The COLOSSUS Lunar LANDER: A Sky Crane inspired Moon lander providing horizontal and vertical mobility for crew and cargo.

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Executive summary

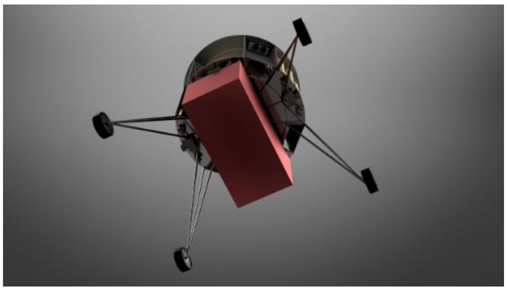
Figure 1 Colossus Lunar Lander

Designing a viable Lunar Lander required the cooperation of thousands of talented engineers and program managers during the Apollo Era. Since I am an army of one, I decided to limit the scope of my competition entry trying to converge on a viable Lunar Lander configuration.

Our design process started by looking intensely at the capabilities of the Apollo Moon Lander and what we could find regarding the proposed Altair Lander of the defunct NASA constellation program. We saw things we liked and did not. Mass is still a severe limitation since the Moon has not changed its orbit nor distance since the 1960'ies. Nor have the laws of physics and orbital mechanics changed. Nevertheless, we are seeing, for the first in multiple decades, real signs of an international cadre and design effort to build out a space infrastructure, not only in LEO but also around and on the surface of the Moon.

We believe that the enabling propellant depots will finally become available at multiple locations in Cislunar space, due to the enormous advantages they offer in reducing the propellant cost in our local neighborhood in the solar system. Large systems like the reusable SpaceX BFR promise to have the operational economics to play an important role in making this possible. In this context, we found a way to converge on a design which is capable of benefiting from the future Ariane 64 or the current affordable commercial capabilities (e.g. SpaceX FH) and has a lot of payload growth potential for the future.

We converged on a design that is as pragmatic as possible and spent less time worrying about design esthetics or a detailed engine study. Aspects that are both badly needed, essential but outside of the scope we had to set ourselves.

Description:

We named our Moon Lander Colossus, after the Colossus of Rhodes, who supposedly had one foot on either side of the harbor mouth.

At just under seven meters tall, seven meters wide and with a center body diameter of 457 cm, 300 cm high, our Moon Lander fits perfectly inside of an Ariane 64 fairing, or BFR or SLS, when its landing gear is folded inwards.

We consistently depict our vehicle without solar panels (e.g. ATV derived) and side blankets (thermal insulation) to show all relevant core structural elements.

Colossus carries payload and propellant tanks on all sides. As a versatile cargo and crew ferry vehicle it offers horizontal and vertical mobility. As a single engine stage configuration that leaves propellant drop tanks behind on the surface, it avoids splitting the vehicle into a heavy descent stage and a light ascent stage. This saves costs.

A 298 cm diameter, 3 m high inflatable crew compartment sits in the center of the lander and is surrounded by a cylindrical volume composed of multiple toroidal tanks. On the outside of these toroidal tanks we have ledges that offer real estate for science equipment, gear, ladders or extra propellant tanks. The Crew Inflatable (CI), is nested inside of a Toroidal Cryogenic Tank Farm (TF). Both rest on top of a Cargo Sling Deck (CS) and inside of an annulus shaped Observation Deck (OD) at the top. The OD housing does not stretch over the CI and TF. An Aerogel-Kevlar Liner separates the CI and TF and serves as a thermal barrier and spall liner (AL). Both the CI and TF can move freely and can be lifted out of the annulus formed by the OD during missions in space or at very late stages in the manufacturing process.

At the bottom of the CS deck extra reinforcement rings form a sparse load bearing structure grid. This stiff structure accepts all loads in tension, torsion and compression. A Reaction Control System (RCS) is attached to the bottom of the CS. The OD and CS are held together by Struts, grouped to form four Engine boxes. Lined with heat resistant material, they accept the loads on the Observation deck and pass them through to the CS and landing gear.

Since we conceptualized the lander as a Sky Crane capable of hovering at ground level, any landing gear do not have to support heavy impact forces and could be equipped with wheels. Many viable alternative light weight configurations exist for both wheels and landing gear suspension. To pick the most versatile one that excels in low weight is a study in itself. We chose to image a simple triangular gear as a place holder. Both RCS and the electric wheels play a role in the attitude control. The wheels save RCS propellant when assuming this role.

The main engines are placed at the top of the vehicle. This enables us to land even without a landing gear; if so desired. When equipped with a landing gear with sufficient ground clearance, Colossus can transport slung cargo. The image above shows a ground clearance of 3,4 meters. Since a high ground clearance is useful in many operational scenarios (see below), an even higher ground clearance (e.g. 7 meters) would be better still.

For scale and reference, the red cargo box has dimensions of 2*2*4 meters. Instead of a cargo box, slightly larger dimensioned cryogenic propellant drop tanks which can be repurposed as a habitat (the so-called wet habitat concept) could be transported in this manner.

The entire vehicle (without a cargo box), weighs ~2000kg or less, depending on whether or not you include EVA spacesuits and consumables (e.g. 150kg water, clothing etc.).

Document Information

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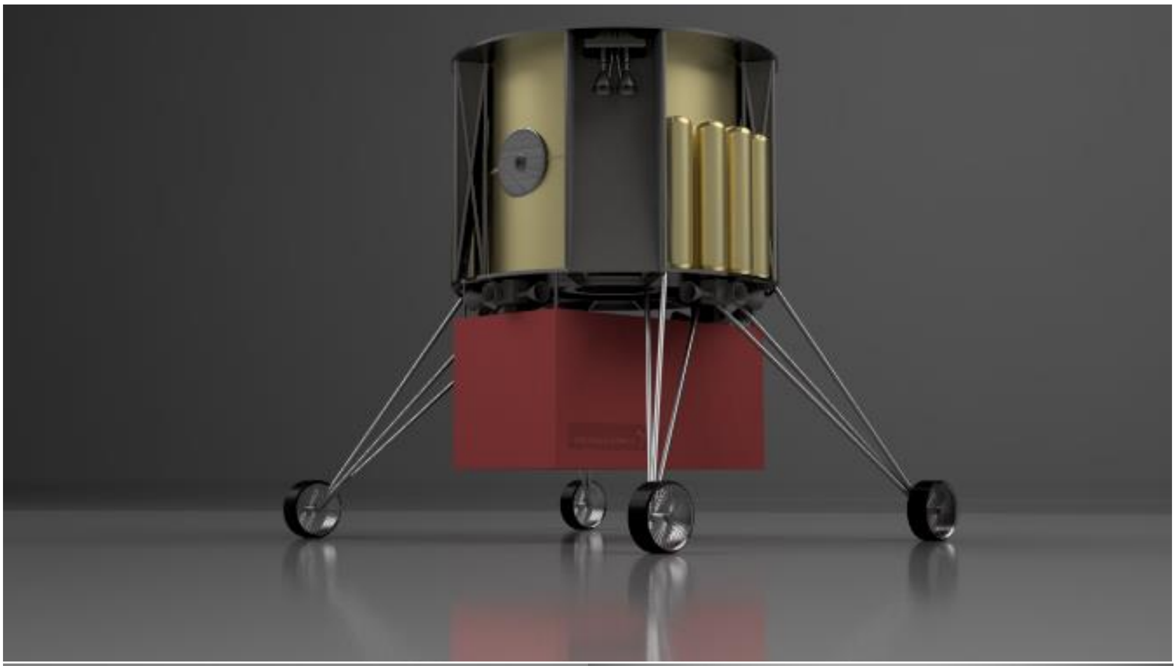
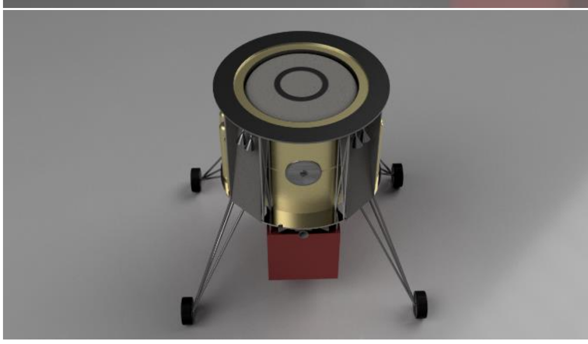
By Joris Luypaert, Sept 2018, Joris.luypaert@onestagetospace.com

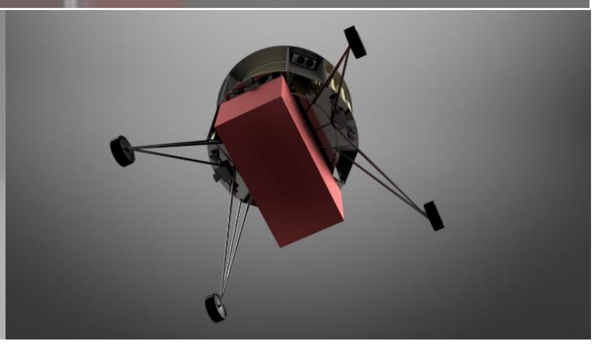
Lunar Lander

Since every child has a name, we decided to call ours COLOSSUS. It is not an acronym.

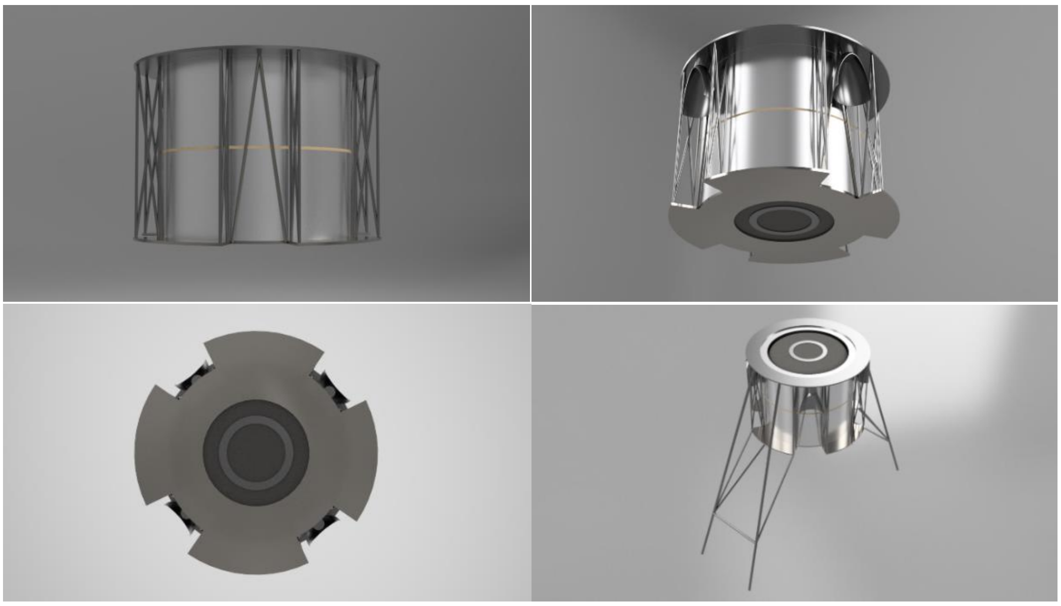
COLOSSUS: What it could look like: Our Final conceptual configuration







Our initial configuration core idea: Nested concentric circles



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Description:

Figure 2 The Colossus as imagined in a 16th-century engraving by Martin Heemskerck (1498-1574), part of his series of the Seven Wonders of the World

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At just under seven meters tall, seven meters wide and with a center body diameter of 457 cm, 300 cm high, our Moon Lander fits perfectly inside of an Ariane 64 fairing, or BFR or SLS, when its landing gear is folded inwards.

We consistently depict our vehicle without solar panels (e.g. ATV derived) and side blankets (thermal insulation) to show all relevant core structural elements in a variety of configurations.

Colossus carries payload and propellant tanks on all sides. As a versatile cargo and crew ferry vehicle it offers horizontal and vertical mobility. As a single engine stage configuration that leaves propellant drop tanks behind on the surface, it avoids splitting the vehicle into a heavy descent stage and a light ascent stage. This saves costs.

A 298 cm diameter, 3 m high inflatable crew compartment sits in the center of the lander and is surrounded by a cylindrical volume composed of multiple toroidal tanks. On the outside of these toroidal tanks we have ledges that offer real estate for science equipment, gear, ladders or extra propellant tanks. The Crew Inflatable (CI), is nested inside of a Toroidal Cryogenic Tank Farm (TF). Both rest on top of a Cargo Sling Deck (CS) and inside of an annulus shaped Observation Deck (OD) at the top. The OD housing does not stretch over the CI and TF. An Aerogel-Kevlar Liner separates the CI and TF and serves as a thermal barrier and spall liner (AL). Both the CI and TF can move freely and can be lifted out of the annulus formed by the OD during missions in space or at very late stages in the manufacturing process.

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The entire structure can rest on landing gears. Since we conceptualized the lander as a Sky Crane capable of hovering at ground level, these landing legs do not have to support heavy impact forces and could be equipped with wheels. Many viable alternative light weight configurations exist for the wheels and a landing gear suspension system. To pick the most versatile one that excels in low weight is a study in itself. We chose to image a simple triangular gear as a place holder. Both RCS and the electric wheels play a role in the attitude control of the vehicle. The wheels save RCS propellant when assuming this role.

