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Orbital Propellant Depot: A Game-Changer for the Future of Space Exploration

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Abstract— ***The space industry has become more prominent than in earlier times and far more advanced. Currently, two-thirds of the weight of rockets is taken up by propellants. Storing such quantities of propellant in the rocket can ultimately lead to fire hazards, destruction of the rocket, and henceforth the loss of life, capital, and effort. After a certain point in the mission, different stages of the rocket would be rendered useless. This is where Orbital Propellant Depots come into the picture. An Orbital Propellant Depot is a supply of propellant that is placed in orbit around the Earth. In simple words, it will ensure that spacecraft travel into space with less weight, make rockets reusable, enable easy refueling, and perform maintenance on the rocket if required. Propellant Depots can be used as Multi Utility Devices. If the stages of a rocket can be refueled in space, it would be possible to reuse these parts instead of generating more space junk. The design of the depot would be in such a way that it is capable of withstanding extreme temperatures. Adequate insulation should be provided to prevent the melting and loss of propellant. When choosing a location for the depot, it is important to consider its accessibility to rockets, as well as the maintenance and monitoring requirements. The successful application of Propellant Depots will aid in the advancement of space exploration.***

Index Terms— ***Maintenance, Orbital Propellant Depot, Refueling, Reusable.***

I. INTRODUCTION

An Orbital Propellant Depot is a propellant supply placed in orbit around the Earth. They allow the refueling of spacecraft while in space. An Orbital Propellant Depot is an infrastructure that enables spacecraft to be locally refueled and maintained while in Lower Earth Orbit (LEO). This capability is not currently possible, but with the establishment of propellant depots, it would become a reality. Currently, two-thirds of the weight of a spacecraft comprises propellant. A propellant is a mass that is burnt to propel a vehicle forward by producing thrust. Regardless of the type of propellant being used in a rocket or spacecraft, they all have one thing in common: they carry a significant risk factor due to their highly explosive nature. A rocket mission can have one of two possible outcomes, it's either successful and performs its required task or it fails and consequently leads to loss of life and capital.

The main objectives of an Orbital Propellant Depot would be to minimize the possibilities of propellant-related accidents, reduce the overall weight of spacecraft, and enable maintenance work on spacecraft in space. Storing propellant in a rocket is dangerous for multiple different reasons, some of which are: they are highly explosive and lead to fire hazards, they must be stored under very specific conditions depending on the type of propellant the rocket requires, fuels can be very unstable, most propellants are highly toxic and corrosive. Most propellants burn spontaneously once in contact with air, so in the event of rocket failure, the propellant stored in the rocket can lead to an explosion. All these above-mentioned points come to say that transporting the propellant as a whole is very difficult due to its many disadvantages. The Falcon 9 rocket from Space X uses around 902,793 lbs of fuel. The Atlas D rocket, which launched the Mercury mission in the 1960s, used 244,056 lbs of fuel, and the Saturn V rocket, which took the first humans to the moon, required 4,578,000 lbs of fuel. According to ex-NASA administrator Mike Griffin at the 52nd AAS Annual Meeting in Houston in November 2005, \$10,000/kg in LEO, two missions per year needs 250 MT of fuel and will be worth around \$2.5B at government costs. Typically, one Kilogram of gas for space is \$1 million [1]. Recently, India successfully launched Chandrayan-3 which cost ISRO 600 crore rupees. If an Orbital Propellant Depot were to come into the picture, not only the overall cost of this mission would have been reduced but also the weight of the vehicle as well.

