Conceptual Design of Commercial Cislunar Space Station for Large Scale Space Development

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Prof. Larry Bell
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Introduction: Mission Statement and Goal

- **Mission Statement:** Design, Build, and Deploy Commercial Lunar Orbit Station by 2040

- **Mission Objective:** Support ULA’s Cis-Lunar-1000 after 2045
  1. To study and develop Future technology
  2. To develop testbed to study future long-human space flight
  3. To develop waystation to enable to access to various destination
  4. To encourage commercialization of Cis-lunar space
Introduction: Mission Assumption

- **Assumption**
  - LOP-Gateway will start building and operating from 2025
  - Initial unmanned and manned lunar and mars exploration has started

- **Environment Assumption**
  - ISRU on the Moon
  - Population on the Moon at 2045 through a year
    - 42 tourists (1 month stay)
    - 128 crew (3~6 month)
  - Need 50 people Transition every month

![Diagram showing future plans and assumptions for lunar and mars exploration](image-url)
Design Requirements

- AXIS Design Requirement

12 crew members (nominal), for 180 days without Resupply

- Closed-Loop ECLSS (95% Water Recovery, >85% CO2 recovery)
- Depends on both Earth and Lunar resupply
- Friendly User Interface
- Well designed for

- Protect Crew from SPE, GCR

- Allow to berth/docking following vehicles concurrently;
  2 × Cycler
  4 × Lunar Lander
  2 × Cargo

- Allow to berth following vehicles on the truss;
  10 × Modular Lander
  2 × Crew Vehicle
  1 × Cargo
Introduction: High-Level Requirements

Science and Technology Requirements

- Science & Technology
- Human Factor and Health
- Orbit Manufacturing
- On Orbit Assembly & Maintenance
- Remote Operations Support
- Small Satellite Service & Communication
- Safe Heaven & Rescue Operation
Design Overview: Orbit Selection

- Near Rectilinear Halo Orbit

<table>
<thead>
<tr>
<th>Orbit Characteristic</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>6-8 days</td>
</tr>
<tr>
<td>Lunar Amplitude Range</td>
<td>2000-75000km</td>
</tr>
<tr>
<td>Station Keeping</td>
<td>10 m/s per year</td>
</tr>
<tr>
<td>No communication Occultation</td>
<td></td>
</tr>
<tr>
<td>Radiators are sufficient for</td>
<td>Heat Rejection (62W/m²)</td>
</tr>
</tbody>
</table>

No communication Occultation

Radiators are sufficient for Heat Rejection (62W/m²)
Introduction: Transportation System

Transportation Cost:
- **LEO to NRHO** = 5 days, $\Delta V = 428.5$ m/s
- **NRHO to LEO** = 5.1 days, $\Delta V = 411.5$ m/s
- **NRHO to LLO** = 0.5 days, $\Delta V = 731$ m/s
- **LLO to NRHO** = 0.5 days, $\Delta V = 730$ m/s

Fuel Depot

Crew Cycler

Fuel Depot
Assumption: Transportation System

- Crew Cycler
- Crew Taxi
- Resupply
- Fuel Depot
- LEO
- CCT
- NRHO
- DRO
Assumption: Available Elements

- Lunar Crew Cycler

<table>
<thead>
<tr>
<th>Lunar Cycler</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of Crew</td>
<td>15</td>
</tr>
<tr>
<td>Support Duration (days)</td>
<td>30</td>
</tr>
<tr>
<td>Pressurized Volume (m^3)</td>
<td>400</td>
</tr>
</tbody>
</table>
Design Overview: Available Element

- **Modular Systems**

  **Modular System**
  - Mass of Structure: 2783 kg
  - Mass of Propellant: 6748 kg
  - Max. Mass of Cargo: 8370 kg

  **Crew Lander**
  - # of Crew: 8
  - Support Duration: 7 days
  - Pressurized Volume: 20 m³
Mission Assumption: Available Element

- **Modular Systems**

  | Modular Lander |
  | Androgynous Connection |

  **Cargo Lander/ Launcher**

  - **33,480kg Class Cargo**
  - **41,350kg Class Cargo**

  | **Modular System** |
  | **Mass of Structure** | 2783 kg |
  | **Mass of Propellant** | 6748 kg |
  | **Max. Mass of Cargo** | 8370 kg |

