Moon Direct:
A Cost-Effective Plan to Enable Human Lunar Exploration

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Abstract

This paper presents Moon Direct, a highly cost-effective plan to enable the exploration and development of Earth's Moon. Unlike many other approaches which begin by looking for things to do with existing or planned hardware, the logic of Moon Direct begins by defining the requirements for a highly cost-effective lunar exploration program. These are maximum access to the lunar surface, minimum development and recurring cost, minimum schedule, and minimum risk. It is shown that by far the most effective transportation system architecture is one that makes use of LOx/H2 propellant produced at a lunar polar base to support the operation of a lightweight Lunar Excursion Vehicle (LEV) flight system with a ΔV capability of 6 km/s or more, enabling sorties to most of the Moon. Such a LEV would also have the capability to fly directly from the lunar surface to low Earth orbit, eliminating the need for any lunar orbit infrastructure, lunar orbit rendezvous, or the delivery of any reentry capsule to any location beyond Earth orbit. Using such an approach recurring lunar missions accessing all parts of the Moon could be done using currently operational launch vehicles with launch costs under $100 million per mission and no expended hardware.

Introduction: Defining the Requirements for an Effective Lunar Program

The most important step in any engineering program is to define its requirements. While it is essential to design things right, before that can even be attempted we must make sure that we are designing the right thing. Therefore, if our goal is to create a transportation system enabling the exploration and development of the Moon, we need to start by considering what the Moon is, and what is required to support a sustainable and effective human presence there.

So let's begin at the beginning. The Moon is not a small place. Rather, it is a world with a surface area equal to the continent of Africa. Its terrain is rough, roadless, and riverless. It therefore cannot be effectively explored using ground transportation systems. Rather, lunar explorers are going to need to fly. While it is theoretically possible that multitudes of locations could be visited by launching scores of missions directly from Earth, the cost of doing so would be astronomical. A much better plan would be to create a base which can produce propellant on the Moon, and thereby support the operation of a rocket propelled flight vehicle enabling global exploration by repeated sorties, with only occasional resupply and crew rotation missions being required. Since the 1990s, a series of missions including Clementine, Lunar Prospector, and LCROSS have produced data showing that deposits of frozen water may be found in permanently shadowed craters near the Moon's poles, which also feature permanently illuminated highlands offering near constant access to solar energy. Such locations are thus the clear favorites for locating a base, as they provide both the energy source and raw material necessary to manufacture hydrogen/oxygen rocket propellant.

Enabling Global Mobility on the Moon

The number one requirement for effective exploration of the Moon is mobility. How much mobility can a practical Lunar Excursion Vehicle (LEV) using LOx/H2 rocket propulsion to travel from place to place on the Moon achieve? Let us see.

If it is to be used for exploration sorties, the LEV must take off, land, take off again to return, and then land. Four burns are thus required for each sortie. If we assume that there are 10% gravity losses on each burn, the real velocity V achievable by for a LEV with a total propulsion ΔV capability is given by;

$$V = 0.9(\Delta V)/4 \qquad (1)$$

The range of a projectile fired with velocity V on a spherical airless planet with Radius R and orbital velocity W at its surface is given approximately by:

$$\text{range} = R(V^2/W^2)/(1-V^2/W^2) \qquad (2)$$

On the Moon, W = 1705 m/s and R = 1737 km.

Combining equations (1) and (2), the range of the LEV is used as an excursion vehicle is shown in fig. 1.

