygen and carbon dioxide are utilized. Since there are no plants in this circulation, carbon dioxide is removed automatically.

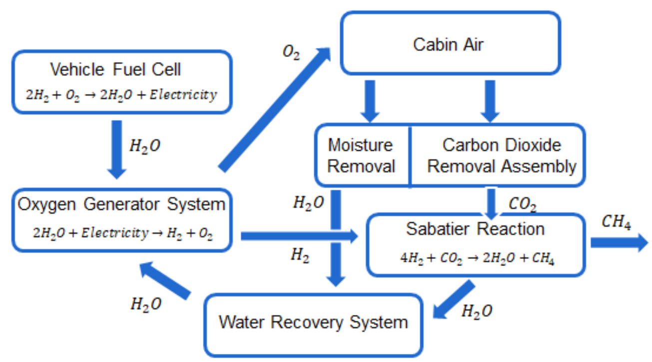

Fig. 5. ECLSS

Table 2 shows the ideal values for each parameter in ECLSS, which are approximately the same as on Earth.

The water recovery system stores water from the moisture removal equipment and the Sabatier reaction (Equation 1) to send it to the oxygen generator system. This system produces enough oxygen for all crew members through the electrolysis of water (Equation 2) and sends it to the cabin air. In this way, oxygen and water in the vehicle circulate through the life support system.

$$4H_2 + CO_2 \rightarrow 2H_2O + CH_4 \tag{1}$$

Parameters	Transport system between DSG and the Moon
Total pressure [kPa]	97.9-102.7
O_2 partial pressure [kPa]	19.5-23.1
CO_2 partial pressure [kPa]	Average=707, peak=1013
Dilute gas	N_2
Temperature [K]	291.5-302.6
Relative humidity [%]	25-70
Ventilation [m/s]	0.051-0.203

TABLE 2
Parameters in ECLSS [10]

$$2H_2O + Electricity \rightarrow H_2 + O_2 \tag{2}$$

Carbon dioxide is generated by the astronauts' breathing. After it is removed from the cabin air with the carbon dioxide removal assembly, it is used in the Sabatier reaction to generate water and methane. This methane could be used in fuel cells to generate power.

Table 3 shows the minimum necessary amount of oxygen for crew members and the average amount of carbon dioxide emitted by them during the trip between the DSG and the Lunar surface.

	Amount per day, one crew	Amount for one-way trip, one crew	Amount for one-way trip, all crew
O_2	588 [L]	64.5 [L]	258 [L]
CO_2	3.1 [L]	0.3 [L]	1.2 [L]

TABLE 3
Amount of O_2 and CO_2 [9]

Electrolysis of water requires a minimum of 237.13 [kJ] of electrical energy input to dissociate each mole [11]. The oxygen generator system in ECLSS generates 258 [L] of O_2 during the one-way flight. This means that 23 [mol] of water is needed for electrolysis. Therefore, the oxygen generator system needs 5454 [kJ] of electrical energy input for the supply of oxygen for all crew members. The oxygen generator works for 2 hours and 38 minutes to generate 258 [L] of oxygen with 5454 [kJ]. Using equation 6 to convert electrical energy in Joule into power in Watts, the amount of electrical energy consumed by the oxygen generator is going to be 0.58 [kW]. For instance, a solar panel normally produces 0.7 [kW] using two and a half hours of full sun [12]. Therefore, the amount of electrical energy input for the supply of oxygen is a reasonable value.

$$P = \frac{E}{t} \tag{3}$$

P : power in Watts [W]
E : energy in Joules [J]
t : time period in seconds [s]

4.2 Cabin Air Revitalization

For the astronauts' health in cabin, the life support system is also equipped with the function of cabin air revitalization [13]. There are five independent air loops in the cabin: the cabin itself, three avionics bays and inertial measurement units. The cabin pressure atmosphere is circulated by the air revitalization system and the circulated air picks up heat, moisture, odor, carbon dioxide and debris with additional heat from electronic units in the crew cabin. The air circulation is necessary for the crew to prevent them from being covered with bubbles of carbon dioxide and not being able to breath properly.

Each cabin fan is controlled by its own cabin fan switch (there are two types of cabin fan, fan A and fan B). Normally, only one fan is used at a time. The cabin air is drawn through the cabin loop and a fine filter by one of two cabin fans located downstream of the filter. Assuming that the crew cabin volume is 65 cubic metre and 8.5 cubic metre of air per minute, one volume crew cabin air change occurs in approximately seven minutes. Approximately 22 air changes occur in two hours and 38 minutes (duration of one-way trip).