  - **Up to the Orbit**
  - **Back to the Surface**
  - **Launch Cargo**
Introduction: Mission Timeline, Phase 1 Preparation

- **2024**: Deep Space Gateway
- **2025**: GPS/Comm.
- **2025**: Initial Lunar Exploration
- **2030**: Small Scale Lunar Mining
- **2030**: Fuel Depot
- **2030**: GEO
- **2035**: NRHO
- **2035**: Fuel Tanker
- **2035**: Initial Mars Exploration
- **2035**: Refuel
Introduction: Mission Timeline, Phase 2 Building

- **NRHO**: Middle Scale Lunar Mining → Fuel Tanker → Fuel Depot 2
- **HEO**: Fuel Depot 2 → H₂O → 60mT/yr
- **LEO**: Commercial Space Station

Timeline:
- 2030
- 2035
- 2037
- 2038
- 2039
- 2040

- Fuel Depot 2 at 2035
- Cargo at 2038
- H₂O > 400mT/yr

Additional Notes:
- > 400mT/yr
- NRHO
- HEO
- LEO
- Commercial Space Station
Overview Design of Axis Station

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Length (+S.Tug) (m)</td>
<td>81m (94.8m)</td>
</tr>
<tr>
<td>Width (m)</td>
<td>36.4m</td>
</tr>
<tr>
<td>Height (m)</td>
<td>43m</td>
</tr>
<tr>
<td>Pressurized volume (m$^3$)</td>
<td>913</td>
</tr>
<tr>
<td>Pressurized Docking Port</td>
<td>11</td>
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</tbody>
</table>

- ROSA: Solar Array
- Utility Module
- Radiator
- Modular Lander & Cargo
- Cupola
- MASH Airlock
- Robotic Arm
- IXION+ Docking Node
- Cygnus Module
- BA330
- Crew Lander Module
- Cargo
- Robotic Arm
- Space Tug
- Crew Lander
Design Overview: Utility Module

- **Li-Ion Battery**
  - NRHO Total Eclipse Time = Max. 3hours
  - Baseline Power = 80kW
  - Total Required Capacity = 240kWh
  - # of Li-Ion Battery Cell = 1367 cells
  - Mass = 783kg

- **Utility Module**
  - Solar Array: 4 ROSA, W=3m, L=22m Each
    Total Power Generation = 130kW
  - Each Radiator W=1.7m, L=12.7m
  - CMGs
  - High-Gain Antenna
  - Rotation Mechanism
  - Moving Rail
  - Circular Moving Mechanism
  - Utility Management ORU
  - Li-Ion Battery
Design Overview: Articulated Octa. Truss Systems

Truss Configuration: Octagonal
H=4.2m, L=25m

Capture Latch & Bar

Robotic Arm

Orbital ATK Articulate Mast systems

1. Fold At Launch

2. Deploy at LEO

3. Deploy Rail and Install On Truss

Rails
Design Overview: Design Concept of Habitation

- ISS or DSG derived Habitation Modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Length (m)</th>
<th>Diameter (m)</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA330</td>
<td>13.6</td>
<td>6.7</td>
<td>330</td>
</tr>
<tr>
<td>Node</td>
<td>6.5</td>
<td>4.4</td>
<td>97.2</td>
</tr>
<tr>
<td>MASH Airlock</td>
<td>5.3 m</td>
<td>4.4 m</td>
<td>75.76</td>
</tr>
</tbody>
</table>

Airlock: MASH (Minialistic Soft Structure Hatch)
Design Overview: Design Concept of Habitation

- ISS or DSG derived Habitation Modules

**Cygnus Docking Node**

<table>
<thead>
<tr>
<th>Node</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>7.7</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>4.4</td>
</tr>
<tr>
<td>TRL</td>
<td>6</td>
</tr>
</tbody>
</table>
Design Overview: Design Concept of Habitation

- ISS or DSG derived Habitation Modules

Ixion LH2 fuel Tank

<table>
<thead>
<tr>
<th>Ixion Tank</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Length (node to node)</td>
<td>14.7m</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.8m</td>
</tr>
<tr>
<td>Volume</td>
<td>242m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Small Node</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>3</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>4.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cupola</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>3.5</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Design Overview: Functional Layout