The failure of spacecraft in the past can be understood and utilized to ensure the same mistakes are not repeated in future space missions. One of the worst accidents in space history was the failure of the space shuttle Challenger. A little over a minute after launch, the O-rings of the spacecraft began the malfunction. O-rings were used to separate the boosters of the rocket [2]. Another traumatic incident in the space industry was the disintegration of the space shuttle Columbia on February 1st, 2003. The fatal incident was caused by the breaking off of a piece of foam that was intended to absorb and insulate the fuel tank of the shuttle from heat and to stop ice from forming during liftoff. On the shuttle's left wing, a large piece of foam fell and created a hole. On reentry into the Earth's atmosphere after the completion of its mission, gases, and smoke entered the left wing through the hole and caused the wing to break off, causing the disintegration of the rest of the shuttle just seven minutes from landing. The crew of seven died in the accident. NASA's space shuttle program was once again suspended after this disaster [3]. The motivation behind this paper is based on the fact that the

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possibility of propellant-based accidents can be minimized and the lives of innocent people. No closed-form solution is universally accepted for an Orbital Propellant Depot. Creating a depot in space would change the entire way we look at space travel.

II. CONCEPTUAL DESIGN

The Orbital Propellant Depot would need to successfully refuel the rocket and perform maintenance work on it if required. Depending on the type of propellant that the rocket functions off of, the fuel will be transported from the storage tanks to the rocket, i.e., a part of the depot will be designated for liquid, solid, hybrid propellants, and so on. The rocket would be propelling at full thrust and would need to be brought to rest on the propellant depot and this will be ensured by the various commands the rocket is set to by default and the ones that are continuously sent to it. The depot must ensure transferability of mass in zero gravity, zero boil-off, and zero vent fill. Mass transfer is the movement of mass from one place to another. One of the most efficient ways to do this in a propellant depot is by non-contact heat transfer. This method does not require any moving parts which will make mass transfer in the propellant depot much less complicated. This method uses a combination of electromagnetic fields and thermocapillary forces to transport heat.[4] Boil-off in a propellant is the vaporization of the propellant because of the heat transfer from the surrounding environment. Boil-off is an unavoidable situation and due to this, the gases produced during this situation must be removed to maintain the pressure inside the storage tank in a process known as venting. Boil-off is predominant in cryogenic propellants and is not significant in non-cryogenic propellants. Minimization of boil-off is possible by providing a thermally insulated environment. In 1998, NASA concluded that a hybrid thermal control system could eliminate the boil-off of cryogenic propellants. The hardware consisted of a pressurized 50 cu ft (1,400 liters) tank insulated with 34 layers of insulation, a condenser, and a Gifford-McMahon (GM) cryocooler that has a cooling capacity of 15 to 17.5 watt (W). [5] The depot would be placed in LEO but no less than 1000 km above sea level and the reasons for this are low latency rates, increased bandwidth, greater survivability, and lower costs.

