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LUNAR PROPELLANT FACTORY MISSION DESIGN TO SUSTAIN FUTURE HUMAN EXPLORATION

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The International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER) is the standard document reflecting the current focus of the leading space agencies that envision space exploration missions beyond Low Earth Orbit (LEO), returning to the Moon and going to Mars in the upcoming years. The roadmap showcases the Moon as a stepping-stone for further human space exploration, by setting up a sustainable space infrastructure on its surface an orbit. Inspired from this vision, we present the result of a phase A study about a lunar propellant factory near the Shackleton south-pole crater relying on In-Situ Resources Utilization (ISRU) to produce and sell Liquid Oxygen (LOX) on the moon surface and in orbit. The overall timeline of the mission is in line with the ISECG exploration roadmap Moon phase, based on realistic technologies of advanced-enough Technology Readiness Levels (TRL). It is a second iteration on the Lunar Propellant Outpost (LUPO) mission architecture, presented during IAC 2018. We preserved and reviewed the original building blocks (Habitats, Crew Mobility Elements, ISRU Facilities, and Lunar Spaceport) of the LUPO mission architecture, and further improved the mission design, supported by trade-off analysis on different mission scenarios. An extensive analysis and optimisation have been performed on ISRU processes and surface electrical power management, the core of our infrastructure. The mission architecture also includes crew on the lunar surface, so life support systems and habitat, as well as operations concepts, have been studied in-depth, and a synthesis of all results is presented. The main aim of this iteration was to improve and refine the baseline infrastructural and technological design architecture of LUPO and reflect on missions going beyond the Moon by providing refuelling services, with sustainability and economic viability in mind.

I. INTRODUCTION

The renewed interest in space, sustained by ground-breaking innovations and new bursts of ambition, is taking the space industry to the edge of a revolution. The active involvement of the private sector by the public institutions paved the ground for what has been defined as the New Space Economy. This spirit underlies the Lunar Propellant Outpost (LUPO) mission's ultimate goal of producing propellant on the Moon to support exploration missions.

Developing In-Situ Resource Utilisation (ISRU) capabilities on the Moon will enable not only the possibility of more extended stays there but also unlock easier, cheaper access to further destinations in the Solar System. LUPO aims to identify the key technologies that need to be studied and propose an architecture capable of achieving these goals.

Overview of the Project

The project presented in this paper is the second iteration of LUPO, carried out by the team in the 11th edition of the Space Exploration and Development Systems (SEEDS) programme. LUPO was initially developed by the 10th edition of SEEDS [1], and this iteration aims to improve and refine the baseline architecture.

This paper will summarise the changes implemented on the different segments, and the philosophy behind these modifications.

Mission Objectives

This project has been built from a mission statement and three primary mission objectives. The mission statement reads as follows:

> *"To produce propellant by exploiting lunar in-situ resources and utilising pre-existing systems, providing the propellant to support future human space exploration."*

The primary mission objectives were derived from this statement:

1. To produce propellant from in-situ resources.
2. To utilise pre-existing lunar proximity systems.
3. To provide propellant to support future human exploration missions.

Additionally, technology transfer for future Mars exploration mission plays an essential role in the design of the systems. LUPO's general goal is not only to fuel space exploration but also enable new technologies for further missions.

II. MARKET ANALYSIS AND DEMAND

LUPO could only be feasible if there is a certain demand for the propellant produced. Therefore, carrying out a market analysis and defining potential customers/users early on the development of the project is essential for its success.

With LUPO set to start its operations around 2035, 16 years in the future, looking for customers and quantifying the demand is not a straightforward task. This section will show the trend analysis done for future missions and how the potential demand was defined.

Global Exploration Roadmap and Future Missions

Due to the high risks and uncertainties of space exploration missions, plans are developed on a timescale of a couple of decades at maximum, with higher accuracy for the near future of 5 to 10 years. The further future is enclosed in space programs that show the direction of the path to follow rather than the single steps: a clear example of this is the Global Exploration Roadmap (GER) [2], whose updated plans until the year 2030 show how the Moon will serve as a stepping stone towards human presence on Mars.

For this reasons, little is known about official plans for missions on other planets for the operational lifetime of LUPO, that is from 2035 to 2050; still, rough predictions can be made by studying the evolution of the trends from the past to the next 10 years, taking into account that the involvement of private investors in the space sector has and will have the effect of cutting the costs of manufacturing and operations, speeding up the processes and developing new technologies. This widespread interest, moreover, will be focused on the cislunar space if a propellant facility like LUPO is established on the Moon, making a refuelling and staging strategic point available.

A study was performed on space missions with destinations to the Moon, Mars, asteroids, Lagrangian points in the Sun-Earth and Earth-Moon systems and other planets that happened or are planned in the years from 2000 to 2050 in line with the GER. This study showed that most of the missions would be directed towards Mars, the Moon or the Earth-Moon Lagrangian point 2 (EML2), while the ones towards Jupiter, Venus and asteroids might make use of flybys around the Moon or Mars so their trajectories and strategies would be harder to predict and estimate.

Tkatchova [3] identifies, among the stepping-stones towards self-sustainable markets, the commercial development of deep-space human and cargo transport vehicles and resources extraction and utilisation systems. This attention shift towards the Moon reflects in the current plans for transitioning the International Space Station into a private-driven space outpost [4]. Many other studies on the topic, like [5], also confirm how the vast majority of the insiders will target the Moon both as a destination and as a stepping-stone to Mars. All these findings led to the conclusion that there is a real interest in developing a lunar propellant outpost, and that its actual development would considerably extend and influence the forthcoming markets.

Potential Propellant Demand

The first iteration of the LUPO architecture [1] was conceived to extract the amount of water required to satisfy the needs of the lunar transfer segment. Due to water stoichiometric ratio, eight parts of oxygen are produced for every part of hydrogen. However, these substances are mixed in a 6:1 ratio to serve as the cryogenic propellant for the transfer segment. This produces an excess of two parts of oxygen every time seven parts of propellant are consumed. The derived excess liquid oxygen was sold on the surface and at the Lunar Gateway. The final amount of liquid oxygen accounted for 64 tonnes/year sold on the surface to reusable lunar landers and 17.3 tonnes/year sold at the Gateway to a Mars mission.

Based on the description given of the future markets and the potential propellant demands in space, several changes have been introduced to the demand and sales strategy upon the second iteration. The market LUPO addresses start from the assumption that at least two missions every year will go to the Moon, each of those might refuel both in orbit and on the surface, and one every two years will travel to Mars in the operational lifetime of LUPO. The production of propellant is sized on the total demand, detailed in Table 1.

Customer	Refuelling location	Propellant demand [t]	Mission rate	Average [t/year]
Lunar landers	Surface	25	2 per year	50
Lunar orbiters	On orbit	25	2 per year	50
Mars crewed missions	On orbit	300	1 every 2 years	150

Table 1: Propellant demand of the identified customers.

Pricing Strategy

For the first iteration of the project, the propellant price was determined by undercutting the cost of sending propellant to the Moon from Earth. In this second iteration, this assumption was replaced, considering that the ultimate goal of the customer is not to perform refuelling on the lunar surface or in cislunar space but to actually reach its final destination in the cheapest way. This is not the only driver in determining a space mission's final strategy, but it has been taken as the worst-case reference. The propellant prices on the lunar surface and in orbit have been thus established by undercutting by 25% the lowest cost that a customer would have to bear if it had to accomplish its mission without LUPO.

III. SYSTEM OF SYSTEMS ARCHITECTURE

To fulfil the objectives, the ISRU segment needs to operate alongside with other systems, either to support the sustainability and logistics operations or to interact with external interfaces.

Design Reference Mission (DRM)

The systems are divided into three segments: Lunar ISRU Segment, Lunar Surface Infrastructure, and Lunar Transfer Segment.

The specifications and operations of the Lunar ISRU Segment will be explained in Section IV. Five different systems form this segment, which exploits the icy regolith to produce propellant: the Regolith Collection System (RCS), the Regolith Transportation System (RTS), the Propellant Production Facility (PPF), the Propellant Transportation System (PTS), and the Propellant Storage Facility (PSF).