- Functional Proximity

- Living (Galley, CQs, Stowage)
- ECLSS & Hygiene
- Exercise
- On-Orbit Assembly & Maintenance
- Operation System
- Research Lab.
- Utility
- Manufacturing
- Cargo

Side View

Top View
Assembly Process

NROH

1st: Fuel Depot

i=28.5, H=600km

120mT

2nd: Truss

i=51.6, H=400km

30mT

3rd: Utility Module

4th: Node, Cupola

5th: MASH Airlock

6th: BA330

30mT

30mT

30mT

V

V

V

V

V

V

V

Earth

1st: Fuel Depot

2nd: Truss

3rd: Utility Module

4th: Node, Cupola

5th: MASH Airlock

6th: BA330

V

V

V

V

V

V

V
Assembly Process

NROH

120mT

30mT

30mT

30mT

Space Tug

LEO

i=28.5, H=450km

Earth

7th : Cygnus Docking Port

8th : Cygnus Docking Port

9th : Cargo
Mission Objective: Ixion Module

- Ixion Module
  - **Goal**: Convert LH2 tank into habitation module
  - **Objective**: Crew Quarters, Kitchen, Wardroom, Hydroponics, and stowage
  - **Functional Requirement**: Air ventilation, ECLSS sensor, fire suppression, LED light, Communication system, Power, water line
  - **Assembly Method**: Autonomous Robot with partially human support

![Diagram showing the process of modifying, retrieving, and converting into a habitat module.](image-url)
Structure Modification: Ixion Module

- Fuel Depot Modification

- Customized Ixion Detail
  - IDSS port at the each end of the fuel tank
  - One end node attached on the mid-deck

- Length (node to node) = 14.7m
- Dry mass = 12.8mT
- Volume = 242m³
Structure Modification: Ixion Module

- Fuel Depot Outer Shell Modification

- Functional Requirement for both fuel depot and habitat
  - Depot: < 0.1%/ day LH2 boil-off rate
  - Habitat: Protect from GCR and SPE
    - 10g/cm² Al equilibrium
    - Internal pressure = 101 kPa
    - Safety factor = 2.5

- Total Mass of External wall = 12.18mT
- Total Tank Mass = 13.9mT
Design Overview: Ixion Module

- Node and Hatch Design

Steel Fuel Tank

Enhanced End-Cone (Aluminum)

Access Hatch
Design Overview: Ixion Module

- Node and Hatch Design

- Steel Fuel Tank
- Diffuser/Air return
- Duct Hose and Utility Connector
- LED
- Front Hatch
- IMV (Inter-Module Ventilation)
Internal Tank Structure

- Overview of Internal Tank Structure

Typical Fuel Tank inner frame

Skin-Stringer

Mobil transfer rail

Random Access Frame (RAF)

RAF Edge Frame
Internal Tank Structure

- Overview of Internal Wall

- Attachment and secure Mechanism
Internal Wall

- Carbon Fiber Reinforcement (CFR) Plate
  - Capture Hall
  - Velcro Tape
  - Attachment
  - Folded End Plate
  - End Dome CFR plate
  - Attach pin
  - Attach Mechanism
Internal Wall

- Radiation Shield: Heat Melting Compactor (HMC) Plate
  - Outer Shell Shield = 10 g/cm² Al equilibrium
  - Inner Shell Shield > 13 g/cm² Al equilibrium
  - HMC plate = 60% of PE equilibrium
  - Total thickness of HMC tile = 11.4cm (n=3) = 9.86 g/cm² Al
  - Estimated Compressed MCTB Thickness = 5cm = 7 g/cm² Al
  - Total inner radiation shield = 16.86 g/cm² Al

HMC tile: $40.6\times40.6\times3.8$cm
- Input = 1100kg garbage, Output = 800kg HMC tile
- Required: 6336 kg HMC = 8,712kg garbage
- 4 crew for 10 years at DSG from 2025 = 16,060kg garbage
- 4 crew for 5 years on the Moon from 2030 = 8,030kg garbage

