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Development of Conceptual Design of Commercial Cis-Lunar Space Station

A Thesis

Presented to

the Faculty of the Department of Mechanical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Space Architecture

by

Shunsuke Miyazaki

May 2018

Development of Commercial Cis-Lunar Space Station

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ABSTRACT

The current space program enables at most six astronauts to live and work on the International Space Station (ISS) at Low Earth Orbit (LEO). The growth of private space sector, however, becomes more and more realistic and affordable to access to LEO and cis-lunar space. Cis-lunar 1000 concept proposed by United Launch Alliance (ULA) aims to establish self-sustaining economy, which enables 1000 people to live and work in space between the Earth and the Moon within 30 years (2046). This project objective is to design commercial Cis-Lunar space station, named AXIS Space Station, to support space exploration beyond 2040, where is expected the growing period of economy in Cis-Lunar space.

The Design process approached same manner as system engineering. The concept design of AXIS space station was developed considering based on the system requirements, technical/ environmental constraints, and safety criteria. The conceptual design finalized through evaluation process, and trade study for its safety provision, emergency response strategies, and future growth potentials.

May 2018

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List of Abbreviations

ACES	= Advanced Cryogenic Evolved Stage
DSG	= Deep Space Gateway
ESA	= European Space Agency
IDSS	= International Docking System Standard
ISRU	= In-Suit Resource Utilization
LEO	= Low Earth Orbit
NASA	= National Aeronautics and Space Administration
NEA	= Near Earth Asteroid
SLS	= Space Launch System
TCS	= Thermal Control System
ULA	= United Launch Alliance

Introduction

1.1 Motivation

The space exploration landscape is changing rapidly as new players emerge and roles as well as responsibilities shift. Since the beginning of the construction of the ISS in the year 1997, privatization of several aspects of space and the growing circle of space fairing nations open up new possibilities.

Private companies are able to offer reliable low cost access to LEO and access to cis-lunar space projected for the near future. The changing landscape gives space agencies the possibility to focus on deep space exploration and to support the development of heavy lift launch systems.

NASA is leading the next steps of human exploration into deep space where astronauts will build and begin testing the systems near the Moon needed for lunar surface missions and exploration to other destinations, including Mars [1].

EAS has original idea to build permanent lunar outpost, called a moon village to enable people to stay and work as a platform for lunar resource utilization and deep space exploration [2].

However, creating self-sustaining economy between Earth and the Moon's surface has problems of cost of launching, building, and operating orbiting facilities. United Launch Alliance (ULA) is addressing these problems through its Cislunar-1000 imitative. Cislunar-1000 that envisions 1,000 men and women working and living in space in just 30years, part of a self-sustaining space economy benefitting those on Earth.

in-space economy that would tap into the vast amount of resources that could be harnessed from objects such as Near Earth Asteroids (NEA) and on the surface of the Moon. Eventually, the community would become self-sufficient via in situ resource utilization (ISRU), while becoming economically viable via the prospecting of precious materials that are rare on Earth but abundant in space [3]. While various proposals have been promoted over recent years, the financial viability of creating such an industry is often out of the reach of the numerous companies that have shown in interest in space prospecting. Realizing these ambitious business needs substantial infrastructure to enable to support each mission. One such infrastructure is the cis-lunar space station. A cis-lunar space station operates as a way station to support reusable transfer vehicles to send to desired place, and provide maintenance work and on-orbit assembly for reusable transfer vehicles. Also, cis-lunar space station provide a large experiment facility, industrial factory to manufacture spare parts and small satellite by using space material. However, one of the major limitations to build a cislunar space station is the launch cost to transfer modular infrastructure into desired orbit from the Earth. This limitation is result of technological limitation of launch rocket systems.

Also, cis-lunar space station around lunar orbit faces several problems including harsh radiation environment without Earth's protective magnetic field, communication resonance, and thermal protection from significant thermal difference. These environment increase the probability of cancer and loss of life, and the complexity of design of a space station. It needs to consider the required specification and the appropriate location of cis-lunar space station in design process. It is important to understand a cislunar space station induced limitations in order to balance tradeoffs in the design of better space station, and too comprehend the impact of these limitations during exploration missions.