The Lunar Surface Infrastructure includes all the surface systems that sustain the ISRU segment and fulfil secondary objectives. The systems in this segment are the Habitat, the Large Crew Rover (LCR), the Surface Power System (SPS), the Communication and Navigation Network (CNN), and the Assembly System (ASM).

Finally, the Lunar Transfer Segment includes the systems that provide a direct interface between LUPO and external entities, such as customers and the Gateway. This segment is comprised of the Spaceport, the RAPTOR, and the Crewed Transfer Vehicle (CTV).

A simplified version of the mission setup is presented in Fig. 1, highlighting some of the most important operational and functional interfaces between the blocks. The physical, mechanical, power and operational interfaces are better visualised in Fig. 2, where the elements are shown in the approximate location they shall be next to the rim of the crater. Finally, the overall mission mass and power budgets are broken down in Table 1, already including a 20% margin at a system level.

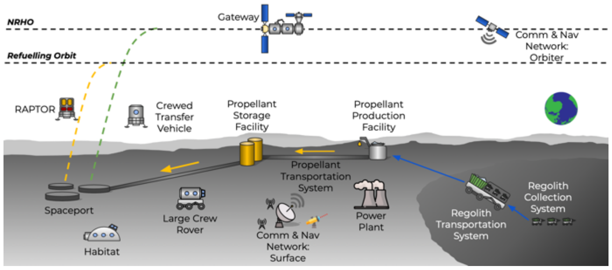

Fig. 1: LUPO's Design Reference Mission.

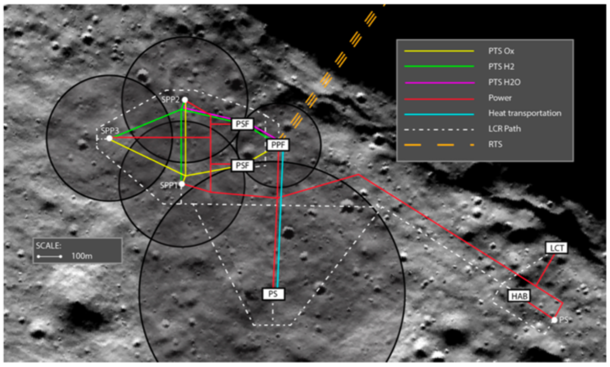

Fig. 2: Placement of most of the systems in LUPO, and their connections to each other.

System acronym	Mass at launch [tonnes]	Power [kW]
RCS	5.4	2.1
RTS	20.8	5.2
PPF	91.1	1 810.0
PTS	10.3	9.2
PSF	19.4	2.3
HAB	17.5	22.1
LCR	4.8	2.0
SPS	55.5	0.0
CNN	1.6	0.6
ASM	15.9	18.0
SPP	3.5	11.0
CTV	11.4	6.7
RAPTOR	13.8	2.2
Total	**271.0**	**1 891.4**

Table 2: Mass and power budgets for the systems included in LUPO's DRM.

External Interfaces

Like any other mission, LUPO has several external interfaces that will shape the strategies and design of the systems and their operations. Fig. 3 summarises some of the many external entities that were taken into account for the development of the project.

Two of the most critical and thoroughly studied interfaces are the customers and lunar resources. The

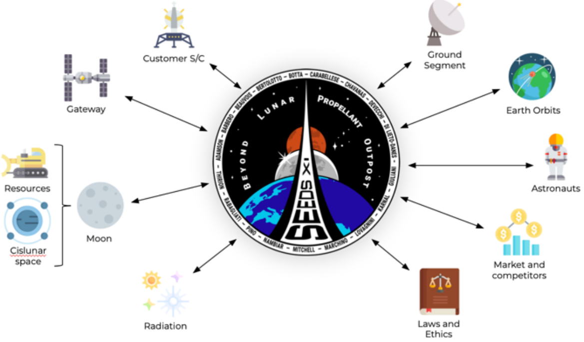

Fig. 3: External interfaces of LUPO.

customers give LUPO a purpose beyond technology demonstration, and it is essential to understand all the challenges that need to be tackled before it is possible to interact efficiently.

The second one, the lunar resources, are the core of LUPO's goal. In order to start producing propellant, we need answers to several questions, including how the icy regolith behaves and what are its properties, what technologies need to be developed to power these processes, and even if there is enough water ice for this mission to be feasible.

IV. ISRU SEGMENT SPECIFICATIONS AND OPERATIONS

As the primary objective of LUPO is to produce liquid oxygen and liquid hydrogen, ISRU operations are a fundamental part of the mission. The technical challenges of defining the specifications for the ISRU segment go beyond the hard environment of the Moon and the permanently shadowed regions of Shackleton crater. With little data on the ice content, mixture properties, regolith mechanical properties, and so on, it is almost impossible to design a system to work with this material.

The best current estimate of ice concentration in the south pole region comes from the analysis done by Li et al. (2018) [6] with data coming from the Moon Mineralogy Mapper (M^3) instrument on Chandrayaan-1. Even though this estimate is undoubtedly helpful, it is not enough, as it only covers the surface concentration (top 2 mm). Through all these missing data, we identified the need for a precursor mission, which will be described in Section VIII.

ISRU Process and Nominal Operations

Each of the building blocks in the ISRU segment has its nominal concept of operations defined. All the nominal operations are fully autonomous, and the systems have the capability of being teleoperated in the case of contingency.

The ISRU operations start with RCS, comprised of a swarm of 29 rovers based on the Regolith Advanced Surface Systems Operations Robots (RASSOR), developed by NASA [7]. The RCS gets carried to Shackleton crater by the RTS, formed by a carriage (designed to transport the RCS on a platform and the icy regolith in a container) and winding mechanism.

At the start of the working day, the swarm of rovers are locked in position on top of the carriage platform inside the PPF, close to the edge of the crater. The carriage moves to the rim of the crater and descends along the slope. Upon reaching the mining area, the carriage's ramp opens to assist the RCS to disembark from the platform, and to proceed with the mining operations. Once the rovers' regolith-carrying capability (150 kg) is reached, it returns to the carriage and unloads the regolith into the container. These operations are repeated until the required regolith is mined, or the regolith capacity of the carriage (11,400 kg) is met.

Once the shift finishes, the rovers gather back on top of the RTS platform, and the carriage is pulled up to the PPF with the help of the winding mechanism. The carriage stops above the unloading area of the PPF and opens its container full of regolith. The carriage and the rovers must recharge in a wireless charging process, which lasts 5 and 8 hours, respectively.

The PPF, formed by six blocks, is where the water gets extracted from the icy regolith. Its operations are continuous unless the facility is shut down for maintenance.

The carriage unloads the material inside a buffer container, where the regolith is then lifted and poured into the hopper, which regulates the regolith flowrate into the heating cylinder. The material gradually flows down, as the ice gets sublimated into water vapour. In this process, the water is heated up using the excess thermal energy from the SPS's nuclear reactors. In the end, the dry regolith is dumped at the open end of the cylinder into a disposal chamber.

The water vapour is collected into a pressurised area with the help of a vacuum pump, where it is condensed. The water is filtered, and some are directly sent to the storage facility, in order to be used in the ECLSS for the habitat. The rest is sent to the electrolysis chamber, where water is separated into hydrogen and oxygen.

The gases are purified from any contaminants before beginning the cryocooling phase. Two cooling stages are necessary to bring the oxygen down to 90 K, while three are required for hydrogen to reach 20 K. The first two phases are shared by both gases; during the first one, they are cooled from 353K to 150K using radiators. The dimensions of the radiators are different for each propellant due to their different thermal properties. In the second stage, a reverse Brayton cycle is used to reduce the temperature of the oxygen to its condensation temperature of 90K, and the temperature of the hydrogen to 25K. The final cooling stage for the hydrogen is achieved by a scaled version of NASA's 20W 20K cryocooler.

The liquid propellant is transferred to the PSF via the PTS, a set of 2350 metres of cryogenically cooled pipelines. The propellant is kept at cryogenic temperatures until required for the transfer vehicles or sale.

More details on the ISRU process and operations can be found in [8].