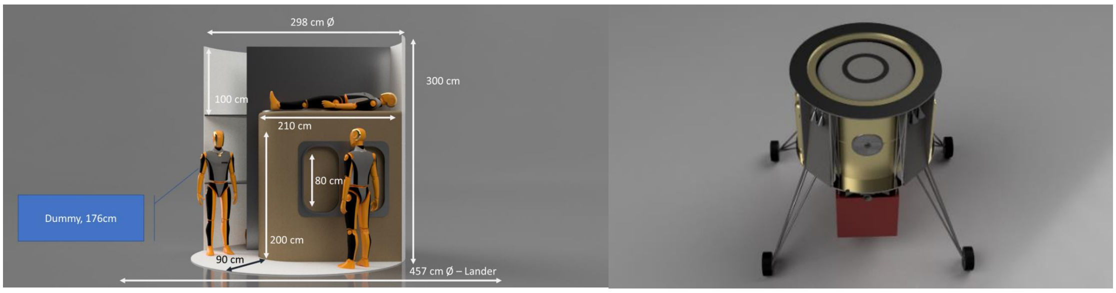
The main engines are placed at the top of the vehicle. This enables us to land even without a landing gear; if so desired. When equipped with a landing gear with sufficient ground clearance, Colossus can transport slung cargo. The image above shows a ground clearance of 3,4 meters. Since a high ground clearance is useful in many operational scenarios (see below), an even higher ground clearance (e.g. 7 meters) would be better still.

For scale and reference, the red cargo box has dimensions of 2*2*4 meters. Flown on vehicles with larger launch shrouds than an Ariane 64, one could envision lightweight structures with standard shipping container dimensions, linking the terrestrial to the interplanetary supply chain with terrestrial form factor standards.

Instead of a cargo box, slightly larger dimensioned cryogenic propellant drop tanks which can be repurposed as a habitat (the so-called wet habitat concept) could also be transported in this manner.

The entire structure (without a cargo box payload), weighs in at ~2000kg or below, depending on whether or not you include EVA spacesuits and consumables (e.g. 150kg water, clothing etc.).

COLOSSUS Essentials



Dimensions

- Height overall: 6550 mm
- Landing Gear footprint box side A: 6954 mm
- Landing Gear footprint box side B: 6070 mm

Main body

- Height: 3050 mm
- Diameter: 4570 mm
- Ground clearance: 3400 mm- 4000mm (in version of Colossus depicted above)

Crew cabin:

Inflatable structure:

- Diameter: 2980 mm
- Height: 3090 mm
- Hull, multilayer: 1-100 mm
- Landed Weight: 2155 kg

Propulsion candidates or similar: always add up to about 400kg and about 40.000N of thrust

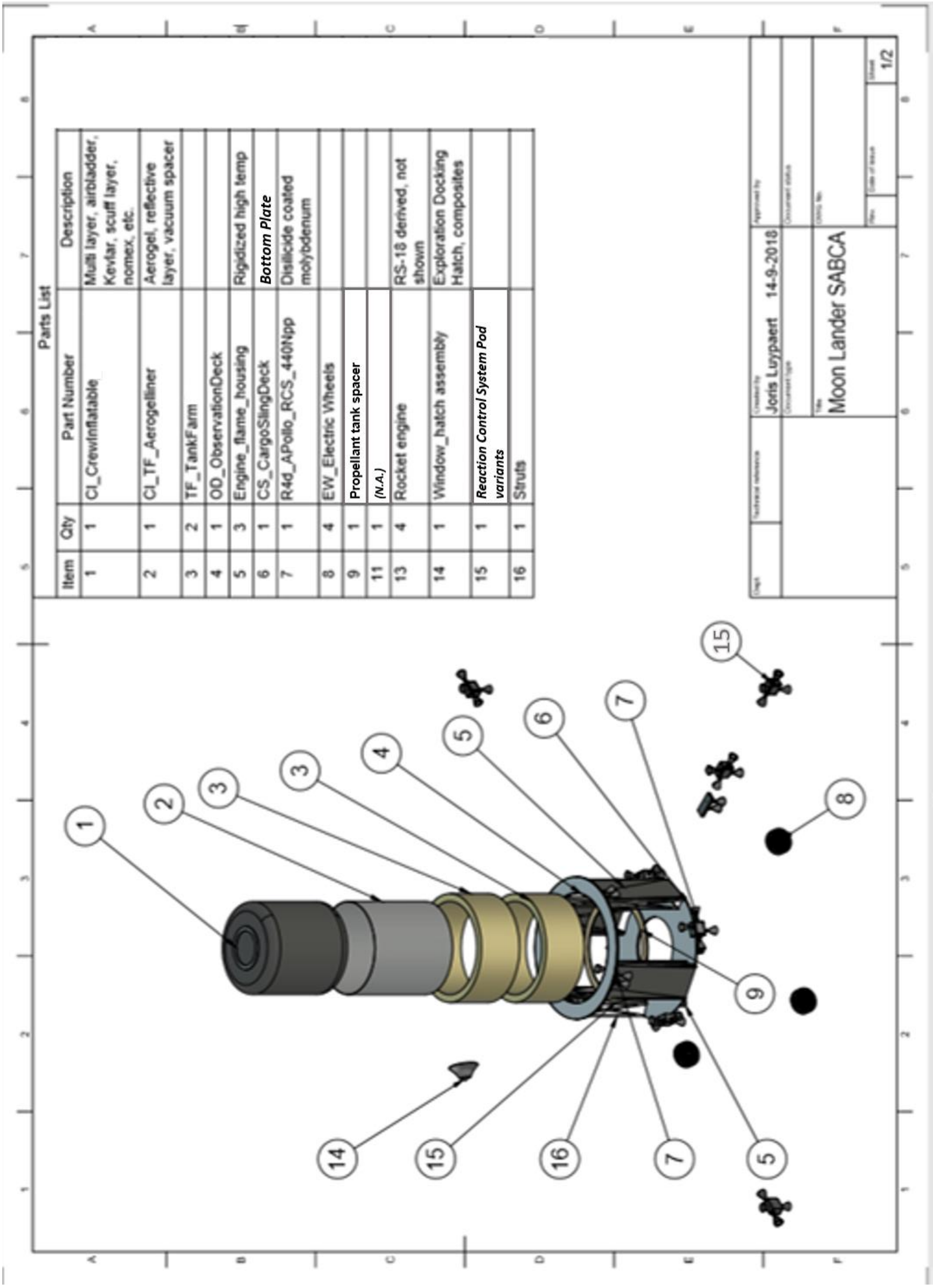
- RS-18: NASA derived Methalox version of the Apollo Moon Lander engine (2005 Exploration Systems Architecture Study (ESAS)[i])
- R4D derived: 440N thrusters in power banks (~92 pieces instead of throttling)
- Arianespace: 400N thrusters in power banks (~100 pieces instead of throttling)
- SpaceX Superdraco equivalent: at about 71000N/pair in 4 redundant pairs
    - Overpowered in most scenarios but the 3D printed engines are an interesting concept.
- Rutherford Engine (Rocket Labs): 24KN/engine (electric pump feed cycle), 311-343 ISP vac.

Our reference ISP: a minimum of 310 ISP
Our reference total thrust: 40000N (Apollo class Lunar lander)
Deep throttleability: to below 10% would be ideal

10KW solar panels
Electric wheels
Radiation shielding: propellant encircles habitat

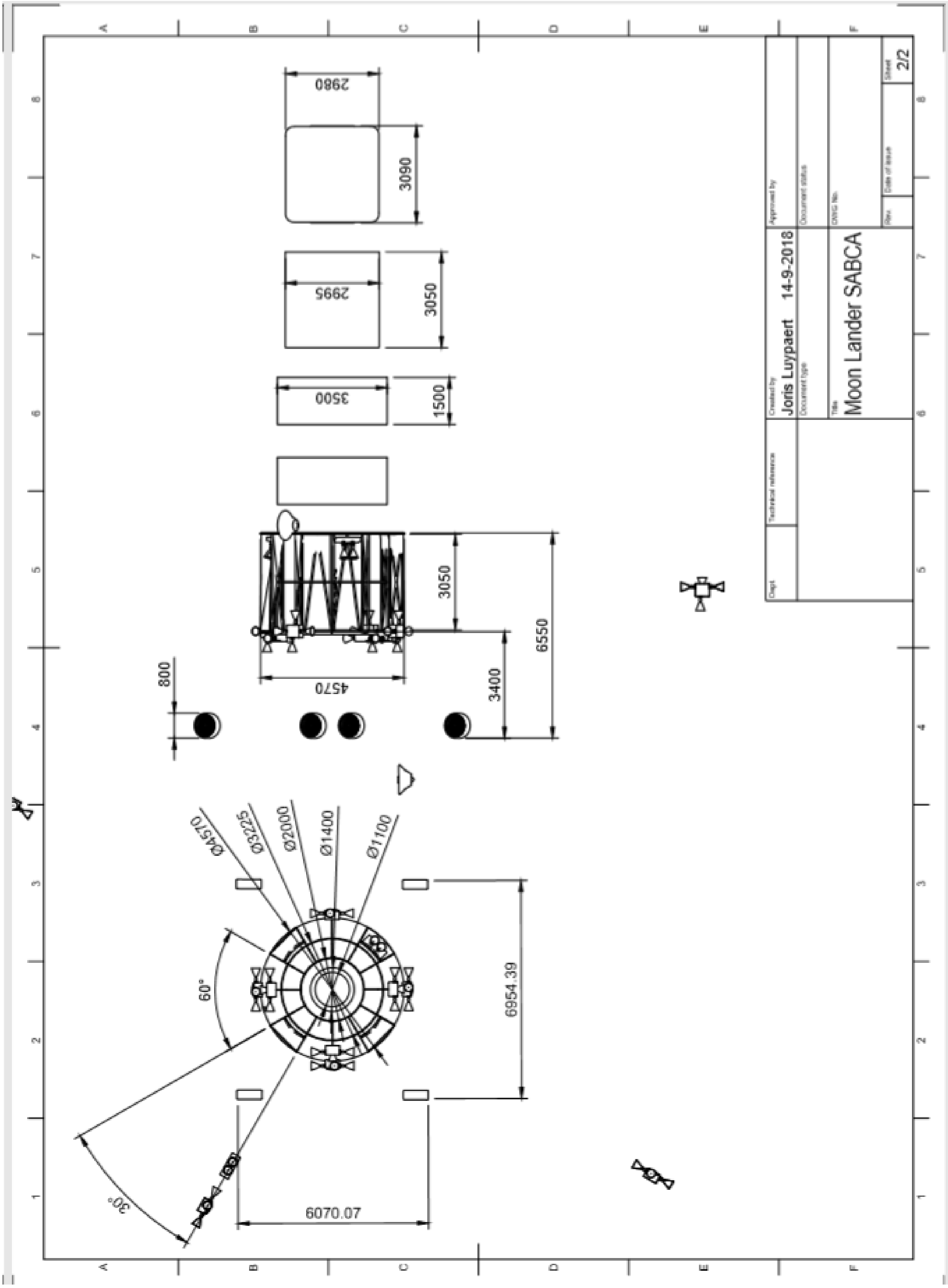
Internal inflatable airlock with suit ports: 2 to 4 suit ports, $6m^3$ inflated $2m^2$ deflated

Drawing 1



Item	Qty	Part Number	Description
1	1	CI_CrewInflatable	Multi layer, airbladder, Kevlar, scuff layer, nomex, etc.
2	1	CI_TF_Aerogelliner	Aerogel, reflective layer, vacuum spacer
3	2	TF_TankFarm	
4	1	OD_ObservationDeck	
5	3	Engine_flame_housing	Rigidized high temp
6	1	CS_CargoSlingDeck	***Bottom Plate***
7	1	R4d_APollo_RCS_440Npp	Disilicide coated molybdenum
8	4	EW_Electric Wheels	
9	1	**Propellant tank spacer**	
11	1	*(N.A.)*	
13	4	Rocket engine	RS-18 derived, not shown
14	1	Window_hatch assembly	Exploration Docking Hatch, composites
15	1	***Reaction Control System Pod variants***	
16	1	Struts	

Drawing 2


Moon Lander SABCA
Joris Luypaert
14-9-2018
2/2
2980
3090
2995
3050
3500
1500
3050
6550
3400
4570
800
Ø4570
Ø3225
Ø2000
Ø1400
Ø1100
60°
30°
6954.39
6070.07

Design Evolution

Configuration

Our design assumptions:

- Maximize versatility, reuse and adaptability to future requirements;
- Do not limit volume to 2 person crew;
- Assume Apollo style mission durations but with growth capability (provide volume and payload capacity for surface stays of weeks);
- Design for horizontal and vertical mobility;
- Assume an autonomous, optionally piloted vehicle;
- Integrate the NASA MSL Mars rover Sky Crane concept;
- Plug-n-play design philosophy, with a rapidly reconfigurable system. We want to be able to swap out propellant tanks, external racks, crew modules, cargo pods, easily without having to redesign subsystems and attachment brackets in the deep innards of the vehicle.
- Ease of manufacture.
- Subsystem layout in which all minor and major subcomponents can be accessed and changed out with no or only minor difficulty only days or hours before launch.
- All critical components can be accessed and repaired or swapped by astronauts in EVA suits.
- Considerable landing weight is taken up by propellant tanks. In some cases (Apollo style lander and beyond) up to 20 metric tons of landing propellant is required. Even the best propellant tanks, require 0.2kg/liter. This means 4000kg of the dry mass of the lander needs to take the form of propellant tanks. To not see lunar landers as an exercise in landing and throwing away empty propellant tanks, we prefer to immediately design them as large dual use drop tanks which, once empty, are ready to be repurposed as habitats, just as the 'wet habitat concept', originally proposed for the US Skylab in the 1970'ies but not implemented. In the USA commercial endeavors like IXION (Nanoracks)[ii] and ORION SPAN (https://www.orionspan.com/) are taking just that approach in designing commercial space stations for mixed use of tourism and research.
- Use non-toxic propellants.

Vehicle and Crew Module sizing

Context

With the LOP-G funded in the US budget and modules being designed for it in the US and Europe, India building its own crew capsule and voicing lunar ambitions, China being successful in its ongoing Moon Lander program, and ESA's Director General Johann-Dietrich Wörner proposing the Moon Village concept, the Space Agencies are actively pushing an effort to create a permanent stay on the Moon. US Vice President Mike Pence even announced this officially in a recent visit in August 2018 to the NASA Johnson Space center[iii].

In 2022 six crewed vehicles are planned to be in use: NASA Orion (4-7p), SpaceX Crew Dragon (4-7p), Boeing CST-100 (4-7p), Indian Crew Vehicle (4p), Russian Soyouz (3p), Chinese Shenzhou (3p). Sierra Nevada Corporation might still decide to build a crewed version of the Dreamchaser (7p). The SpaceX BFR will follow shortly afterwards.

