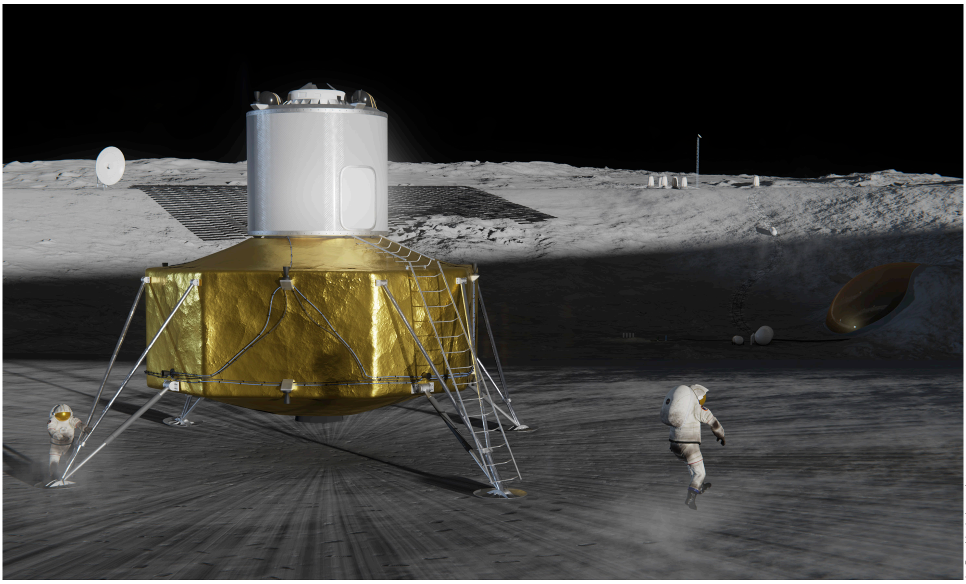
The New Atlantis
A Journal of Technology & Society



Moon Direct

A Purpose-Driven Plan to Open the Lunar Frontier

Robert Zubrin

The American human spaceflight program, armed with a clear goal, stormed heaven in the 1960s. But for almost a half-century since, it has been adrift, spending vast sums of money with no serious objective beyond keeping various constituencies and vendors satisfied. If it is to accomplish anything, it needs a real goal. Ideally, that goal should be sending humans to Mars within a decade. But after all these years of stagnation and bureaucratization, NASA lacks the will to attempt such a feat. A second-best alternative—one that could potentially transform NASA back into the can-do agency it once was, and that it needs to be again if it is ever to attempt to reach Mars—is to reverse the retreat by reopening the lunar frontier. For this reason, the Trump administration has announced that it has set such a goal, to wit, that America should return to the Moon, this time to stay.

***Robert Zubrin**, a* New Atlantis *contributing editor, is president of Pioneer Astronautics and of the Mars Society. An updated edition of his book* The Case for Mars: The Plan to Settle the Red Planet and Why We Must *was published in 2011 by The Free Press.*

Unfortunately, there is no evidence that this putative goal is meaningfully driving the administration's actions. Rather, the administration is funding NASA at roughly the same levels as the Obama and Bush administrations, while also continuing to approve the agency's wasteful investment in useless projects. Astonishingly wasteful is NASA's work on the Lunar Orbital Platform-Gateway (formerly known as the Deep Space Gateway). The gateway is a planned space station that will orbit the Moon, supposedly serving as an outpost for human explorations to the Moon, Mars, and deep space. NASA's Orion spacecraft will serve as the module for crews to travel back and forth between the gateway and Earth. The agency currently projects that Orion would take its first crew around the Moon by 2023, while Vice President Pence has recently stated a goal of putting astronauts on the gateway by the end of 2024.

Essentially, the gateway is a vestigial form of the Obama administration's defunct and discredited Asteroid Redirect Mission (ARM). As NASA describes it, ARM's aim was "to develop a robotic spacecraft to visit a large near-Earth asteroid, collect a multi-ton boulder from its surface and redirect the boulder into orbit around the moon, where astronauts would have explored it and returned to Earth with samples." The Lunar Orbital Platform-Gateway is the ARM except with a space station instead of an asteroid, all to come up with something for astronauts to do in lunar orbit.