Scaling the Propellant Production

A significant difference in the ISRU segment with respect to the first iteration is the modular approach. As already mentioned before, several uncertainties make the scaling of the Propellant Production Facility and its associated systems challenging. Therefore, in order to reduce the risk and impact of these unknowns and to produce a design that could be used in the case of a change in the assumptions, some parts of the production were separated into modules.

Water Separation Modules

The Water Separation Modules (WSM) are based on the design of fluidised bed dryers [9], whose schematic is presented in Fig. 4.

The ideal thermal power required for the WSMs is found to be 97.1 kWt from the performance requirements and the equivalent specific heat of the icy regolith. However, due to the actual behaviour of the regolith, the heat exchangers of the WSMs shall provide 142 kWt, while the block requires a maximum peak thermal power of 252 kWt.

Each WSM processes 88 kg of icy regolith in 9 minutes, extracting 12.5 kg of water in each cycle. These modules do not operate continuously, so additional time for contingency should be added. In LUPO's current architecture, 3 of these modules are considered to produce 1,500 kg/day of water vapour.

Propellant Production Modules

The Propellant Production Modules (PPM) are designed to be simple and compact in order to fit two PPMs on board of a single lander. Each module is 5 m in length, 4 m width, and 2 m high (during nominal operations, with the radiators unfold). The sizing also includes an additional 30 cm micrometeoroid shielding. A schematic of a PPM is shown in Fig. 5.

Six of these PPMs are included in the current architecture of LUPO. These can condense up to 35.9 kg/hour of water vapour, of which up to 3.7 kg/hour is liquified and up to 32.2 kg/hour is electrolysed. Of these, and accounting for losses, up to 19.9 kg/hour of O_2 and 3.4 kg/hour of H_2 are cryocooled.

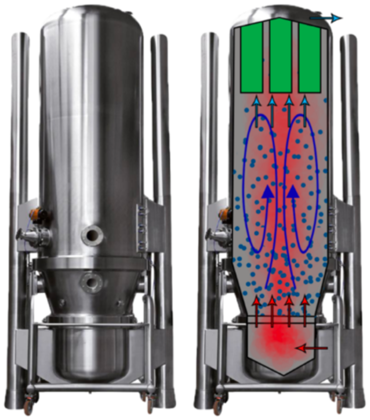

Fig. 4: Typical layout of a fluidised bed dryer. For LUPO, this system would be raised 1.5 metres above the ground to allocate the systems required for the Regolith Disposal Block.

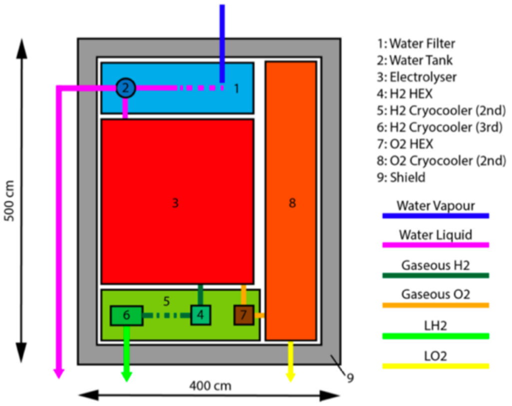

Fig. 5: Schematic showing the top view of the internal layout of a PPM. The heat pipes and connection to the external radiator are not shown.

Mining Artificial Intelligence Operations Structure

The RCS operations are autonomous, using a distributed artificial intelligence (AI) with a "follow the leader" architecture. This means that there is a "leader" rover, which will be followed by the other rovers with swarm intelligence.

Furthermore, from the data available, it is highly probable that the ice distribution in Shackleton crater is not uniform [6]. Therefore, having the RCS pre-programmed to follow the same digging route is inefficient. The options of including AI plant control selection of the route or an AI-controlled explorer rover for crater mapping were traded off against other alternatives, such as a satellite guidance network or human selection.

The winning solution was the explorer rover: this rover would autonomously explore the crater ahead of the RCS and communicate the ice distribution of several digging site locations. The appropriate site would then be selected either by the explorer rover, which could electronically flag the location to the RCS or by the AI controlling and overseeing the plant operations and management.

V. SURFACE POWER GENERATION AND DISTRIBUTION SYSTEM

Designing power systems for space applications is always a challenge. For the second iteration of LUPO, with a peak power generation requirement in the order of 2,000 kW (Table 3), such a system needs to be chosen carefully, as it would have a significant impact on the launch mass of the mission, and, therefore, the total cost.

This section will look into the Surface Power System (SPS) which will provide electrical power to the nonautonomous systems in the surface segment of the mission. It will cover the requirements for the SPS, the different power generation architectures considered and their trade-off, and the Power Management and Distribution (PMAD) system redesign.

Power Generation System

The peak power required by LUPO's surface segment is shown in Table 3. The table does not report the real power to be generated from the SPS because the losses on the powerlines must be accounted too.

The habitat has an independent solar power system, which is also employed in the first phases of the mission assembly to power the ASM. It is as well used in the contingency scenario of complete loss of the SPS to mitigate the collateral effects should the crew be present on the surface.

A preliminary technological trade-off was performed to select the most convenient architecture for power production, further explained in [10]. This trade-off compared different nuclear architectures (fuelled with High and Low Enriched Uranium, HEU and LEU, respectively) and solar power systems. The figures of merit used, and their weights are listed in Table 4.

The results of the trade-off are given in Fig. 6. The selected architecture is a nuclear configuration with LEU. The solar configurations performed poorly due to the high-power requirements, which would lead to a massive power plant. Moreover, the use of a nuclear power plant has a positive effect on the ISRU segment, enhancing the theoretical availability to 100% (and therefore reducing the mass and cost of its systems), and providing thermal power which reduces the electric power required for the water separation and condensation processes. The LEU architecture is preferable to the HEU one because of the intrinsic safety and the possibility of involving private companies into the development and operation of the system. Finally, there is a growing interest in low-power LEU nuclear reactors for Earth applications [11, 12], thus boosting the possibility of technological transfer.

The final power system employs two redundant reactors called Low-enriched Uranium Nitrate fAst Reactor (LUNAR). These are connected to two Power Conversion Systems (PCS), also for redundancy.

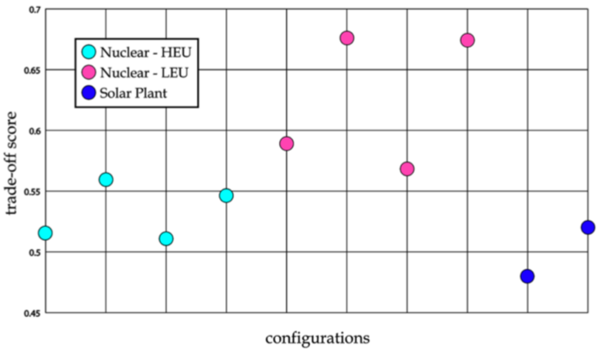

Fig. 6: Trade-off results for the selection of the power generation architecture.

Block	Peak power [kW]
Habitat	28.8
LCR	20.1
SPP	13.2
PPF	1 508.0
PSF	1.9
PTS	9.2
CNN	0.6
Total	1 582
Total + 20% margin	**1 898.4**

Table 3: Peak power required from the systems included in the LUPO Surface Segment.

Figure of merit	Weight [%]	Description
Mass	8.74	Mass of the system.
RDTE+TFU	8.74	Research, development, manufacturing, verification and integration costs.
ISRU	8.74	Cost of integration with the ISRU Segment.
Assembly	4.37	Cost of assembling the system.
TRL	5.64	Current TRL.
Technological transfer	39.15	Impact of the development for transferring the technology to the Earth, Mars, Deep Space and Nuclear Propulsion systems.
Contingency	5.66	Power reduction in case of contingency.
Safety	15.94	Safety of operations, both in space and on the lunar surface.
Maintainability	3.01	Ease of maintenance.

Table 4: Figures of merit and their weights for the power generation architecture trade-off.

LUNAR

The technology selected for LUNAR is a Fast Spectrum Reactor cooled through integrated sodium heat-pipes. The design is intrinsically failure tolerant at equipment level [13], therefore increasing the reliability and safety of the reactor. For more details on LUNAR, see [10].

