IN-ORBIT REFUELING. TECHNICAL AND ECONOMIC FEASIBILITY OF MOON-MINED PROPELLANTS: TRANSPORTATION, STORAGE AND DISTRIBUTION SYSTEMS

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IN-ORBIT REFUELING. TECHNICAL AND ECONOMIC FEASIBILITY OF MOON-MINED PROPELLANTS: TRANSPORTATION, STORAGE AND DISTRIBUTION SYSTEMS

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INTRODUCTION

Scope: *analysis of the technical feasibility and economic sustainability of Moon-mined propellants' transportation, storage and distribution to final users*

Evaluation of technical feasibility and performance

- **Moon mined propellant**
- **Architectures**
- **Propellant storage characteristics**
- **Depot optimal placement**
- **Transportation and distribution system**

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Economic sustainability analysis

- **Market analysis**
  - ➢ Market structure, demand/supply and competition analysis
- **Pricing strategies**
- **NPV** of the transporter/distributor company
- **Risk analysis**

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IN ORBIT REFUELING

***In orbit servicing*:** Inspection , Orbit modification and maintenance, Upgrade and repair, Assembly, Debris mitigation, **Refueling**

In orbit refueling using space resources

LEO and L1 depots as selling points for beyond-Earth ISRU propellant production

***Benefits of in-orbit refueling*:**

- Reduce risk of mission failure
- Extend mission lifetimes
- Increase payload capacity for launch vehicles:
  - Reduce mission cost
  - Improve mission flexibility
  - Expand space activities and enable new missions

***Potential market for in-orbit refueling*:**

- Satellite servicing in LEO, GEO, MEO
- Gateway, Lunar and Mars missions
- Companies looking to ***develop cislunar space (and beyond)***

LUNAR SUPPLY AND BENEFITS OF MOON MINED PROPELLANTS

By leveraging lunar ice, rockets could potentially refuel once they get to space, allowing them to ***reach distant locations.***

The Moon has less gravity than Earth, meaning that the lunar departure requires a ***lower amount of energy.***

MAIN BENEFEFITS

Direct link between Earth and Moon

Supporting space missions and space exploration

Encourage the development of new technologies to support ISRU

PROPELLANTS EXTRACTION SEQUENCE

Sublimation of H2O from lunar poles → Splitting of Hydrogen and Oxygen *[LH2/LOX]* → Liquefaction for storage

↓

Propellant storage has to be in ***cryogenic conditions*** for the entire mission duration

OVERVIEW OF DIFFERENT ARCHITECTURES

ARCHITECTURE 1

Heavy Lift Launchers

Several launchers are involved to support an in-space mission

The system ***is designed for a specific mission***; in order to reach the Moon space a sequence of launches is required, which means less reliability

COMMON REQUIREMENTS

- Launchers' staging
- Reliability of the system
- Automatic docking
- Right altitude and launch window
- Leveraging of existing launching systems

ARCHITECTURE 2

Orbiting depots

Depot located in LEO and Moon orbit or in a Lagrangian point to support an in-space mission

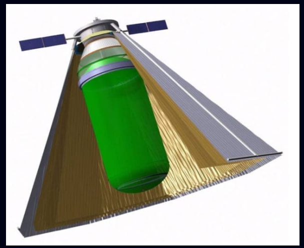
The system ***is flexible and adaptable*** and can be easily launched in an ***assembled configuration***

TECHNICAL REQUIREMENTS FOR IN-SPACE PROPELLANT STORAGE

How to guarantee cryogenic conditions?

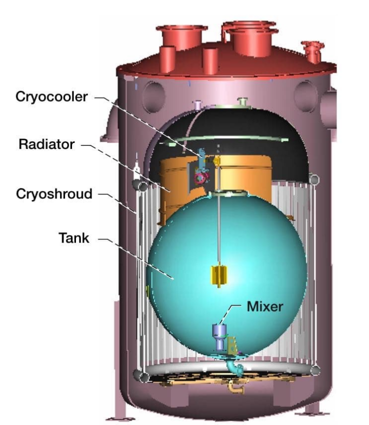
Thermal insulation

- MLI
- SUN SHIELDS
- ADVANCED MATERIALS TO LIMIT HEAT TRANSFER



Minimal boil-off

- PRESSURISED TANKS
- VENTING AND VAPOR COOLING SYSTEM
- UTILIZATION OF VAPORED GASES FOR STATION KEEPING



How to design the system?

Low weight obtained with a common bulkhead for both tanks

Fluids management and fluids transfer with:

- Propellants settling
- Spin around longitudinal axis
- Tether settling
- Electromagnetic propellant settling

Trade off between ***different orbits and missions' objectives*:**

STORAGE PERIOD VS TANK'S DIMENSIONS

Already existing advanced technologies and materials enable to fulfill these requirements

DEPOT CENTRIC ARCHITECTURES

OPTIMAL ARCHITECTURE

ORBITING DEPOT TO SUSTAIN MOON EXPLORATION

Higher mass at lift off + no new concept of launchers

The system is ***always available*** and ***completely adaptable to any kind of mission*** since it is not going to be discharged after its usage

Flexibility of the mission can be guaranteed thanks to several systems:

- Crew transfer vehicle
- Aerobraking system
- Reusable upper stage

→ Supporting manned missions, continuous delivering of propellants and experiments, lower costs