NASA is leading the next steps into deep space near the moon, where astronauts will build and begin testing the systems for challenging missions to deep space destinations including Mars. The Deep Space Gateway (DSG) will be used to achieve lunar science objectives while simultaneously laying the groundwork for future deep space mission. Astronauts will be on-board the DSG for up to 60 days initially each year. Mission duration will increase with each mission up to 180 days with increased cargo capacity and increased water recycling in the life support system. The crew will be able to perform scientific experiments in the DSG and also support other lunar science from cis-lunar space involving surface telerobotics. The transport would take full advantage of the large volumes and mass that can be launched by the Space Launch System (SLS) rocket, which has capability to deliver 10 metric ton elements to ci-lunar space in a single launch co-manifested with Orion, crew transfer vehicle. The disadvantage of SLS are high ongoing maintenance cost, high cost per launch, low flight rate and very large sacrifices of payload. Although DSG is still developing architecture design but the available volume for scientific and technological development is limited and less future growth.

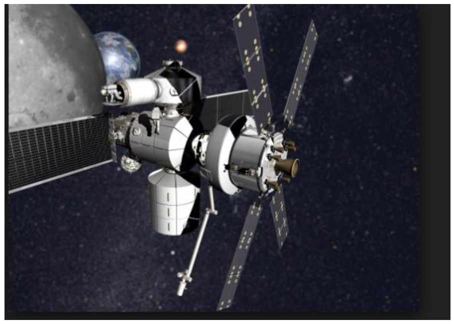

Figure 1: Deep Space Gateway[1]

1.2 Contribution

A cis-lunar space station is one of key infrastructure to support expanding human presence and activities into the solar system. It can contribute to advance exploration, science and technology innovation to benefit to humanity.

The ultimate goal of this thesis is to develop the conceptual design of a commercial cis-lunar space station, named AXIS, located in NRHO. Mission of AXIS station is to support Cis-Lunar-1000 vision which aims to enable 1000 people to live and work in space between LEO and Moon, and beyond. AXIS station work as a way station to transport crew and cargo to Moon surface and other orbit to conduct repair and resupply work for deep space transporter or satellites orbiting lunar orbit. AXIS station provide the docking port or truss system to berth spacecraft for on-orbit assembly and repayment work on the station. Unlike NASA DSG, AXIS can provide the large space for scientific and technological experiment to induce innovation for further deep space exploration.

This large scale space station in lunar orbit has the problem of transportation cost. Thus, AXIS will starts building in 2037 when initial ISRU provide propellant produced with extracted water from the south pole of moon surface, enabling on-orbit refueling to reduce the transportation cost from LEO to lunar orbit. The operation of AXIS station will begin in 2040 before starting large scale lunar immigration, asteroid mining, and Mars exploration. The technical goal of this thesis is to propose the reduction of construction cost by reutilizing a spent fuel tank of duel depot into habitation module, and used materials.

1.3 Problem Statement and Hypothesis

AXIS space station is a lunar orbiting station to provide a platform not only for transportation transition but also research, technology development, and industrial manufacturing which has capability to response various customers' demands. Rational problem designation helps design better station design.

1.4 Thesis Outline

This thesis is comprised of 7 chapters. Chapter 1 covers the motivation for designing the AXIS cis-lunar space station, including introduction of expected future human space exploration planned by space agencies and commercial companies. Problem statements and hypothesis are also covered in Chapter 1. Chapter 2 elaborates on on-going deep DSG design proposed by five commercial companies working with NASA. Chapter 3, the Concept development section, details of the design requirement, design constraints, functional and technical requirement, including the assumption of available infrastructure by AXIS building. Chapter 4 describes concept of operation, explain the mission timeline before, during building the station, including launch system option. This chapter describes the operation scenario to explain station function to response to multi-purpose mission. The focus shifts to the design of AXIS station, followed by the assembly process in Chapter 5. Chapter 6 describes the internal architecture, mainly focus on how to convert a spent fuel tank into habitat module. The final chapter is the conclusion and recommendation that reviews the major results of work, limitations, future work and the broader impacts of the study.

2.0 Background

Thanks to many years of accumulation of knowledge and experience through human space flight from Apollo program to international space station, the design scheme of a space station correlated to human factors is developing. However, the purpose of current space station is limited for scientific research and technological development for deep space exploration for space agencies. This research addresses the cost reduction to build a large scale commercial cis-lunar space station by utilizing space resources and reutilize a spent materials to support ULA's Cislunar-1000 vision in 2040. The following is a review of the literature on deep space gateway, lunar orbit space station, currently developing by NASA and five commercial companies. A review of the state-of-the-art show the DSG shows each company's stations is combined a conservative hard module verified through the ISS experience and novel technologies such as inflatable habitation module. However, the DSG will be used to achieve lunar science objectives while simultaneously laying the groundwork for future deep space missions. Four astronauts will be on-board the DSG for up 60days initially each year. The DSG's capability to support much longer durations will increase with each mission up to 180 days with increased cargo capability and increased water recycling in the life support system. Orion would dock at the DSG and permit extended stays of several days of several months. In the future, the DSG could also provide a docking station for a reusable lander which would offer astronaut access to both the near and far side of the Moon's surface.