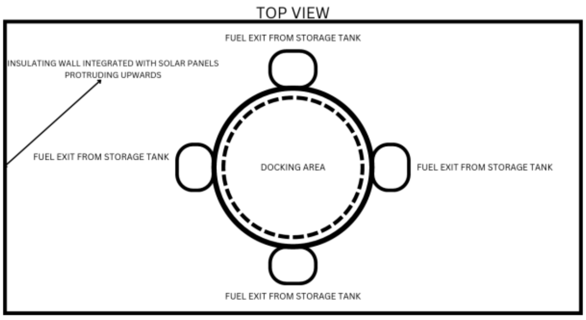

Fig 1. Top View of Depot

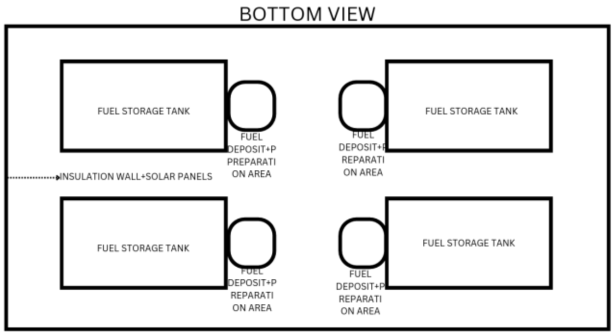

Fig 2. Bottom View of Depot

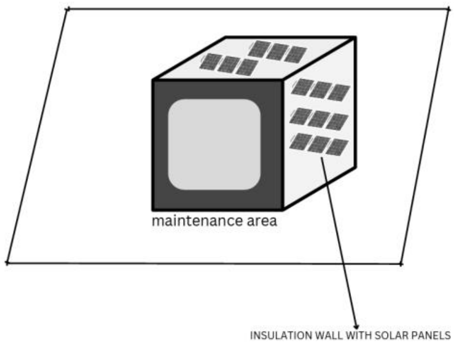

Fig 3. Maintenance Area

A. Materials Used

Due to their many advantages, one of the main materials to be used in this depot will be carbon composites. Carbon composites are an excellent choice for the OPD (Orbital Propellant Depot) as they have high temperature resistance, thermal shock resistance, low thermal expansion coefficient, small heat capacity, and low density. These properties make them ideal for use in the harsh environments of outer space. Carbon composites are naturally resistant to oxidization, making them very well-suited for the environments of space where they can be exposed to salt water or corrosive chemical agents. Furthermore, they have high strength and are lightweight, which are important qualities for space applications since the weight of materials is a critical factor. The materials used to construct the Orbital Propellant Depot will be similar to those used to construct the International Space Station. Some of these materials used are titanium, Kevlar, and high-grade steel. These materials can withstand the high temperature and environment the OPD will be subjected to.

B. Storage Tank

The main requirement of the storage tank is that it should be able to store the propellant at the required pressure. For safety purposes, all parts of the tank should be made of metal. The specifications of the storage tank will vary depending on the type of propellant it is meant to store. The storage system will be equipped with Thermal Control System (TCS). It must be able to cope with the external environment, which can vary in a wide range as the depot will be exposed to the extreme coldness or the intense sunlight of outer space. A TCS can eject heat passively through the method of natural infrared radiation of the spacecraft itself, or actively through an externally mounted infrared radiation coil. The depot would need to house a few storage tanks, each of which holds a different kind of propellant. One of the biggest advantages of the depot would be the fact that the propellants would not need to be continuously transported to the depot. After the development of the depot, the necessary propellant would be transported to space and stored in the depot and would be prepared within it. A section of the depot can be dedicated to the preparation and supply of biofuels. Biofuels would ensure the usage of "green fuels" and replenishment of the fuel with the help of microorganisms when stored in the right environment with favorable conditions. From the storage tanks, valves, and piping can be put to use. The pipes would need to be constructed in such a way that completely prevents backflow. Common backflow preventers that can be utilized are Double Check Valve Assembly, Reduced Pressure Zone Assembly, Air Gap, and Barometric Loop. Heat sinks would be integrated into the backflow assembly as well. Delivery of a fueled propellant transfer vehicle to the proximity of the depot can make the process of refueling the depot easier. The vehicles can support delivery to the orbit of fueled transfer vehicles. Once on-orbit, these transfer vehicles would separate from the launch vehicles, autonomously rendezvous with the depot (similar to Progress or ATV), transfer propellants to the depot, and then safely deorbit.[6] Tugs can also be considered to be used during the time of refueling. Tugs can transport the transfer vehicle to and from the depot and make operations much easier.

C. Docking

Docking is the process of joining two space vehicles together. In this case, the two space vehicles would be the propellant depot and the rocket that is to be docked to it. The docking system should be capable of capturing the rocket (both soft and hard capture) and also providing it the means to push off. For the rocket to gain momentum to regain flight, the docking system would also need to function as a launch pad. Like all other launch pads, the OPD's launch pad would need to perform the basic functions of fixed service structures to provide one or more access platforms to assemble, inspect, and maintain the vehicle and to allow access to the spacecraft, including the loading of the crew. The pad will need to contain a flame deflection structure to prevent the intense heat of the rocket exhaust from damaging the vehicle or pad structures. Another method of lift-off from the Depot would be by soft undocking of the rocket or spacecraft as performed by Soyuz. In this method, the vehicle would be undocked from the docking system and would begin to float away from the Orbital Propellant Depot. Once it reaches a safe distance, the rocket can start burning propellant, regaining momentum, and continuing its mission. This would prevent any sort of damage that the Depot would endure in the case of lift-off from the Depot. The docking system would be required to rotate at a very low speed for the fuel inlet port to be aligned with the nozzle. Tugs can be utilized here as well. The tug can move the rocket to a safe distance for it to restart its mission without causing damage to the depot structure.

