Moon exploration with the Deep Space Gateway Deep Space Gateway Design

Friedrich Franke, Joakim Storfeldt, Joanna Szymanska, Ernst Wehtje, and Joshua Williams

Abstract—This paper on a project aims to characterize the main parameters of a long duration human mission in a Moon orbit, also known as the Deep Space Gateway, only achievable with life support systems contained in limited sized modules. Pictures were modeled in Solid Edge ST9 and rendered using Key Shot 6. This paper will, through assumptions and facts prove the feasibility of the mission and highlight the main aspects and concerns of it. Different configurations are proposed in order to increase capabilities of the station for future intended missions. The final optimal station for the mission consists of six modules, at a total weight of 62 tons, housing four astronauts permanently for six months without resupply.

CONTENTS

1 Introduction

Two teams have been assigned a project to conceptually design a Lunar exploration mission with the Deep Space Gateway (DSG), a concept being seriously considered by space agencies around the world as one of the next advances into human spaceflight. Each team consists of four groups: Overall coordination, Deep Space Gateway design, Transport systems between the DSG and the Lunar surface and the Lunar exploration itself. The work compiled in this report was done by the Deep Space Gateway design group of the Red Team. The Deep Space Gateway is a well-spoken recent topic in the space exploration communities. It is said to be the next goal for future international human space exploration. Initiated by NASA, but now an international cooperation between ESA, NASA, Roscosmos, JAXA and CSA. The project is still in the early stages, although it could become the successor to the International Space Station. [1]

1.1 Mission Requirements

For the purpose of this project, some guidelines for the Deep Space Gateway were given. It should be a station in the Lunar vicinity and used for further explorations of the Moon. The long term goal for human spaceflight is to be able to travel to Mars, therefore operating around and on the Moon is necessary to gain vital knowledge. The station will be able to house four astronauts permanently. This project does not have to explain how the DSG station parts itself were put in the chosen orbit around the Moon. But for the sake of interest, the station is designed realistically launch capabilities of today. Abbreviations and definitions and definitions can be found in Appendix A. A conceptual picture can be found in Appendix B, Fig.10.

2 SPACE STATION LAYOUT

To design a space station one has to investigate previous, current and future concepts of space stations. This chapter will give the reader a first picture of the proposed DSG station.

2.1 A brief history of space stations

The first space station Salyut 1, later also Salyut 2-7, was launched by the Sovjet in 1971-1986 and the Americans had a counterpart Skylab launched in 1973-1979. All of these early stations were designed to be launched in one piece and then abandoned when visited by astronauts and used up. These gave important information for the next generation stations to come.

In 1986 the Sovjet launched a modular station Mir, which were improved in many ways. Modular design led to more flexibility, lower payload mass of rocket launches and longer lifetime due to resupply of necessities. USA did not directly provide a counterpart, which instead led to cooperation: Shuttle-Mir program 1995-1998 and later the ISS.

The ISS started as a merge of NASA's project Freedom and Russia's Mir-2 as well as contributions from ESA, JAXA and CSA. ISS is also a modular station and the first module was launched in 1998 and is still operational.

In 2011 China launched their first space station Tiangong-1 which in 2012 was docked with a crewed Shenzhou 9.

Space stations provide access to the alien environment of space. They provide access for humans, not only for a shorter time, but more or less permanently, which opens the door to conduct all type of science. This leads to an further understanding of our Earth, Solar system and Universe but also gain critical insight into how humans handle space and what's needed for us to survive in space. [2] [3]

2.2 Modular solution

When designing a space station there are quite a few systems to consider and to be housed in modules. When looking at space stations one can find some typical modules and parts are used: [4]

- Power and propulsion unit
- Service module
- Habitable module
- Laboratory
- Airlock
- Extra nodes for storage
- Robotic arm

- Docking ports
- Escape vehicle

Most of these modules have always been constructed as fixed, stiff structures. But a new concept is underway, inflatable structures. At ISS it has been proven once so far, by Bigelow company whose small module BEAM attached to ISS was pressurized in 2016. It grew from a packed volume of 1.4 m3 to expanded state of 16 m3, which is a huge increase and may not be feasible for bigger modules. [5] Bigelow is in the process of constructing a new 6 astronaut space station called B330 - Bigelow 330, because it will have pressurized volume of 330 m3 when fully expanded. When comparing the 20 ton B330 with 15 ton ISS Destiny module with a pressurized volume of 106 m3, one sees that by increasing 30 % in mass, one get an increase by 200 % in volume, inflatable modules are therefore efficient in the way that they gain a lot of volume for a smaller increase in mass compared to fixed modules. They also use less volume in the launchers. A difficulty is how to construct the expanding walls to be protective of radiation and meteoroid impacts. This part serves as a guideline for the design of the DSG. [6] [7]

2.3 DSG station configuration 1,2 and 3

After a detailed investigation into the construction of ISS among others, it was decided that DSG will have a modular design and be launched in parts. With mission requirements in mind and the typical space station modules, the DSG station configuration was found and split into three categories.

- The minimal DSG station - configuration 1

Firstly a combined module (marked as 1 in Fig.11 in Appendix B), propulsion, power and service (PPS) module will be launched. This modules will store propellant and have thrusters for station-keeping and attitude control, be equipped with solar arrays which trap the energy from the sun and convert it to electrical power either stored in the module's batteries or used directly and finally it will function as a service-module, housing a lot of electronics. It will also have radiators to control the heat. The propellant tanks will also support the Lunar Transport Vehicles. The PPE will not be pressurize except the propellant tanks and only have one docking port. All docking ports will be of IDSS.

Then a main habitable module (marked as 2 in Fig.11 in Appendix B) will dock to PPS, it will in total have 6 docking ports, and serve as a center piece in the DSG station. It will provide the astronauts with pressurized volume to work and live in, with room for laboratory equipments. A robotic arm will be attached to the module to help with berthing for docking. An inflatable airlock (marked as 3 in Fig.11 in Appendix B) will be attached to one of the center docking ports.

A docking module (marked as 4 in Fig.11 in Appendix B) will also be attached to a center docking port, this module will give an increase in the pressurized volume and give another 4 docking ports which will be used by Lunar Landers, resupply ships from Earth, other modules and possibly by spaceships stopping by for the long trip to Mars.