In 2040, it is assumed that more than 100 people live and work in lunar orbit and on the surface of the moon. Also, the scale of deep space exploration, especially, asteroid mining mission will be prompt to utilize the resources. This project aims to propose to apply DSG's habitat technologies to build larger station in lunar orbit compared to the DSG, which support more commercial activities and work as a way station to allow several spacecraft to berth simultaneously.

2.1 NASA NextSTEP Deep Space Gateway

NASA issued the contracts, part of the agency's Next Space Technologies for Exploration Partnerships (NextSTEP) program, to Boeing, Lockheed Martin, Orbital ATK, Sierra Nevada Space Systems and Space Systems Loral. Each company will perform studies regarding how they would develop the Power and Propulsion Element for the proposed gateway. The module, as currently envisioned, will generate electrical power for the gateway and move the spacecraft through cis-lunar space with a solar electric propulsion system, as well as provide communications.

2.1.1 Bigelow Aerospace LLC

Bigelow Aerospace will develop and test based on a 330 cubic meter expandable habitat and test platform for deep space hardware. The testing conducted on this platform will advance approaches for deep space missions and serve as a basis for commercialization in low-Earth orbit. BA330 leverages the lessons learned from the Bigelow Expandable Activity Module (BEAM), a 16-cubic-meter expandable spacecraft, which was deployed on the space station in June 2016.

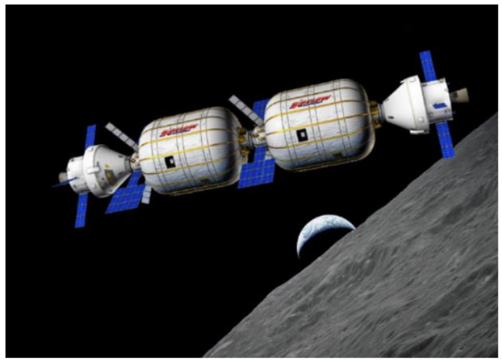

Figure 2: Bigelow Aerospace DSG Plan [4]

2.1.2 Boeing

Boeing is developing a modular habitat system that leverages experience in designing, developing, assembling on-orbit and safely operating the International Space Station for more than 15 years. This includes the production of a full-scale habitat that will provide design analysis and high-fidelity demonstration and test capability to simulate how humans can safely live and work in deep space for extended periods of time. This ground demonstrator will test and validate interface standards, systems functionality and critical exploration technologies.

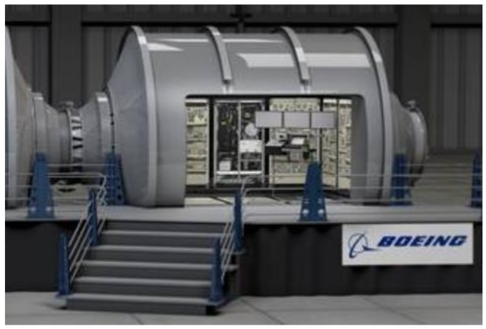

Figure 3: Boeing DSG Plan [4]

2.1.3 Lockheed Martin

Lockheed Martin will refurbish a multi-purpose logistics module, like those that were used to carry equipment and supplies to and from the station aboard the space shuttle, into a full-scale habitat prototype that will include integrated avionics and ECLSS. The high-fidelity ECLSS prototype will provide risk reduction and form and fit testing. The avionics prototype will prove data communication between the habitat and Orion and demonstrate crew interfaces between a deep space habitat and Orion. Lockheed Martin will also use virtual prototyping to validate the habitat module's form, fit and function.

Figure 4: Lockheed Martin DSG Plan [4]

2.1.4 Orbital ATK

Orbital ATK will mature the mission architecture and design of their initial cislunar habitat concept, based on the Cygnus spacecraft that currently services the space station. Orbital ATK will create their prototype to support testing of critical interfaces with Orion and other modules. They will mature the Cygnus-derived habitat design for long-term operation in deep space and establish a proposed roadmap that leads to Mars exploration.