The impressive NASA SLS is providing a 100 mton LEO capability and SpaceX Falcon Heavy and Blue Origin New Glenn are providing the world with a commercially attractive 12-16ton TLI capability. In fact, the very capable Falcon Heavy is between 5 and 20 times cheaper than a NASA SLS, depending on how you amortize development costs. This enables all sorts of mission types deemed too expensive only some short years ago. Europe is building an Ariane 6 which is about twice as cheap as an Ariane 5. China is building an SLS class vehicle with its Long March 9, which is expected to be flying in 2030.

We design a Moon Lander that can benefit from the 4.57 internal diameter usable space of the cargo fairing of the Ariane 6. It can fly on the SpaceX FH, the 8.5 m diameter NASA SLS and SpaceX BFR cargo version. What vehicle you choose depends on mission requirements, availability, commercial investment or customer appetite and/or government subsidies. The lander can adapt to all cargo or crew scenarios that do not involve direct return into an atmosphere, since the lander has no heat shield.

We will have to wait and see if the reusable and in orbit refuellable SpaceX BFR with its 150 mton to LEO materializes, but in delivering on its promises SpaceX has a better track record than most space agencies, except maybe for the cost effective ISRO. We do not see the Moon Capable BFR as a competition for a European Moon Lander since they offer a complementary capability. In many scenarios the BFR or SLS is overkill. At the same time, the reusable BFR has an excellent future as a vehicle delivering propellant cheaply, much cheaper than all legacy alternatives, to CISLUNAR orbiting and surface outposts. Our Moon Lander could become a customer for that propellant.

The existing momentum and the desire to increase crew sizes drives our choice in designing a Lunar Lander that is ready to ferry more than a skeleton crew of two astronauts to the Moon and back.

Crew Module location and propellant selection

The crew module is situated @ center of vehicle surrounded by propellant tanks.

Advantage:

- The most precious items on board, the crew, are better protected against space debris;
- The propellants in the 50 cm wide toroidal tanks (depicted in gold) provide some welcome radiation shielding.

Disadvantage

Two opposing requirements:

- The need to keep the cryogenic fluids cool and shield them from boil off, fights with
- the need to keep the crew compartment at room temperature (e.g. 25 °C). This creates a temperature delta of ~200C° with room temp and up to 320 °C in direct sun exposure. The same cryogenics must also be protected from the space environment (-100°C in shade +120 °C in sun).

Strategies exist to limit and counteract the boil off with passive and active means.

Propellant selection

The density of the onboard propellants and the infrastructure needed to use them in an engine and the engines, a.o. determines the size and weight of a space vehicle. Usually, determining this density has to be done first.

We opted however to design our vehicle in a modular fashion allowing us to quickly swap out components, or attach them in several locations, and be as agnostic as possible to the choice of propellants and engines. This makes it easier for our concept to have a future in an industry consortium with, possibly, an evolving composition of partners and suppliers. That being said, we do have a preferred propellant choice.

> Remark: The CAD sketches at the end of the document show some possible options in the trade space regarding engine / propellant / landing gear choices and their location on the vehicle. (images in back of document)

The volumetric requirements of monopropellants and hypergolic bi-propellants, so called storable propellants, are lower. We do however prefer Methalox or even Propane and Oxygen since they are non-toxic, safe when handled correctly and pose no contamination risk to the crew or landing site.

Monopropellants are reliable, storable and denser than e.g. methane resulting in smaller tanks and more compact vehicles which at first sight are structurally lighter. They are simple systems. Methalox systems are more complex and possibly more prone to failure but outperform the classic storable propellants by such a large margin that they end up being lighter at the mission level. As stated, you need to passively (by shielding) and actively (by cryocooling) protect them from propellant boil off, which introduces extra complexity and the possibility of mission failures.

The US and Europe each funded green propellant studies. Some down selected mono or hypergolic bi-propellants offer density and performance benefits over for instance hydrazine. They are less toxic or not toxic at all.

Still, even in the light of the above, we prefer Methane and Oxygen, since they offer a better ISP over the mono and hypergolic propellants and even the green propellants. Every increase in ISP directly impacts how much payload you can deliver to your destination or how much you can still do if you accidentally lose a part of your propellant supply. Methalox engines also hold more promise as throttleable and reusable engines, while monopropellants and hypergolic propellants tend to be corrosive for containers and all that touches them.

Our design goal is not ultimate mass optimization but to create the most versatile vehicle possible for Cislunar operations. Since the industry mindset is evolving from a propellant scarce to a propellant abundance paradigm for space (ISRU, confirmed H2O deposits on the Moon, SpaceX FH and BFR capability, recent commercial in space refueling technology development demonstrations) we can be somewhat tolerant to small mass increases if it results in a more versatile mission envelope capability.

Liquid Methane and Liquid oxygen also come with well understood safety hazards but the advantage of the latter propellant combination balances out the disadvantage of the others. As indicated, we have a use for the larger tanks that are required to carry these propellants. They can be repurposed as habitation spaces but also to hold resources and gases resulting from ISRU operations.

Both Methalox and Hydrolox are compatible with wet habitat concepts. Because Methalox, as a less deep cryogenic mix than Hydrolox, causes less embrittlement and other issues with propellant tank materials than Hydrolox and therefore is somewhat safer, we prefer it as our cryogenic propellant of choice. Dual use tanks can be constructed in aluminum (e.g. Alu Lithium alloys), titanium (e.g. tanks on the NASA Space Shuttle orbiter) stainless steel or carbon fiber composites in the COPV (metal carbon overwrap pressure vessels) or all composite liner less pressure vessel variant. All-composite liner less carbon fiber pressure vessels are the lightest option (till graphene overwrap becomes available). They weigh as little as 0.2kg/ liter for liquid methane and liquid oxygen applications. Variants of this Carbon Fiber pressure vessel technology have matured enough, and can be considered safe since 2013 (when a NASA program obtained success). In Europe a similar effort was funded under the EPF programs and demonstrated a cryogenic all composite tank. SpaceX has tested the technology with success and is now building a 9-meter diameter version for its Big Falcon Rocket.

The single most important argument to select Methalox can be said to be the planned BFR missions to deep space. Since this vehicle requires multiple refuelings for a single MARS mission, and Elon Musk has every intention of following through, and because he wants to enable propellant manufacture on Mars while at the same time optimizing the usage frequency of his vehicle in CISLUNAR space, there will exist more chances to refuel methane-based propellants than mono- or hypergolic propellants.

Methane can also be produced on the Moon by combining water in the polar ice reserves with Carbon (exists in trace amounts but can also be imported) in Sabatier reactors.

- Selected propellant: METHALOX
- Selected propellant for the Reaction Control System (RCS): METHALOX
- Selected igniter: Aero-acoustic igniters[iv] or spark igniters.

Lander Sizing as a result of Delta-V requirements

Departing in Low Earth Orbit (LEO), direct missions to the surface require a Delta-V of about 6000 km/s.

The return trip adds about 3000 km/s depending on the route followed.

It is safe to say you have to design for a roundtrip Delta-V of 9000km/s. This means every kilo in LEO destined for a Moon roundtrip, requires another 19-20kg of propellant.

Refueling in orbit would make these equations more benign. If depots are available, that same 6km/s Delta-V only requires 40% as much propellant.

The 9km/s scenario would now require 8kg of prop per kg in LEO, a remarkable improvement.

Our golden design rule. Design a compact vehicle that is flexible enough for both direct and indirect missions to the surface and has enough room to accommodate extra small diameter (e.g. 50cm) AND large diameter propellant tanks (e.g. 2-3m diam).

Result: We noticed that our requirements and European lift capabilities correspond to a lander with a dry weight that is almost identical to the Ascent stage, or upper part, of the Apollo Moon Landers: ~2000kg.

Large propellant volumes and corresponding weights enabling large payloads can be accommodated with temporarily attached drop tanks. The vehicle just has to be designed to be strong enough to drag them around.

The worst-case scenario assumes a Falcon Heavy launch, no refueling and a small payload of science equipment and cargo but already perfect for a crew ferry mission. Our lander is designed to be capable of more when lifted on a SLS or BFR. When benefiting from en route refueling launching on Ariane 64 becomes a solid option.

The simplified mass breakdown table (see addenda) can give some insight in what we already include in our weight estimation. We include for instance the mass of the space suits and suit port fixture, but also essentials like 150kg of water and other consumables that will always be present. Not including them in the dry weight of the essentialia of a lunar lander would be somewhat fraudulent given that we have a historical example in the Apollo program. If we leave them out, we have a much more beneficial mass equation.

The need to lobby for orbital depots.

Refueling at depots instead of carrying all propellants along would dramatically lower the propellant requirements on each leg of the ferry mission[v]. In a terrestrial analogy, if we want to use a car to circumnavigate the continents, we could choose to pull a propellant tank trailer. Everybody understands more energy needs to be expended to pull that trailer instead of only the car. But in space the difference is much bigger due to the very large velocity increments.

(In endnote we give a simplified numerical example.[vi])

Resulting Proposal

Moon Lander Internal Volume

The proposed crew module is a cylindrical inflatable, 3m diameter and 3-meter-tall, providing a volume of 21m³. Since it is a Kevlar/airbladder inflatable, it weighs mere tens of kilograms. Larger versions can be envisioned. We prefer this compact volume because it can serve both 2-person crews as well as future 6- to 7-person crews. The NASA Orion has a pressurized volume of 19.56m³ for up to seven crew. In comparison, the crew dragon (SpaceX Dragon 2) has 10m³ for up to 7-person ISS ferry missions. All will be used in a 4-person configuration due to the demands of the mission lineup and the limited number of docking ports and agreed crew capacity on the ISS if no extra habitation module is added.

For long duration deep space missions, NASA studies recommend a 25m³ per person volume, but this is not required for short duration ferry missions to the Moon[vii]. We expect a buildup of modules on the lunar surface to happen sooner than later, now that the dominant space agencies are actively funding moon efforts lessening the need for a bigger pressurized volume.

There is one egress/docking hatch on the bottom, opening to the lunar surface and one egress/docking hatch on top, opening to a docking vehicle in space or a lunar habitation module or extra lunar airlock. The lunar lander can be equipped with a docking port on the side.

Influence of Suit ports

NASA is currently designing EVA suits with integrated suit-ports. The most famous example is the Z-2 suit, designed by ILC Dover. To accommodate a suit port would require an extra module, since putting Z-2 suits on the outside of a lander would contaminate them with Lunar/Martian dust and possibly lethally toxic rocket propellant. This would mean that, in an emergency situation, e.g. with an unconscious astronaut or a jamming suit port, the crew would need to go inside through another port, exposing the inside of the vehicle to toxic substances. While the Z-2, at 65 kg, is considerably lighter for an astronaut than the 90 kg Apollo Suit, it does require a 100 kg suit port mating structure, and the combination actually increases the landed weight over Apollo Suits.

Contrary to that, IVA suits (Intra Vehicular Activity suits) of the new generation weigh less than 10kg. They are much less mobile than EVA suits but can provide limited EVA use if one uses a thermal insulation ‘overcoat’. That being said, IVA suits will probably be on board as a task specific suit and possibly as an emergency backup, not as a replacement for the EVA suits.

NASA most likely wants to test the Z-2 space suit in lunar conditions before going to Mars, for this reason we design for its use.

Figure 3 NASA Left: Crew Exploration Vehicle Study article and integrated suit port assembly – Right: NASA Z-2 prototype – credit NASA

Our design choice: an internal inflatable air lock with an integrated suit port.

Inside, central on the floor of our 21m^3 crew habitat volume, we dedicate room to an extra internal inflatable airlock equipped with suit ports. Crew planning an EVA inflate the pressure rigidized hollow airlock walls, climb into the suits through the suit ports and exit the lander. This large extra internal airlock helps with dust mitigation, which was a problem on the Apollo Missions that did not have a dedicated area to donn and doff the suits.

At 6m^3 it has dimensions and a layout similar to the NASA Crew Exploration Vehicle Suit Port area in figure 3.

This internal airlock is equipped with two suit port interfaces (optionally four) an internal and an external hatch but not located sideways, as in the CEV, but in the Bottom. If the suit ports fail, the crew can still close the external hatch, decontaminate as good as possible with anti-electrostatic dust devices, wipes, etc. and then enter through the internal hatch. A disadvantage is that the EVA suits cannot be left behind together with a detachable airlock, which would be a method to save weight on the return trip. In our configuration-logic we reuse the suits for their entire design life.

Inside on the airlock ceiling, is a winch allowing an astronaut to vertically lift a second incapacitated astronaut into the airlock and have enough room to close the hatch beneath him.

Because it is an inflatable airlock, it also serves as a 'closet' for up to four Z-2 suits. Once deflated, it could be stored away under a floor board or table area taking up less than 2m^3, opening up the internal crew habitation volume.

On the next page we show some layout sketches.

EDH Docking hatch.

The International Space Station saw the introduction of the International Docking Adapter to welcome visiting (commercial) vehicles. Every company is free to build to this open source standard. However, at 1000 lbs. or about 500 kg, the IDA is much too heavy for a Moon Lander or deep space missions. For such reasons, NASA designed the EXPLORATION DOCKING HATCH or EDH, a weight optimized system and much lighter, but still compatible with the IDA.

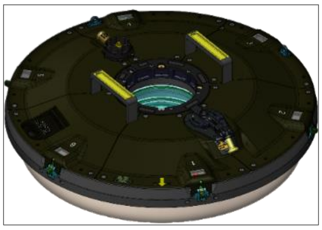


Figure 4 Exploration Docking Hatch (EDH) -credit: NASA

We were unable to find the correct mass for this EDH on the NASA website, we only learn that it has:

- an assembled mass 65% lower than legacy designs;
- a pressure carrying capability 56% higher than legacy designs;
- an air leak rate 200x lower than typical requirements;
- Had TRL 7 in 2017

(Source: https://techport.nasa.gov/view/79552, Lead center: Johnson Space Center (JSC), Human Exploration and Operations Mission Directorate (HEOMD)).