With this configuration the crew (marked as 5 in Fig.11 in Appendix B) could arrive with a spacecraft and inhabit the DSG station temporarily, provided that there is enough supplies. The spacecraft will then serve as an escape vehicle in case of emergencies. When crew rotation occurs, the new crew will arrive with an vehicle which the first crew can return to Earth with.

- The habitable DSG station - configuration 2

Even with two pressurized modules, the free volume not occupied by devices, so called habitable volume, will not be enough to support four astronauts permanently and therefore a second habitable module (marked as 6 in Fig.12 in Appendix B) is attached to one of the center docking port. This module will be inflatable and provide additional pressurized volume for living, storage, laboratory and other.

- The optimal DSG station - configuration 3

The optimal DSG station will have all of these previous mentioned modules and parts, and also a tank module (marked as 7 in Fig.13 in Appendix B) , with capability of 200 000 kg of cryogenic propellant. It will also be attached to one of the center docking ports. As seen in Fig.12 and Fig.13 in Appendix B the X-axis is the direction of flight and Z-axis is the direction towards the center of the Moon.

2.4 Major DSG systems

The DSG will have six major systems, embedded in these previous described modules, which more or less provide and control everything on-board the space station:

- ″Command and Data System″ where all other system are controlled by providing different interfaces for the system in question, briefly described in the subsection ″Inside layout″.
- ″Motion Control System″ includes orbital navigation and propulsion as well as attitude determination and control, described in section ″Choice of Orbit″.
- ″Communication System″ for all types of communication to and from the station, briefly described in the section ″Choice of Orbit″.
- ″Environmental Control System″ which also can be described as the LSS, which provides a habitable environment for the astronauts, describe in the section ″Life Support System″ as well as the subsection ″Inside layout″.
- ″Electrical Power System″ to supply all equipment with power, described in the section ″Energy Capture and Consumption″.
- ″Thermal Control System″ protects from both overheating and cooling to keep delicate parts working and astronauts alive, also described in the section ″Life Support System″.

  Most of what these systems include will be described in more detail in this report.

3 CHOICE OF ORBIT

While designing a space station in the vicinity of the moon, there are four orbits, that should be considered for its position. The Low Lunar Orbit, the Lagrange point Orbit, the Distant Retrograde Orbit and the Near Rectilinear Halo Orbit. When it comes to choosing the optimal orbit, there are three main criteria that are taken into account. The access of the orbit from earth, the state of the space station within the orbit and the accessibility of the lunar surface from the chosen orbit.

3.1 Selecting the NRHO

After comparing the properties of the various orbits the NRHO is chosen, because it offers the most advantageous set of properties. Within a NRHO the station is located in a thermal environment, which is comparable to a deep space station, which makes is easier to cool down, because there is no additional heat radiation from a nearby celestial body. The orbit itself is mostly stable [13] and there appear no occultations, which enables an uninterrupted communication with the mission control center on earth. The orbit also provides a good power solar power input due to its infrequent eclipses. Reaching the orbit from earth, as well missions to the lunar surface and back are possible and comparatively cheap. The primary purpose of the space station is a safe haven and supply dock for lunar exploration, but it should also be able to function as a starting and refueling point for future missions into the solar system. Because of this it is necessary for the station to operate in a position, which is energetically advantageous. This way ships can refuel on the DSG and venture out into space conserving fuel, which would otherwise be needed to escape the earths or the moons gravity.

3.2 Orbit stability and energy

Orbit Stability and Energy. Stability and Energy of the station are roughly estimated through the Cislunar Restricted 3 Body Problem, which describes the motion of a massless spacecraft, effected by the gravity of two celestial bodies in near circular orbits. For the CR3BP there exists an integral for the motion, called the Jacobi Integral.

$$J = 2U * v^2 \tag{1}$$

With v being the total velocity of the spacecraft and U representing the so called Pseudo Potential Function. The integral identifies a path of motion in the CR3BP and is a rough approximation of the Energy of the orbit. The smaller J, the higher the energy of the orbit. To enable the fuel efficient usage of the DSG as a fuel station for interplanetary travel, the Jacobi constant should be relatively high. For more exact calculations the ephemeris force model, which is a high fidelity, computer simulated force model, that takes up to 6 celestial bodies into account is applied. A good indicator for orbit stability and therefore the maintenance cost is the stability index v. The smaller the value of v the higher the stability of the orbit, with v=1 representing a marginally stable orbit. It is calculated with the eigenvalues of the Monodromy Matrix, which is the name of a State Transition Matrix after exactly one orbit Period. A STM describes the variation of the dynamic properties of a singular mechanical object after a given amount of time.

$$v = \frac{1}{2} * (\lambda_{max} + \frac{1}{\lambda_{max}}) \tag{2}$$

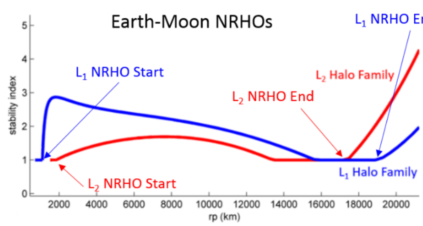

Fig. 1: Stability Index of L1, L2 NRHO over Perilune Radius

As can be seen in the graph there are two ranges for the perilune radius, in which the stability index approaches one. Either for the L2 family right at the beginning between 2000 and 4000 km or for both the L1 and L2 families at around 16000 km. But once these possibilities are plugged into the ephemeris model it becomes clear, that only the closer L2 family is a reasonable choice, because the apse angle has to be considered. The apse angle is the angle at which the line, that connects the closest (perilune) and the farthest point (apolune) of the elliptical orbit lies to the moon.

It can be seen, that the apse angle of the 15000km orbit is unstable, which results in higher station costs and a number of complications for the maneuverability of the space

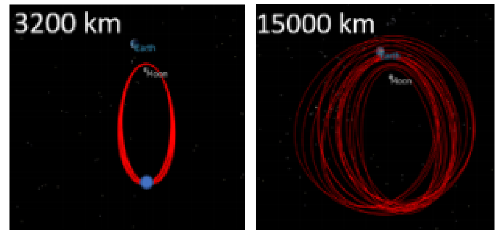

Fig. 2: L2 Southern NRHOs with rp: 3200km(left) and rp=15000km (right), simulated with the ephemeris force model for 50 revolutions

station. Thus the 2000 4000 km range of the L2 orbit family is chosen.