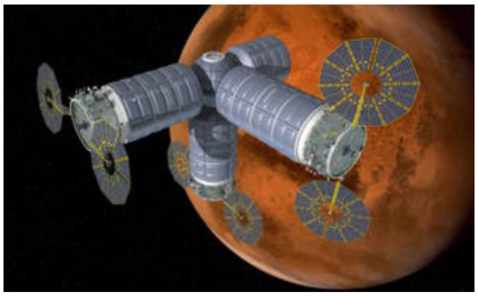

Figure 5: Orbital ATK DSG Plan [4]

2.1.5 Sierra Nevada Corporation

Sierra Nevada Corporation will study and refine a flexible architecture and concept of operations for a deep space habitat that leverages three to four commercial launches to construct a modular long-duration habitat. Their prototype will be based on the Dream Chaser cargo module as a foundation for the SNC NextSTEP-2 proposal and will allow SNC to assess their ability to meet the criteria for each operation phase and identify risks. After launch from the Dream Chaser spacecraft, the SNC NextSTEP-2 module will be combined with a large inflatable fabric environment module, ECLSS system, and propulsion system. The design and prototype will confirm the proof-of-concept and ensure critical subsystems seamlessly integrate together.

Figure 6: SNC DSG Plan [4]

2.1.6 NanoRacks

NanoRacks conducts a comprehensive feasibility study regarding the conversion of an existing launch vehicle's upper stage, or propellant segment, into a pressurized habitable volume in space with partners including Space Systems Loral and the United Launch Alliance, referred to collectively as the Ixion Team. The feasibility study will provide insight into this innovative and low-cost approach that can be used for any rocket system, including SLS.

Figure 7: NanoRacks, DSG Plan, Ixion [4]

2.2 Summary

The conceptual design of the DSG has been developing by NASA and commercial companies. These modules take advantage of easiness of system integration, large habitable module. These advancements have established the groundwork for a large cis-lunar space station for this thesis.

The problem of the DSG is the transportation cost because NASA plans to use SLS to send modules to lunar orbit along with technological verification test. SLS has capability to send extreme mass and volume of cargo at a time, but current or next generation commercial rockets are able to send cargo with single or multiple launch in combination with on-orbit refueling. This thesis shows a new transportation scheme between the Earth and Moon to build a lunar orbital station.

3.0 Conceptual Development

This chapter describe conceptual development with system engineering manner. First, it review the mission statements along with the mission requirements, constraints, and assumption. Space design and functional assumptions describe the minimum requirement to support of crew and operate required missions. Last section introduces the assumption of available infrastructure during the construction.

3.1 Mission Statement

AXIS cis-lunar space station provide a large platform for scientific and technological research facility to contribute to improve human life for both further deep space exploration and on Earth. AXIS provide manufacturing facility to produce commercial product with lunar or asteroid materials to realize the self-sustaining economy in cis-lunar space. Also, AXIS work as a way station to allow people to access to their destination anytime by providing several ports to berth. It allows to support on-orbit maintenance, assembly, resupply mission.

3.2 Mission Objective

3.4.1Science and Technology Research

AXIS station shall provide various scientific and technological research facility to response customer's demand.

3.4.2 Manufacturing

AXIS station shall provide manufacturing facility which can produce valuable products such as nanofiber and metal alloy from lunar and asteroid resources. Manufacturing system shall create variable parts for small satellite or spare parts for maintenance. 3D printer shall provide a part for small satellite and combined with a part sent from the Earth, and then deploy from AXIS station.

3.3.3 Waystation

AXIS station shall provide multiple docking ports and berthing ports to allow serval spacecraft to attach the station simultaneously. AXIS station shall enable people to transit from cis-lunar cycler to a lander or taxi vehicle to deep space transfer vehicle orbiting in other lunar orbit. AXIS station shall provide redundant vehicles to stand for two failures.

3.3.4 On-orbit Maintenance, and Assembly

AXIOM station shall support on-orbit maintenance for lunar lander or crew taxi vehicle. Crew onboard taxi vehicle depart from the AXIS, they will conduct on-orbit maintenance service of lunar orbit satellites using spare parts printed out with 3D printer.

3.3 Mission Constraints

Mission constraints include the cost of transportation, cost of manufacturing, schedule, and harsh environment. The building cost is dependent on the transportation cost. Harsh environment of lunar orbit increase the risk of cancer and loss of life. Fuel produced by using extracted

3.4 Mission Assumption

This section will describe the assumption of mission environment including crew number, available infrastructure, and available launch system. This assumption was made based on the ULA's Cis-Lunar-1000 plan between 2035 and 2045. The AXIS station will be designed to have capability to support activities after 2045.