A bypass duct carries cabin air around the cabin heat exchange system and mixes the air with the revitalized air. Through this process, temperature in the crew cabin is controlled in a range between 291.5 and 302.6 [K].

4.3 Redundant Design

The transport system might break down on the way. In such an emergency, another vehicle would arrive for rescue from the DSG. However, the astronauts in the broken vehicle might be in danger while waiting to be rescued inside the vehicle. For instance, if the transport system catches fire or if the life support system does not work properly. Therefore, the life support system on the vehicle should have a secondary system for redundancy.

Extravehicular Activity Mobility Units (EMUs) are also suggested for redundancy in case of such an urgent situation. Figure 6 illustrates the redundant design of vehicle. The EMUs provide the necessities for life support, such as oxygen, carbon dioxide removal, a pressurized enclosure, temperature control and meteoroid protection during an extravehicular activity (EVA) [13]. The EVA suits are made personally for each crew member and the astronauts wear them during the trip between the DSG and the moon. The EMU is pressurized to 4 psi and designed for a 15-year life with cleaning and drying between flights. It consists of a hard upper torso, lower torso assembly, gloves, helmet and visor assembly, communications carrier assembly, liquid cooling and ventilation garment, urine collection device and operational bioinstrumentation system. In case of emergency, the suits have a primary life support of two hours.

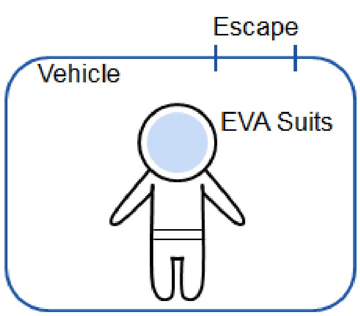

Fig. 6. Redundant design of vehicle

Moreover, the space suits have its own propulsion system, which enables astronauts to control their posture. This function would be useful in case the vehicle catches fire and astronauts have to escape.

5 Communication System

Figure 7 illustrates how to keep in touch with astronauts during the mission.

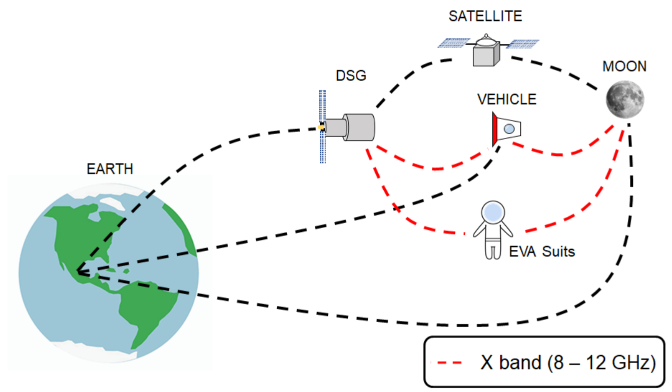

Fig. 7. ECLSS

In this paper, only the red dotted lines are mentioned (the black ones are explained by the Overall Coordination group). There are four lines of communication between the DSG, the vehicle, the astronauts and the Lunar surface as shown in figure 7.

5.1 Frequency Bands

For communication in space, a variety of frequency bands can be used and designations have been developed so that they can be referred to easily. In general, higher frequency bands have larger data capacity. The following table and figure show the details.

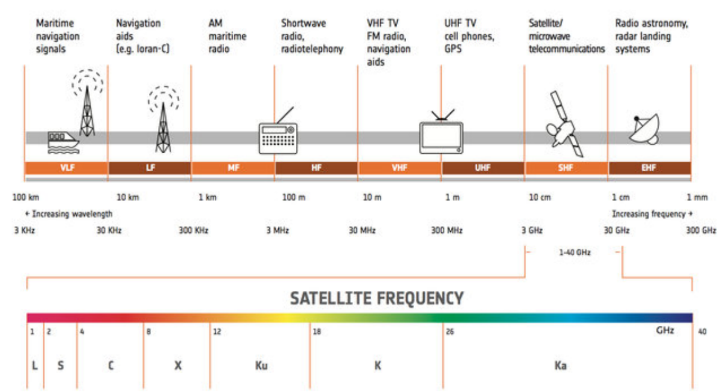

Fig. 8. Frequency band [14]