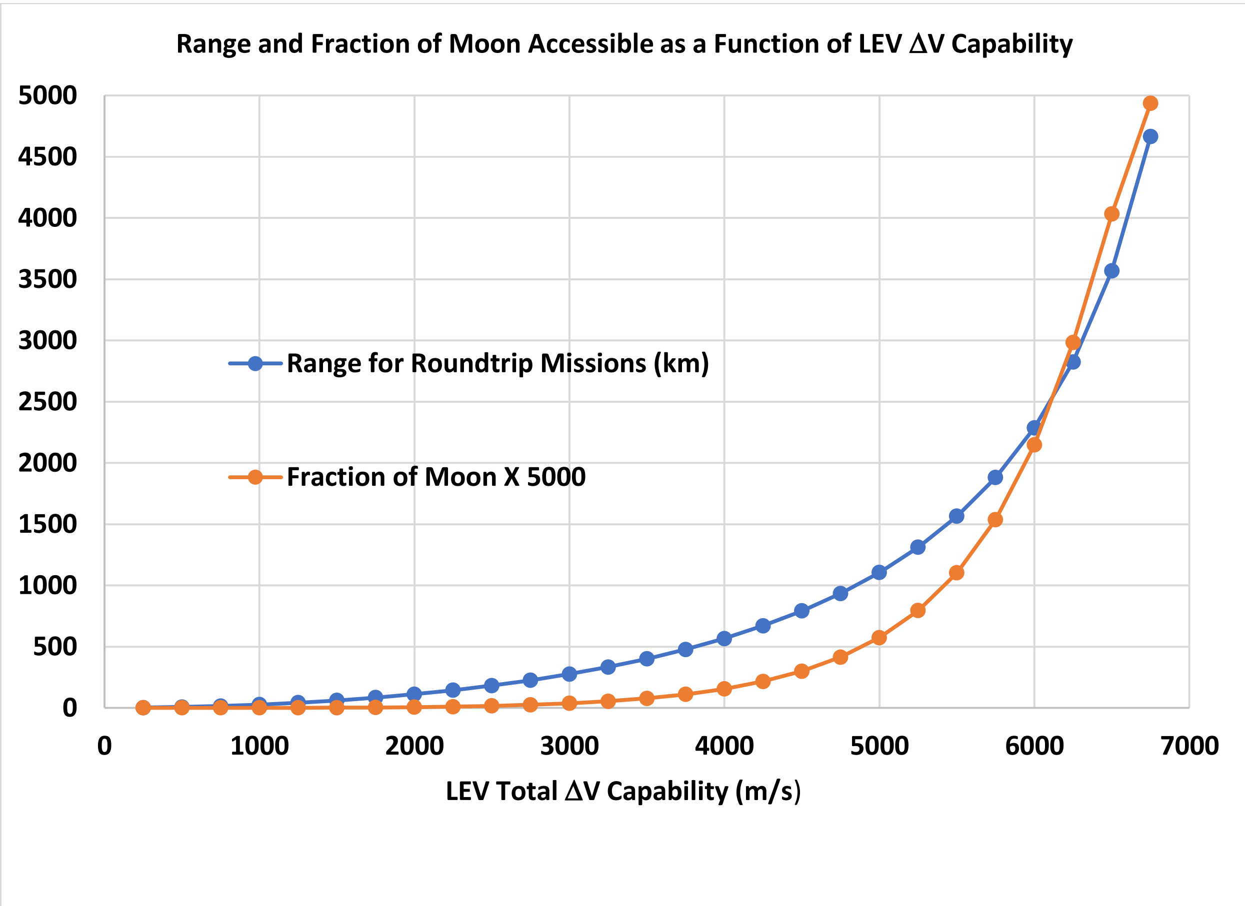

Fig. 1 Range of LEV if used as a round trip lunar excursion vehicle is shown in blue. Fraction of the total lunar surface made accessible is shown in orange (5000 = 100%).

It can be seen that a LEV with a ΔV capability of 6 km/s or more provides substantial global access. It also provides sufficient range to go one way (for example from one polar base to base on the other pole) in a two-burn flight.

So, 6 km/s is what we need. Can we get it in a practical LEV?

The Apollo Lunar Excursion module (LEM) had a dry mass of about 2 metric tons. The LEV is also lightweight vehicle lacking a reentry system, so we will assume 2 tons for its dry mass as well.

In Fig 2 we show the wet mass and payload of the LEV as a function of its total ΔV capability. The LEV's LOx/H2 propulsion system is assumed to have an Isp of 450 s and a dry mass equal to 11% of the propellant it carries.