D. Power Generation

The power required for the entire Depot can be provided by utilizing solar energy and incorporating solar panels into the design. To prevent high amounts of heat and radiation from reaching the depot, shields will be necessary. The solar panels required can be built into these shields and should be set up at the position in which the most radiation and heat will be suffered by the depot. The energy that is absorbed by the panels can then be diverted to the components that require energy to function and excess energy can be stored and optimized when any components require it.

E. Maintenance Work Performed by the Depot

The depot would also be capable of performing basic maintenance works on the rocket/spacecraft. There would be a shed-like structure on the depot into which the rocket can enter. Upon entering the structure, the rocket would undergo a full body scan and data would be collected, a report created and sent back to Earth. The scan will also check the remaining capacity of components and inspect whether replacement of components is required. If so, with the help of robotic arms, the necessary components would be retrieved from inside the shed and replace the worn-out components. The outer walls of this structure would need to withstand the extreme heat and radiation, so this structure would also need shields and solar panels can be incorporated into them as well to provide power for the various operations to be conducted within the structure.

F. Preparation of Solid Propellant

One of the main benefits of solid propellants is the fact that they can remain in storage for a long period and still maintain the capability of burning and avoiding propellant degradation. In present times, there are two different types of solid propellants that are utilized. They are double base propellants and composite solid propellants. Double-base propellants consist of nitrocellulose, nitroglycerine, and additives. These propellants can be prepared by using extrusion or casting techniques. Cast double-base propellant compositions are usually prepared by curing a mixture of nitrocellulose-nitroglycerine containing casting powder and nitroglycerine containing casting liquid. For composite propellants, separate fuel and oxidizer components are used. The oxidizers which are normally used are ammonium nitrate, potassium chlorate, or ammonium chlorate, and often comprises as much as four-fifths or more of the whole propellant mix. The fuels used for solid propellants are hydrocarbons, such as asphaltic-type compounds. Typically, the preparation of solid propellant involves preparing the fuel and oxidizer components separately for mixing. In this, the oxidizer is a powder and the fuel is a liquid. Under controlled conditions, these components are blended and poured into the prepared rocket case as a semisolid. Under controlled temperature and pressure, they are made to set in the curing chambers. The quality of the prepared propellant can be ensured by using the same techniques conducted on Earth. Methods utilized on Earth for the prevention of degradation of propellants will also be performed by the OPD.

G. Preparation of Liquid Propellant

Liquid Propellant is widely preferred in the space industry due to its high specific impulse, stability, and ease of transportation when compared to solid propellants. However, the preparation of liquid propellants is far more complicated than solid propellants. Some of the various methods through which the synthesis of liquid propellants can be achieved are:

- Direct hydrogenation of CO_2: In this method of liquid propellant preparation, CO_2 is hydrogenated to liquid hydrocarbons through tandem catalysis of reverse water as explained in the research article Synthesis of liquid fuel via direct hydrogenation of CO_2 written by Zhenhong He Meng Cui et al.[7]. The main research conducted in this paper is the utilization of Carbon Dioxide and Hydrogen to synthesize liquid propellant. This paper signifies how using carbon dioxide can benefit humanity by leaning towards sustainable development in future space missions. The main results of the work concluded that Co_6/MnO_x nano-catalyst could catalyze CO_2 hydrogenation to normal C5+ hydrocarbons at lower temperatures.
- Fisher Tropsch Method: This method involves the conversion of syngas (CO/H_2) into different types of liquid fuels without subsequent hydro refining post-treatments of Fischer-Tropsch waxes as proven in Integrated tunable synthesis of liquid fuels via Fischer Tropsch technology [8]. This theory provides us with a method that is simple and effective for the direct preparation of liquid preparation which will ultimately benefit the preparation of fuel in the OPD itself.
- CO_2 hydrogenation: This is the method of coupling homogeneous and heterogeneous catalysis. Typically for this method, hydrocarbons that contain more than five carbons are used. Hydrogenation of CO_2 occurs through heterogeneously catalyzed reverse water gas shift reaction to create CO and subsequently cause CO hydrogenation to hydrocarbons via the above-mentioned Fisher Tropsch Method.[9]

H. Refueling of the Depot

For the first design of the OPD, initially prepared propellant would need to be transported to the depot which can directly be utilized by the rocket or spacecraft. The prepared propellant would be transferred to the various storage tanks and then deposited into the rockets. After the success of the basic operations of the OPD more advanced techniques can be adopted for the preparation of propellant in space itself. This would make the process of transporting much easier and convenient for the operation of the depot. Some of the methods that can be applied for the future developments of the depot can be:

- The usage of biofuels to create "green" fuel. If proper conditions are provided for our source of biofuels, the preparation of biofuels in space could soon become a possibility.
- Plastic is one of the biggest pollutants on the Earth's surface and its water bodies. Animals and humans alike are being affected by the rising threat of plastic that is not being disposed of properly. Plastic can be converted to kerosene and utilized for the preparation of propellants.
- Due to a wide range of reasons such as accidents and the end of life of space devices, the amount of space junk orbiting the Earth has increased tremendously. If a proper disposal method for these materials can be created, then the need for transporting raw materials from Earth to space for the preparation of fuel in space.
- During space missions, some propellant goes unburnt and will be present in space. If the presence of this propellant can be detected and properly collected, it can be stored in the depot and supplied. The quality of this propellant would need to be inspected before being utilized for refueling.
- According to recent research, asteroids have proven to be sources of various resources. Mining asteroids could provide an ultimate solution to propulsion problems by providing fuel for rockets. C-type asteroids are known to be abundant in water. The constituents of water i.e. hydrogen and oxygen are two main components in rocket propellants. Mining these asteroids would ensure a continuous supply of the materials required to produce propellant in space without the need to transport these materials from Earth to the depot for the depot's continued use. If the mining of asteroids is successful, there will be a tremendous reduction in the amount of pollution that the Earth is forced to suffer, and henceforth the production of harmful gases and the depletion of the Ozone Layer could be reduced by a large extent
- The production of propellant on Earth doesn't necessarily need to be transported to space via the use of rockets. The company SpinLaunch created the world's first kinetic space launch system. The development of such technology has successfully reduced the fuel required to reach space by four times and reduced the cost of a space launch by almost 10 times. The SpinLaunch technology ensures that a greater amount of payload can be launched into space at a single moment and it also ensures that multiple launches are possible in a day. This would ensure that a greater quantity of prepared propellant can be transported to space in a time of need.

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III. INTERNATIONAL SPACE STATION AND ITS SIMILARITIES

Similar to the way the International Space Station (ISS) was set up, the Orbital Propellant Depot would need to be set up as well. As it is not possible to send the entire depot into space all at once, it would need to be sent as parts that would be put together by astronauts and cosmonauts. Due to atmospheric friction, ISS continually falls towards the Earth and hence needs periodic rocket firings to keep it in its Orbit. Similar techniques will be needed to ensure the proper working of the OPD.