Since it was unclear which legacy design was meant, we conservatively assume a mass of 100kg or less for the EDH. (The forward hatch on the Apollo command module weighed 80 lbs. or 36,3 kg for ~30inch diam, ~76 cm)[viii]

Internal layout

The preceding results in the following preliminary internal layout sketch:

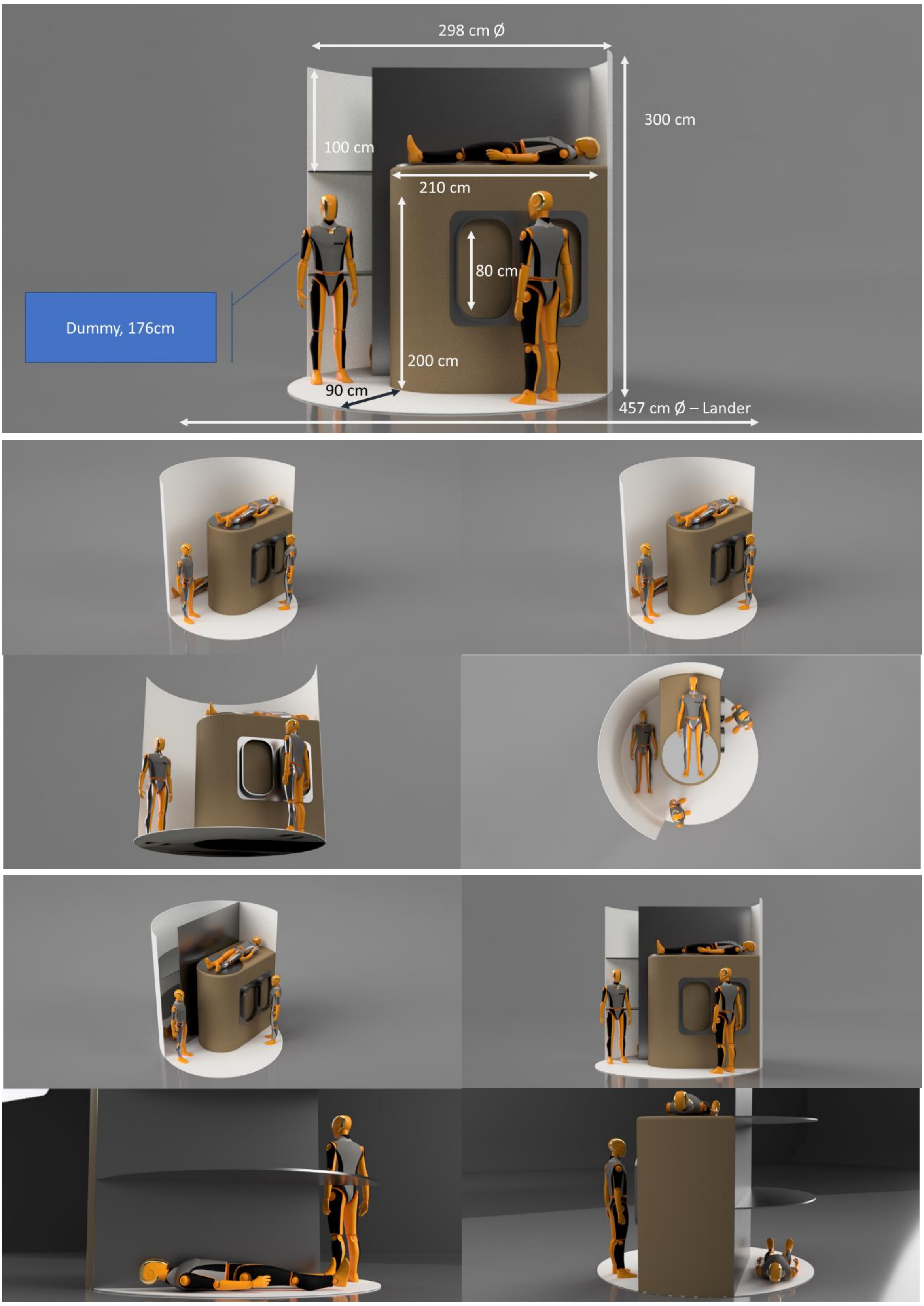


Figure 5 Lunar Lander Internal Layout sketches with inflated Internal Airlock. Configured for 3 or 4 crew. Total living space 21m³ (2,98 m diameter and 3m high. The pressure rigidized hollow wall inflatable airlock when Inflated: 6m³, deflated 2m³. It could be stowed away under a floor board or table section.

Autonomous Sky Crane and e-wheels.

Sky Crane.

Figure 6 Image Credit: NASA/JPL-Caltech

The Mars MSL Sky Crane demonstrated the advantage of pin point landing accuracy and the ability to hover close to the surface on a different celestial body. What can be done on Mars can be done by Europe on the Moon.

Despite the failure of the MARS Beagle Lander, the failure of the ExoMars Schiaparelli EDM lander demonstrator and the failure of the Philae lander on the Rosetta Mission, Europe is willing to risk gaining experience landing on other celestial bodies with pinpoint accuracy. Investment in this area is at a higher level than ever before at many national European space agencies. Dedicated facilities are built (see e.g. DLR below) and used.

At the same time, we see other European commercial lunar lander projects taking shape, such as the ALINA rover, a cooperation between Part Time Scientists-Vodafone-Nokia-Audi-Red Bull. (Source: https://ptscientists.com/) They are planning to launch in 2019.

All this aids in expanding the European lunar landing expertise.

Across the ocean, NASA invests in many small businesses exploring lunar landing technology by organizing prize competitions and by direct investment. (e.g. Morpheus lander, Pixel, etc.)

Autonomous, optionally piloted.

Vehicles have gained sufficient level of autonomy and safety that we can entrust the lives of crew to these robotic systems. Human crew will mainly take on a role as supervisors of the landing operation verifying the on-board computers. In the unlikely event on board computers fail, the option will be there for them to go into abort mode (another autonomous system) or pilot and land the vehicle.

Test programs exist at DLR In Germany (e.g. TRON – Testbed for Robotic Optical Navigation, https://www.dlr.de/irs/en/desktopdefault.aspx/tabid-11361)

Wheels

Colossus can not only ferry goods between the surface and lunar orbit, but also between locations around a lunar base.

It can land at a safe distance from an outpost. Using its e-wheels and simple winches, it hauls and repositions cargo from the landing area to where it needs to be. It can also be equipped to reposition lunar resources or sensors. Inspiration can be derived from the NASA Athlete program[ix].

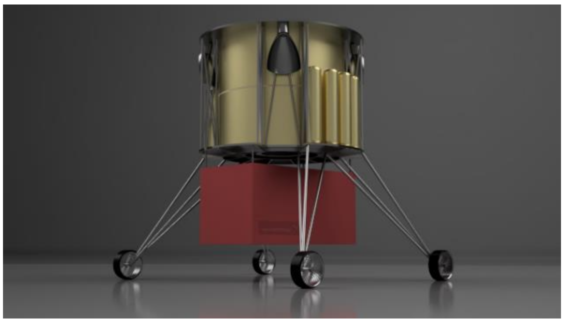


Figure 7 Wheels on a lunar Lander? Get used to the idea.

Landing gear in 6 versions:

It is clear that we are of the opinion that a landing gear is a good idea. But it might not always be necessary to carry one. We explore six options.

A) The simplest landing gear is no landing gear.

An accurately controlled Sky Crane can guarantee soft impact landings, requiring no landing gear. We saw the potential of this idea on the 2012 MARS MSL rover Curiosity.

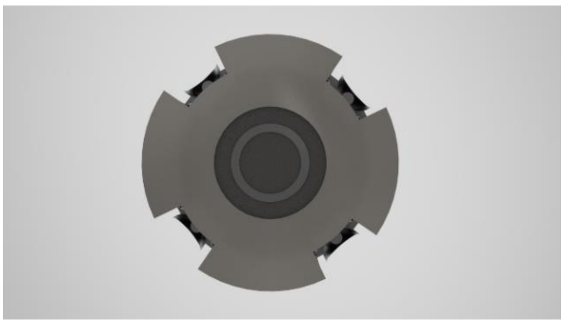


Figure 8 Colossus imaged from below without a landing gear and descending to the lunar surface in Sky Crane mode

Mitigating dust, preventing contamination of the research area with toxic rocket fumes were some of the considerations why a Sky Crane was combined with a wheeled rover being winched down from a rope.

Today we no longer need hydrazine propellants and our lander could land in the area of interest forgoing the need for a winch. Also, robotic systems can be trained to mitigate dust and sensor fog. To mitigate any problems with robotic vision an extra safety feature could be to drop micro navigation beacons or cameras during the landing phase, beaming back high-resolution footage or terrain elevation data and quickly informing the lander about the landing area. Total mass of this additional system can be as little as 1-5 kg.

B) Air bags

Demonstrated on MARS, airbags can also be used on the Moon. They are a mass efficient system, lighter than a landing gear. If someone can create an airbag system where the bags can be reused as say a habitable module or shelter, I would consider them a good option.

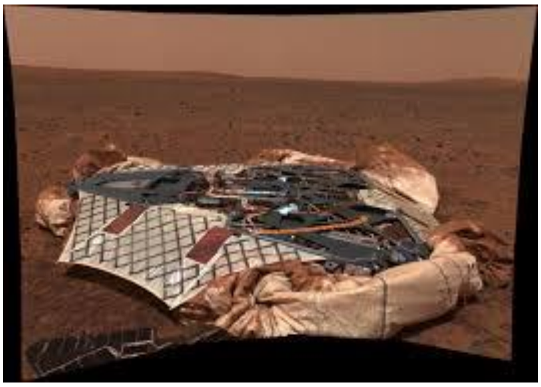


Figure 9 MER (Mars Exploration Rover) Airbags after deflation, used on MER Spirit and MER Opportunity -credit NASA)

C) Apollo Style landing gear

We could simply copy the 250kg Apollo Landing gear, since it worked. The problems with the Apollo Landing gear are that it was overdesigned for its purpose (better safe than sorry); that it provided too little ground clearance (engine on Apollo 15 was pushed into the lunar soil); that it did not provide enough ground clearance for slung cargo; that it was purely stationary. The vehicle was unable to translate horizontally once landed.

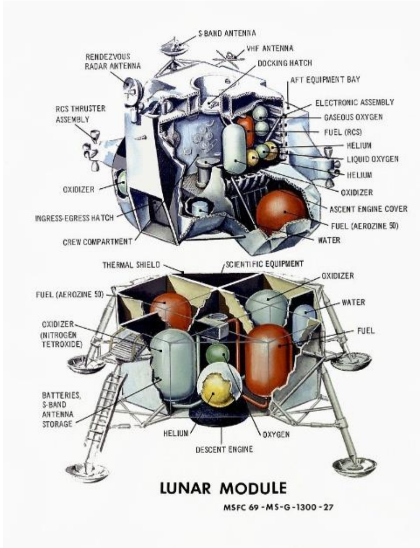


Figure 10 (Apollo Lander Diagram - Credit Nasa)

D) Landing gear with modest 3,5 m ground clearance

The landing gear depicted below is what we deem to be a short version with modest ground clearance.

It gives a clearance of 3.5m between the bottom of Colossus and the Lunar surface.

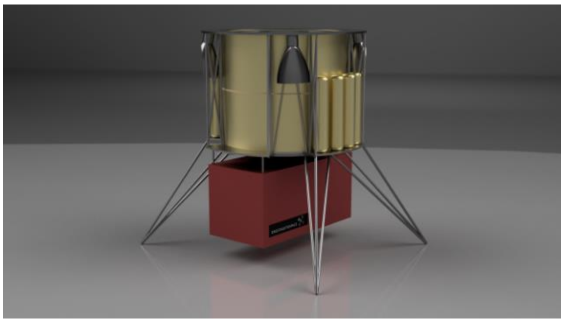


Figure 11 Colossus Lunar Lander with 3,5 m ground clearance allowing for slung cargo

We believe we can provide this ground clearance and easily remain within the 250kg mass budget of the Apollo landing gear.

We dare to gamble that material technology has advanced enough to allow for an even taller landing gear enabling slung cargo, but that statement would of course require validation.

Also, because we are much better at ultra-soft landings compared to the days of Apollo, the strength margins can be matched more closely to what is actually needed. This translates into less overdesigned and lighter structures.

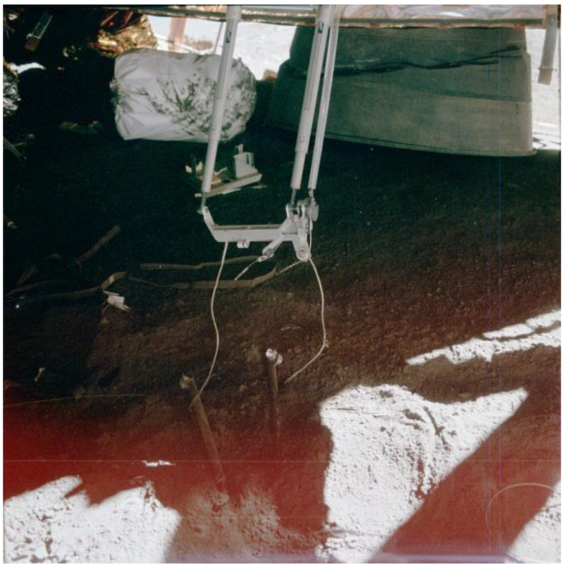


Figure 12 Decreased clearance led to buckling of the extended descent engine nozzle on the landing of Apollo 15 (upper right). Credit- NASA

E) Landing gear with 7 m ground clearance

If possible, we would prefer a clearance of seven meters and e-wheels.

Figure 13 Tall 7m landing gear variant

There are a lot of practical applications for a wheeled structure with a 7-meter clear vertical span. Not only are we all familiar with container movers in terrestrial shipping ports, the spindly structure can also be used to attach additive manufacturing equipment, an essential technological capability in most future proof ISRU base building scenarios.