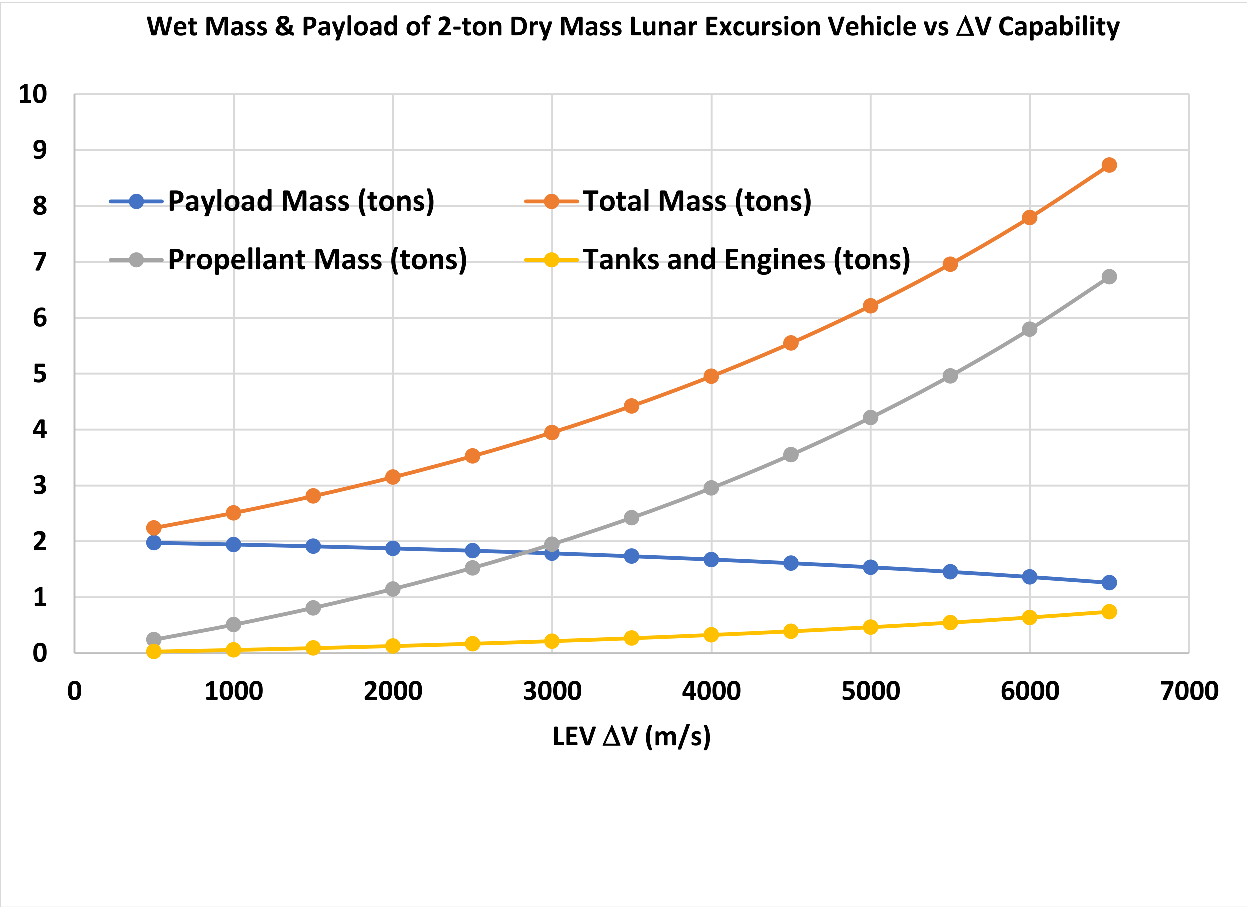

Fig. 2 Wet Mass and payload of a 2-ton dry mass LEV as a function of ΔV.

Examining fig. 2, we note that at the critical 6 km/s performance point, the LEV would have an ample cabin payload mass of about 1.4 metric tons, and a total wet mass of about 8 metric tons. About 6 tons of propellant are required for each 6 km/s ΔV trip.

<u>Earth-Moon Transportation</u>

The Apollo missions used a flight plan known as Lunar Orbit Rendezvous, (LOR), in which the heavy Command Module reentry capsule was left in lunar orbit, and only the lightweight LEM, carrying two of the three crew members, left lunar orbit to travel to the surface and back. This concept was key to the success of the Apollo program, because it reduced the mass of the mission substantially compared to what would have been required if the whole spacecraft, fueled for direct return to Earth, had been landed on the Moon. This mass saving allowed the mission to be accomplished within the lift capability of the Saturn V. That said, however, LOR, while useful for brief Apollo-style missions to the Moon, is very undesirable as the flight mode for supporting a lunar base. This is so because it is one thing to have someone playing the role of Michael Collins hanging out in Lunar orbit for a few hours or days while Neil and Buzz are making a few footprints on the Moon, but quite another to leave someone behind in such a manner doing nothing useful while soaking up cosmic rays for months. We could, of course, leave no one in orbit, but it hardly seems prudent to have our mission-critical Earth return system left behind in orbit with no one minding the store. Some are now proposing that this problem be remedied by leaving the Earth return capsule at a lunar orbiting space station, but this approach will add tens of billions in cost to the program, both to construct it and maintain it, sapping the program of funds and delaying any real accomplishments for many years without adding any real capability.

While as useful as it might have been for Apollo, for a lunar base direct return is the way to go. It's much simpler and much safer. There are no liabilities to maintain on orbit. Furthermore, viewed from the surface of the Moon, the Earth is always at exactly the same point in the sky, so the return launch window is always open. In contrast, a LOR mission needs to phase its return to match the orbit of its return vehicle, which may not be convenient. There is no shielding material available on orbit, but infinite amounts available on the Moon. The material to make propellant is on the surface of the Moon, and the science and engineering tasks to be done are on the Moon. If we are sending crews to explore the Moon, it's crazy to leave a substantial fraction of our critically limited exploration teams cooped up in cans on orbit where they can't contribute. Finally, once lunar-produced propellant is available, direct return is actually a lower mass approach to lunar missions than LOR.