Power Distribution System

As nuclear reactors are used, a safety and compatibility radius of 500 metres needs to be maintained from the SPS to all the other systems [14]. The layout selected for the PMAD, seen in Fig. 7, has an advantage in terms of mass and complexity against other configurations.

To reach the one-failure tolerance, the lines are double, with the exception of the powerline from the SPS Node to the Habitat, given that it has the autonomous solar power plant.

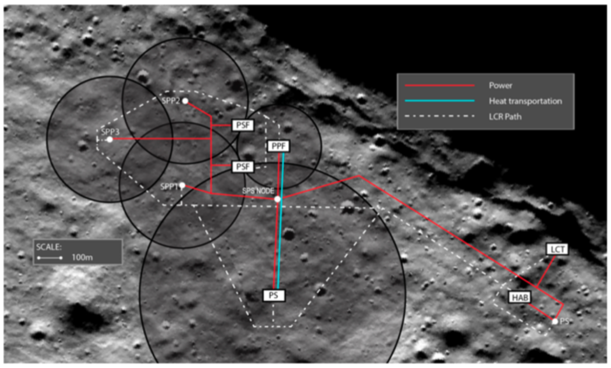

Fig. 7: Layout of the SPS, and links to other systems.

VI. REFUELLING OPERATIONS

LUPO's mission statement highlights the primary objective of refuelling for further space exploration. Then, it is crucial to analyse what is the best refuelling strategy for the targeted missions, i.e. to the Moon and Mars.

For the design of the on-orbit refuelling operations, the demand was assumed to cover the full on-orbit market. However, this is not all the propellant LUPO has to produce, as the refuelling vehicle requires propellant as well, impacting on the requirements for the ISRU segment. In order to get a feasible strategy, LUPO's side of the fuel consumption will also be taken into account for the trade-off.

Refuelling Strategies

Several strategies could be adopted for the on-orbit refuelling operations. In this project, two different concepts of operations were analysed: a single on-orbit depot, and a reusable refuelling vehicle.

The single on-orbit depot has the advantage of having a more straightforward concept of operations and being safer. On the other hand, it would limit the potential benefits of refuelling in cislunar space, as all missions would have to refuel in the same orbit.

A reusable refuelling vehicle is a substantial operational and technological challenge, as it has to refuel the customer directly in multiple refuelling operations. This vehicle requires high reusability and deals with a complex concept of operations. However, it would enable the customer to maximise the benefits of refuelling in lunar orbit, as it allows for flexibility.

These alternatives were compared in a trade-off in a concurrent design session at the CDF in ESA's ESTEC. It was decided that the reusable refuelling vehicle was the best option for the new business philosophy.

With this decision, an in-depth trajectory analysis and, afterwards, two trade-off analyses were performed to select the potential refuelling orbit/s, one for Moon customers and another for Mars ones.

Trajectory Analysis

Several families of orbits were considered to assess which orbit/s would be the best candidates for the refuelling operations: Low Lunar Orbits (LLO), Distant Retrograde Orbits (DRO), and L1/L2 Southern and Northern Halo Orbits (including Near Rectilinear Halo Orbits, NRHO).

The trajectory analysis was performed for the transfers from Low Earth Orbit (LEO) and from LLO to these candidate orbits (and back), and from these orbits to Low Mars Orbit (LMO). The results obtained were ΔV and time of flight (ToF).

Refuelling Orbits: Trade-off

In order to carry out the trade-off analyses, the figures of merit were identified, and their weights were calculated using the Group AHP method. The list is given in Table 5.

The trade-offs were done using the TOPSIS method, and an example of the results, for Moon customers, is shown in Fig. 8. For Mars customers, the results are similar. A sensitivity analysis was performed, which validated the results obtained.

It is evident that, with the criteria adopted, LLOs and small DROs are the best refuelling orbits for both Moon and Mars customers.

Case	Figure of merit	Weight [%]		Description
To Moon and Mars	ΔV to Ref. Orbit (Earth)	16.40	7.94	ΔV to the refuelling orbit from LEO.
	ΔV to Ref. Orbit (Moon surface)	13.65	8.25	ΔV to the refuelling orbit from the lunar surface.
	ToF to Ref. Orbit (Earth)	39.38	22.72	ToF to get to the refuelling orbit from LEO.
	ΔV SK	3.26	2.54	ΔV for station keeping, per year.
	Waiting Time	27.31	43.89	Measure of the time required for ref. ops.
To Mars	ΔV to Mars	N/A	14.68	ΔV to get to LMO from the refuelling orbit in 180 days.

Table 5: Figures of merit and their weights for the refuelling orbit trade-offs.

Other considerations

Even though the figures of merit adopted could be the most critical ones, several additional parameters are essential to operate in cislunar space. Some examples are risk and safety, communications, navigation and orbit determination, thermal control considerations, and other technological limitations, such as the gear ratio of the refuelling vehicle, defined in equation (1).

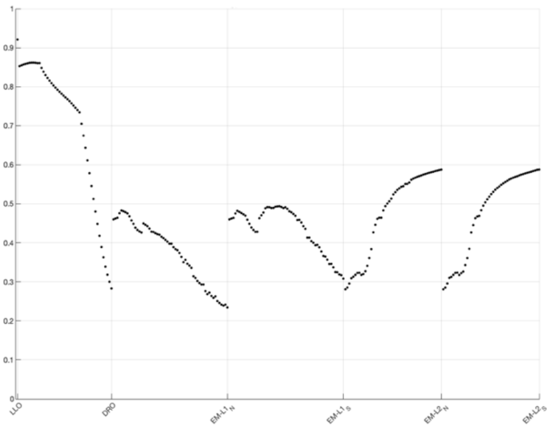

Fig. 8: Trade-off results for Moon customers.

$$GR = \frac{m_{payload}}{m_{payload} + m_{transport}} \quad (1)$$

The challenge of the orbit estimation should be tackled to allow for the rendezvous and docking operations. The current infrastructure would not be suitable for the level of precision required in order to carry out these operations safely with crewed spacecraft [15].

Defining the gear ratio of the refuelling vehicle is a way to limit fuel consumption, and, therefore, have more efficient operations. If the gear ratio were too high, LUPO would have to increase the propellant production to unfeasible levels. Therefore, it was decided that the limit gear ratio shall be 4, thus limiting the orbit range obtained from the trade-off.

Final Orbit Range

The final orbit range in which the refuelling vehicle will operate could depend on several factors. However, in this preliminary design, it was limited by the maximum gear ratio, set to 4. The limitation is plotted against different LLOs in Fig. 9, and the final orbit range is shown in Fig. 10.

Reusable Refuelling Vehicle (RAPTOR) Specifications

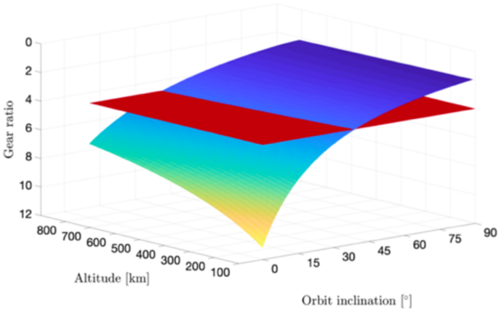

Fig. 9: Limitation of the potential refuelling orbits to achieve a GR<4.

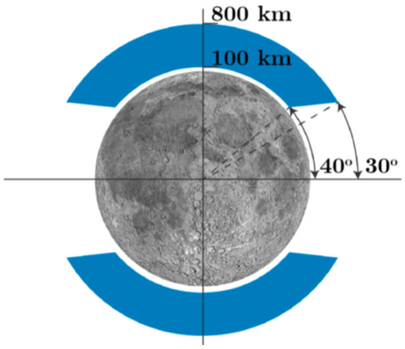

Fig. 10: Final refuelling orbits range.

The Reusable Autonomous Propellant TranspOrt Rocket (RAPTOR) was specified to carry the propellant to orbit and refuel LUPO's customers. Its constraints and requirements are based on the mission analysis, the market demand, and customers' needs.