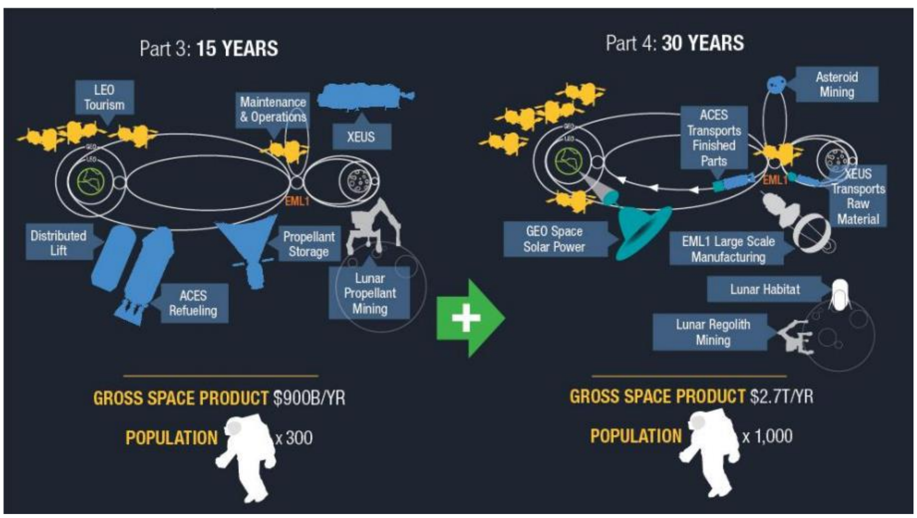

Figure 8: ULS's Cis-Lunar Plan [5]

3.4.1 Population

This thesis assumed that the population who live and work in space between LEO and Moon based o ULA's plan. 30 people (23 crew and 7 tourists) will live on the surface of the moon at 2030. At 2045, total population who live on the moon surface is assumed 168, and 140 crew member work for lunar colonization and 28 visitors will stay for one month. The crew on-board the AXIS station will be 12 crew members when it starts operating at 2040.

3.4.2 Infrastructure

This section describe the main infrastructures which are necessary to build and operate AXIS station after 2035.

3.4.2.1 ULA, Advanced Cryogenic Evolved Stage

Advanced Cryogenic Evolved Stage (ACES), new generation upper stage rocket developing by ULA will achieve performance and capability to support long duration mission to transfer crew or cargo to lunar orbit []. ACES has capability to transfer cargo up to 20mT with 30mT on-orbit refuel. This innovative propulsion system will allow to send

3.4.2.2 Cis-lunar Cycler

One of key element is lunar cycler which can transport 14 crew at a time from LEO station to AXIS. The cycler is adaptable to ULA's Vulcan rocket. After the launch, an inflatable module in cargo bay will be deployed to provide enough space to support crew during five days transfer (maximum up to 14 days). Nose cone of a cycler has international Docking System Standard (IDSS) to dock with both LEO station and AXIS station. It assumes that at least three cycler will operate at a time.

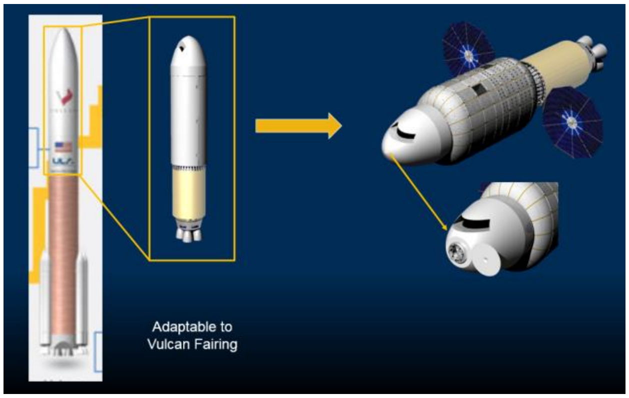

Figure 9: Cis-lunar Cycler

3.4.2.3 Modular Lander

A reusable modular lander (ML) supports to transfer crew from AXIS station to the surface of the moon. A single lander would be sufficient to transfer crew vehicle with seven crew member. Also, some single modules will be ganged together to produce more thrust to transfer cargo, up to 24,900kg cargo with three MLs, and up to 33,200kg cargo with four MLs. Single modular system can work as a service module of a space tug or a taxi vehicle to send crew or cargo to deep space transfer vehicle locating in other lunar orbit. The increase of commonality will contribute to reduction of production cost and operational cost.