The problem however, that until lunar produced propellant is available, it remains the case that a direct return plan puts the mission outside of the capabilities of existing launch vehicles. For example, we estimate that a Dragon capsule, with its service systems, has a mass of about 8 metric tons. (Orion is over 20 tons.) If so, then if it has to be delivered to the Moon with a fully fueled LOx/H2 propulsion system capable of providing it with the 3 km/s ΔV needed to shoot it directly back to Earth, it would represent a payload of about 18 tons. Delivering this would require a LEO lift capability of about 100 metric tons, putting it outside the capability of any existing launch vehicle. Instead such a delivery would require either a SLS-block 2 or the SpaceX BFR, but these launchers have yet to be seen.

But there is another way. We can use the LEV. The fueled LEV only has a mass of 8 tons, making it much lighter than a Dragon equipped with the propulsion needed for direct return. The ΔV to go from the lunar surface to trans-Earth injection (TEI) is 3 km/s. Once on TEI, a further ΔV of 3.1 km/s could be used to capture the LEV into low Earth orbit (LEO), where it could rendezvous with a Dragon, an Orion, the ISS, a Soyuz, or any other spacecraft launched from Earth. So, the same ~6 km/s ΔV-capable LEV used to enable lunar exploration could also be used to return directly from the lunar surface to LEO, to discharge its crew. It could then be refueled on orbit and used to take another crew back to the Moon.

It will be recalled that the LEV requires 6 tons of propellant to perform its 6 km/s ΔV. Thus, the recurring mission to the Moon could be done by means of a single Falcon 9 launch delivering a Dragon for crew exchange plus 6 tons of propellant. The launch cost of such a mission would be under $100 million.

This would provide the basis for a very sustainable lunar base program.

The Moon Direct Plan

We see that a Moon base producing LOx/H2 propellant to support a LEV would enable global access, direct return, and very low recurring costs. These are the prime requirements for a highly cost-effective lunar exploration program.

There are three phases required for such a program.

Phase 1: Automated missions deliver a hab module and other cargo one way to the lunar surface to preposition the base in advance of the crew.

Phase 2: Initial piloted missions to make the base operational. These missions must be flown without the benefit of in-situ propellant production (ISPP). A key objective of this phase is to make ISPP operational.

Phase 3: The recurring piloted mission, which can be done making use of ISPP.

A diagram showing the Moon Direct flight plan for each of the three phases is presented in Fig. 3.