A preliminary design was studied, which resulted in the configuration presented in Fig. 11 and the mass and power budgets in Table 6.

RAPTOR is capable of taking 20 tonnes of payload propellant to orbit per operation, following the timeline in Fig. 12. These operations shall be repeated until the customer is fully refuelled.

Subsystem	Mass [tonnes]	Power [W]
Structures	5.76	0
Mechanisms	0.34	1 057
Propulsion	2.13	0
TT&C	0.02	93
GNC	1.46	280
EPS	0.18	120
TCS	0.24	0
Total	10.14	1 557
Total with margins*	13.38	2 245

Table 6: Mass and power budget for RAPTOR. *Margins are 15% for mass and 20% for power.

Potential Benefits

Considering the ΔVs obtained for the final refuelling orbit range, and a direct transfer from LEO to Mars, it is possible to estimate the propellant mass saving when refuelling in cislunar space. As the customer will refuel, it can be assumed that the spacecraft's dry mass is lower, as it requires smaller tanks. Taking this into account, for a payload mass of 30 tonnes, the propellant mass saved by refuelling in LLO is, approximately, 10%.

VII. CREWED ELEMENTS

Whether having humans on the loop or not is beneficial (or even necessary) is a matter of debate. However, it is undeniable that there are many challenges to solve before we can put crew on the Moon for longer than three days.

In LUPO, we believe that facing these challenges will enable technologies for future crewed missions to Mars, taking full advantage of the Moon as a stepping-stone.

Fig. 11: RAPTOR vehicle configuration.

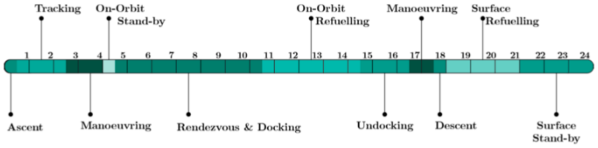

Fig. 12: RAPTOR's operations timeline.

This mission assumes a crew of four people, staying on the Moon for 30 days. They will perform maintenance on the ISRU segment and will carry out scientific experiments.

In this section, the different crewed segments and systems will be described, along with their objectives, operations, and specific challenges faced in their design.

Elements and subsystems	Open loop Mass [kg]	 Power [kW]	Semi-closed loop Mass [kg]	 Power [kW]
Habitat				
Thermal control	1 827	1.2	1 827	1.2
Structures	5 707	0	5 707	0
ECLSS	3 798	3.0	5 265	7.2
Crew equipment	1 487	2.8	1 487	2.8
Electrical power	1 943	2.6	1 943	2.6
Communications	24	0.07	24	0.07
Command & data handling	60	0.7	60	0.7
EVA	900	2.0	900	2.0
LCR	TBD	3.0	TBD	3.0
Assembly Segment	TBD	TBD	TBD	TBD
Science Segment	300	2.5	300	2.5
Support Segment	0	0	0	0
Total	**16 046**	**17.9**	**17 513**	**22.1**

Table 7: Mass and average power budgets for two ECLSS configurations, including 20% margin.

Atmosphere Selection

In order to improve the efficiency, an in-depth study on the atmospheric composition and pressure level of the crewed elements was performed. The study, described in detail in [16], had the aim of reducing the pre-breathing time while keeping at a minimum the probability of Decompression Sickness (DCS).

First, the design space was identified in the Volume Percent Oxygen vs Total Pressure plane, according to the flammability limit, the hypoxic boundary, and the normoxic equivalent. This design space is shown in green in Fig. 13.

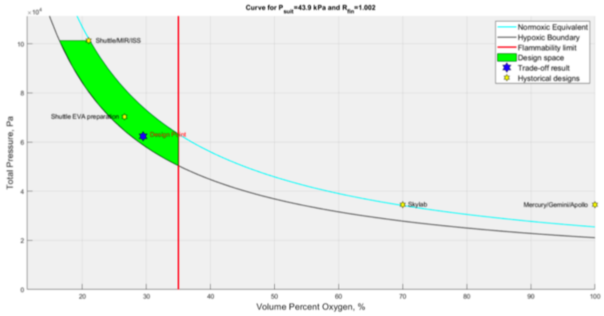

Fig. 13: Atmosphere selection trade-off solution and comparison with historical data.

Then, a methodology consisting of multi-objective optimisation coupled with multi-criteria decision analysis was used to derive the design solution. Five variables were selected: Pressure level of the modules, oxygen percentage in the modules, suit pressure, supersaturation ratio, and type of inert gas.

A cabin pressure of 62.4 kPa and a percentage of oxygen of 29.5% gave the best performance. The result also shows that an atmosphere with oxygen and neon minimises the DCS probability, also reducing the cost of the mission and eliminating the need for pre-breathing time. The suit pressure identified by the trade-off was 43.9 kPa; this result is optimal for reducing the DCS probability but arises problems with the dexterity of astronauts during EVA. Different solutions to the latter problem exist, like variable pressure suits. The final atmospheric composition and pressure level of the crewed modules is given in Table 8.

Parameter	**Value**	**Unit**
Cabin pressure	62.37	kPa
Suit pressure	43.87	kPa
Oxygen concentration	29.5	%
Supersaturation ratio	1.002	-
DCS probability	0.09	%
Pre-breathing time	0.27	minutes
Leakages	30.23	kg/s/m^2
Emergency time	9.63	minutes
Cost	6.41x10^7	$

Table 8: Atmosphere composition and pressure level of the crewed modules [16].

Even though this trade-off showed that neon is a better option than nitrogen or helium, it should be analysed further: there are no data on long-term human exposure to neon, and the absence of nitrogen may cause physiological problems. A three-gases atmosphere may be adopted, with a mixture of oxygen, neon and nitrogen.

Habitat ECLSS

Although the habitat design was kept from the work done in LUPO's first iteration [1], the ECLSS strategy was re-evaluated. The habitat is still required to support four crew members for 30 days. Additionally, a nominal mission includes 4.67 hours of EVA per day. The ECLSS changes were focused on taking advantage of the ISRU Segment as a source of consumables for the habitat.

Different configurations were analysed and compared using the Equivalent System Mass (ESM) method, and the final configuration was defined according to the break-even point. These alternatives were open loop, semi-closed loop (ISS-like technology), and closed-loop (Mars testbed). Their ESM behaviour against mission duration is plotted in Fig. 14.

The final design consists of two phases, with the budgets listed in Table 9:

1. 2033-2036: A simple configuration based on an open-loop ECLSS. All the consumables are provided, and only the necessary technologies to support life in space are carried.
2. 2036-2050: A configuration based on ISS technologies with improved performance. Water and oxygen supplies are provided by ISRU, while only a small part of consumables is sent from Earth.

The second phase exploits the in-situ resources, decreasing significantly the consumables required from Earth. Additionally, the selected technologies are based on the ones used on the ISS, improved in terms of efficiency and rate capability. It is evident that this scenario has higher hardware mass at the beginning of the mission; however, the break-even point is reached in 73 days, i.e. after three crewed missions.

	Open loop		Semi-closed loop	
	Mass [kg]	Power [kW]	Mass [kg]	Power [kW]
Needs				
Water	928	0.0	226	0.0
Oxygen	316	0.0	159	0.0
Inert gas	202	0.0	202	0.0
Food	336	0.0	336	0.0
Garments	723	0.0	723	0.0
Waste				
Water	912	0.0	78	0.0
Solid waste	274	0.0	274	0.0
Tanks	2 980	0.2	1 421	0.2
Technologies	818	2.8	3 844	7.0
Equipment	1 487	2.8	1 487	2.8
Total	**8 976**	**5.8**	**8 757**	**10.0**

Table 9: 30 days consumables and technologies, with 20% margin.