3.3 Eclipse environment

While orbiting the moon on a NRHO the DSG can experience solar as well as lunar eclipses. To maximize the Energy input of the sun it is crucial to minimize the amount and duration of all eclipses. The Eclipses caused by the shadow of the earth are significantly less frequent than those caused by the moon (about 1-2 times a year compared to 1-2 times a month), but their duration is distinctly longer. While lunar eclipses for NRHOs of about 4000km last between zero and 1.4 hours, earth eclipses can go on for up to 5 hours, which would cause serious problems for the power supply of the DSG. The first thing that can be done is choosing an orbit, that provides a synodic resonance like 9:2. This means, that the station will revolve around the moon nine times in the same amount of time as is needed for the moon to revolve twice around the sun. By doing so a continuously repeating geometry is achieved 3, which, if initiated at the correct timing enables the space station to evade all earth eclipses for a really long time (approx. 19 years) without executing a single maneuver. The second measure are evasion maneuvers, which further minimize the time, the DSG has to be operational without solar power. These maneuvers demand surprisingly little fuel and are for the most part easy to execute [13], which will enable the space station to dodge all eclipses of durations longer than 30 minutes. Because of this the **southern NRHO around**

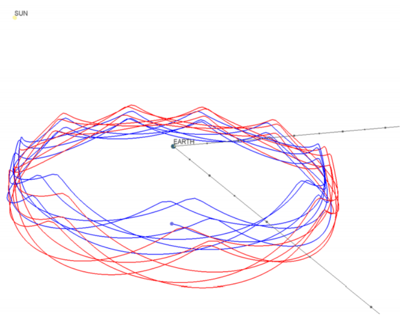

Fig. 3: 9:2 lunar synodic resonant NRHO in Earth-centered Sun-Earth rotating frame

the L2 Lagrange point with a 9:2 synodic resonance, a perilune radius of 3233km, resulting in a revolution duration of 6.68 days, stability index v=1.22, Jacobi constant J=3.04 is chosen for the DSG. This orbit also has one of the highest values for J, which suggests, that it is well suited to be a starting point for missions beyond the earth moon system.

3.4 Station-keeping and attitude control

Every satellite or space station requires station keeping to maintain its orbit for a number of reasons, such as for example the small instability of the orbit. When it comes to orbit maintenance, there are two big subgroups of space vehicles. Those that are manned and those that are remotely controlled. The latter being referred to as a quiet spacecraft design, while those, that house humans are called noisy. The difference in maintenance cost between the two is huge, because with astronauts there come life support systems. So as a conclusion it is important for the DSG-maintenance cost estimations to distinguish those two. Although for the most part of the lunar exploration mission the Deep Space Gateway will not be manned, the approximations for the station keeping are done with a noisy spacecraft assumption. This is done, because the estimations should include a scenario in which a crew has to stay and work on the DSG for a prolonged amount of time. This would be the case for repairs or certain research, that requires humans in a space environment. Of these errors 4 the Pressure Swing Adapter Puffs and the urine dumps are inherent for human spaceflight and do not appear in unmanned vehicles. PSA puffs, which are nothing but CO2 expulsion from the atmosphere inside the craft as well as urine dumps are executed with a pressure gradient, which leads to a force acting upon the craft. This, as well as the other errors have to be corrected via station keeping. Methods of station keeping/X-axis Crossing Control When applying X-axis crossing control the system applies a maneuver to target a user defined position in the future. For the following calculations a system was created, which targets the reference orbit about 6 revolutions down the line. The position and timing at which the orbit corrections are carried out have a big influence on the required delta v. Previous missions, that revolved around a NRHO (for example ARTEMIS) applied up to 5 maneuvers per revolution, but with new calculation methods one maneuver per revolution is sufficient. Because the spacecraft is most susceptible to disturbances at perilune, which would amplify navigation errors, maneuvers are to be applied at apolune. If the navigation fails to reach the target position 6 revolutions later the horizon is reduced, which means, that a closer target (for example 4 revolutions down the line) is chosen. Then the thrust level and duration is updated and a new maneuver is plied at the next apolune.

Noisy spacecraft errors. Fixed magnitude, random direction.		
Error Type	*magnitude (m/s)*	*frequency*
PSA Puffs	8.3480E-4	every 10 min
Attitude deadbands	2.0043E-5	every 70 min
Attitude slews	6.9751E-4	every 3.2 hours
Urine dumps	1.8840E-3	every 3.0 hours

Fig. 4: spacecraft errors, noisy configuration

3.5 Maintenance cost

When estimating maintenance costs, it is important to consider the fact, that the navigation system itself might also fail. The maneuver might be ill timed or the burn missed entirely. This is considered by the NF (Navigation Failure)-factor, which represents navigation errors. To calculate the required delta v the Monte Carlo analysis applies X-Axis crossing control over 50 revolutions, which amounts to a year. The Monte Carlo code is run 500 times to evaluate a mean value as well as a maximum and a minimum. The method does not always return the same value, because of the integrated sigma factor which creates navigation errors at random intervals. The exact way of the Monte Carlo/ X-Axis Control interaction can be read in Orbit Maintenance and Navigation of Human Spacecraft at Cislunar NRHO by Diane Davis. The results for the 3233km NRHO orbit are as follows: Added to this cost

Navigation Failure	mean annual delta v (m/s)
NF=1	1.26
NF=10	2.26
NF=100	20.27

TABLE 1: Navigation Failure

there are additional maneuvers that need to be considered, like the previously mentioned eclipse avoiding or meteorite evasion. A single eclipse avoidance maneuver for the NRHO at 3233km was carried out with the Monte Carlo Program resulting in a successful evasion and a 1.5-hour epoch shift. The cost for this maneuver was 2.67 m/s. And for further calculations it is assumed, that every avoidance maneuver will have a required delta v of the same magnitude. Attitude control and overall delta v Like on the ISS attitude control in the DSG will be achieved with 4 control moment gyroscopes. The ones in the DSG can be significantly lighter and smaller than the ones in the ISS, because the DSG will not experience the atmospheric drag and thereby induced torque the way the ISS does. For urgent cases, if rapid attitude adjustment is necessary, small, auxiliary thrusters can be activated. However, this will be a very rare exception and is therefore not included in the overall delta v estimation. To calculate the overall annual delta v, the mean delta v of the moderate failure assumption was chosen as a reference value. Then it was approximated, that each year there would be no more than an average of two evasion maneuvers, because only the longest moon eclipses are worth avoiding. This adds up to a total delta v of about 8 m/s. The necessary fuel is obtained with the Tsiolkovsky rocket equation:

$$\Delta v = v_e * \log(\frac{m_0}{m_f}) \tag{3}$$

ve=40 km/s representing the exhaust velocity of the NEXT xenon thrusters, mf the dry mass and m0 the total mass. This leads to a **fuel consumption of only 12kg a year.**