The idea is silly. There is no need to have a space station circling the Moon in order to go to the Moon or Mars or anywhere else. And there is not much research worth doing in lunar orbit that can't already be done on the International Space Station, in Earth orbit, or with lunar probes and robots. NASA claims the gateway would create an opportunity to test state-of-the-art propulsion, communication, and other technologies at a greater distance from Earth; tele-operated rovers could be sent from the gateway to the Moon; and planets and stars could be observed from a different vantage than from the ISS or current telescopes. But none of these activities requires human presence in lunar orbit. These are not reasons for having a gateway, but rationalizations.[1]

Like the ISS and the space shuttle but much more so, the gateway is a means in search of an end. If the space shuttle was a tragedy, the gateway is a farce. Even when we do go—initially only once per year for as little as 30 days at a time, says the agency—having crews stop at the gateway en route to the Moon will have no purpose other than justifying the gateway, but will hamper such missions by adding to their propulsion requirements. It will cost tens of billions of dollars, both up front for construction and later for maintenance, sapping funds and delaying any real accomplishments for many years without adding any meaningful capability. When we could be going directly to the Moon or Mars, the Lunar Orbital Platform-Gateway is a pointless project, more aptly named the Lunar Orbit Tollbooth.

If we want to explore the Moon, and prepare to go beyond, we don't need a space station in lunar orbit—but we could use a base on the Moon itself. A Moon base would be much more than a stopping point; it could also be a site for producing hydrogen–oxygen rocket propellant from water on the Moon. This is a powerful propellant that has been a mainstay of rockets for decades, used by the Saturn V and the space shuttle. After years of scientific speculation that there may be deposits of frozen water in permanently shadowed craters near the Moon's poles, a study published just this August provided the first definitive proof of water ice in the craters, finding that in some areas it may be present in concentrations of 30 percent by weight in the topmost layer of soil. Mining this water and electrolyzing it into hydrogen and oxygen would allow vehicles to refuel on the Moon. This would provide the means not only to return from the Moon, but also to travel from place to place on the Moon, thereby markedly lowering the ongoing cost and increasing the capability of a sustained lunar exploration program.

What we need is a plan for establishing a propellant production base on the lunar surface and sending humans back and forth, using technology we already have or could readily create within the next few years. In particular, the recent spectacular success of SpaceX's reusable Falcon Heavy rocket, first launched in February and offering a much lower per-pound cost than previous launchers, opens up dramatic new possibilities for establishing an ongoing crewed lunar mission on the cheap. NASA has for years been building its own massive rocket, the Space Launch System (SLS), which is projected to cost the agency over $2 billion per year for the next five years and is currently scheduled to first fly in 2020. But the Falcon Heavy and the smaller Falcon 9—both already flying—put the goal of a Moon base within reach, and at a much lower price.

By choosing to establish a base on the Moon, we can restore the confidence of the human spaceflight program and enable it to take on the greater challenges awaiting us on Mars and beyond. We can reaffirm our identity as a nation of pioneers and make a powerful statement that the future belongs to the forces of liberty by once again astounding the world with what free people can do. We can do this all—if we proceed with purpose.

Global Mobility on the Moon

The most important step in any engineering program is to define its requirements. While it is essential to design things right, before that we must make sure we design 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 like, and what is required to support a sustainable and effective human presence there.

The Moon is not a small place. It is a world with a surface area larger than the continent of Africa. Its terrain is rough, roadless, and riverless, so astronauts cannot effectively explore it using surface vehicles. Lunar explorers are going to need to fly. While it is theoretically possible that multitudes of locations on the Moon could be visited by launching scores of missions directly from Earth, the cost of doing this would be astronomical. This is why we need to create a base that 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 missions from Earth being required to resupply consumables and switch out crews.

Where should such a base be located? The Moon's poles are ideal not only because they have nearby permanently shadowed craters with water, but because they also feature near-permanently illuminated highlands offering reliable access to solar energy. The poles are thus the clear favorites for a base, as they provide both the raw material and the energy source necessary to manufacture hydrogen–oxygen rocket propellant.