Name of band	Frequency	Used for
L-band	1-2 [GHz]	Global Positioning System (GPS) carriers, satellite mobile phones
S-band	2-4 [GHz]	Weather radar, surface ship radar and some communications satellites
C-band	4-8 [GHz]	Satellite communications
X-band	8-12 [GHz]	The military and radar applications including continuous-wave, pulsed, single-polarization, dual-polarization and synthetic aperture radar

TABLE 4
List of frequency band [14]

For the communication between the DSG, the Lunar surface, the vehicle and the astronauts, the X-band is chosen because it has been recently used in many applications and it has been proven to be reliable. Normally, crew members in the vehicle keep in touch with other astronauts in the DSG or in the Lunar base with the communication tools equipped within the vehicle itself. They exchange important information during docking to the DSG or landing on the Lunar surface. In emergency cases, such as breakdown of communication tool on the vehicle, the crew uses the communication tool equipped within the EVA suits.

6 Crew Protection

The vehicle has to resist environmental attacks, namely micro-meteorites and radiation. Though achieving such a protection is not especially hard during the trip from the DSG to the Moon since it only lasts a couple of hours, we should also consider that the lander then has to stand on the Moon: even without crew, the lander has to protect itself in order to be able to go back to the DSG.

6.1 Global Design

The global design is shown in Figure 9. The concept is the following: the radiation protection is partially protected from the micrometeorites impacts by an aluminum bumper that is not very sensitive to radiation (heat). Then, the inner wall of the lander has more protection with a fiberglass layer. That layer is sensitive to heat, hence it has to be protected by the radiation insulation. That wall technology is often used for mobile spacecrafts (that need to stay light). Its nominal weight is $2.7\, kg/m^2$. The external area of the lander should then be as small as possible to maintain a low weight.

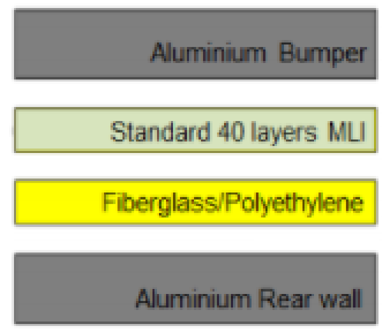

Fig. 9. Standard protective wall [14]

6.2 Micro-Meteorite Shield

The micro-meteorite shield is composed of three layers: the outer aluminum wall, that has minimum strength against different types of attacks (impacts, scratches, dust, radiation), a tough fiberglass inner layer (other materials can be used as well) and the inner wall often made of aluminum. This wall should never be damaged, especially the parts that protect crew and fuel. Yet, this protection is not sufficient against larger, trackable space debris. The schedule of the trip between the Moon and the DSG has to take it into account to avoid at all cost to operate when there is a risk of large debris. When on the Moon or attached to the DSG, Whipple shields have to be attached on the exposed face of the lander to protect it against micro-meteorites.

6.3 Radiation Protection

The radiation protection is also of cardinal significance for both lander and crew. Though the radiation dose is not significant for a 2.5 hour journey, radiation is also a very powerful heating mechanism. The main purpose of the radiation protection is therefore to ensure that there is not too much heat due to the Sun's radiation, and too much heat loss on the side of the lander that is not exposed to the Sun.

The material used is the Multi Layer Insulation. The basic idea is to use many thin layers (40) made of a black body. The first outer layer gets a power P from the Sun and at equilibrium it gives a power P. But that power is half radiated outside and half radiated inside: the second layer only receives a power of P/2 from the first layer. Since the third layer receives P/4 from the second layer, it's also radiating a bit more than P/8 on the second layer. The second layer receives a bit more than P/2, but overall, for each supplementary layer, the amount of transmitted power is decreased.

7 Thermal Aspects

The lander has to be kept at the right temperature, roughly T=300 K, and it has to stay homogeneous since the face exposed to the Sun heats up while the other gets cold. The power to dissipate during the journey is close to 5 kW. The power to dissipate on the Moon or on the DSG is unknown but it seems reasonable to assume it is much lower. Chosen solutions are shown in Figure 10.