3.6 Communication

An other important aspect of DSG is communication, both internal and external. Since the DSG station will not primarily be permanently inhabited by the astronaut in this mission, a detailed concept for the communication system was not performed by the DSG design group. Instead Lunar Transportation group as well as the Overall Coordination group performed the analysis, hence the reader is referred for details to those reports. Briefly described, a radio communication system will be used for telemetry and scientific data links to and from mission control centers on Earth and DSG station. DSG will also communicate with a satellite in orbit around the Moon to provide a link to the Lunar base on Moon's surface to eliminate the communication downtime between the DSG and the lunar base. Furthermore, communication is established with any vehicle approaching the station and EVA suits.

Calculation of communication downtime between DSG and lunar base: Equation for the Energy constant J

$$J = 2\Psi - v^2 \tag{4}$$

*With Psi being the pseudo potential function, approximated with potential integral and J=3.04 for the selected NRHO.

$$\Psi \approx \int F ds = G*(\int(\frac{M_{earth}}{(R_{earth})^2})dr + \int \frac{M_{mond}}{(R_{perilune})^2}dr) \tag{5}$$

*With R-earth being distance to earth, R-perilune being the perilune radius, G = Gravitational constant.

The mass of the DSG can be neglected, because it does not have an influence on the velocity in orbit. For reasons of simplification the Orbit north of the moons equator is approximated to be a semi circle instead of an ellipse. This semicircular orbit corresponds closely to all the positions, in which the DSG and the lunar base are unable to communicate.

$$T_{down} = \frac{2\pi R}{2v * 3600} \tag{6}$$

This leads to a communication downtime of 1.2489 hours.

4 HUMAN PROTECTION

The astronauts visiting the DSG station have to be protected against several threats. In this chapter the reader will learn how they are being protected against the two most critical outer threats: radiation and meteoroids.

4.1 Radiation

Radiation in the space environment can be divided into three sources. Energetic particles trapped in a planets magnetic field. It is worth mentioning that the moons magnetic field is weak and the moon is too far away from earth to be significantly affected by trapped particles in earth's magnetic field, commonly known as the Van Allen radiation belt. It mainly consist of mid-energy electrons and protons. SPE mainly consists of protons(ionized hydrogen) and electrons. 5-10% α particles (ionized helium) and roughly 1% heavy ions. The particles can have a high thermal energy, enough to phase into plasma, the fourth state out of solid, liquid and gas. The sun regularly shoots bursts of these particles out in the solar system from the corona (upper part of the atmosphere). If you find yourself on an EVA in space, it can be quite handy to have reliable "weather forecasts" giving off warnings when a blast comes your way. Mid to high energy particles. Galactic Cosmic Radiation, consists of gamma rays and particles traveling near speed of light, 85% protons ,14% α particles, 2% electrons, 1% heavy ions. Even though heavy ions represents a small part of the radiation, their high energy weighting factor makes it have large effects on most living organisms. GCR originates from galaxies far away. Supernovas are thought to accelerate particles and create high energy photons, more commonly known as Gamma radiation.

Gamma radiation and the charged particles has enough energy to break bonds in the DNA, of which can cause harm to a person if exposed. High energy protons pose a threat such that the protons are absorbed by a atomic nuclei of which often creates a secondary reaction. Low-z, atomic number materials are good for minimizing secondary reactions. Alpha radiation can be stopped by a piece of paper. Beta radiation (electrons), can penetrate skin and clothes but can be stopped by materials such as wood, plastic and aluminum, low-z. Gamma radiation is hard to stop. It requires thick dense materials with a high-z, such as lead, to significantly reduce a gamma ray's energy. Gamma rays appears when a neutron collides with a nucleus of a atom. Secondary radiation of protons and neutrons are commonly shot out in these events. Neutrons can also penetrate most materials. Water have showed good performance in neutron protection. Out of this, a layer of low-z material, followed by a high-z material and a layer of water, would be good for a safe zone on the DSG. At the intersection of the modules of the DSG, a lot of material is protecting against radiation, also the Orion capsule is made to protect against radiation as seen in figure 14. This area of the station could provide good shelter for the crew in case of a radiation event. [16]

4.2 Meteoroids

A meteoroid is commonly a fragment of an asteroid consisting of rock and/or metal. The size of meteoroids varies from one meter wide objects to particles smaller then a grain of sand, so called micro meteoroids. Everyday Earth's atmosphere is struck by millions of micro meteoroids. Because of the intense heat generated by the friction when passing through the atmosphere they are vaporized and therefore never reach Earth's surface. The bodies accumulate speeds generally around 25 km/s, this would result in great hazard to objects in absence of an atmosphere. With multi-layered shielding and redundant bladders of woven kevlar-material covering the DSG will give the primary protection from micro meteorites. These protective strategies do little if the particle is larger then 10 cm. With a meteoroid detection device, the larger meteoroids will be detected and accordingly the route for the DSG can get adjusted to avoid a collision. [20]

The walls of the DSG station will be constructed differently depending on if the module is inflatable or not. The protection of the inflatable modules can be done in the same way as Bigelow is planning. Layers and layers of woven kevlar material which can expand in some directions, providing inflatable properties as well as keeping the same level of protection. A conceptual picture of DSG can be found in Appendix B, Fig.14. The reader can see how the tank module are being protected by a ”skirt”.

5 LIFE SUPPORT SYSTEM

To keep the astronauts alive while on the DSG, a life support system has to be implemented. Humans have evolved on Earth over thousands of years; not in the alien environment of space which includes both vacuum and weightlessness. To counter the effects of these two phenomena, the DSG must be made as comfortable as possible for the Astronauts, containing breathing oxygen, food, water and have a working waste (CO2 and human waste) removal system. A space station could therefore be viewed as an artificial Earth, with the LSS as the most important element.