The top requirement for effective exploration of the Moon is the mobility of our lunar explorers, which can be enabled using a system we are going to call a *Lunar Excursion Vehicle* ("LEV" from now on). The LEV, which will use liquid oxygen and liquid hydrogen for propellant, is in many ways the centerpiece of the Moon Direct plan we will present here. As we will see, the multiple functions of the LEV, along with our ability to produce propellant for it on site, are the keys to creating a human lunar exploration program at far lower cost than NASA's current plan, and doing it with launch vehicles that are already available. If you want to form a mental picture of the LEV, it will be a lightweight system similar to the Apollo Lunar Module, the vehicle that astronauts used to land on the Moon, except that it will be a single-stage vehicle using hydrogen and oxygen for propellant.

How much mobility can a LEV achieve on the surface of the Moon? Before considering this question, we need a quick primer. In the kingdom of rocketry, the coin of the realm is *delta-V*. This measures the total amount of change in velocity a spacecraft or rocket can obtain. For example, in order for a ship to travel from Earth's surface into low Earth orbit, the destination of everyone who has ever traveled to space except for Apollo astronauts, it must achieve a velocity of at least 8 km/s. The rocket that launches the ship must therefore be capable of at least this much delta-V.

For exploration sorties on the Moon, the LEV must first take off from the base, then land at its destination, then take off again to return, and then land back at the base. This means that four burns are required for each sortie, as both liftoff (acceleration) and landing (deceleration) require fuel. So to think about the vehicle's mobility on the Moon we need to think about how much delta-V it will need for these four burns, and about how much weight and propellant it will have to carry.

For traveling between places on the Moon, we are going to give our rocket-propelled LEV a total delta-V capability of 6.1 km/s (about 13,600 miles per hour). We will later see why this number is significant. For now, let's just see how far that gets us on the Moon. We can see in Figure 1 (see page 35) that a LEV with a delta-V capability of 6.1 km/s provides substantial global access. On round trips, the LEV could reach up to a quarter of the lunar surface and still be able to return to its starting point. For one-way trips—for example, if we built not one base but two, one on each pole, and traveled between them—this delta-V would allow the LEV to reach the entire globe, with fuel to spare.

We can estimate the weight of this vehicle by considering the Apollo Lunar Module (LM). As noted, our LEV will have a similar profile: lightweight; intended to fly only in space and around the lunar surface, meaning it would not need a thick shell and heavy heat shield to protect it during re-entry into Earth's atmosphere; and capable of carrying some cargo, a crew of two, and life support for up to a few days.

The Apollo LM's dry mass (its weight with crew and cargo but without fuel) was 5.2 metric tons. However, the LM carried two rocket engines and propulsion systems—one for descending from lunar orbit onto the Moon's surface, another for ascending back to lunar orbit. The ascent portion (the "ascent stage"), which contained the crew cabin, crew, and life support equipment, is most similar to our purposes here. Its dry mass was 2.3 tons. If we used this figure for estimating the weight of our LEV, we would also need to add the weight of the landing legs, and make various other adjustments. But given a half-century of improvements in materials and avionics science and engineering, a LEV could surely make significant improvements in the weight. We will therefore estimate 2 tons for the LEV's dry mass, again, including crew and cargo.

In Figure 2 (see page 37), we can see the mass requirements of our 2-ton LEV. In addition to the dry mass, about 6 tons of propellant are required for each mission that uses 6.1 km/s of delta-V. So the total mass (known as the "wet mass"), including ship, cargo, and propellant, is about 8 tons. Also, the required weight of the tanks and engines—which take up part of the 2-ton dry mass—still leaves 1.3 tons for the crew, crew cabin, and other cargo.

Earth–Moon Transportation

The Apollo missions used a flight plan known as *lunar orbit rendezvous.* The heavy Command and Service Module (29 metric tons), which included the capsule that would be used to re-enter Earth's atmosphere, was taken to lunar orbit and left there. Meanwhile, only the lightweight Lunar Module, carrying two of the three crew members (Neil Armstrong and Buzz Aldrin on Apollo 11), left lunar orbit to travel to the Moon's 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 rocket. Note that this is similar to the flight plan NASA could use for the Lunar Orbital Platform-Gateway if they were also funding a lander, except that the gateway would be left in a less convenient lunar orbit, while a lunar lander would travel to the Moon's surface and back.