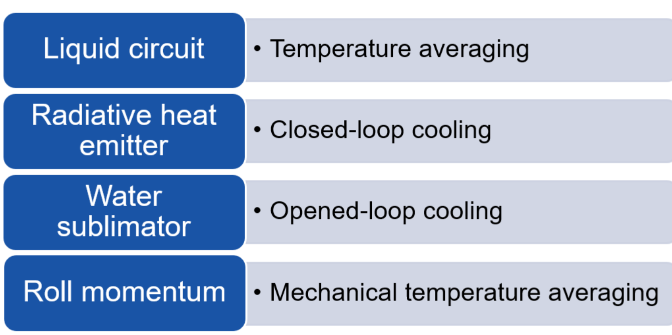

Fig. 10. Chosen solutions [14]

7.1 Cooling System

Landers usually have a liquid cooling system. This makes it possible to obtain a reasonably homogeneous temperature in the whole lander, especially in the crew compartment. It also transports the heat to the cooling devices. The circuit is doubled for redundancy in case of breakdown. The liquid is not pure water, it contains glycol and other additives. Therefore, they also need to be brought for repairs.

The closed loop emitter is a basic radiator. Its main advantage is the ability to run for a very long time without consuming water. This has to be present on the lander to help it stay cool when attached to the DSG or when waiting on the Moon. It cannot be used during the journey because its efficiency depends a lot on orientation. It is also quite fragile when unfolded and could break due to inertia forces.

The open loop emitter is a water sublimator. Unlike the radiator, it uses a significant amount of water. It is the main heat emitter of the lander since it has great cooling power and can be used during journey. Its water efficiency is around 1.5 kWh/L. The total cooling system weight with redundancies is around 400 kg.

7.2 Other Concepts

The lander should not have windows. They greatly reduce the structure strength (resulting in heavier structure). They also make it very difficult to control radiation and heat. With current technology, it is reasonable to assume that the manual lander driving mode could be handled with cameras.

Another innovative concept is to keep the vehicle slowly rolling during the journey. Having every side partially exposed to the Sun lowers the weight of the cooling system. Since the temperature is more homogeneous, it's easier to stay in a reasonable temperature range everywhere. It can be easily achieved using the Flywheel Energy Storage System: two counter rotating flywheels make it possible to use energy without rotation, and then by using one flywheel more than the other, the vehicle counter rotates. This combined energy storage and control system is already being used in satellites [15].

8 Power Systems

Power systems usually account for around 25% of the dry mass of a lander. Therefore, optimizing its mass efficiency is of great importance.

8.1 Energy Storage

The energy storage is responsible for the considerable mass of the lander power system. Therefore, the objective is to give the best solution in terms of mass efficiency and reusability.

Technology	Li-ion battery	Fuel cells	FESS
Lifetime	500 cycles (or less than 3 years)	1 cycle (without fuel)	10000 cycles
Energy vs Mass	400Wh/kg	1800Wh/kg wet mass	300-800 Wh/kg
Power vs Mass	300W/kg	100W/kgdry mass	3-10 kW/kg
Thermal behavior	Good efficiency (Need heat)	Low efficiency (Generate heat)	Good efficiency
Complexity	Low	Advanced	Advanced
Cost	Low	High	High

TABLE 5
Comparison of energy storage technologies [14]

The most commonly used means of energy storage, Li-ion battery, has mediocre performance. Yet, it has often been used due to its simplicity and low cost, especially in the past (since other technologies are becoming easier to use now). The main problem with Li-ion batteries, besides their poor efficiency, is their very short lifetime (3 years) and their need to be maintained. Therefore, fuel cells seem the best choice for this vehicle for the excellent efficiency. There is however a drawback: the impossibility to reuse them without refueling. The last competitor, FESS (Flywheel Energy Storage System) is only just starting to be used thanks to the emergence of game-changer technologies such as magnetic bearings that allow for high efficiency, high rotational speeds and therefore high energy density, and also composite materials that allow for fast spinning rotors (high energy density). Flywheels are very different in the fact that they have no thermal behavior (fuel cells pose a real heat problem, Li-ion batteries have to be kept warm), a higher auto-discharge (1% hour with non supra conductor magnetic bearing), no maintenance needed, and last but not least they are mechanical: they have an impact on mechanical behavior of the lander.

On the one hand, this allows for rolling momentum control (previously evoked in thermal aspects), on the other hand this needs to be designed carefully to avoid undesired behavior. If well designed, that is if the flywheel is on the roll axis of the lander and that the two counter rotating flywheels are properly controlled, that energy storage would have no side effect on the maneuvering of the lander. The $size/mass/speed$ compromise of the flywheel is given by the following law:

$$E_{stored} = \frac{1}{2} m R^2 \Omega^2$$

The former estimations for FESS energy density were made for $R = 30\,cm$, $\Omega = 50000\,rpm$. Further design sequence should include investigations of what materials can be used to build the rotor which withstands huge centrifugal forces.