5.1 Astronaut consumption

To calculate how much food, water and oxygen the crew of four on the DSG would consume, the data of consumption on the ISS was continually used. Using this information found on NASA.com and from a report written at Colorado University titled ”Mars or Bust” the total mass value of these life support elements can be calculated. According to the above sources, each day a single Astronaut would need 1.2kg of food, 1.3kg of drinking water, 0.5kg of water used for toilet flushing, 0.89kg of water to do dishes, and 0.08kg of water for EVA’s. Combining with this a value of 1.41kg of O2 creation, the total mass value per astronaut per day is 6.28kg. Extrapolating this for the entire crew, this would lead to a value of 25.12kg per day.

The Red Team’s Lunar Exploration group calculated that a value of 3.457kg of O2 could be recycled into H20. Further from this, it is estimated that using the Water Recovery System and a modest value of 65 percent recovery, 12.662kg of water could be recycled per day. This leads to a total value of 16.119kg of H20 that ca be recycled per day. Combining all of these values, it was calculated that on the first day of DSG operation (where no recycling occurred the day before) the mass value would be 45.12kg. After this, using the recycling mentioned above as well and extrapolating all values for the entire crew over six months, it is estimated that 1642.68kg would be required. Therefore the total mass amount for the crew’s life support elements would be 1687.8kg.

EVA suits will be used at DSG for various reasons. These are not being described in this report, but analyzed by the Lunar Base group. EVA suits also provide a LSS to keep the astronauts alive during spacewalks for example.

5.2 Thermal control system

In space temperatures can become much lower and much higher than on Earth. Lots of equipment has generally optimal performance within a certain temperature range, and in some case do not work outside this range. Therefore a thermal control system is essential to guarantee that components work. Thermals control can be either passive or active and both systems are used on the DSG. Passive cooling is implemented in form of multi-layering for insulation. The active thermal system consists two water coolant fluid loops collecting heat in the station, heat is then transfered from the water loops to a fluid ammonia coolant loop running into radiators located outside the station, radiating towards deep space. The amount of heat rejected from the radiators is a function of the radiator’s area, therefore they can be dimensioned according to the amount of heat needed to be rejected. A conceptual picture of DSG, its thermal system and marked pressurized modules can be found in Appendix B, Fig.15.

5.3 Atmosphere

As seen in Fig.15, Appendix B, five modules and components of the DSG station will be pressurized with 1 bar, having the same atmospheric composition as on Earth: 78 % nitrogen, 21 % oxygen and 1 % of other gases such as water vapor, argon and carbon dioxide. [12]

6 ENERGY CAPTURE AND CONSUMPTION

To power the DSG, it was decided that a solar panel system would be used. As the orbit selected was done so to try and maximize the amount of sunlight the DSG would receive (i.e. minimizing eclipse occurrences) and also the fact that the DSG will never travel anywhere too far from the Sun to make solar power ineffective, this makes sense as a suitable choice for energy capture. As mentioned previously in the Life Support System section, data from the ISS usage was used to compare and to use as a basis for the selection of size and power required.

6.1 Energy solution

According to NASA.gov, the ISS requires between 70-90kW to power the station, with a maximum value of 120kW available if necessary [21]. If 90kW is assumed, then the power required for the DSG (not including thrusters) can be scaled by the number of inhabitants. As there will be one third less crew on the DSG, the power required was calculated to be 60kW. Scaling the maximum value also, the DSG would therefore be able to achieve 70kW. However the DSG will also contain four NEXT Ion Thrusters, which will require 54.8kW combined. The thermal system on the DSG will also require about 0.5kW of power. This will total to a required power value of approximately 100 kW for the DSG. The graph below shows the power is being divided among the DSG sections. The LSS power was found by looking at the ISS ECLSS and will consume around 7 kW. [8] A remaining 35 kW will be available for science, data, communication and other various needs. If an efficiency of almost 30 % is assumed, the DSG's solar panel design can improve on the ISS's values as it would only require a solar panel area of three hundred square meters. This is a lot smaller than the current two thousand and five hundred square meters on the ISS. This also decreases the weight of the system from 4450kg to just 1000 kg. The solar intensity between the two stations is very similar, with the ISS having a value of 1366 watts per square meter, and the DSG having a value of 1368 watts per square meter. The watts per kilogram (specific power) of the solar panels on the DSG is increased dramatically from that of the ISS, with a value of 110W/kg compared with 29.96W/kg. The watts per square meter value will also increase dramatically, from 48 on the ISS to 350 on the DSG. These values listed above lead to a an efficiency on the DSG of 25.58 %, compared with the ISS value of 3.51 %. Advanced technologies such as photo-voltaic tiles (such as the Tesla Solar Roof) [18] and Solar Paint [19] were investigated, however due to the complex shape of the DSG, were found to be inefficient as only a percentage of the surface would be receiving direct sunlight at any given time. The solar paint was not used as it requires water vapor to be present in the air to complete the chemical reaction, which is not present in the space environment.

Required Power [kW]	100
Available Power [kW]	110
Specific Power [W/kg]	110
Solar Array Area [m2]	320
Solar array weight [kg]	1000
Efficiency	26 %

TABLE 2: DSG station energy data

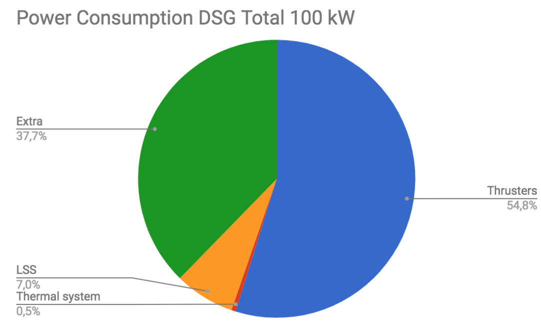

Fig. 5: Energy consumption in percentage

7 FINAL SOLUTION DSG STATION

With all previous chapters in mind, the DSG station design finalizes. In this chapter the final solution will be shown and explained in detail. The modules of DSG were decided to be of cylindrical shape, similar to modules on the ISS, because firstly, they have to be fitted into cylindrical launch vehicles and secondly, cylindrical structures are much stronger than rectangular, box shaped structures for any given weight.