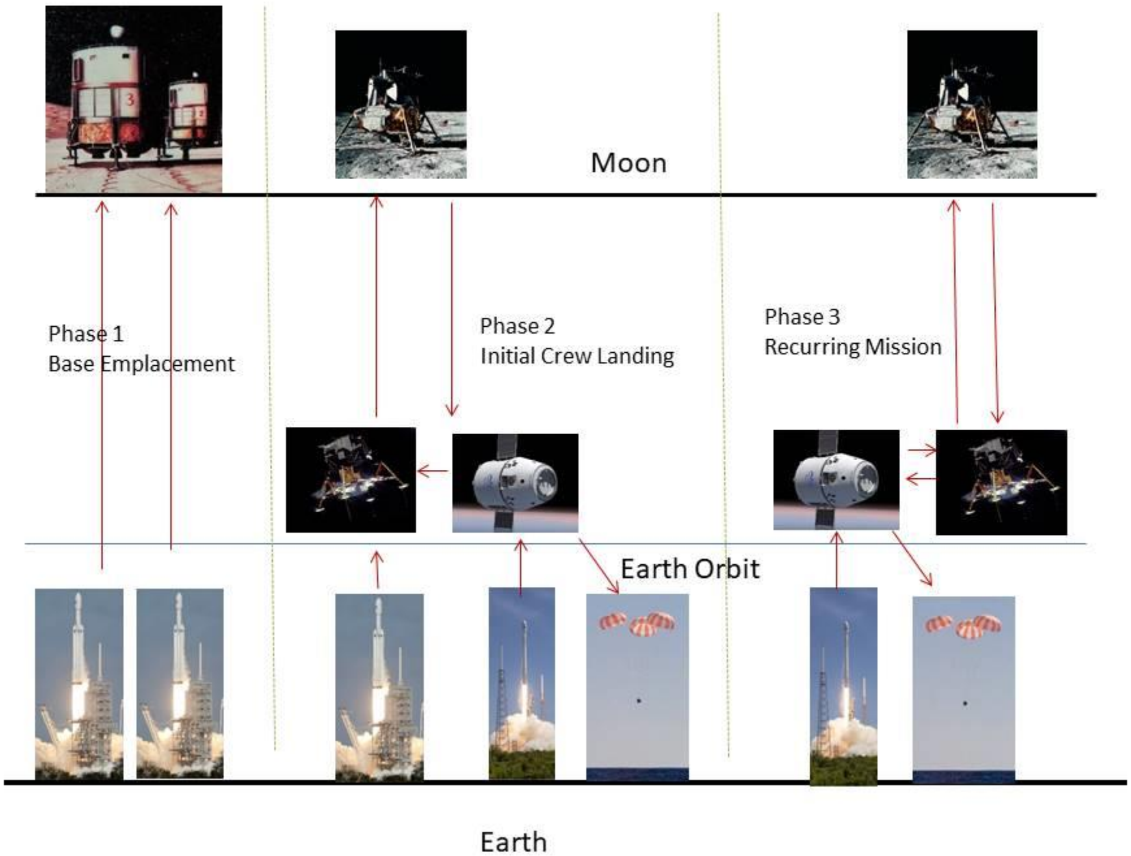

Fig. 3. The Moon Direct program. In Phase 1, two Falcon Heavy boosters are used to emplace base habitation modules and other cargo on the Moon. In Phase 2, 1 Falcon Heavy and 1 Falcon 9 are used to deliver the crew to the Moon in a fueled LEV. In Phase 3, only 1 Falcon 9 is used to deliver the crew to orbit and refuel the LEV. The crew then flies to the Moon in the LEV, which refuels at the lunar base.

We discuss each of these phases in turn.

Phase 1

Aside from the LEV itself, we have need for only one kind of cargo lander, which we will use to deliver the base hab modules and other cargo in Phase 1, as well as the fueled LEV that needs to be delivered in Phase 2 to the Moon until local propellant production is operational.

In Table 1, we show the cargo that could be delivered to the Moon with a single launch of a variety of boosters, using only a single stage system that takes the cargo from a staging orbit to the lunar surface.

In the analysis presented, we used ΔVs of 6.1 km/s for LEO to the lunar surface (LS), 3.7 km/s for geosynchronous transfer orbit (GTO) to LS, and 3 km/s for trans lunar injection (TLI) to LS. For the cargo lander propulsion system, we consider both LOx/CH4 with a 375 s Isp, 0.07 stage dry fraction, 800 kg/m^3 density, and a LOx/H2 with 450 s Isp, 0.11 stage dry fraction, 300 kg/m^3 density.

Flight systems considered include: Falcon Heavy with 62 tons to LEO, or 26 tons to GTO, 5 m fairing; SLS with 90 tons to LEO, 8 m fairing; New Glenn with 45 tons to LEO, 7 m fairing; Vulcan with 30 tons to LEO, 5 m fairing; and BFR 150 tons to LEO, or if refueled 150 tons to TLI, 8 m fairing.

Table 1. Cargo Lander Mission (single stage)

Launcher	Staging Orbit	Propulsion	Tank Length	Payload Delivered
Falcon H	LEO	LOx/CH4	3.2 m	8.3 tons
Falcon H	GTO	LOx/CH4	1.05	8.3
Falcon H	LEO	LOx/H2	7.9	10.4
Falcon H	GTO	LOx/H2	2.5	9.6
New Glenn	LEO	LOx/CH4	1.12	6.0
New Glenn	LEO `	LOx/H2	2.85	7.5
Vulcan	LEO	LOx/CH4	1.54	4.0
Vulcan	LEO	LOx/H2	3.8	5.0
SLS	LEO	LOx/CH4	1.9	12.0
SLS	LEO	LOx/H2	4.45	15.0
BFR	LEO	LOx/CH4	3.2	19.9
BFR	TLI	LOX/CH4	2.5	60.0

It can be seen that the Falcon Heavy can deliver over 8 tons to the lunar surface with any of the four options considered. It can thus deliver both cargo modules in this class, as well as the wet LEV that must be sent until lunar propellant production is operational. New Glenn and Vulcan cannot deliver adequate mass, although New Glenn can come close and its large fairing could make it interesting for delivering high-volume/low mass payloads. (Note: The 45 ton to LEO capability advertised for New Glen may be an underestimate, as its BE4 engine was recently upgraded from 400,000 lbf thrust to 550,000 lbf thrust. With the upgrade its payload capability may match the Falcon Heavy.) SLS can deliver more than what is required and BFR much more. However neither these systems or the New Glenn, are yet available. We therefore focus on the Falcon Heavy.