The chosen energy mix is the following:
- regular power will be stored with FESS, for better weight efficiency, less maintenance, and roll momentum control;
- emergency power will be stored using fuel cells: this allows for the lightest emergency power source and it uses the same tanks as the propulsion system.

8.2 Energy Production

Energy production is specific to this vehicle since most landers are not reusable. The recharge rate of the system is not very important and has to be a bit higher than the consumption of the lander at rest. Considering that today's space solar panels have an efficiency of about 250 W/kg, the solar panels weight to power the lander at rest (500 W) is insignificant and can be estimated less than 25 kg with power converting systems. The same stands for recharging the storage system. Yet, further design should consider the fact that solar panels have to be cooled, resulting in heavier cooling system.

Fuel cells could eventually be reloaded using the fuel mined on the Moon. This supplementary energy production would make the storage system fully rechargeable.

9 Structure

Looking to the basic structure of the transportation vehicle between the DSG and the Lunar surface, it is without question that this style of construction must be resilient against static as well as dynamic loads. In order to address this requirement, most current spacecraft utilize a simple truss and panel sandwich technique [16]. This allows the craft to handle different loading scenarios while simultaneously reducing the overall structural mass of the spacecraft. This strategy will be combined with stiffened shells structures and frames as seen below.

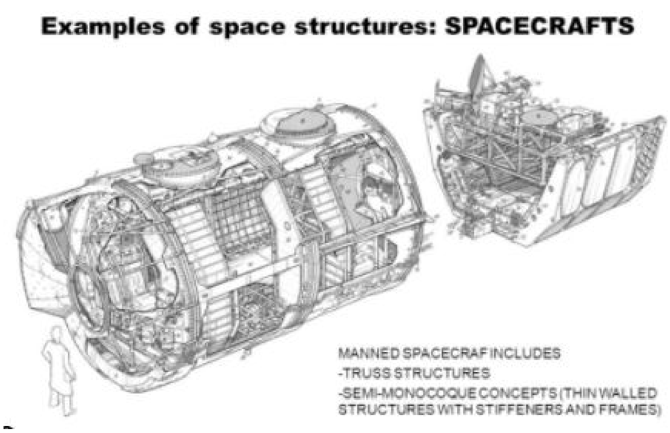

Fig. 11. Sandwich and stiffened panel method

With the spacecraft requiring a cargo hull capable of hauling automated machinery, lunar material, water, etc. and having the capacity to carry a maximum of four crew members, this higher efficiency design specific to a vehicle of this magnitude is an absolute necessity. While the manufacturing of these stiffened shells are difficult and complicated due to their complex geometry, its superior structural performance outweighs these difficulties [17].

9.1 Materials

As for materials, aluminum is the traditional choice when it comes to any flight project. While this metal is not incredibly strong on its own, it is combined into an alloy that dramatically increases its strength as well as other desired characteristics. The specific aluminum alloy this transportation vehicle will be comprised of is an aluminum-lithium alloy.

Property	2090	2091	8090
Density, g/cm^3	2.59	2.58	2.55
Melting range, ^{0}C	560-650	560-670	600-655
Elastic modulus, GPa	76	75	77
Poisson's ratio	0.34		
Thermal conductivity at 25^{0}C, W/m-k	84-92.3	84	93.5
Specific heat at 100^{0}C, J/kg-k	1203	860	930

Fig. 12. Mechanical properties of Aluminum-Lithium alloys [18]

This substitute to conventional aluminum alloys has a lower density providing a 7 to 20 percent saving in weight. Additionally, this particular combination of elements has increased stiffness and toughness even at cryogenic temperatures making this property very desirable as the environment the vehicle will be operating in is subject to extreme conditions [18]. These enhanced features are also essential to fuel tanks containing the liquid oxygen and hydrogen propellant the craft will employ. As for the manufacturing of this material, the practices used to fabricate the traditional aluminum alloys are the same so next extra expense is wasted on specialized machining tasks.

9.2 Sketch

The following section will introduce the transportation crafts features as well as elaborate on the the specific use of these aspects of the vehicles design.

At the top of the vehicles structure is where the crew is housed. Instead of the crew module being outfitted with windows the capsule has cameras providing a 360 degree view. The decision to omit windows from the design is because of the influence the windows have on the thermal system of the craft as they provide an area for the thermal equilibrium to be disrupted depending on the orientation of the vehicle and the sun. This completely cabin will provide an easier environment for the thermal systems to manage.