7.1 Launch vehicle

All parts are designed with some respect to the biggest launcher available today, the newly demonstrated (6 Feb 2018) SpaceX Falcon Heavy. Falcon Heavy can put 26,700 kg in GEO and 16,800 kg on Mars, which could mean roughly 20,000 kg on the Moon. The fairing protecting the payload is 13.1 meters high and 5.2 meters in diameter, setting the dimensions for the maximum payload to roughly 12 meters long and 4.5 meters in diameter. SpaceX has a standard payment plan of 90 million US dollars for a launch with Falcon Heavy. [11]

7.2 Detailed modular overview

For configuration 1 the table below shows type of module, type of structure, dimension in diameter and length and mass.

	Propulsion Power Service	Habitation Laboratory	Airlock	Docking
Type	Fixed	Fixed	Inflatable	Fixed
Diameter, length [m]	4.5, 7	4.5, 10	4, 4	4.5, 10
Mass [kg]	11 000	10 000	2 100	10 000

Fig. 6: Modular overview configuration 1

As mentioned in the section Space Station Layout the crew can arrive and temporarily inhabit the DSG with configuration 1. Enough supplies for six months for the crew will be present at this stage, but the living volume for the astronauts is not optimal in size with this configuration. The spacecraft which the astronauts arrive with, the crew vehicle, is not included in the tables shown in this subsection. As it seems in the near future, there will be two crew vehicles available, Orion and Crew Dragon, if one would not construct a new. Both of these could for crew transport to and from DSG.

For configuration 2 and 3 the table below again shows type of module, type of structure, dimension in diameter and length and mass, as well as the increase of total mass and volume between the configurations.

	Configuration 1				Configuration 2	Configuration 3
	Propulsion Power Service	Habitation Laboratory	Airlock	Docking	Habitation Laboratory	Tank
Type	Fixed	Fixed	Inflatable	Fixed	Inflatable	Fixed
Diameter, length [m]	4.5, 7	4.5, 10	4, 4	4.5, 10	6, 10	4.5, 10
Mass [kg]	11 000	10 000	2 100	10 000	12 000	16 000
Total pressurized volume [m3]				280	480	480

Fig. 7: Modular overview configuration 1,2 and 3

A cost calculation will not be fully presented in this report, the reader is referred to the report of the Overall Coordination group. But worth mentioning in this report is the predicted development and production cost of 9.7 billion US dollars for the DSG station, which is a rather small contribution to the total overall cost for the DSG Lunar mission of 122 billion US dollar, including development, operations for 10 years, management and more.

DSG station comparison

A comparison of volume and mass was completed of the DSG station and other stations and space habitats. The comparison of volume focus on pressurized volume, habitable volume and volume per astronaut. Therefore the comparison could only be made with space station designed for a specific number of habitants i.e. Mir (3 habitants), the ISS (6) and B330 (6). The following graphs and table show the result. (Fig.8.)

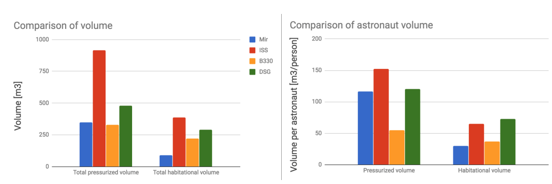

Fig. 8: Comparison of volume

Pressurized Volume [m3]	480
Habitable Volume [m3]	290
Pressurized Volume [m3/person]	120
Habitable Volume [m3/person]	72.5

TABLE 3: DSG station volume

The DSG has roughly half the total pressurized volume as ISS but roughly two-thirds the pressurized volume per astronaut, meaning that the DSG station is rather efficient in volume compared to the ISS. The optimal amount of volume for each astronaut is not yet known, one can only try to find reasonable value.
The comparison of mass focus on weight and density and is made between Mir, the module Destiny of ISS, the ISS, the inflatable module BEAM of ISS, B330, and the DSG station. The graphs and table below show the result. (Fig.9.)

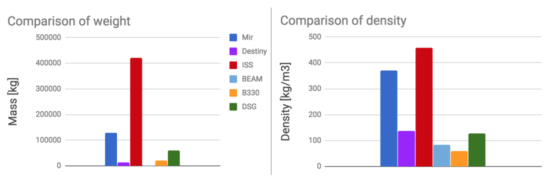

Fig. 9: Comparison of mass

Mass [kg]	62 100
Density [kg/m3]	127

TABLE 4: DSG station mass

As mentioned, the DSG station has roughly half the pressurized volume of ISS, but less than 20 % of the total weight. The density of the DSG station is almost the same as Destiny, which is a module and not an entire space station. Therefore one can also claim that the DSG station is rather efficient in mass too. [5] [6] [7] [9] [10]

7.3 Inside layout

As mentioned, five parts will be pressurized on the full version of DSG. Three of these will be more or less aimed for living space, the main habitable module, the inflatable module and the docking module. The airlock and the crew vehicle will not be primarily be used for living space. The main habitable module is the first living space to arrive at DSG. Both this module and the inflatable habitable module will include, in their pressurized volume, electronics for all kinds of systems on board such as the Command and Data the Environmental Control System. Also there will be a lot of storage, food preparation stations and space for having dinners. Four sleeping stations will be located in the main habitable modules, as well as two small stations for toilet and hygiene. Space will also be made for, among others, conducting science.

7.4 Human rating

To achieve human rating in systems on board, redundancy in subsystems is implemented throughout the station, accommodating human needs with sufficient certainty. Back-up systems are used to prevent total failure and in the most critical cases two-fault system are installed, providing the possibility of two separate system failures with a third separate system still working.

8 OFF-NOMINAL SCENARIO

Planning is vital for human spaceflight. This includes planning for all sorts of events, both expected and unexpected. Some unexpected, so called off-nominal. In this chapter one off-nominal scenario, a meteoroid impact, found in Appendix C, will be presented along with related checklists, found in Appendix D.