The tall structure can also be used as an attachment point for cable robots or can serve as a vault for an equipment hangar. When Kevlar and Whipple shields or MMOD blankets are attached, as structure protecting an inflatable habitat underneath.

F) all of the above, with e-wheels for horizontal mobility

Weight penalty, less than 100kg.

We converged on a 3,5 m ground clearance landing gear with e-wheels and believe 250 kg is achievable.

In the last 5 years commercial motors regularly reach a performance of 9 KW-e per kg. That is more than enough for our needs.

- The Belgian startup Magnax can provide inspiration https://www.magnax.com/
- as can the Siemens Electric aircraft motor effort (5KW/kg and 250KW in a 50kg package, https://w3.siemens.com/topics/global/en/electromobility/pages/eair.aspx)

Additional uses for e-wheels.

The e-wheels are not mere dead ballast when ferrying between destinations in space. In fact, as an aid to the attitude control system, they assume the role of reaction wheels. As such, they help in reducing the demands on the RCS system and save mission propellant. To do this, they are designed to be swiveled in order for them to rotate in the XY, YZ, and XZ plane.

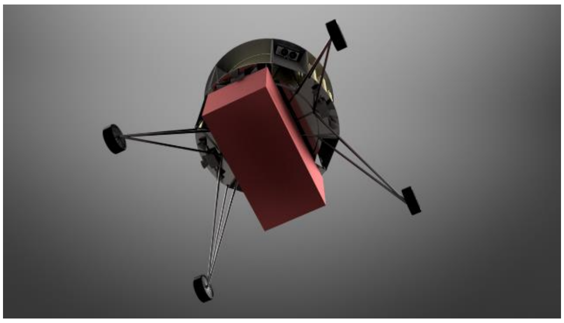


Figure 14 Colossus with 3.5m ground clearance and electric hub motor wheels

Are electric wheels light and strong enough?

NASA has designed a nickel titanium memory alloy airless spring tire wheel to replace the aluminum wheel used on the 2012 MSL rover which deteriorated much more rapidly than expected. A major advantage, next to its light nature, is that it can deform and reassume its shape after being heated up electrically[x].

Structure

Materials

A limited selection of space grade metals and Carbon Fiber honeycomb panels. A final selection was not made in the preparation for this competition.

-Alu Li 2219 structure, a very good performer, or Better

-e.g. it is possible to use ALLITE, a novel magnesium alloy that is 33% lighter than aluminum, 56% stronger than grade one titanium, and has a melting point of 650°C and 20 times greater shock absorption than aluminum. The corrosion rates are similar to corrosion resistant aluminum. It has prior use in aerospace. We have not checked availability in Europe. (Source: https://alliteinc.com/). This material is cheaper to fabricate, mold or use than Carbon Fiber

- Carbon Fiber mastery has now matured to the point where it is good enough for very light all composite cryogenic tank structures[xi]. (below)

Not shown: Once we have converged on a design and know the stresses on all parts, we could lighten the structure further with so called generative design software; which places materials only where it is needed. (e.g. Autodesk)

Load bearing structures

While some designs would use the propellant tanks as load bearing structures to save weight, we intentionally avoid doing this to be able to replace them at any stage of the manufacturing process or during the space mission. All subassemblies and components or tanks can be easily replaced or scavenged for parts to repair other vehicles and equipment or serve in another role.

Struts, two plates and a landing gear give our vehicle its rigidity.

- Struts
  - Strongest boxes on the vehicle
  - Used as engine mounts
  - Give shape to the heat resistant engine compartment boxes
  - Carbon Fiber or better

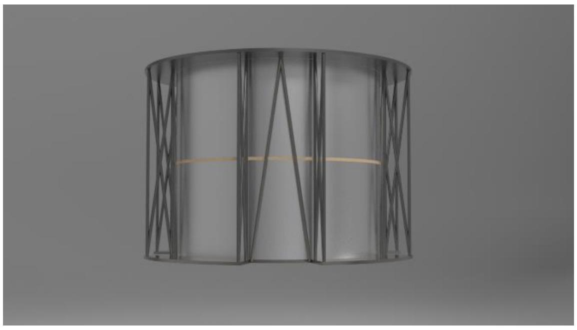


Figure 15 Struts give shape to the 4 engine boxes

- Upper plate: Observation deck
  - Location for Additional air lock/habitat/cargo/sensors/radiation shield
  - Honeycomb

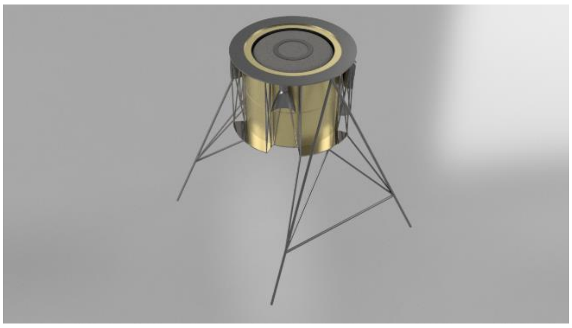


Figure 16 Observation Deck (OD), the concentric ring on top

- Lower Plate: Cargo Sling

Concentric rings and sparse grid structure for strength. Strongest ring is right beneath our golden propellant tanks.

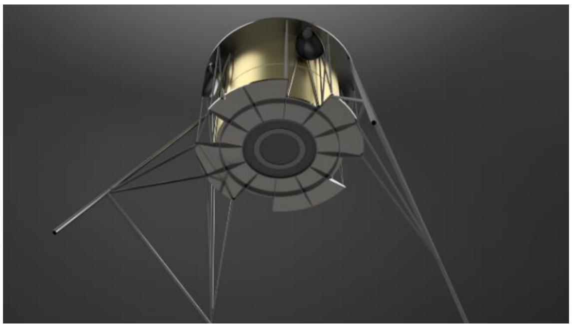


Figure 17 notice the ring-shaped grid structure on the bottom of the lander, it receives all forces

- Landing Gear (described above). If you attach it to bottom of CS, access to gear is unhindered

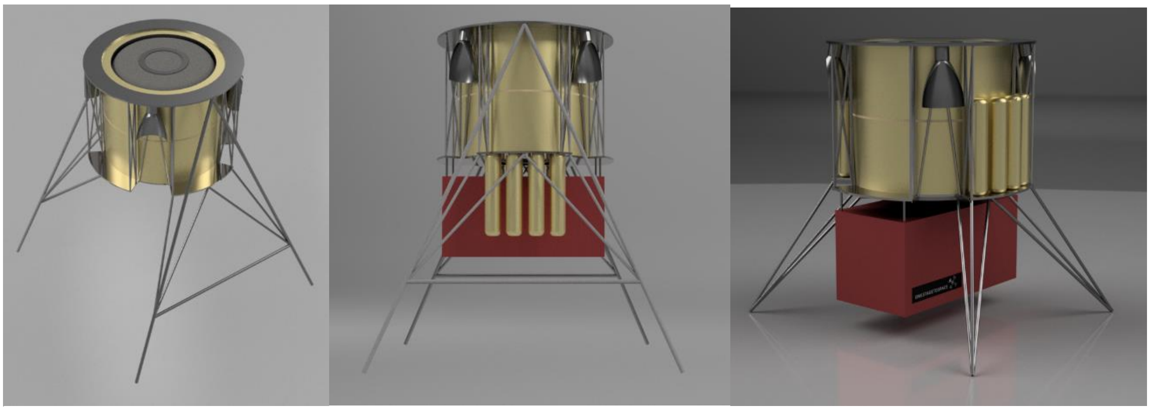


Figure 18 Propellant tank locations. Toroidal tanks are placed around the centrally located crew inflatable. Landing Gear attached only to bottom plate (right) leaves access to all other gear unhindered. Important for surface operations.

Propellant Tanks

Our flexible design allows us to attach propellant tanks to multiple locations depending on preferences and mission scenarios.

One of the possibilities is to position toroidal tanks around the crew inflatable. They are depicted in gold. Toroidal tanks are a safe option and when they do explode, they explode outwards. This is due to the fact that wound composites have more material on the inside radius of the toroid (where the hole of the doughnut shape is) than on the outside.

Not depicted is the fact that multiple toroidal tanks are stacked on top of each other, each with their bipropellant component.

Even if the propellants are at cryogenic temperature, thermal insulation can limit boil off. In combination with commercially available cryocoolers, boil off can be reduced to near zero at moderate energy expenditure.

Possible locations:

- Cylindrical tanks on Outer edges
    - Minimum of 8 m^3 available in 50 cm diam tanks and more if desired:
    - Either conformal on sides, or
    - Conformal on bottom or top (middle image in figure 18)
    - Axial (you can take the red box 2*2*4 m as a stand in for a cylindrical propellant tank that doubles as a wet habitat)
- Toroidal tanks surrounding the habitat
    - Comparable internal volume
    - In conjunction with or replacement of the cylindrical tanks depicted
    - If used, more room is available on the side platforms where cylindrical tanks are depicted

Carbon fiber tanks or better. They come in at 0.2kg/liter.

Figure 19 Up to seven 50cm diam toroidal propellant tanks can fit in the 3m tall volume (inner diam 300 cm, outer diam 350 cm). Seven tanks can hold 28m³, which usually is overkill. It could be smarter to lift equivalent volume as one big slung cargo propellant drop tank doubling as wet habitat. One or two toroids suffice to ascend to LLO depending on prop mix density (1800kg prop/~360kg tanks/1870 m/s Delta-V). Seven tanks is future proof design but only needed in full ISRU base environment operations.

Thermal insulation

Passive Thermal Control System (PTCS);

- Modern MLI (Multi-Layer insulation)
- Radioisotope heater units

Active Thermal control system (ATCS).

- Phase change materials hold promise
- as does boil off from the propellant supply
- Cryocoolers

Novel idea

- Graphene films and carbon nanotubes are high performers in redistributing heat around a vehicle.

MMOD protection (Micro Meteoroids and Orbital Debris)

No specific effort is made. In comparison with the LEO environment, CISLUNAR space is a more benign volume of space to operate in. Risk of collision with MMOD is much lower, which allows for a lighter vehicle.

A basic Kevlar layer is part of the outer shell of the vehicle, providing some protection against dust moved by the engine exhaust and in extension offering some limited protection against MMOD.

Long surface stay missions could benefit from Whipple Shields.

If the busy crew has the time, or autonomous robots can fabricate it, a Regolith shield could be constructed.

Radiation shielding.

No extra heavy shielding on the lander. We use the propellant as a shield. Metal structures are kept to the minimum in order to limit secondary radiation. Also, regolith shielding is only effective from about 5-10 meters thickness, because it also causes secondary radiation. Regolith is effective as a MMOD shield.

Before the ascent to LLO or EM-L1 or L2, the propellant tanks contain 50 cm of liquid Methane and liquid oxygen. This mass protects the crew somewhat against radiation.

If the propellant tanks are constructed from Carbon Fiber instead of metal, there would be less secondary radiation, which would be better. We prefer the use of all composite Carbon Fiber tanks.

There is not enough equipment on board to create a decent radiation shelter. However, when the internal airlock is inflated, the mass of the astronaut suits contained in it aid in protecting the crew. All material and equipment can be gathered around that central location, and combined with water vests, giving the crew the best protection available.

Easy way to improve the protection: land the vehicle with heavier payloads or migrate to a protected area (e.g. Lunar Lava tunnel).

Water vests are a workable option to reduce exposure to radiation. Crews that have no access to dedicated surface habitat infrastructure will have no good protection against solar flares.

If the crew volume becomes part of a semi-permanent habitat (e.g. because its engines have reached the end of their rated life) we can replace the remaining propellants in the toroidal tanks with water; since it is an effective radiation shield.

Spalling Liner

In between habitat and toroidal propellant tanks

Kevlar + Foam/internal whipple shield. The exact thickness depends on the risk tolerance.

Engines

Options

- RS 18 40000N (Apollo Lander Derived) Methalox. -Times four + RCS = 400kg
- R-4D 440N - Times 92 = 400kg Hypergolic
- SpaceX SuperDraco 71000N – Times four = Unknown (could not find engine weight) Hypergolic
- Ariane Group 400N Monopropellant Hydrazine Thruster (210 to 220 ISP) – times 100 for 400kg

A detailed engine selection with European or US alternatives is beyond scope of this exercise due to time constraints. We were mainly focused on the form factor.

310 ISP or more, methalox, deep throttling capability to below 10%, engine redundancy, carefree igniter systems and all at reasonable cost are on our wish list.

All the options above gave a 300-400kg mass. It should be possible to do better without splitting the vehicle in an ascent and descent stage. We want to avoid two engine stages at all cost.

Payload Performance

Depends on Launch vehicle and refueling or not en route to Moon and departure point.

Assumptions

For minimum payload capacity we assume a minimum Colossus engine performance of 310 ISP and a thrust similar to Apollo Lander (~40.000 N)

Colossus Cargo capability on Ariane 64: Not enough to make it back into LLO/Orbital space if no refueling en route. Falcon Heavy, NASA SLS and SpaceX BFR are good candidates for this moon lander if refueling is not an option.

Departure point

The location of the orbiting lunar space station, formerly LOP-G or “Lunar orbital Platform Gateway”, and already re-baptized into the handier “Gateway”, is still being debated. While there is talk to position it in NRHO orbits (Near Rectilinear Halo Orbits), stations in these relatively slow orbits are not ideal as staging points for missions to the surface of the Moon. They are more difficult to access quickly or frequently during lunar ascent, which means astronauts spend more time in transit wasting resources being idle, instead of using them during exploration on the surface.

Furthermore, the powerful propulsion module of the Gateway (PPE) should be capable of transferring and repositioning the outpost into the L1 and L2 Lagrange points, respectively in between the Moon and Earth and on the other side of the Moon invisible from Earth. Indeed, many scientists would like to obtain data in these and other orbits with the same instruments (radiation, astrophysics, heliophysics).

For Lunar Surface missions L1 and L2 are better staging points but still not ideal (see addendum 2 for simplified Delta-V requirement diagrams).