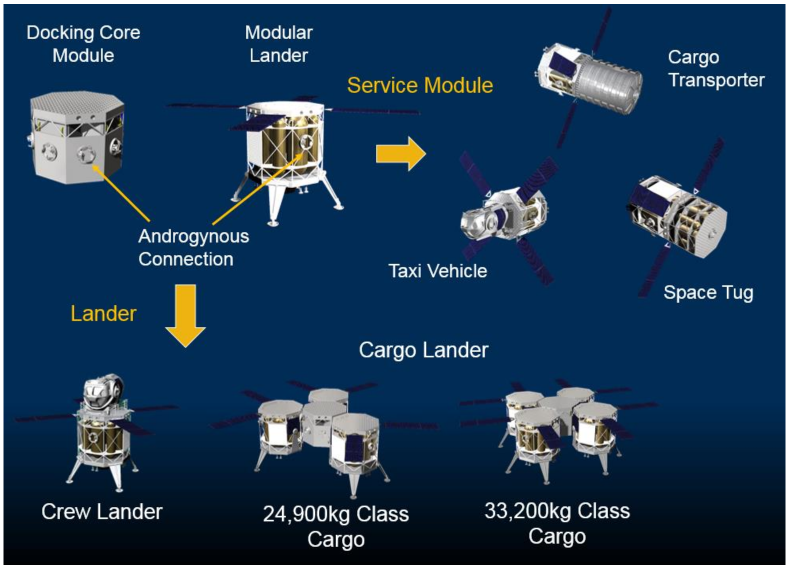

Figure 10: Modular Lander

3.4.2.4 ULA Fuel Depot

The ACES depot is an ACES 41 mated to a modified ACES 71 fuel tank with deployable sunshield installed. Using the ACES stage, the depot would hold 121mT of propellant (106mT of LO_2 and 15mT of LH_2). One fuel depot is located in GEO and another is located at NRHO. Propellant produced with water extracted from the south pole of the surface of the moon will be used to refill the tank. Propellant loss rates in LEO and NRHO are suppressed using passive TPS. The depot is designed to primary boil-off and vent GH_2 due to its factor of 10 higher thermal capacitance than GO_2. This vent GH_2 is used in LEO and NRHO to satisfy the substantial station keeping requirements.

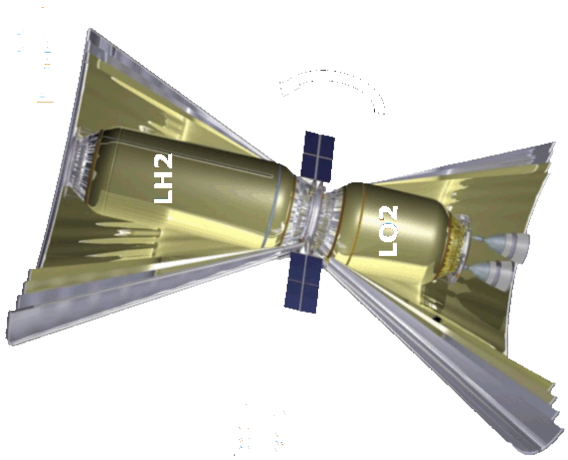

Figure 11: ACES Based Fuel Depot [5]

3.5 Functional Assumption and Constraint

3.6 Operational Assumption and Constraint

4.0 Concept of Operation

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6.4 Ixion

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6.4.3 ECLSS

6.4.4 Crew Quarter

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6.4.6 Construction Process

7.0 Conclusion

Reference

[1] NASA. (2018). *Next Space Technologies for Exploration Partnerships (NextSTEP)*. [online] Available at: https://www.nasa.gov/feature/next-space-technologies-for-exploration-partnerships-nextstep-projects.

[2] European Space Agency. (2018). *Moon Village*. [online] Available

at:https://www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village

[3] Nasaspaceflight.com. (2018). *ULA laying the foundations for an Econosphere in CisLunar space – NASASpaceFlight.com*. [online] Available at: https://www.nasaspaceflight.com/2018/03/ula-laying-foundations-econosphere-cislunar-space/ [Accessed 19 Apr. 2018].

[4] Gerstenmaier, W. (2017). *Progress in Defining the Deep Space Gateway and Transport Plan*.

[5] On Orbit Refueling: Supporting a Robust Cislunar Space Economy. (2017).

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