9 CONCLUSION

In conclusion, the Deep Space Gateway design was based around the requirements of the Lunar Exploration mission, and was designed to be as efficient, recyclable and as cost effective as possible. The station will consist of a modular design that will include fixed and inflatable modules, fuel tanks, docking stations, research laboratories and habitable modules. The DSG will be powered by a solar panel system, that will be much more efficient than the current ISS and thrusting is performed by ion-thrusters. A total of 62 tons will orbit the Moon in an NRHO. The crew of four will be able to live and enjoy the DSG for up to six months, without resupply. The design will not only fulfill the purpose of this mission but is highly adjustable for a variety of future missions.

References

[1] *Deep Space Gateway*. http://exploration.esa.int/moon/59374-overview/
[2] *Space Stations History*. http://edition.cnn.com/TECH/space/9811/23/station.history/
[3] *Tiangong-1*. https://www.space.com/27320-tiangong-1.html
[4] *ISS Components*. http://www.pbs.org/spacestation/station/components.htm
[5] *ISS Components*. http://bigelowaerospace.com/pages/beam/
[6] *ISS Components*. http://bigelowaerospace.com/pages/b330/
[7] *Bigelow Aerospace - Colonizing Space One Module At A Time Erik Seedhouse*.
[8] *LSS ISS Power*. https://www.colorado.edu/ASEN/project/mob/MOBFinalReport.5.pdf
[9] *ISS Data*. https://www.nasa.gov/feature/facts-and-figures
[10] *Mir Data*. http://www.braeunig.us/space/specs/mir.htm
[11] *Falcon Heavy*. SpaceX http://www.spacex.com/falcon-heavy
[12] *Earth Atmosphere Data*. https://www.space.com/17683-earth-atmosphere.html
[13] *Orbit Maintenance*. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001347.pdf
[14] *Eclipses in NRHO*. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001352.pdf
[15] *NRHO stability*. https://engineering.purdue.edu/people/kathleen
[16] *Gamma Rays*. http://www.messenger-education.org/instruments/grns.php
[17] *Food Intake*. https://www.nasa.gov/vision/earth/everydaylife/jamestown-needs-fs.html
[18] *Tesla Solar Roof*. https://www.greentechmedia.com/articles/read/the-economics-of-teslas-solar-roof#gs.znk8xrA
[19] *Solar Paint*. https://www.rmit.edu.au/news/all-news/2017/jun/solar-paint-offers-endless-energy-from-water-vapour
[20] *Meteroids*. https://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Micrometeoroids_Space_Debris.html
[21] *Power Consumption*. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050175881.pdf

Appendix A
Abbreviations and Definitions

CR3BP - Cislunar Restricted 3 Body Problem
CSA - Canadian Space Agency
DSG - Deep Space Gateway
ECLSS - Environmental Control and Life Support System
EVA - Extra Vehicular Activity
ESA - European Space Agency
GEO - Geostationary Earth Orbit
IDSS - International Docking System Standard
ISS - International Space Station
JAXA - Japan Aerospace Exploration Agency
LSS - Life Support System
NASA - National Aeronautics and Space Administration
NF - Navigation Faliure
NRHO - Near Rectilinear Halo Orbit
PPS - Propulsion/power/service module
SPE - Solar Particle Event
GCE - Galactic Cosmic Radiation
Roscosmos - Roscosmos State Corporation for Space Activities