Another complication is that although there is much talk about visiting the Lunar poles, especially the South Pole with its confirmed ice reserves, to do In Situ Resource Utilization missions (ISRU) which test technologies to turn Lunar Ice and minerals into propellant and other resources, a decision has not been made. Polar destinations require more energy to reach, and it also depends to a large degree from which orbit you start.

For these reasons, we revert to an energy efficient staging point that has proven to work in the past, and gives human crews access to equatorial and mid latitude regions on the Moon: Low Lunar orbit or LLO. In this manner we can compare results with historical data from the Apollo Lunar Missions, where rendezvous in LLO was an essential part. I do believe the poles are more interesting destinations, especially if we can find a protective lunar lava

tunnel ideally situated right next to a lunar ice deposit. Lunar lava tunnel offer a great potential for exploration, research, resource utilization and habitation.

Only for the sake of simplicity in our example, and to use Apollo as a reference, we start in Low Lunar Orbit (LLO), which is a sensible departure point for many mission scenarios.

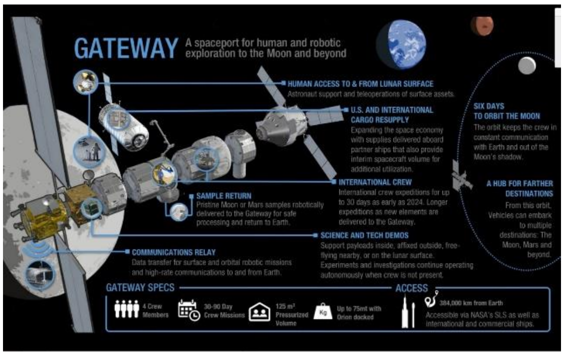


Figure 20 credit - NASA -
https://pbs.twimg.com/media/Dln8ytJVsAAY5og.jpg:large, Public Domain, https://commons.wikimedia.org/w/index.php?curid=72773616

Example

We conservatively assume an ISP of 310. In reality performance would be much better, but 310 is a common baseline across the acceptable engine options we encountered. Drop tanks are included as reusable cargo for ISRU collection (or wet habitat).

From LLO, and taking into account a delta-V to ground of 1870 m/s, we can deliver 1000kg of cargo to the lunar surface, together with our fixed 2155 kg lander mass, and make it back to LLO, if we have in our propellant tanks 1800 kg of fuel for the return trip and 4163 kg for the down trip, for a total of ~6000 kg of prop and an LLO vehicle departure weight of 9163 kg. No cargo, nor rocks are brought back from the Lunar surface.

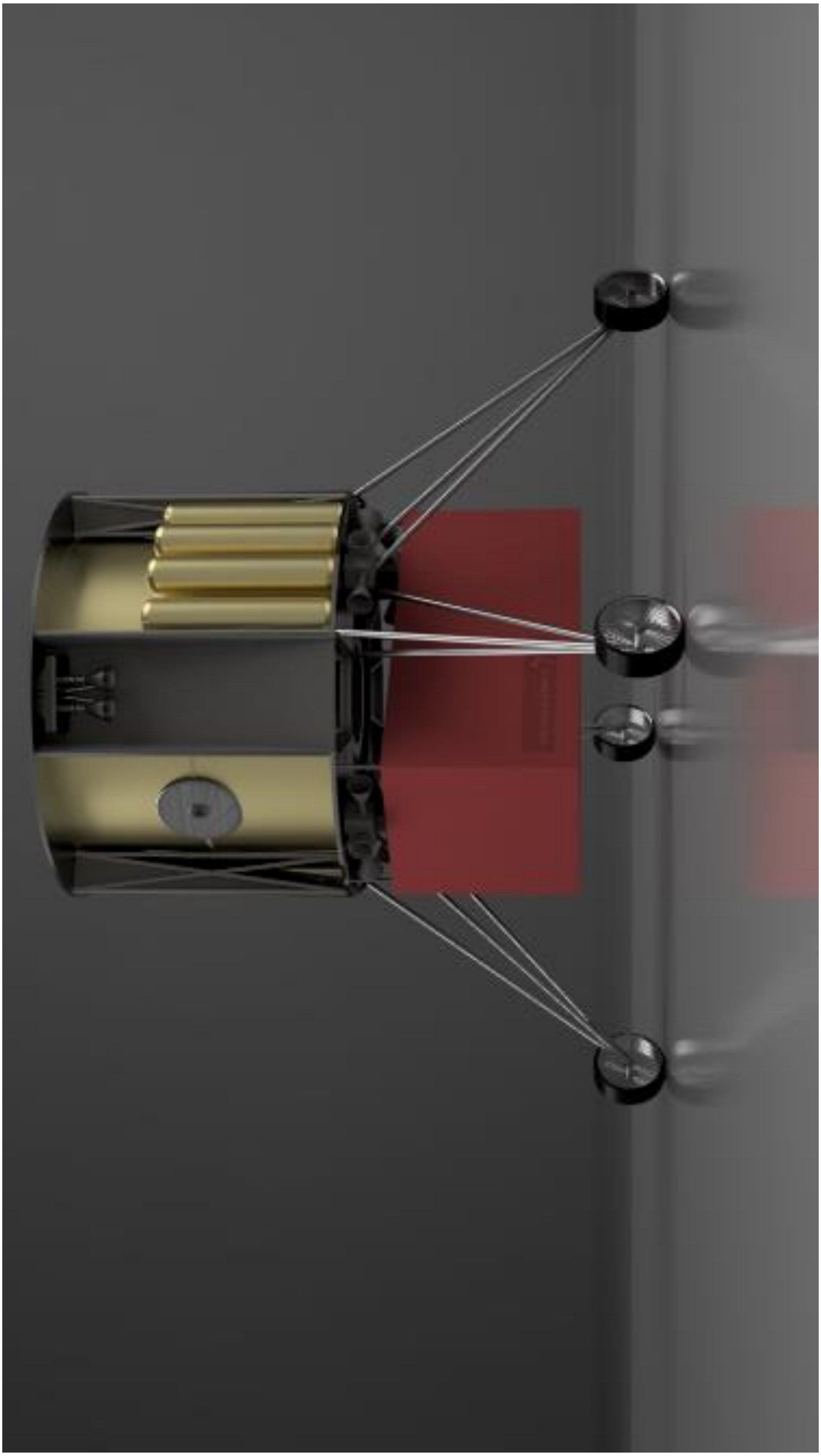
If you desire to land with 1000 kg of cargo and also return with 1000 kg of cargo (rocks/other) the mission from and to LLO requires a starting mass of 10594 kg (2155 for the lander + 1000 kg cargo down/up + 7439 kg of propellant).

Payload performance requires a thorough analysis beyond the scope we set ourselves for the moon lander design effort.

We were mainly focused on a viable form factor.

Conclusion

In our opinion the configuration presented would constitute an excellent starting point for an in-depth feasibility study.



ADDENDA

ADDENDUM 1: Simplified mass break down:

SABCA Moon lander - Reusable option

Component	Weight in kg	Source
Single Stage construction		
OD_Observation deck		
Outer Ring	67	
Inner Ring		
AscenderPropellant Tanks and housings (Tube or Donut shaped)		
AscenderPropellant Tanks and housings (Tube or Donut shaped)	382	Steven S. Pietrobon, Ph.D,Analysis of Propellant Tank Masses, https://www.nasa.gov/pdf/382034main_018%20-%2020090706.05.Analysis_of_Propellant_Tank_Masses.pdf
Titanium tanks would wheigh at one mm and 4.506 g/cm3 density: 321/tank total 642 kg		
Droptanks and tanks that can be left behind	100	Composite overwrap tanks can be half the wheight of metal tanks, "The mass of a pressure vessel is proportional to the mass of the gas it contains. "No matter what shape it takes, the minimum mass of a pressure vessel scales with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of the construction material." Source; Oxygen Storage Tanks Are Feasible for Mars Transit, Harry W. Jones, NASA Ames Research Center, 47th International Conference on Environmental Systems ICES-2017-89, 16-20 July 2017, Charleston, South Carolina,https://ttu-ir.tdl.org/ttu-ir/bitstream/handle/2346/72915/ICES_2017_89.pdf?sequence=1&isAllowed=y
Aerogel /kevlar Heat and MMOD barrier	10	
Other thermal insulation	10	
Struts	20	
CS_Cargo Sling Deck	133	
Ring	100	
Landing Gear		
A)Long version (400kg)	0	
B)Short Version (apollo) 250kg	250	
C) Airbag (100kg)	0	
Avionics	10	
E-Power 8-10KW		
Solar panels Vanguard THINS - 400-400W/kg-20kg	20	
Batteries	20	solar power and storage much more reliable than earlier decades, lunar night capability would require extra power packs
Graphene heaters	0,5	https://space.stackexchange.com/questions/12824/lightest-possible-solar-array
Lighting	0,2	
Cabling	1	
Computer and screens	3	
Manuals on paper/epaper	1	
Engines		
A) 4x RS-18 Scenario (Methalox) 310 ISP or above 4x82kg	328	Liquid Oxygen / Liquid Methane Test Results of the RS-18 Lunar Ascent Engine at Simulated Altitude Conditions at NASA White Sands Test Facility, John C. Melcher IV* NASA Johnson Space Center, Jennifer K. Allredt NASA Johnson Space Center, conference paper,45th AIAA/ASME/SAE/ASEE Joint Propulsion; 2-5 Aug. 2009; Denver, CO; United States, pub: Aug 02, 2009, https://ntrs.nasa.gov/search.jsp?R=20090026004
B) OTHER alternatives also result in about 400kg		
R-4D RCS thrusters, 3.63 kg/piece+housing gives =~4kg :sixteen x 490 N in four quads, specific impulse: 312 s (6,93Bar chamber pressure) eight: 0.55 m,Diameter: 0.28m, Thrust 490 N (110 lbf), Isp 312 s.	64	R-4D , rated for one hour of continuous thrust and 20,000 individual firings, https://en.wikipedia.org/wiki/R-4D, weight found on http://www.apolloartifacts.com/2013/11/marquardt-r-4d-apollo-spacecraft-attitude-control-engine.html
RCS thrusters propellant (see below)		
Crew compartment		
Inflatable hull:	20	
Windows (no), otherwise 10kg)		
2 Docking hatches: NASA DOCKING EXPLORATION HATCH (comatible with International Docking Adapter)		https://catalog.data.gov/dataset/exploration-docking-hatch
Astronaut seats 5 seats (inspired on WOII Alu bomber seats) 2kg/piece*2	4	
Other furniture budget	10	
Coolant: 25 pounds (11 kg) of ethylene glycol / water solution	25	
Consumables		
Air	100	On Apollo Ascender: Atmosphere: 100% oxygen at 4.8 psi (33 kPa), https://en.wikipedia.org/wiki/Apollo_Lunar_Module
Water	40	
Water in leave behind tanks	150	
Filter Water recycing (even urine) (1kg)	1	Commercial hiking water filters with nanopores
Food	50	
Clothing (single use)	20	
hygiene	10	
not the 2x-90kg Apollo astronaut suit but the 2*65 kg Z-2 suit from ILC dover	130	
Personal items	10	
Bags	2	
Repair kit and tools (intra vehicular)	2	
ECLSS		
Plasma torch (O2 and CO2 separation)	2	
Lithium Hydroxide canisters (backup)	50	
Toilet?		
A) none: diapers: 10kg	10	
B) yes: 20kg		
Science Gear Budget 200kg	0	
Buggy 200kg	0	
Surface inflatable 500kg	0	
	Total Dry Weight	
	2155,7	**Apollo ascent stage was 2,150 kg dry and gross 470kg, cf. wikipedia https://en.wikipedia.org/wiki/Apollo_Lunar_Module**