Garbage

HMC

3x

HMC tile

MCTB

42×50×50cm

Velcro tape

Packed HMC tile

42×20×50cm
Interior System

- HMC Radiation Shield

  Total 570 MCTB or 1710 HMC tiles
Interior System

- Diffuser, LED lighting, Sensors

Diffuser/ Return Air Fan Assembly

Utility Board

Utility Connector

LED

Flexible Cable Connector

Duct hose

Water Line
Interior System

- Diffuser, LED lighting, Sensors

Diffuser/Return fan Assembly

LED

Utility Connector

Utility Board
Interior System

- Air Ventilation
Ixion Outfitting: Functional Arrangement

Zenith

Starboard

Forward

Afterward

Nadir

Port

Crew Quarter
Kitchen
Hydroponics
Wardroom
Stowage
Interior System

- Craw Quarter
  - CQ Functional Requirement:
    - Air Ventilation
    - LED Light
    - Utility cable
  - CQ Dimension:
    - $W = 1.2\, \text{m}$, $L = 1.0\, \text{m}$, $H = 2.0\, \text{m}$, $V = 2.28\, \text{m}^3$
  - Ventilation Assembly
    - $W = 0.2\, \text{m}$, $L = 0.7\, \text{m}$, $H = 1.7\, \text{m}$
Interior System

- Craw Quarter Assembly

Attachment Mechanism
  - Rotation Lock

Fold Door Assembly
Deploy
Outfit Interior

Capture pin
Interior System

- Kitchen/Wardroom

- Food Warmer
- Drink Dispenser
- Water Dispenser
- Food 3D Printer
- Refrigerator
- Garbage Box
- Stowage
Interior System

- Virtual Window/ Projector

Virtual Window / Projector
(W: 3m × L: 0.8m × H: 2m)

Folded
(Thickness: 0.14m × L: 0.8m × H: 2m)
Interior System

- Hydroponics

- Collapsible Hydroponics

- Fertilizer, CO2 tank, Control Assembly

- Fluidic & gas Line
Interior System

- Cargo
  - Ixion has capability to store $18\text{m}^3$ (2\text{m}^3 each stowage)
  - Cloth, food, spent items, spare parts,

RAF Frame
Folded Cargo Space
Deploy
Ixion Outfitting: Hardware Requirement

- FARO 3D Laser Scanner

- Distance accuracy up to ±1mm
- Range from 0.6m up to 70m
Ixion Outfitting: Assembly Hardware Requirement

- Autonomous Assembly Robot (A2R)

- Capture mechanism

- Robotic Arm

- Power: Li-ion Battery
- Wireless Communication

Dimensions:
- 3.2m
- 4.8m
Ixion Outfitting: Hardware Requirement

- Robonaut 2

243cm

Max. 355cm
Ixion Outfitting: Hardware Requirement

- RFID: Radio Frequency Identification
  - Identify the location of the Cargo
  - “Just-In-Time” system

Cargo Transfer Scenario

- R.A. #1: Search & Pick up Cygnus Cargo
- Multi Docking Port
- R.A. #2: Transfer
- A2R receive
- Ixion LH2 Tank
- Cygnus Cargo
- R.A. #1 Search & Pick up
- R.A. #2 Transfer
Assembly Process

1. Vent all residual Propellant and gas
2. Transfer to AXIS
3. Docking
4. Bleed O2 and N2, Stabilize inner temperature

A: A2R, R: R2, H: Human
Assembly Process

5. Crew open the Hatch
6. Install Target Marker
7. Install MT and Scanner
8. Scan Internal Tank

A: A2R, R: R2, H: Human
Assembly Process

A: A2R, R: R2, H: Human

H
9. Install A2R

A
10. Attach CFR plate

A
11. Attach HMC
Assembly Process

A: A2R, R: R2, H: Human

R
12. Attach Secondary Structure

A
13. Attach Manifold

A
14. Install Diffuser & Return Air Fan Assembly
15. Connect Duct Hose

16. Install LED and Utility Board

17. Cable Connection
Assembly Process

A: A2R, R: R2, H: Human

A
18. Kitchen

A
19. Install Projector

A
20. Install Hydroponics
21. Install Crew Quarters

A: A2R, R: R2, H: Human
Assembly Process

A: A2R, R: R2, H: Human

22. Remove rail

23. Install CFR plate and HMC wall
Assembly Process

A: A2R, R: R2, H: Human

24. Install Cargo
Future Consideration

- How to convert a spent stage rocket into hab.
- Application for lunar base or deep space exploration habitatation
Thank You

Queries?..