Appendix B
DSG Pictures

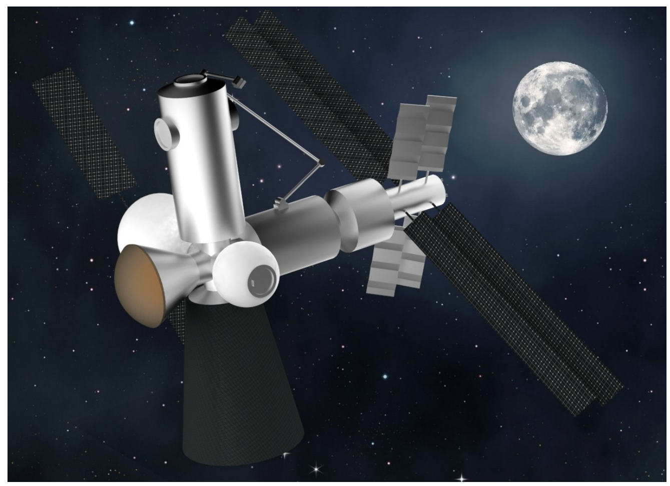

Fig. 10: DSG

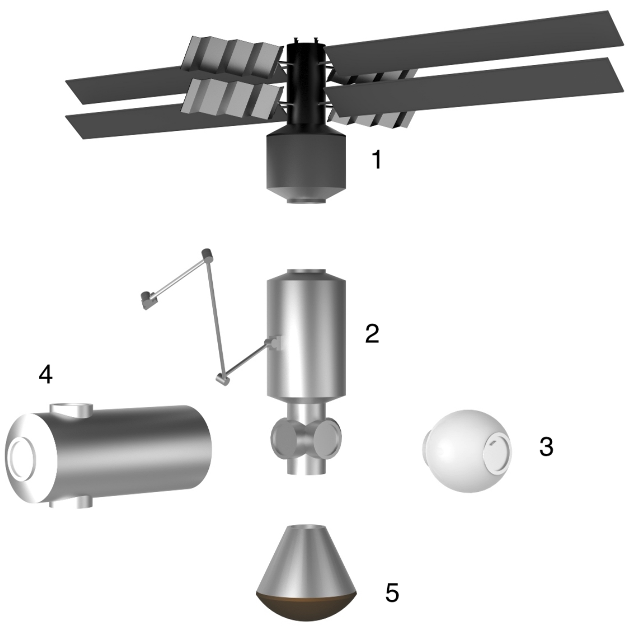

Fig. 11: Configuration 1

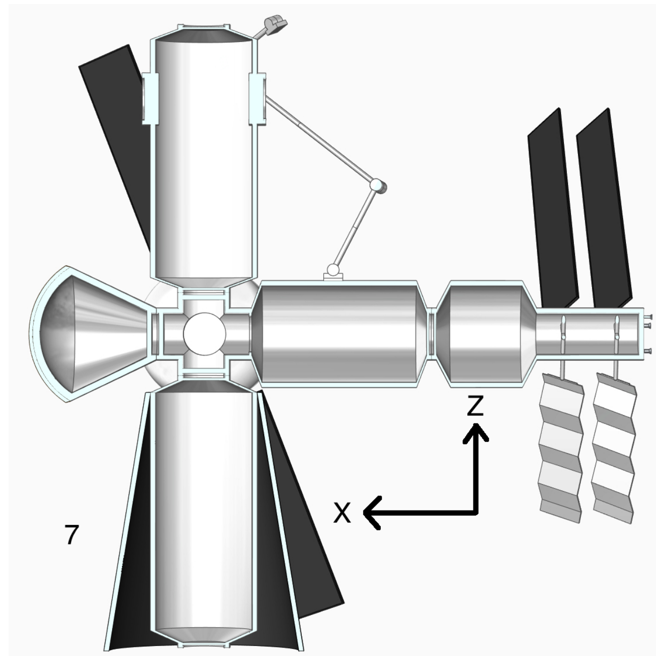

Fig. 13: Configuration 3, X-Y plane

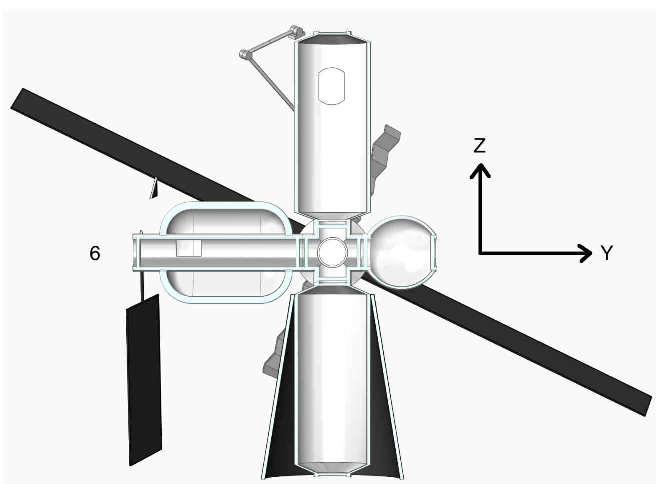

Fig. 12: Configuration 3, X-Y plane

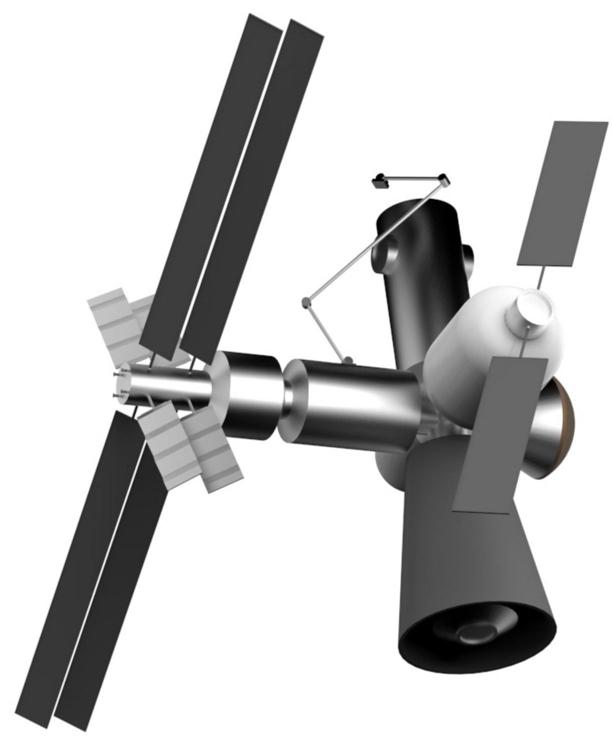

Fig. 14: DSG

Appendix C
Off-nominal Scenario

A micro meteoroid impact occurs and damage the PPS module on the DSG while the entire crew of 4 is on board the space station.
Following the impacts the Command and Data System displays warnings of a rapid pressure drop in the xenon fuel tank used for station-keeping located in the PPS module and the fuel is leaking into space.
The Command and Data System also shows warnings of that a liquid coolant loop is damaged as well as the power processing unit, both also located in the PPS module. Spare parts are needed to keep the DSG functional.

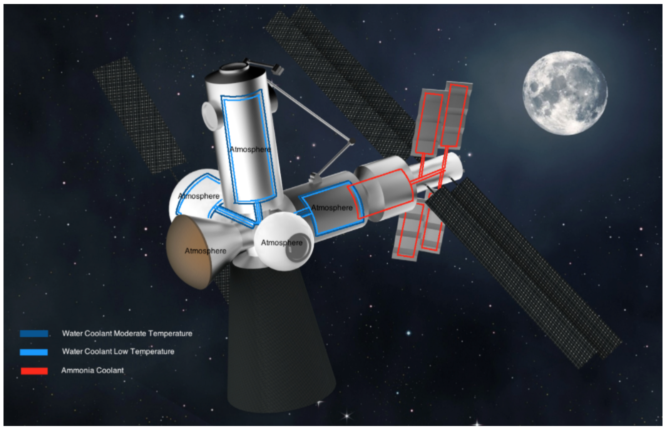

Fig. 15: Thermal Control System and Pressurized Modules of DSG

APPENDIX D
CHECKLISTS

Four main checklist are used for the scenario. Other checklist for certain simpler tasks exist but are not included in this special case.

- PRESSURE DROP XENON FUEL TANK (40 min)
  All crew members abort tasks and enter main habitable module.
  Close all docking ports hatches to main habitable module except to escape vehicle.
  All crew put on space suits and enter escape vehicle.
  Contact Control Center and perform damage report.
- RETAIN ORBITAL CONTROL (60 min)
  Turn off non-vital energy consuming devices.
  Calculate new reference orbit.
  Use Lunar Landers as thrusters.
- PHYSICAL DAMAGE INSPECTION (70 min)
  Two astronauts perform EVA and inspect station.
  Find damage and compare with damage report.
  Inspect propulsion system, power system and thermal system.
  Evaluate mission situation.
- ABANDONING STATION IN CONSERVATION MODE FOR REPAIR (60 min)
  Put DSG station into extreme energy conservation mode, only consuming energy at apolune for orbital maintenance.
  Crew members evacuate the station in the escape vehicle.
- ARRIVAL OF NEW CREW TO REPAIR THE DSG (- min)
  Detailed planning of repair mission.
  New crew arrives with spare parts to repair the DSG station.