ADDENDUM 2: SIMPLIFIED DIAGRAMS TO CONCEPTUALISE THE DELTA- V requirements

Disclaimer: These diagrams do not replace proper trajectory calculations

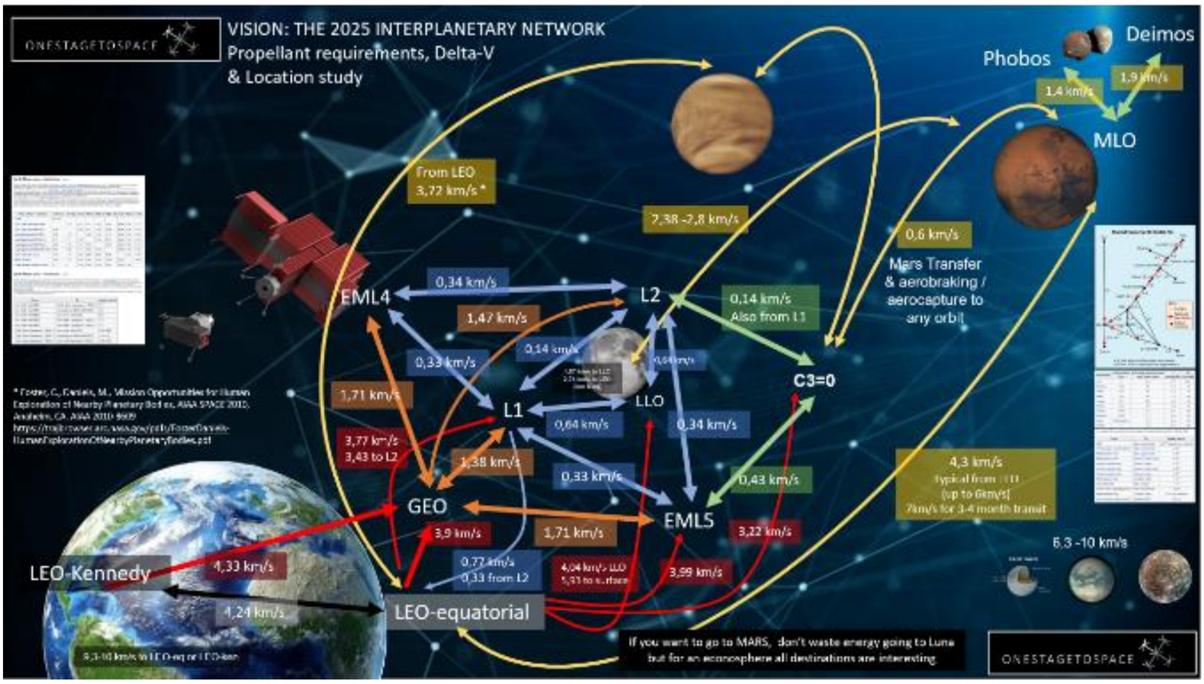


Figure 21 Credit - ONESTAGETOSPACE, JORIS LUYPAERT

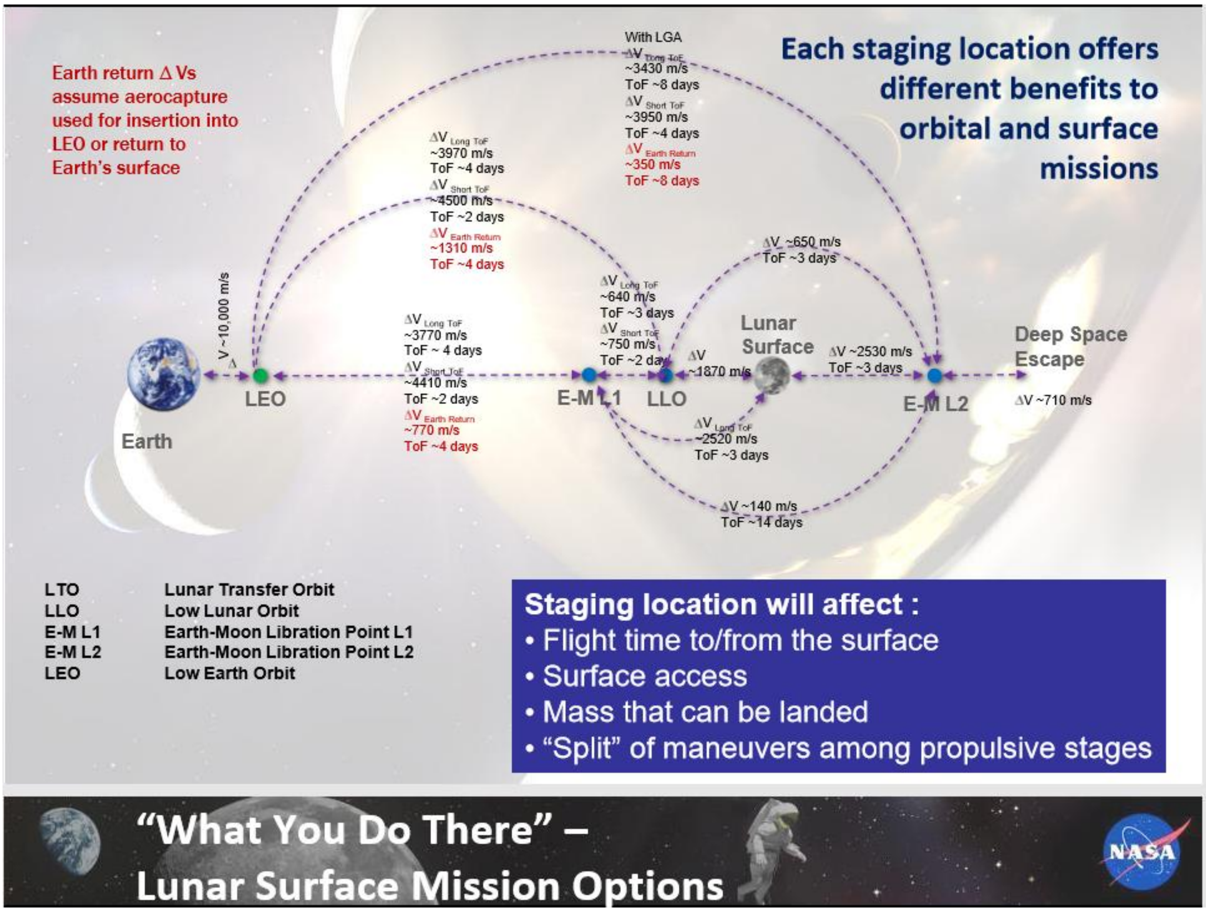
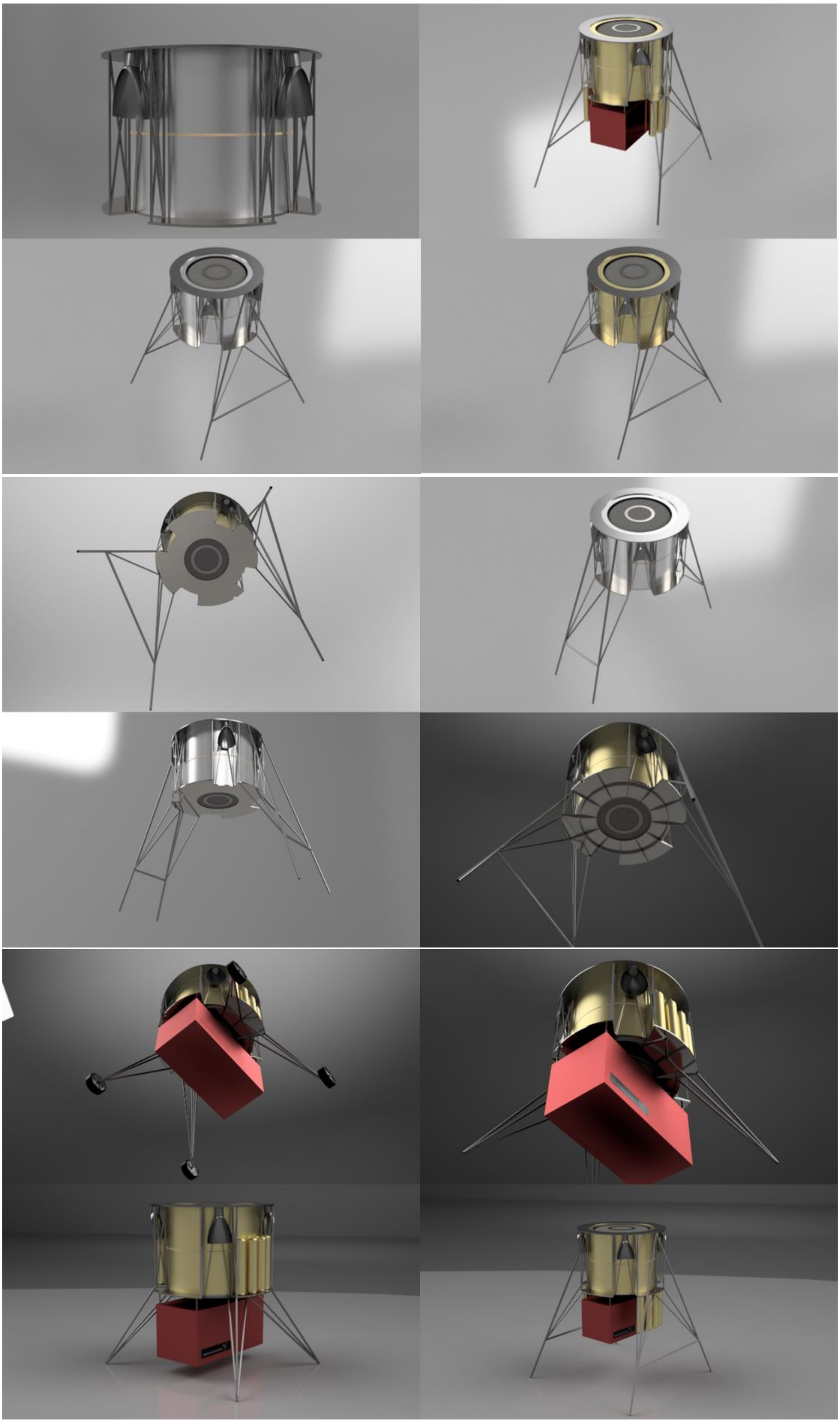
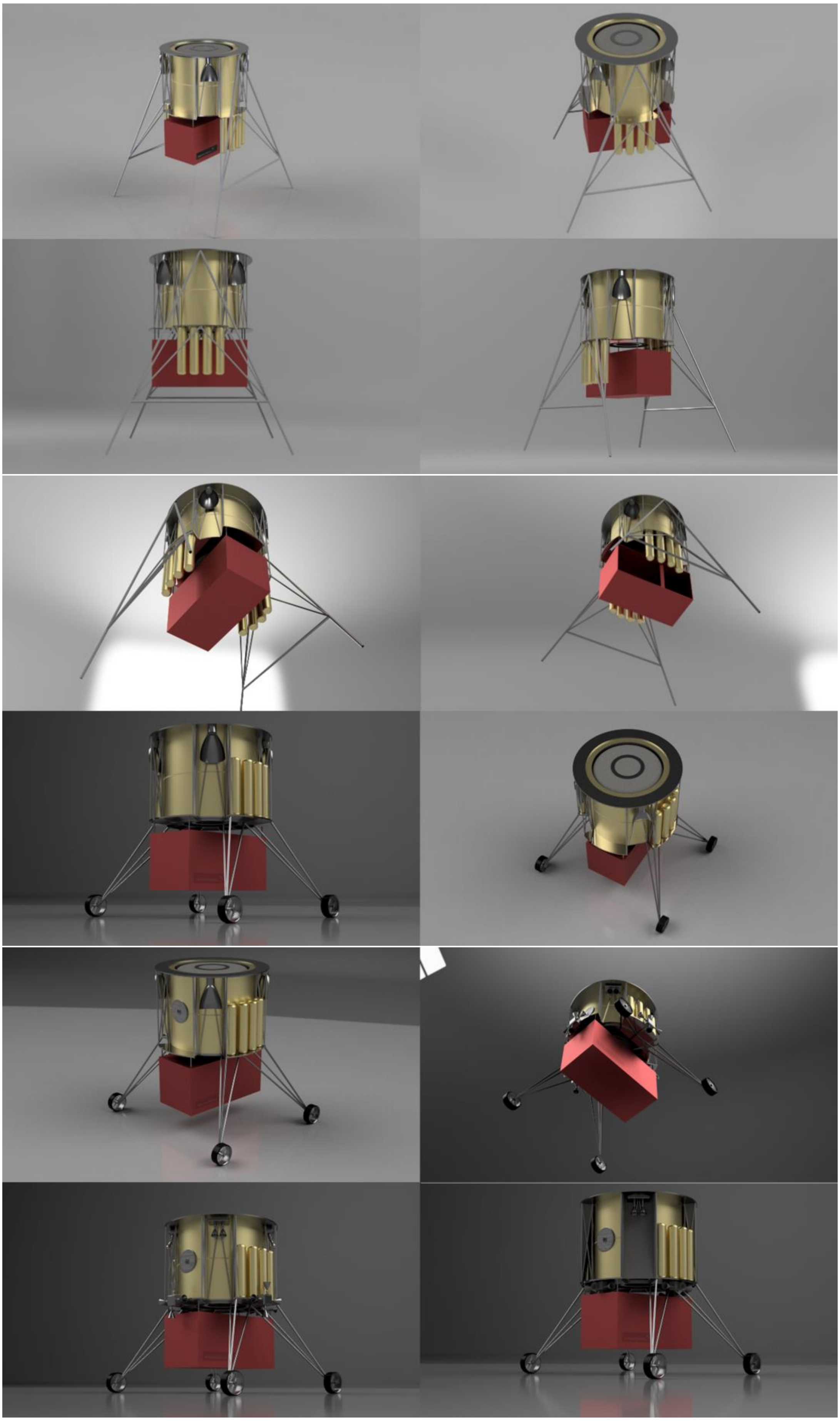
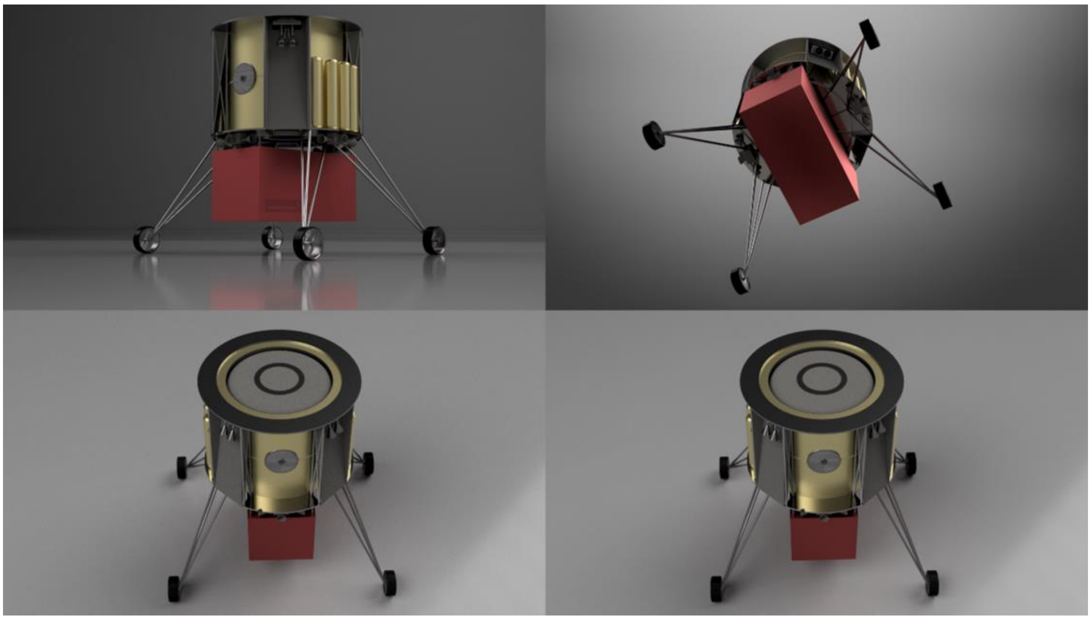