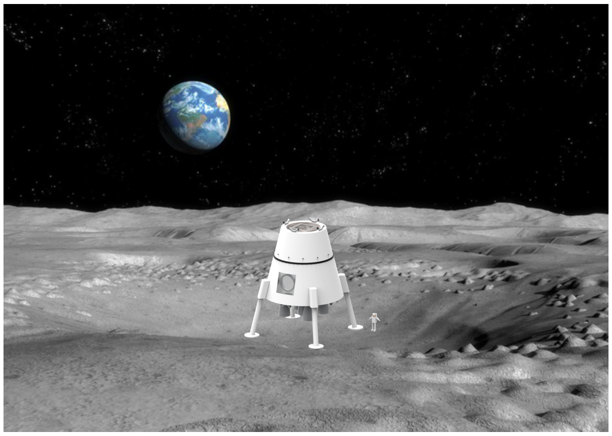

Fig. 13. Transport vehicle (Background: https://pixers.us/wall-murals/moon-surface-8611410)

The next portion is the crew module adapter which is responsible for keeping the crew module pressurized. Moving to the docking adapter, it is positioned on the side of the spacecraft because of the design a pressurized retractable bridge of some sorts that connects the transport vehicle to the lunar base. The lower portion of the spacecraft is a cargo bay responsible for housing machinery and material necessary for the specifications and success of lunar surface operations. Below the cargo bay level there are two tanks containing the vehicles fuel, liquid hydrogen, and the oxidizer tank. Focusing on the exterior of the ships design multiple thruster control ports can be seen. These thrusters are responsible for adjusting and reorienting the crafts position. The reaction controls would be used in orbiting maneuvers, debris countermeasures, landings, etc. The retractable landing legs are solely used for surface landings and this main objective is to provide soft landings while simultaneously protecting the capsules main engines from the lunar and potentially Martian landscape. The dimensions of the crew module are comparable with the Apollo and Orion crew modules. The Apollo crew module had a radius of 3.9m and a height of 3.2m while Orion has a radius of 5m and a height of 3.3m [19]. The crew capacity for each of these capsules are three and two to six respectively. The dimensions seen for the crew module on Figure 13 easily allow for a crew capacity of four.

10 Maintenance

When it comes to vehicle maintenance for the transportation craft between the lunar surface and DSG very few of these endeavors will be focused on the actual vehicle structure itself with the exception to extravehicular activities meant to clear possible camera obstructions and other minor services to the capsules exterior. For the most part these maintenance adjustments will be for the crafts on board systems.

10.1 Flight Software

FSW or flight software will be the primary reason for servicing the transport craft. Because this entire mission is a practice run for a future colony and missions to Mars, it is essential that the ships computers be operating properly as FSW is a mission critical element. The flight software is directly correlated with the transports functionality and performance that cannot be allowed to operate at anything other than perfect at all times.

When it comes to staffing this portion of the mission there are a couple options as to what individuals are responsible for the FSW as their interface with the vehicle is almost entirely on-board software.

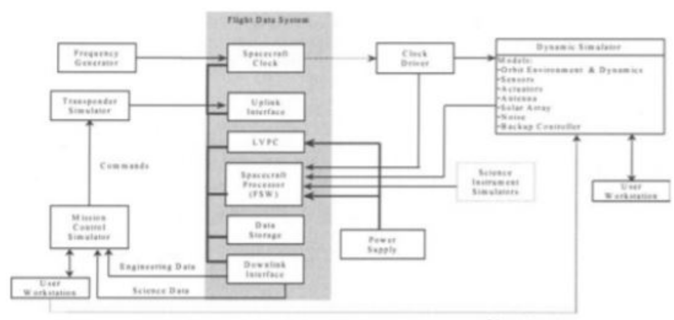

Fig. 14. Closed-loop FSW test facility [20]

There are three approaches to staffing FSW maintenance, them being to use the original developers, use mission operations personnel, or assemble a center of excellence FSW support team [20]. Out of these options, it is the most efficient to use the original developers because they created the on-board software and would therefore be the most suited individuals to fix and the adjust the system. The staffs responsibilities will consist of interpreting FSW statuses, explain FSW characteristics, adapt to new operations, and the list goes on [20]. This is a fundamental part of the transport and overall mission success.