DEPOT DESCRIPTION

BASIC CONCEPT

- Orbiting depot assembled on Earth
- 2 tanks + avionics
- Fluid transfer and handling with spin around longitudinal axis

ADDITIONAL MODULES

- Crew module to support man equipped missions
- Reusable upper stage for payload delivering in a suitable position of the trajectory

OPTIMAL PLACEMENT: LEO DEPOT AND L1 DEPOT

OPTIMAL PLACEMENT

LAUNCH WINDOWS	From LEO DEPOT (i=28.5 ° h = 476 km)*	From L1 DEPOT
To Lunar surface	Every 9 days	Continuously open windows
To Earth	Continuously open windows	Continuously open windows
Interplanetary departure	Not guaranteed during an interplanetary transfer window due to depot's orbit precession over time	Guaranteed throughout the launch season propellant efficient transits between Earth and SEL1/SEL2 can require weeks or months
TECHNICAL REQUIREMENTS	**LEO -** complex fluid management and thermal insulation	**L1 -** better thermal insulation

POTENTIAL MARKET

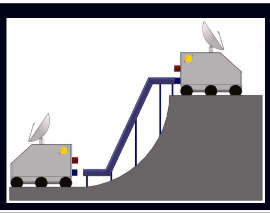
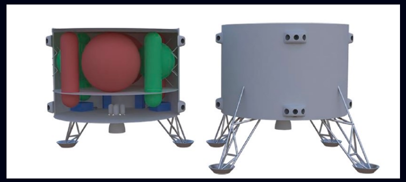
CUSTUMERS / DEMAND for propellant	LEO	L1
Type of mission	Lunar and GEO missions	Interplanetary missions: Mars departures
Demand	210 MT of propellant in LEO per year (1,260 MT/year of propellant on lunar surface)	280 MT of propellant every 2 years

PROPELLANT PRICING

PROPELLANT COST	From EARTH	From MOON
Earth surface	$ 1/kg	-
LEO	$ 4000/kg	$ 3000/kg
GTO	$ 8000/kg	$ 1500/kg
GEO	$ 16000/kg	$ 1500/kg
FML1	$ 1200/kg	$ 1000/kg
LUNAR SURFACE	$ 36000/kg	$ 500/kg

Notes: *i=28.5° optimal inclination to maximize IMLEO; *h= 475 km to standardize depot rendezvous transit times and procedures and minimize aero drag losses.
Source (propellant pricing): Sowers

LUNAR SUPPLY – TRANSPORATION AND DISTRIBUTION SYSTEM

PHASE	VEHICLE	MAIN FEATURES	VISUAL ILLUSTRATION
Lunar surface	• Lunar Outpost Inc • Piping system • Autonomous robotic “tankers”	Moving the product from the processing and storage facilities to a landing site for distribution to customers	
Lunar surface to orbit	• To L1: CSDC’s Moon shuttle • To LEO Space tugs equipped with landing legs	CSDC’s reusable LO2/LH2 Moon shuttle is sized to deliver 25 mT from EML1 to the Moon’s surface and return without refueling	
In space storage and distribution	ULA –ADVANCED CENTAUR: Cislunar Transfer Stage	Reusable lunar ISRU propellant transport based on hydrogen and oxygen	

PROPELLANTS DELIVERING SEQUENCE

Lift-off from lunar surface → docking with the depot → fluids transfer → returning to lunar surface

Source: Sowers

ECONOMIC SUSTAINABILY ANALYSIS -METHODOLOGY

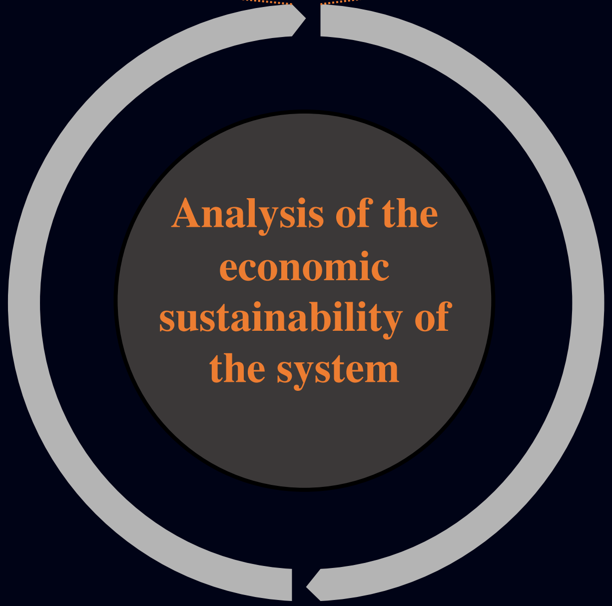
Strategic analysis

Internal environment

- Operating costs
- Investment costs

External environment

- Customers
- Competition arena



Financial analysis

Risk analysis

- Construction and operational phase

Project cash flow

- Estimation of operating cashflow

Capital structure and valuation

- WACC and NPV and IRR valuation

Scenario and simulation analysis

- Sensitivity analysis and Monte Carlo simulation

CONCLUSIONS

- POSSIBILE ARCHITECTURES:

  different technical options for propellant distribution and storage → HEAVY-LIFT

  → DEPOT → SELECTED AS OPTIMAL SOLUTION

- MOON MINED PROPELLANTS: A FUNDAMENTAL RESOURCE TO SUPPORT AND ENCOURAGE FUTURE MISSIONS

- ECONOMIC SUSTAINABILITY ANALYSIS

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