In Table 1, the column labeled “tank length” refers to the length of the propellant tankage required for the cargo lander, if it is considered as a cylinder, ignoring additional length required for hemispherical end caps. The lander propulsion system would also need further additional length for engines. In addition, the booster fairing would also have to accommodate not only the lander, but its payload. So as much as 8 m (2 for end caps, 2 for engines, and 4 for payload might need to be added to the cited figures to determine the required fairing length. The current Falcon Heavy fairing is about 11 m long. Therefore, the while the option of using a single LOx/H2 stage to take cargo from LEO to LS theoretically delivers the most mass, it would not fit into the current fairing. One answer to this would be to extend or expand the fairing, a modification that would appear modest compared to the other developments that SpaceX has achieved. If this is not done, however, any of the other Falcon Heavy options appears to be feasible.

We therefore proceed by sending two cargo landers to our planned base location near the Moon's South pole, each carrying over 8 tons of payload. The first cargo lander carries a load of equipment, including a solar panel array, high data rate communication gear, a microwave power beaming set up with a range of 100 km, an electrolysis/refrigeration unit, two crew vehicles, a trailer, and a group of teleoperated robotic rovers. After landing, some of the rovers are used to set up the solar array and communication system, while others are used to scout out the landing area in detail, putting down radio beacons on the precise target locations for the landings to follow.

The second cargo lander brings out an 8-ton habitation module, loaded with food, spare spacesuits, scientific equipment, tools, and other supplies. This will serve as the astronauts' house, laboratory, and workshop of the Moon. Once it has landed, the rovers hook it up to the power supply and all systems are checked out. This done, the rovers are redeployed to do detailed photographing of the base area and its surroundings. All this data is sent back to Earth, to aid mission planners and the science and engineering support teams, and ultimately forming the basis of a virtual reality program that will allow millions of members of the public to participate in the missions as well.

Phase 2

The base now being operational it is time to send the first crew. A Falcon Heavy is used to deliver another cargo lander to orbit, whose payload consists of a fully-fueled LEV. This craft consists of a 2-ton lightweight spacecraft like that used by the Apollo era Lunar Excursion Module together with a 6-tons of hydrogen/oxygen propellant, capable of delivering it from the lunar surface to Earth orbit. A man-rated Falcon 9 rocket then lifts the crew in a Dragon capsule to LEO where they transfer to the LEV. Then the cargo lander takes the LEV, with the crew aboard, to the Moon, while the Dragon remains behind in LEO.

After landing at the Moon base, the crew completes any necessary set up operations and begins exploration. A key goal will be to travel to a permanently-shadowed crater and making use of power beamed to them from the base, use telerobots to mine water ice. A diagram depicting a concept for supporting such beamed power-enabled water mining is presented in fig. 4.

Hauling this treasure back to the base in their trailer, the astronauts will feed the water into the electrolysis/refrigeration unit, which will transform it into liquid hydrogen and oxygen. These products will then be stored in the empty tanks of the cargo landers for future use- primarily as rocket propellant but also as a power supply for fuel cells and a copious source of life support consumables.

Having spent a couple of months initiating such operations and engaging in additional forms of resource prospecting and scientific exploration, the astronauts will enter the LEV, take off and return to Earth orbit. There they will be met by a Dragon – either the one that took them to orbit in the first place or another that has just been launched to lift the crew following them - which will serve as their reentry capsule for the final leg of the journey back home.