However, a rendezvous point in lunar orbit, while useful for brief Apollo-style missions to the Moon, is very undesirable for supporting a lunar base. 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 scattering footprints on the Moon, but quite another thing to leave someone behind in such a manner doing nothing useful while soaking up cosmic radiation for months. We could, of course, leave no one in orbit, but it hardly seems prudent to have our base and mission-critical Earth-return system left behind in orbit with no one minding the store. NASA's plan to leave a space station in lunar orbit long-term as a rendezvous point for recurring lunar explorations would add a very expensive liability, as well as mission risk, to any lunar base program.

As useful as it might be for quick, one-off missions from Earth to the lunar surface, lunar orbit rendezvous is very unattractive for a lunar base. Direct-return trips—either to Earth's surface or to low Earth orbit—are the way to go. There are many advantages of a direct approach compared to lunar orbit rendezvous. With direct trips, there are no liabilities to maintain on lunar orbit. Furthermore, for the same reason that on Earth we always see the same side of the Moon, viewed from the surface of the Moon, the Earth is always at the same place in the sky—so the window for the return launch is always open. In contrast, with lunar orbit rendezvous, the lunar spacecraft needs to carefully time its return to match the orbit of its rendezvous spacecraft, which may not be convenient.

Further, because the Moon lies largely beyond the protection of Earth's magnetic field, astronauts stationed in lunar orbit will receive unnecessary doses of cosmic radiation, violating the principle that radiation doses should be kept as low as reasonably achievable. In contrast, there are vast amounts of shielding material readily available on the Moon. And again, the material to make propellant is on the Moon. Once lunar-produced propellant is available, the mass and expense of recurring lunar missions drop dramatically, as we will see.

Most importantly, compared to lunar orbit, the Moon itself offers far greater opportunities for interesting science and engineering. If we are sending crews to explore the Moon, it's crazy to leave a substantial fraction of our critically limited exploration team cooped up in cans on orbit, where they can't contribute.

The problem, however, is that until lunar-produced propellant is available, a conventional direct approach puts the mission outside of the capabilities of existing rockets. This plan would require lifting enough propellant for a fueled spacecraft to go all the way down to the surface of the Moon, then launch again from there to return all the way to Earth.

Consider, for example, Dragon 2, SpaceX's human-rated capsule now scheduled for its first crewed test flight in December. (The current Dragon, without a crew and launched on a Falcon 9, has been on recurring missions to low Earth orbit for NASA since 2010.) Dragon 2, with its service systems, a full propellant load, and a small payload would optimistically weigh about 9 metric tons.[2] But even a maximum propellant load would only be enough for the Dragon 2 to maneuver in low Earth orbit, perform powered re-entry to Earth's surface, or do short-range sorties on the lunar surface. It cannot on its own make the trip from Earth orbit to the lunar surface or back. In order to have enough delta-V to launch from the lunar surface and directly re-enter Earth's atmosphere, it would need to be delivered to the Moon with an additional propulsion system and propellant load, bringing its total mass to about 20 metric tons. Delivering this payload to the Moon would first require lifting about 118 tons from Earth to low Earth orbit.[3] This is beyond the lift capability of any presently available launch vehicle. It would require either NASA's SLS Block 2 Cargo launcher (a larger, later planned version of SLS) or SpaceX's Big Falcon Rocket, but these launchers have yet to be seen.