Figure 22 credit - NASA

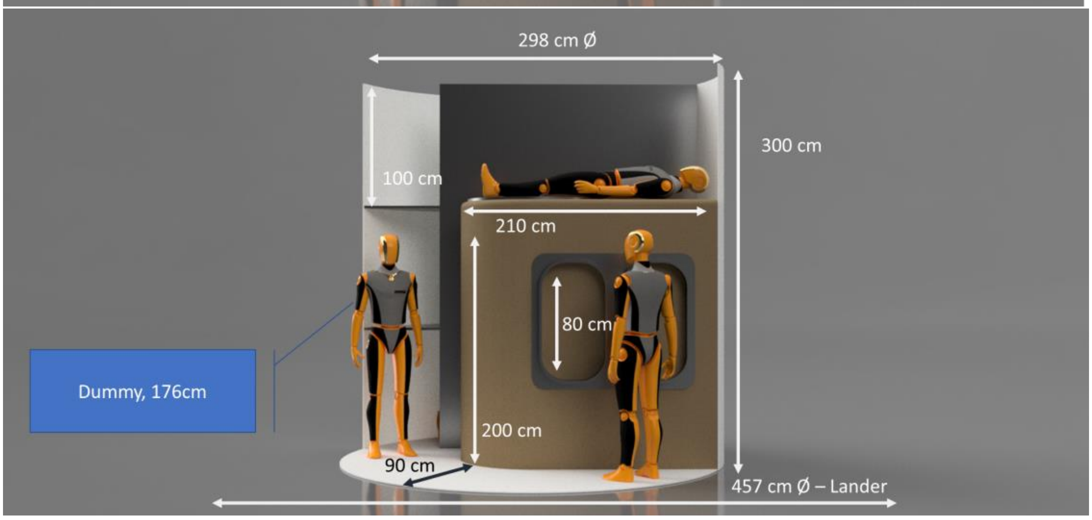
ADDENDUM 3: Extra images

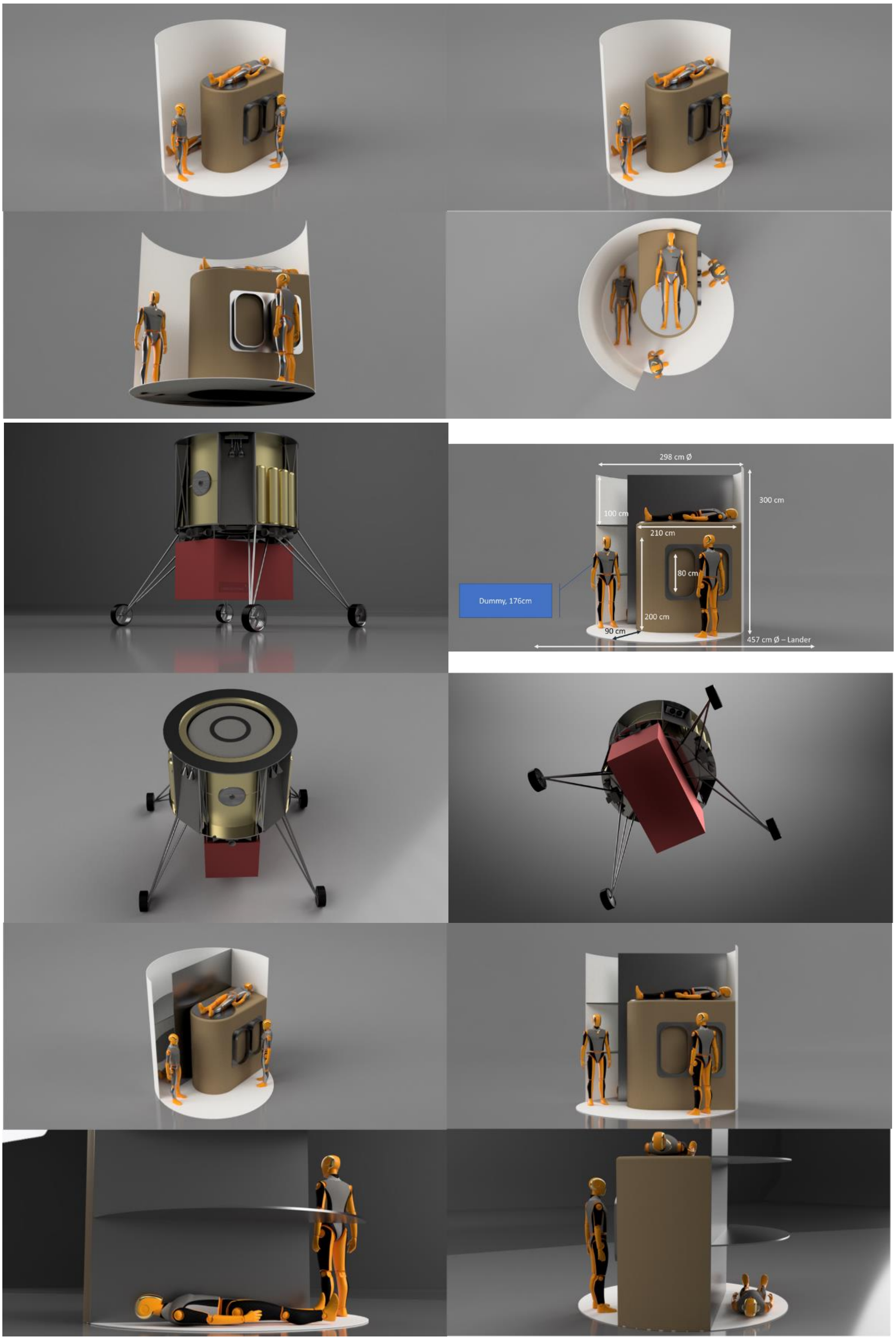







Internal
Layout
SABCA Lunar Lander
3m diameter By 3m high
Internal stow away inflatable airlock (brown)
Config on short surface stay
2-4 crew depicted
(option for 3 more)


298 cm Ø
300 cm
100 cm
210 cm
80 cm
Dummy, 176cm
200 cm
90 cm
457 cm Ø – Lander


298 cm Ø
300 cm
100 cm
210 cm
80 cm
Dummy, 176cm
200 cm
90 cm
457 cm Ø – Lander

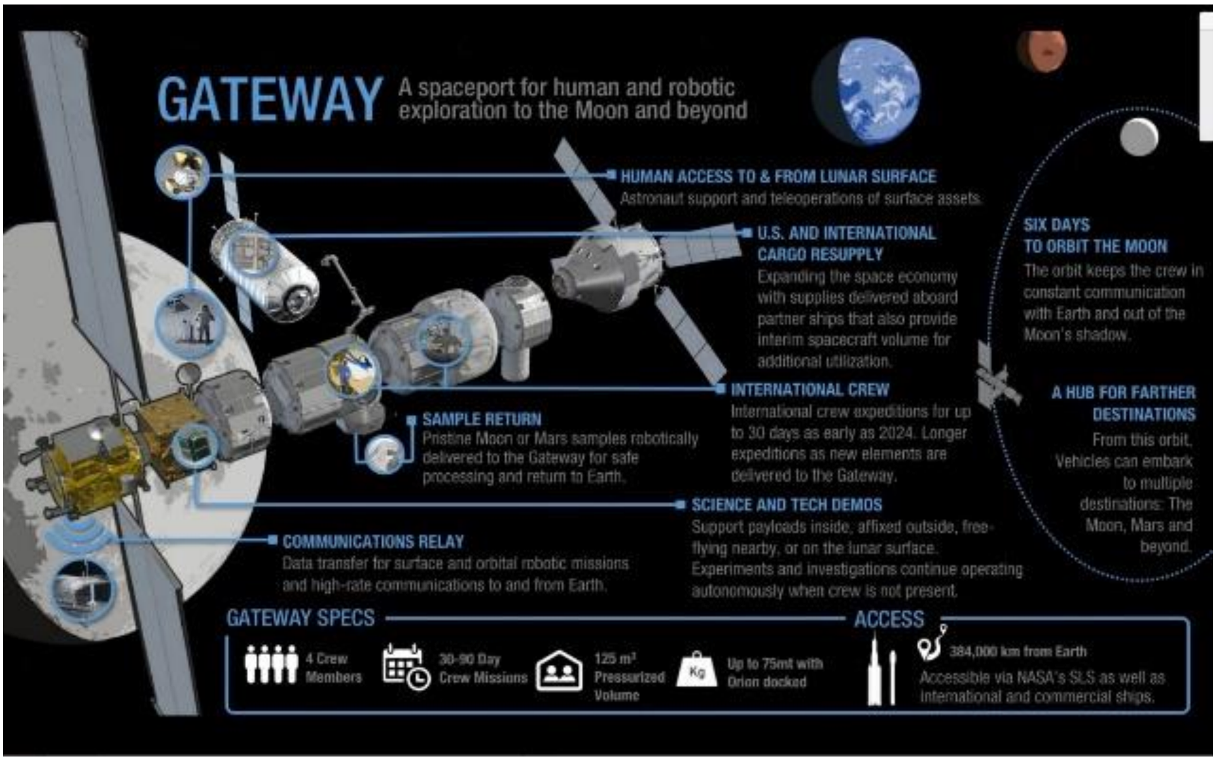


Figure 23 Credit - NASA - https://pbs.twimg.com/media/Dln8ytJVsAAY5og.jpg:large, Public Domain, https://commons.wikimedia.org/w/index.php?curid=72773616

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ENDNOTES

[i] John C. Melcher IV and Jennifer K. Allred (2008). "Liquid Oxygen / Liquid Methane Test Results of the RS-18 Lunar Ascent Engine at Simulated Altitude Conditions at NASA White Sands Test Facility" , https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090026004.pdf , AIAA.

[ii] "*A five-month study supported by NASA has concluded that it is technically feasible to convert a launch vehicle upper stage into a habitat module that could be used on the International Space Station or future commercial space station. Jeffrey Manber, chief executive of NanoRacks, discussed the results of the study, part of NASA's Next Space Technologies for Exploration Partnerships 2 (NextSTEP-2) effort, in panel discussions Dec. 6 at the SpaceCom Expo*". Source: "*Study validates NanoRacks concept for commercial space station module*"
by Jeff Foust — December 6, 2017, Spacenews.com https://spacenews.com/study-validates-nanoracks-concept-for-commercial-space-station-module/

[iii] For a video of the speech:" Vice President Pence Visits the Johnson Space Center to Discuss Future Exploration", published August 23 2018, https://www.youtube.com/watch?time_continue=634&v=uGI-8_G7dQY

[iv] Acoustic igniter and ignition method for propellant liquid rocket engine, US6199370B1, https://patents.google.com/patent/US6199370

[v] Simple, Robust Cryogenic Propellant Depot for Near Term Applications IEEE 2011-1044, http://sciences.ucf.edu/class/wp-content/uploads/sites/58/2017/02/Propellant-Depots-IEEE-2011.pdf , 24p.

[vi] As a take away, we give you an example of how strongly the rocket equation rewards regular refueling at intermediate depots.
If it takes about a Delta-V of 6 to get from LEO to the surface of the Moon, and have 6 legs starting in LEO and ending on the lunar surface, you have to refuel at 3 intermediate stops 1km/s velocity increases apart, and 3 refueling stations (but this could be increased) you would only require 0.401 as much propellant as when you go from LEO to surface directly. (the last leg, landing and taking off from the moon, always requires 1870km/s or in our approximate rounded off calculation about ~2 DV). Only 40%. Given the launch costs of propellant and the maturing of orbital refueling technology, it pays off to put a minimal refueling outpost infrastructure in space.
In that scenario, at 310 ISP our 2000mton dry weight lander would not need 12414 kg of propellant but only 4965.6 kg. Put otherwise, an Ariane 6, with ~20mton LEO capability would be able to send a 2775kg lander to the surface of the Moon consuming 17225kg of propellant in the process. If we use that same amount of propellant, but distributed along refueling stations, we could transport 6915 kg to the surface of the Moon.

[vii] "Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions", Subject Matter Expert Consensus Session Report, NASA Human Research Program, NASA/TM-2015-218564, https://ston.jsc.nasa.gov/collections/trs/_techrep/TM-2015-218564.pdf , p. 3 of 20

[viii] NASA command module overview, p.47, https://www.hq.nasa.gov/alsj/CSM06_Command_Module_Overview_pp39-52.pdf

[ix] "The All-Terrain Hex-Legged Extra-Terrestrial Explorer, known as ATHLETE, is a six-legged robotic lunar rover under development by NASA. ATHLETE is capable of rolling over undulating terrain. The vehicle can "walk" over extremely rough or steep terrain, so robotic or human missions on the surface of the moon can load, transport, manipulate and deposit payloads to most any desired sites of interest." Source, https://www.nasa.gov/audience/foreducators/robotics/imagegallery/r_athlete.jpg.html

[x] Source : Super elastic Tire, A viable alternative to the pneumatic tire https://technology.grc.nasa.gov/patent/LEW-TOPS-99, link found on https://www.nasa.gov/specials/wheels/

[xi] NASA Tests Game Changing Composite Cryogenic Fuel Tank, NASA press release July 2, 2013 https://www.nasa.gov/content/nasa-tests-game-changing-composite-cryogenic-fuel-tank_marshall_news, ; Final Results of Advanced Cryo-Tanks Research Project CHATT, 6TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS) 2015 an EU-FP-7 funded study, https://elib.dlr.de/101483/1/EUCASS2015-CHATT.pdf (CHATT, Cryogenic Hypersonic Advanced Tank Technologies): "In future projects the lessons learned of CHATT will be useful to bring European composite tank technologies forward. Currently, the European TRL of such cryotanks is still in the range between 3 and 4 while the TRL in the US is considerably more advanced, already approaching full launcher scale dimensions with ground tests run using liquid hydrogen fuel. The next step in the development of a European composite cryotank should focus on a single, fully integrated tank demonstrator including thermal protection and some health monitoring equipment to be tested with LH2 in multiple cycles."; SpaceX Successfully Tests Carbon Fiber Tank for Mars Spaceship
Evan Milberg, November 29, 2016, http://compositesmanufacturingmagazine.com/2016/11/spacex-successfully-tests-carbon-fiber-tank-mars-spaceship/