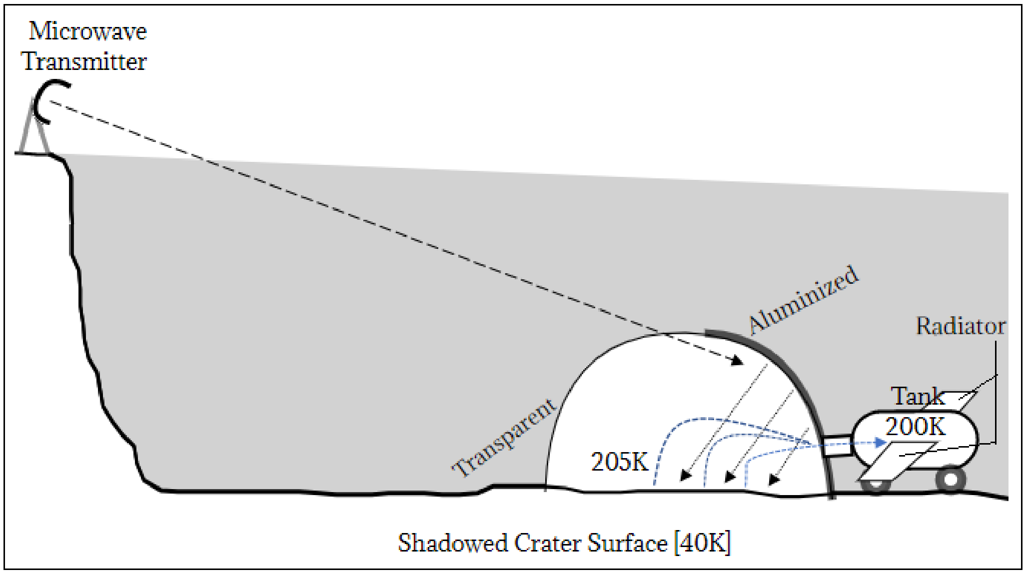

Fig. 4. Concept for using beamed microwaves to extract water vapor from permafrost in a permanently shadowed lunar polar crater.

Phase 3

Until lunar propellant production is operational, each mission that follows will require just one $120 million Falcon Heavy and one $60 million Falcon 9 to accomplish. As soon as propellant production is operational, however, crews will be able to fly back to the Moon in a LEV refueled with 6 tons of propellant in LEO, *allowing recurring missions to be done with just a single Falcon 9 launch each.* Furthermore, once the base is well-established, there will be little reason not to extend surface stays to 4 months or more. So, assuming that the program hardware purchases will roughly equal its launch costs, we should be able to sustain a permanently occupied lunar base at an ongoing yearly cost of less than $400 million. This is less than 2 percent of NASA's current budget.

As noted, the astronauts will not be limited to exploring the local region around the base. Refueled with hydrogen and oxygen, the same LEV spacecraft used to travel to the Moon and back can be used to fly from the base to nearly anywhere else on the Moon, land, provide onsite housing for an exploration sortie crew, and then return them to the base. We won't just be getting a local outpost: we'll be getting complete global access to an entire world.

Alternative Flight Systems

In this paper we have focused on the Falcon boosters and Dragon capsule, as these are the most cost-effective. However it may be noted that for the recurring mission, any of the New Glenn, Vulcan, or Atlas V could replace the Falcon 9 as the Dragon's launch vehicle, should a stand down of the Falcon 9 be required. Also, if the Dragon needs to stand down, it could be replaced by the Orion, Boeing Starliner, or Sierra Nevada Dream Chaser, if the New Glenn or Vulcan were used as the launch vehicle. The transportation system architecture is thus extremely robust.

Power Requirements

Each Moon Direct mission requires 6 tons of propellant to be made on the Moon for flight back to Earth. It also requires 6 tons of propellant for each long distance roundtrip surface to surface sortie from the base to a distant location of the Moon. For purposes of analysis, we assume that once the base is operational, there will be a roundtrip mission every 4 months, with one long-range exploration flight per month while the crew is on the Moon. The propellant manufacturing requirement would therefore be 6 tons per month, equivalent to 200 kg/day, or 2.315 grams/s.

The dominant power requirement will be for water electrolysis itself, as the energy needed to do this is 277 kJ/mole, compared to 68 kJ/mole to vaporize 40 K ice. Electrolysis units are available with efficiencies of 85%. Based on this number, electrolyzing 2.315 gm/s of water will require 35.6 kWe. Microwaves can be generated at 65% efficiency. Taking into account other losses, we assume a total efficiency of 30% of microwave generation to ice evaporation. In this case, the microwave-driven water mining process will require 8.7 kWe. Allowing a further 16 kWe for cryogenic liquefaction of the H_2 and O_2 products, and 10 kWe for base life support, we estimate a total power requirement of 70 kWe for supporting such an highly active lunar base program.

Comparison with Other Mission Modes

We consider five alternative mission modes. These are:

A. Program of Record: First construct a Lunar Orbit Gateway (LOG), and then use it as a node to send the Orion spacecraft to low lunar orbit (LLO), and then conduct the mission to the surface via LOR, with a LEV type vehicle going from LLO to the lunar surface (LS) and back. Orion then returns the crew to aeroentry at Earth

B. LOR-Orion: Same as option B, except no LOG is constructed.

C. LOR-Dragon: Same as option C, except a Dragon is used instead of Orion.

D. Direct Return: Dragon delivered to surface. Dragon flies directly back to TEI, aeroentry.

E. EOR (Moon Direct): Crew to orbit in Dragon. Goes to Moon in LEV. Direct return to rendezvous with capsule in Earth orbit.

Each of these has the same three phases as Moon Direct; that is Phase 1 automated pre-emplacement, Phase 2 initial crew missions before ISPP, Phase 3 and recurring crewed missions after ISPP.