11 Off-Nominal Case

The largest issue that could occur during a transport mission is a major system, such as communications, propulsion, life support, electrical, failed leaving the crew to take immediate action in order to ensure their safety. As a solution to this possible complication, the DSG will house two separate transport vehicles both having a cargo bay and four person crew capacity as well as being fully automated while still having the ability to be piloted manually. The two crafts will be equipped with reserve oxygen tanks and space suits in case of some sort of life support error or problem requiring an EVA. Since the total transit time between the lunar surface and the DSG is under three hours, scheduled check-ins will be required in an effort to defend against communication loss so that, if contact with the transport is lost, there can be a quick and prompt response to recover the vehicle and crew.

12 Conclusion

To design a transport vehicle between the Deep Space Gateway and the Lunar surface, several aspects were studied. First of all, the transfer maneuvers set the duration of the journey and the Δv requirement. Secondly, the fuel consumption was analyzed. The next steps focused on the human aspects such as life support system, communication and crew protection. After discussing the thermal problems and the power system, we were finally able to present the vehicle structure. At last, maintenance and off-nominals cases were examined.

References

[1] Dong-Hyun Cho, Donghoon Kim, and Henzeh Leeghim. Optimal Lunar Landing Trajectory Design for Hybrid Engine. (accessed: 03.10.2018). [Online]. Available: https://www.hindawi.com/journals/mpe/2015/462072

[2] [Online]. Available: http://jwilson.coe.uga.edu/EMAT6680Fa05/Bacon/hohmanntransfers.html

[3] (accessed: 03.09.2018). [Online]. Available: http://www.instructables.com/id/Calculating-a-Hohmann-Transfer

[4] (accessed: 03.09.2018). [Online]. Available: https://www.researchgate.net/figure/Mission-Scenario-for-the-Powered-Descent-and-Landing_fig3_316663100

[5] Owen E. Maynard, John R. Sevier. Apollo Lunar Landing Mission Symposium, Manned Spacecraft Center, June 1966, Volume 1, General Mission Summary, Figure 2, NASA-S-66-6074 JUN. (accessed: 03.10.2018). [Online]. Available: https://commons.wikimedia.org/wiki/File:ApolloEnergyRequirementsMSC1966.png

[6] NASA. NASA's Exploration Systems Architecture Study. (accessed: 03.10.2018). [Online]. Available: https://www.nasa.gov/pdf/140649main_ESAS_full.pdf

[7] NASA For Educators. How Long Does It Take to Get to the ISS? (accessed: 03.05.2018). [Online]. Available: https://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/TSD_Launching_Video.html

[8] NASA. Space Shuttle. (accessed: 03.05.2018). [Online]. Available: https://www.nasa.gov/mission_pages/shuttle/main/index.html

[9] ——, "Closing the Loop: Recycling Water and Air in Space," *9-12 National Science Standards*.

[10] Carol Norberg, *Human Spaceight and Exploration*. Springer, 2013.

[11] Wikipedia. Electrolysis of water. (accessed: 03.06.2018). [Online]. Available: https://en.wikipedia.org/wiki/Electrolysis_of_water

[12] Solar Power Rocks.com. How much electricity does a solar panel produce? (accessed: 03.06.2018). [Online]. Available: https://solarpowerrocks.com/solar-basics/how-much-electricity-does-a-solar-panel-produce/

[13] NASA. Human Spaceflight. (accessed: 03.06.2018). [Online]. Available: https://spaceflight.nasa.gov/shuttle/reference/shutref/orbiter/eclss/cabinair.html

[14] ESA. Satellite Frequency Bands. (accessed: 03.06.2018). [Online]. Available: https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands

[15] Kutlay AYDIN, , Mehmet Timur AYDEMIR. Sizing design and implementation of a flywheel energy storage system for space applications. [Online]. Available: http://journals.tubitak.gov.tr/elektrik/issues/elk-16-24-3/elk-24-3-7-1306-206.pdf

[16] Laurence J. Adams. Technology for Small Spacecraft. (accessed: 03.09.2018). [Online]. Available: https://www.nap.edu/read/2351/chapter/7

[17] Biaosong Chen, Gang Liu, Jian Kang, Yunpeng Li. Design optimization of stiffened storage tank for spacecraft. (accessed: 03.09.2018). [Online]. Available: https://link.springer.com/article/10.1007%2Fs00158-007-0174-7

[18] TotalMateria.com. Aluminum-Lithium Alloys. (accessed: 03.09.2018). [Online]. Available: http://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=326