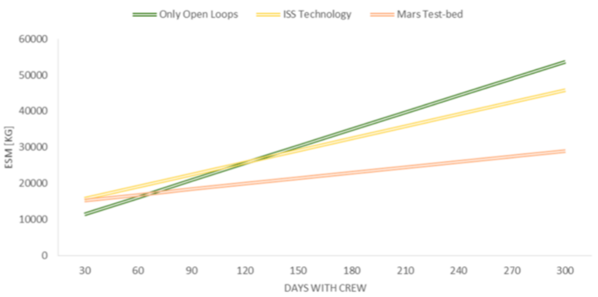

Fig. 14: Equivalent System Mass (ESM) comparison and break-even point between three ECLSS configurations.

Large Crew Rover

During the first iteration of LUPO [1], a Large Crew Rover (LCR) was already designed to support crew transfer between the spaceport and the habitat, as well as the maintenance of the lunar installations with the use of a robotic arm. Additionally, it provided EVA capabilities and mobility inside the base.

This second iteration of the LCR preserves all these features but adds the capability to conduct scientific expedition missions. One of the main drivers for this redesign is to establish a commonality of hardware between Moon and Mars missions. By doing so, development costs can be shared, resulting in an overall more cost-efficient program.

The concept of operations of the LCR was defined with the following assumptions: a crew of two people is assigned to the scientific expeditions with a maximum duration of 7 days, and an average speed of 10 km/h. The mass and power budgets are given in Table 10.

Taking into account these assumptions and all the capabilities envisioned for the LCR, the primary mission scenarios are:

1. Crew arrival on the lunar surface: The rover (automated or teleoperated) moves to the SPP to transfer the crew and cargo from the CTV.
2. Crew transportation: The rover (piloted) transports the crew from the SPP to the habitat.
3. Maintenance operations: The rover (piloted or teleoperated) is used to perform maintenance activities to LUPO's systems.
4. Science expeditions: The rover (piloted or automated) is able to perform long-range trips to enable science missions far from the habitat.
5. Rescue: In case of contingency (such as an incorrect landing site of the CTV or the RAPTOR), the rover (automated or teleoperated) moves to rescue the crew.

The rover uses a methane-oxygen internal combustion engine, providing high power to run experiments remotely from the base, and establishing even more commonality of hardware with future Mars missions. Exhaust gases are contained in a closed loop: they go through heat exchangers that control temperature inside the cabin, water is condensed and used for life support, and CO_2 is recirculated in the engine, cooled, mechanically compressed, and stored until the rover returns to the base. At the base, a system feeding from the waste CO_2, and clean water regenerates them into liquid methane and oxygen. The wastewater is treated through the habitat's regenerative systems. This rover "gas station" weights around 400 kg and requires 17 kW_e to regenerate the whole rover consumables over 3.5 days. It is a one-third scale pilot mission for the actual propellant production facility that will be needed on Mars to refill Earth-return rockets on the Martian surface.

Subsystem	Mass [kg]	Power [kW]
TCS	91	0.07
Crew Systems	374	0.10
Structure & Mechanisms	2 066	1.00
CDH	112	0.14
TT&C	39	0.05
Mobility	237	3.99
GNC	13	0.20
ECLSS	249	0.27
EPS	809	-
Total	3 989	5.82*
Total with 20% margin	4 787	-

Table 10: Mass and power budget for the LCR. *Margin already applied at subsystem level.

Crewed Transfer Vehicle

The Crewed Transfer Vehicle (CTV) transports the crew from the Gateway to LUPO's spaceport on the Moon, and back. The design has not been modified in this iteration [1], as the size of the crew and operations did not change. The only modification was the atmospheric composition and pressure levels, as discussed in previous sections.

VIII. PRECURSOR MISSION REQUIREMENTS

The need of a precursor mission has been identified during the development of the first and second iterations of LUPO. Since the poles of the Moon are vastly unexplored, there are many unknowns that make LUPO's mission even riskier. Therefore, the requirements and potential instrumentation of a precursor mission were studied. This mission was called Explorer Rover for NEar-Surface Telemetry, or ERNEST. Its mission statement is:

To determine the concentration by weight of the water ice and the mechanical properties of the regolith in the target area of the Shackleton Crater, in order to assess the scale and the architecture of the lunar ISRU operations."

From the mission statement, four primary objectives were derived:

1. To determine the concentration by weight of the water ice in the target area of the Shackleton Crater.
2. To determine the mechanical properties of the regolith in the PSRs.
3. To assess the scale of the lunar ISRU operations.
4. To assess the architecture of the lunar ISRU operations.

The next sections will describe what criticalities of LUPO's mission shall be address with ERNEST and the instrumentation that could achieve these goals.

Criticalities

As stated in Section IV, the viability of LUPO's propellant production is currently based on data from the M^3 instrument, and the analysis done by Li et al. (2018) [6]. This study identified a water ice concentration in the Shackleton crater regolith of between 5%wt and 20%wt, with an expected average of 15%wt at the surface. This data has severe limitations, however, with the instrument only capable of measuring ice content in the top 2 mm of regolith.

Additionally, the mechanical properties of the regolith are unknown. These are also extremely hard to approximate, due to the uncertainty on the ice content and the mixture properties.

A list of the most critical factors for LUPO is given in Table 11. ERNEST aims to answer some of these questions, lowering the risks for LUPO's mission.

Importance	Critical factor	Relevant system/segment
High	1. Ice concentration by weight in the target volume	PPF & RCS
	2. Regolith mechanical properties	RCS
Medium	3. Spatial distribution as a function of depth	RCS
	4. Spatial distribution as a function of position	RCS
	5. Volatile purity	PPF
Low	6. Validation of radiation models	Habitat & LCR
	7. Mineralogy	Potential ISRU
	8. Regolith and ice grain sizes	Potential ISRU

Table 11: LUPO criticalities rated by importance.

Instrumentation

A preliminary analysis of the instrumentation was performed, considering different techniques in order to address each of the science goals listed in Table 11. A small selection of the most promising options is summarised in Table 12, with their suitability to the science goals on a qualitative scale of 0-1 (1 = technique can fulfil the goal, 0 = technique cannot address goal). The final column shows the weighted total of each instrument's scores, with science goals 1 and 2 weighted with a factor of 3; goals 3 to 5 with a factor of 2; and goals 6 to 8 with a factor of 1. These factors are considered as a first approximation and could be refined in a future analysis.

Precisely which instruments shall be included in a final version of ERNEST is dependent on which science goal are to be addressed. However, the score provided in Table 12 can give a first indication as to the versatility of an instrument.

Instruments	High		Medium			Low			Score
	1	2	3	4	5	6	7	8	
IR reflectance spectrometer (drill)	1	0	1	1	½	1	¼	½	9.75
IR reflectance spectrometer (drill + load sensors)	1	½	1	1	½	1	¼	½	11.25
Pressuremeter	0	1	0	0	0	0	0	½	3.5
Piezocone meter	0	1	0	0	0	0	0	½	3.5
Raman spectroscopy	1	0	1	1	1	1	¼	½	10.75
Laser induced breakdown spectroscopy (drill)	1	0	1	1	1	1	¼	0	10.25
Laser induced breakdown spectroscopy (drill + load sensors)	1	½	1	1	1	1	¼	0	11.75

Table 12: Matrix showing a selection of the instruments considered, along with their suitability for each science goal (numbered according to Table 11).

Operations

ERNEST's operations start when it egresses from the lander, and it drives from the landing spot to the rim of the crater. Then, it enters the PSR and continues driving to the target area, where it will take the first sample.

The sampling operations, described in the second half of the timeline in Fig. 15, will be repeated until the target number of samples is met. In this preliminary design, the goal is to take 27 samples.

IX. COST ANALYSIS

For this second iteration of LUPO, a bottom-up approach has been chosen: all building blocks were designed, and then a cost model based on their components and subsystems mass was used to evaluate the cost of development and operations for each building block. The USCM, AMCM, and NAFCOM99 models have been used. These cost models, based on historical data, do not fully capture the revolution of new space currently happening that makes space hardware cheaper and smaller, so they are not to be considered as final values [5]. The estimated costs of the various building blocks are listed in Table 13.