IV. CONCLUSION

- With the advancement of technology on almost a daily basis, the construction of an orbital propellant depot comes closer to becoming a reality.
- The chances of failure of a rocket would be minimal, and the loss of human life and capital would become almost negligible along with it.
- This paper discusses the construction, maintenance, and working of an Orbital Propellant Depot.
- A functioning Orbital Propellant Depot would potentially allow more space missions and deeper exploration of space.
- The money and time that would be spent on space missions could instead be utilized for the other priorities of space agencies.
- A fully operational OPD would benefit the whole world. It will motivate other countries and space agencies to widen their horizons and explore parts of space they never before thought possible.
- Once basic operations are successfully performed by the Orbital Propellant Depot, in the forthcoming years it will be possible for the functioning of the depot to become more advanced.

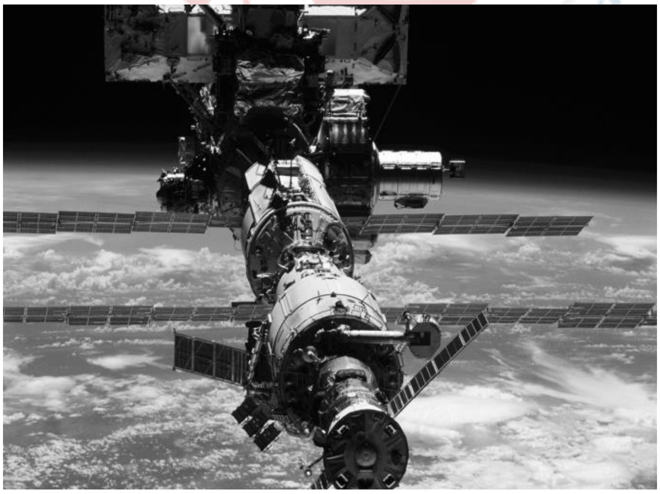

Fig 4. International Space Station
(Source: https://pixabay.com/photos/eat-space-station-11114/)

REFERENCES

[1]. Welcome to How Things Fly. (n.d.). https://howthingsfly.si.edu/ask-an-explainer/how-much-fuel-would-it-take-shoot-rocket-out-atmosphere

[2] Hogeback, J. (n.d.). 7 Accidents and disasters in spaceflight history. Encyclopedia Britannica. https://www.britannica.com/story/7

[3]. Efficient Microgravity Heat and Mass Transfer with no Moving Parts - NM NASA EPSCoR. (n.d.). NM NASA EPSCoR. https://nmnasaepscor.com/efficient-microgravity-heat-and-mass-transfer-with-no-moving-parts/

[4]. Zero boiloff storage of cryogenic propellants at SMIRF. (n.d.). https://web.archive.org/web/20080922224443/http://www.grc.nasa.gov/WWW/RT/RT1998/5000/5870plachta.html

[5]. Kutter, B., Zegler, F., Pitchford, B., & Alliance, U. L. (2008). A Practical, Affordable Cryogenic Propellant Depot Based on ULA's Flight Experience. https://doi.org/10.2514/6.2008-7644

[6]. He, Z., Cui, M., Qian, Q., Zhang, J., Liu, H., & Han, B. (2019). Synthesis of liquid fuel via direct hydrogenation of CO2. Proceedings of the National Academy of Sciences, 116(26), 12654-12659. https://doi.org/10.1073/pnas.1821231116

[7]. Li, J., He, Y., Tan, L., Zhang, P., Peng, X., Oruganti, A., Yang, G., Abe, H., Wang, Y., & Tsubaki, N. (2018). Integrated tuneable synthesis of liquid fuels via Fischer–Tropsch technology. Nature Catalysis, 1(10), 787-793. https://doi.org/10.1038/s41929-018-0144-z

[8]. Cui, M., Qian, Q., Zhang, J., Wang, Y., Asare Bediako, B. B., Liu, H., & Han, B. (2021). Liquid fuel synthesis via CO2 hydrogenation by coupling homogeneous and heterogeneous catalysis. Chem, 7(3), 726-737. https://doi.org/10.1016/j.chempr.2020.12.005