[19] Size comparison of Apollo, Orion and Dragon spacecraft. (accessed: 03.09.2018). [Online]. Available: https://commons.wikimedia.org/wiki/File:Size_comparison_of_Apollo,_Orion_and_Dragon_spacecraft.svg

[20] Elaine Shell, Yvonne Lue, Martha I. Chu. Spacecraft Onboard Software Maintenance An Effective Approach which Reduces Costs and Increases Science Return. (accessed: 03.09.2018). [Online]. Available: https://link.springer.com/chapter/10.1007/978-94-015-9395-3_48

APPENDIX

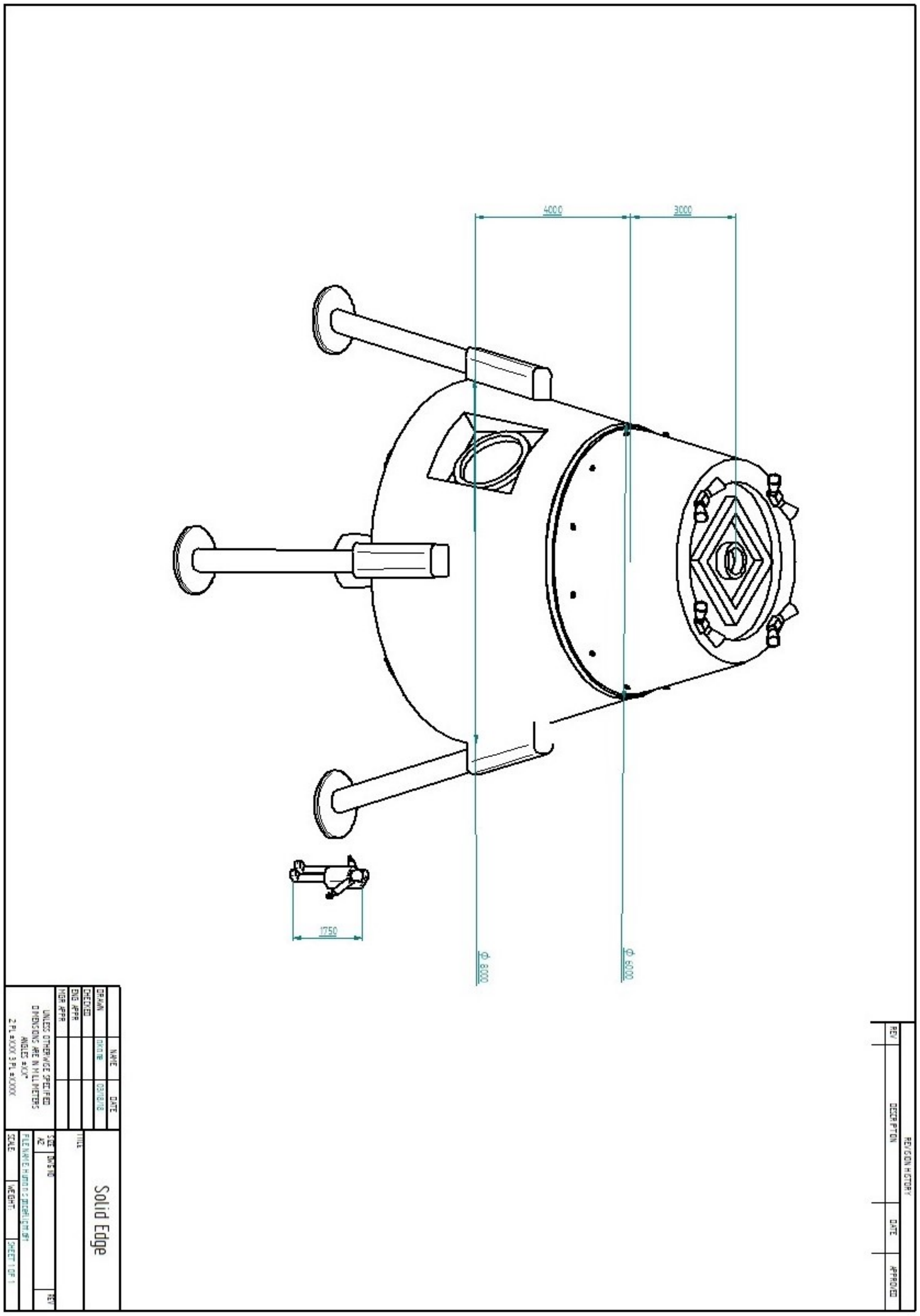

Fig. 15. Draft of the vehicle (Unit: mm)