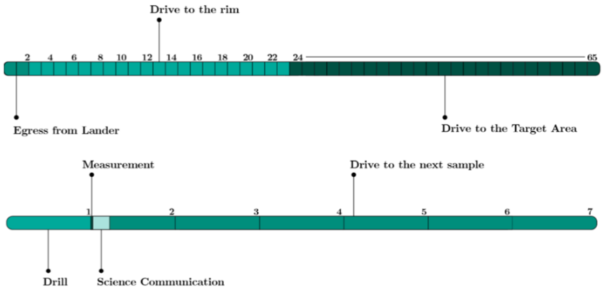

Fig. 15: Operations timeline of ERNEST in hours. The second part of the timeline corresponds to the sampling phase, and it is repeated 27 times.

The spending timeline has been optimised to start producing propellant in 2035, as shown in Fig. 16, but still delaying as much as possible any spending past the start of operations of the precursor mission, ERNEST, to reduce investment risks. The cost analysis is further developed in [17].

Element	Model	Def. + Impl. Cost	Assembly Cost	Ops. Cost
ERNEST	Best Guess	1 800.0	10.0	11.0
ASM/MANE	AMCM	2 000.0	107.4	106.8
ASM/FANGS	AMCM	2 700.0	18.3	249.5
ASM/PAWS	AMCM	1 000.0	6.9	117.8
Power/Solar + PMAD	USCM7	1 500.0	286.3	858.9
CNN/Orbiter	USCM8	379.4	3.0	280.5
CNN/Surface	USCM7	238.8	36.2	156.2
ATT	USCM7	697.8	24.2	65.5
MLR	USCM7	236.3	8.6	2.2
PTS	USCM7	146.1	11.6	59.6
Habitat	USCM7	3 500.0	20.4	380.2
LCR	USCM7	2 200.0	13.8	293.9
Power/Nuclear	NAFCOM 99	14 400.0	1 200.0	7 200.0
PSF	USCM7	1 400.0	224.7	647.1
RCS	AMCM	4 700.0	87.0	2 100.0
RTS	AMCM	8 000.0	346.2	3 600.0
PPF	NAFCOM 99	11 800.0	2 800.0	6 600.0
CTV	USCM8	3 000.0	17.7	245.4
RAPTOR	USCM7	3 500.0	4.9	29.2
Habitat upgrade	USCM7	1 500.0	10.5	201.8
Launches and landings				17 800.0
Logistics				12 000.0
Astronauts				9 000.0
Total				**127 000.0**

Table 13: Cost structure. Values expressed in FY2018 M$.

Business Case

From the market analysis, the total yearly revenue from propellant should be around 3.5B$, or 52.5B$ over 15 years of operations. For such a risky business, investment over 30 years should return ten times the initial investment. A budget of around 5B$ is, therefore, the target. Compared to the estimated 127B$ using cost models and optimistic assumptions for the logistics of delivery to the Moon surface, that does not seem feasible, even considering tuning down the output from the cost model estimates.

An additional crucial point for the business model is that investing for 30 years in a given lunar infrastructure aiming to undercut propellant prices by 25% somewhere in space versus delivering it from Earth, is betting that Earth launch costs will not fall by more than 25% over 30 years. Otherwise, LUPO would not be selling cheap enough to attract customers of lunar-made propellant. Given the current trend of the space launch industry, that would be a dangerous bet, and investors probably would be asking for a higher risk premium, resulting in an even lower initial budget to accomplish the mission.

An alternative financing scheme organised around a public-private programme has been investigated. Under such organisation, public agencies would be financing the lunar infrastructures (set-up elements, habitat, rover, landers) while a private entity would be financing the ISRU and power generation segments (as ISRU is driving 99% of the power requirements). Assuming an 8-fold cost reduction versus cost models, as has been achieved SpaceX new hardware development costs [18], the initial investment would be around 25B$ for the private company, for a 52.5B$ revenue. The target return on investment and coverage of risk is still not achieved.

To improve their potential profitability, a private lunar propellant production company should focus on the high-margin surface market, like the one of refilling reusable Moon shuttles. Delivering propellant to orbit oversizes the infrastructure because lifting propellant to orbit requires propellant itself, and propellant can be sold for less in orbit because it is closer to Earth in terms of velocity change. Agencies should, therefore, focus on sponsoring the development of a large lunar surface base to foster the development of a sustainable private economy based on the utilisation of lunar resources.

X. PROJECT TIMELINE AND LOGISTICS

LUPO's mission is expected to be operational by 2035, although not at full capacity, due to the implementation of several modules for the ISRU segment continuing until 2036. The aim of spreading out in time the setup phase is to reduce the risk for the investments. The detailed timeline is given in Fig. 16.

Setup Phase Logistics

The setup phase is planned to follow five steps:

1. 2032: the ASM, CNN, SPP, PTS, and part of the SPS are launched. The ASM starts the surface assembly operations. Priority is given to the CNN and the solar power system for the habitat, which, together with the complete PMAD of the SPS, will provide electrical power to FANGS and the surface segment of the CNN. At this point, astronauts can only descent to the surface using systems outside LUPO's architecture.
2. 2033: the habitat and LCR are launched. The habitat is equipped with open-loop ECLSS technologies to simplify the initial setup.
3. 2034: the first ISRU block is launched together with the rest of the SPS. It includes one extraction, transportation, collection, and water separation line, two MMPs, and one tank for each fluid. It also includes the two LUNAR, the PCS, and the pipeline to transfer the thermal power to the WSM. At the end of this year, the PPF shall become operative together with the PTS. Finally, the first pad of the SPP shall be completed.
4. 2035: the second ISRU block is launched. The production is now enough to sustain the operations of the CTV twice a year. The second ISRU block shall be operative before the end of the year.
5. 2036: the third and final ISRU block is launched. The production is now sufficient to enable on-orbit refuelling operations. Thus, RAPTOR is launched and starts performing test operations. The final upgrade of the habitat is also launched to provide the equipment to switch to a semi-closed loop ECLSS. By the start of 2037, the mission setup is complete.

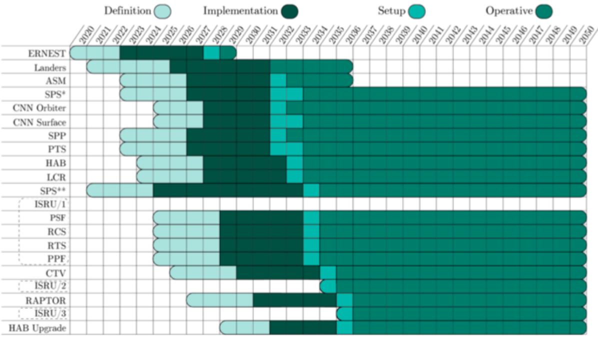

Fig. 16: Detailed timeline of the mission architecture. *Includes the PMAD and the solar plant for the habitat. **Includes the LUNAR reactors, the PCS, and the radiators.

Launch Strategy

During the first iteration, the setup phase was achieved with an upgraded version of SpaceX's Falcon Heavy [1]. Although it could be theoretically possible for SpaceX to provide such a system, it seems unlikely due to their efforts to push the development of the BFR (Super Heavy and Starship). Therefore, in this second iteration, the selected launch vehicle is BFR, taking advantage of its cost and capabilities.

The following assumptions were made to perform the

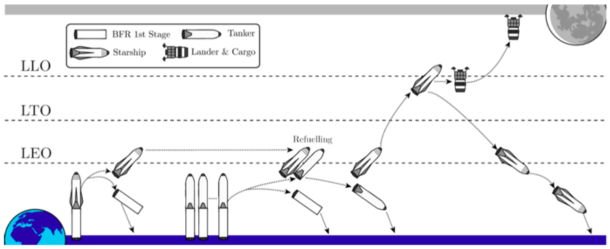

Fig. 17: Schematics of the standard launch strategy during the Setup Phase.

launch strategy analysis:

- There is full availability of BFR launches during the timeframe of interest.
- BFR's first stage is completely reusable and able to lift to LEO either Starship or a tanker-like system added to the 150 tonnes of payload.
- A reusable Starship is used as a cargo delivery system for the space segment.
- The dry mass of the landers and service module are constant regardless of their payloads.

The specifications assumed for the BFR and Starship are listed in Table 14. The landers (expendable) are sized following the same assumptions as of the first iteration, leading to the parameters listed in Table 15.