We consider Initial Mass in Leo Earth Orbit (IMLEO) requirements each of these mission modes in each phase. We also consider a total program consisting of Phase 1, two Phase 2 missions, and 20 Phase 3 missions.

A. Program of Record
    1. Phase 1. Must deliver LOG to LLO (120 t IMLEO) plus two cargo flights to LS. Total IMLEO 240 t.
    2. Phase 2. Orion does 5.1 km/s roundtrip to LLO. (110 t IMLEO). LEV goes 1-way from LEO to LLO. LEV does 4 km/s roundtrip from LLO to LS and back. Two-ton dry LEV has wet mass of 5 t, (16 t IMLEO). Total mission IMLEO is 126 tons.
    3. Phase 3. Orion does 5.1 km/s roundtrip to LLO. (110 t IMLEO). LEV goes 1-way from LEO to LLO. Reusable LEV does 4 km/s roundtrip from LLO to LS and back using ISPP (0 t IMLEO). Total mission IMLEO is 110 tons.
    4. Total Program IMLEO for Phase 1, PHASE 2 (2 flights), and Phase 3 (20 flights) = 2692 tons

B. LOR-Orion
    This is the same as option 1 except that we don't bother with the LOG.

So we have:
1. Phase 1. IMLEO 120 t
2. Phase 2. IMLEO 126 t
3. Phase 3. IMLEO 110 t
4. Total Program IMLEO = 2572 tons

C. LOR-Dragon
1. Phase 1. Same as option B. IMLEO = 120 t.
2. Phase 2 Phase 2. Dragon does 5.1 km/s roundtrip to LLO. (40 t IMLEO). LEV goes 1-way from LEO to LLO. LEV does 4 km/s roundtrip from LLO to LS and back. Two-ton dry LEV has wet mass of 5 t, (16 t IMLEO). Total mission IMLEO is 56 tons.
3. Phase 3. Dragon does 5.1 km/s roundtrip to LEO to LLO to TEI. (40 t IMLEO). LEV goes 1-way from LEO to LLO. Reusable LEV does 4 km/s roundtrip from LLO to LS and back using ISPP (0 t IMLEO). Total mission IMLEO is 40 tons.
4. Total Program IMLEO = 1032 tons

D. Direct Return.
1. Phase 1, Same as options B & C. IMLEO = 120 tons
2. Phase 2. Fueled Dragon on the Moon has a mass of 18 t using LOx/H2. IMLEO=120 t
3. Phase 3. Unfueled Dragon delivered to Moon. Refueled on moon with ISPP. IMLEO = 53 t.
4. Total Program IMLEO = 1300 tons.

E. EOR (Moon Direct)
1. Phase 1. Same as options B, C & D. IMLEO = 120 tons
2. Phase 2. Dragon flies to LEO (IMLEO 8 t). Crew transfers to LEV for flight from LEO to LS and back to LEO. (IMLEO 60 t.) Total IMLEO 68 t.
3. Phase 3. Dragon flies to LEO (IMLEO 8 t). LEV is refueled in LEO (IMLEO 6 t) Crew transfers to LEV for flight from LEO to LS. LEV returns using ISPP propellant. Total IMLEO mission 14 t.
4. Total Program IMLEO = 536 tons.

The results of the above analysis are shown in Table 2. Phase 1 result is total Ph.1 IMLEO. Phase 2, 3 results are IMLEO per mission. Total program IMLEO assumes Phase 1, two Phase 2 missions, twenty Phase 3 missions. It should be noted that each recurring lunar direct mission gets to visit 4 sites, compared to just one landing site per mission for each of the other modes.

Table 2. Comparison of Lunar Mission Options

Option	A. LOG	B. LOR-Orion	C.LOR-Dragon	D. Direct Return	E. EOR-Moon Direct
Ph 1 IMLEO	240	120	120	120	120
Ph 2 IMLEO	126	126	56	120	68
Ph 3 IMLEO	110	110	40	53	14
Total IMLEO	2692	2572	1032	1300	536
LS % Access	3	3	3	42	42

Conclusion

It can be seen that the Moon Direct approach is decisively the best. Its advantages include:
1. Lowest total program launch mass. (~1/2 that of closest alternative)
2. By far the lowest recurring mission launch mass. (~1/3 that of closest alternative)
3. By far the greatest exploration capability (6 km/s LEV has 14 times surface access as 4 km/s LEV). Lunar Direct also enables multiple distant landing site visits per mission.
4. No need for lunar orbit rendezvous.

There is no point going to other worlds unless we can do something useful when we get there.
Turning local materials into resources is the key.
Let us therefore choose to be resourceful, that we may open the trail to the stars.