The launches schematic is shown in Fig. 17.

Parameter	**Value**
Dry mass	85 t
Maximum payload to LEO	150 t
Fairing volume	850 m^3
Propellant	LOX/CH4 (mixture ratio 1:3.8)
Maximum tank capacity	1,100 t
Specific impulse	380 s
Cost per launch	300M$

Table 14: Specification assumed for the BFR, the launch vehicle selected for the launch strategy.

Parameter	**Value**
Maximum payload	17.2 t (defined by LUNAR)
Dry mass to propellant ratio	15 %
Specific impulse	310 s

Table 15: Specification assumed for the landers.

Setup Traffic Plan

The traffic plan for the setup phase is designed to tackle the incremental strategy described previously. It is presented in Table 16.

Year	**Systems**	**Mass [t]**	**LEO Refuel**	**Land.**	**Cost [M$]**
2032	ASM, CNN, SPP, PTS, SPS[1]	42.6	4	4	2 771
2033	HAB[2], LCR	20.8	2	2	1 536
2034	SPS[3]	42.3	3	3	2 154
	PSF (LH2 tank)	3.4	0	1	618
	PSF (LOX and water tanks)	3.4	0	1	618
	ISRU (1)[4]	46.0	4	4	2 771
2035	CTV	11.4	0	0	300
	PSF (LH2 tank)	3.4	0	1	618
	PSF (LOX and water tanks)	3.4	0	1	618
	ISRU (2)[5]	35.7	3	3	2 154
2036	RAPTOR	13.8	0	0	300
	PSF (LH2 tank)	3.4	0	1	618
	PSF (LOX tank)	2.6	0	1	618
	ISRU (3)[5], HAB[6]	37.1	3	3	2 154
Total			**18**	**25**	**17 847**

[1] Solar plant for the habitat and PMAD.
[2] Habitat with open-loop ECLSS equipment.
[3] LUNAR, PCS and radiators.
[4] One extraction, transportation, collection, and water separation line, heat transport pipeline, and two PPMs.
[5] Same as ISRU (1) but without the heat transport pipelines.
[6] Equipment to upgrade the habitat to semi-closed loop ECLSS.

Table 16: Traffic plan during LUPO's Setup Phase. Each line represents a single Starship launch.

XI. CONCLUSIONS

A second iteration of the LUPO project presented during the IAC 2018 was carried out by the SEEDS-XI team. The most critical aspects and building blocks of the infrastructure were thoroughly revised, and several optimisations and changes were introduced, bringing a deeper level of detail to the architecture. These updates were driven by a new vision for LUPO, embracing both the related business challenges and opportunities, as well as by the strategic value of the mission for future Mars exploration.

An investigation of the future economy emerging from the renewed interests and capabilities in space transport and resources utilisation led to a considerable increase in the propellant demand forecasts. Additionally, the propellant pricing strategy changed, and the suggested prices were strongly decreased.

A detailed analysis of the optimal refuelling location identified a family of Keplerian circular lunar orbits where this critical operation can be performed in the most time- and propellant-effective way. A dedicated refuelling vehicle, RAPTOR, refuels the customer's spacecraft in these selected orbits. This new strategy led to exclude the Gateway from the on-orbit propellant distribution strategy. Furthermore, the trajectories study revealed moderate propellant saving can be achieved for large payload mission headed to Mars if refuelling in lunar orbit is included.

The updated propellant demand set a new productivity goal for the ISRU segment, whose design was also impacted by other factors. The scale-up in demand also required a drastic change in the primary power source of the outpost, which has been turned from solar into nuclear. Finally, the ISRU segment was reconfigured to be modular, and to have its capabilities and performances increased gradually throughout the mission. This design choice reduces the risks and optimises costs and operations.

Special attention was paid to resources availability, as it has an enabling role in the whole mission. The requirements for a precursor mission, ERNEST, were defined to shed light on the current uncertainties on water concentration and subsurface ice distribution in the designated excavation zone.

With a less risky and optimised ISRU segment and propellant distribution strategy, the economic implications were explored to reassess the potential of such propellant outpost to be profitable. This investigation revealed how the real value of LUPO can be fully exploited by leveraging the surface market while promoting Moon development, relying on solid and wide public-private partnerships.

Behind the complex and difficult economic scenario, however, the value of LUPO for the advancement of human and robotic exploration has been magnified. During the various trade-offs, special attention was dedicated to the technology transfer for applications on Mars. The Large Crew Rover, now running on methane and utilising a Sabatier reactor for the recycling of the carbon dioxide, is a perfect test for this type of propulsion that will be fundamental on Mars, with its CO2-rich atmosphere. The need of a high-power nuclear power plant will push towards breakthrough technologies and operational insight for space-rated high temperature reactors. The crewed missions to Mars were the core of the market analysis that shaped the whole architecture. The ECLSS for the crewed habitat was designed to be gradually evolved into a Mars testbed, implementing bioregenerative technologies relevant for long-duration human missions on the Red Planet.

Overall, LUPO was improved in this second iteration to not only fuel space exploration but to serve as a technology demonstrator, enabling future missions to further destinations.

XII. REFERENCES

[1] Guardabasso et al. (2018) ‘Lunar Outpost Sustaining Human Space Exploration by Utilizing In-Situ Resources with a Focus on Propellant Production’, *69th International Astronautical Congress (IAC)*.

[2] International Space Exploration Coordination Group (2018) *The Global Exploration Roadmap*.

[3] Tkatchova S (2017) *Emerging Space Markets*.

[4] NASA (2018) ‘International Space Station Transition Report’. Technical report.

[5] Kornuta et al. (2018) Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production.

[6] Li et al. (2018) ‘Direct Evidence of Surface Exposed Water Ice in the Lunar Polar Regions’, *Proceedings of the National Academy of Sciences (PNAS)*, Vol. 115(36), pp. 8907-8912.

[7] Mueller et al. (2013) ‘Regolith Advanced Surface Systems Operations Robot (RASSOR)’, *IEEE Aerospace Conference*.

[8] Rabagliati et al. (2019) ‘Regolith Mining in Shackleton Crater: Propellant, Building Materials and Vital Resources Production for a Long Duration Manned Mission’, *70th International Astronautical Congress (IAC)*.

[9] VDI Gesellschaft (2010) *VDI Heat Atlas*.

[10] Lovagnini A and Barbero D (2019) ‘Systems Architecture for Power Generation, Management and Maintenance of a Nuclear Plant on the Lunar Surface for In-Situ Resource Utilization’, *70th International Astronautical Congress (IAC)*.

[11] McClure P (2015) ‘Design of Megawatt Power Level Heat Pipe Reactors’. Technical report, Los Alamos National Laboratory.

[12] Arafat Y and Van Wyk J (2019, March-April) ‘eVinci^{TM} Micro Reactor’, *Nuclear Plant Journal*, pp. 34-37.

[13] Poston et al. (2019) ‘Results of the KRUSTY Nuclear System Test’, *Nuclear and Emerging Technologies for Space Proceedings 2019*.

[14] Mason LS (2006) ‘A Comparison of Fission Power System Options for Lunar and Mars Surface Applications’, *AIP Conference Proceedings*, Vol. 813(1), pp. 270-280.

[15] Davis et al. (2017) ‘Orbit Maintenance and Navigation of Human Spacecraft at Cislunar Near Rectilinear Halo Orbits’, *27th AAS/AIAA Space Flight Mechanics Meeting*.

[16] Barbero et al. (2019) ‘Atmosphere Selection of Lunar Surface Modules to Minimise Decompression Sickness Probability and Improve Crew Performance During EVAs’, *40th Annual Meeting of the ISGP and Space Life Science and Medicine Meeting*.

[17] Pino et al. (2019) ‘Business Model for a Long Duration Manned Lunar Mission: Refuelling, Resource Commercialisation and New Revenue Streams’, *70th International Astronautical Congress (IAC)*.

[18] Zapata E (2017) ‘An Assessment of Cost Improvements in the NASA COTS/CRS Program and Implications for Future NASA Missions’, *AAIA Space 2017 Conference*.