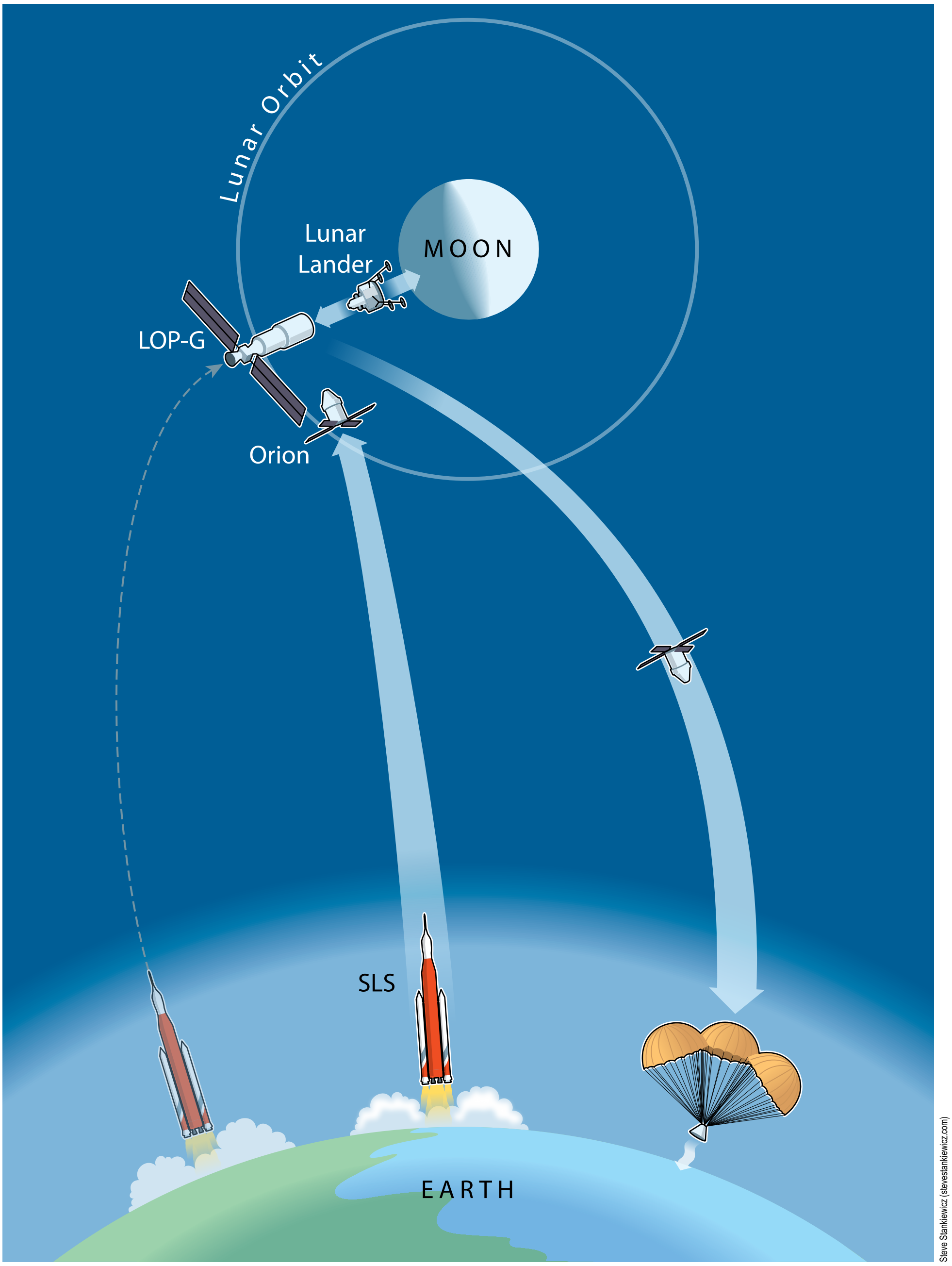
But there is another way. We can use the LEV. Remember that because it is designed to fly only in space and on the Moon and therefore has no need for a bulky heat shield and atmospheric re-entry system, the fueled LEV weighs only 8 tons. The delta-V to go from the lunar surface to trans-Earth injection—the path that takes a spacecraft out of the Moon's realm of gravitational influence and into Earth's—is about 3.0 km/s. Once on trans-Earth injection, a further delta-V of 3.1 km/s could be used to bring the LEV into low Earth orbit. So to return from the Moon's surface to low Earth orbit, the LEV needs a total delta-V capability of 6.1 km/s.

The LEV of course cannot enter Earth's atmosphere. Instead, it could rendezvous in Earth orbit with a Dragon 2, an Orion, the International Space Station, a Russian Soyuz, or any other spacecraft launched from Earth. The LEV's crew could then transfer into this ship for return to the Earth's surface. The LEV could in the meantime be refueled on orbit, and then used to take another crew back to the Moon.

We can call this concept *direct Earth orbit return*, as the LEV, returning directly from the lunar surface, would meet in low Earth orbit with a spacecraft launched from Earth. This concept avoids all the risks and costs of maintaining a vehicle on orbit around the Moon. And with so many low Earth orbit launchers and crew vehicles available today or coming online in the next few years, and at relatively low cost, this plan is effectively as good as a direct return.

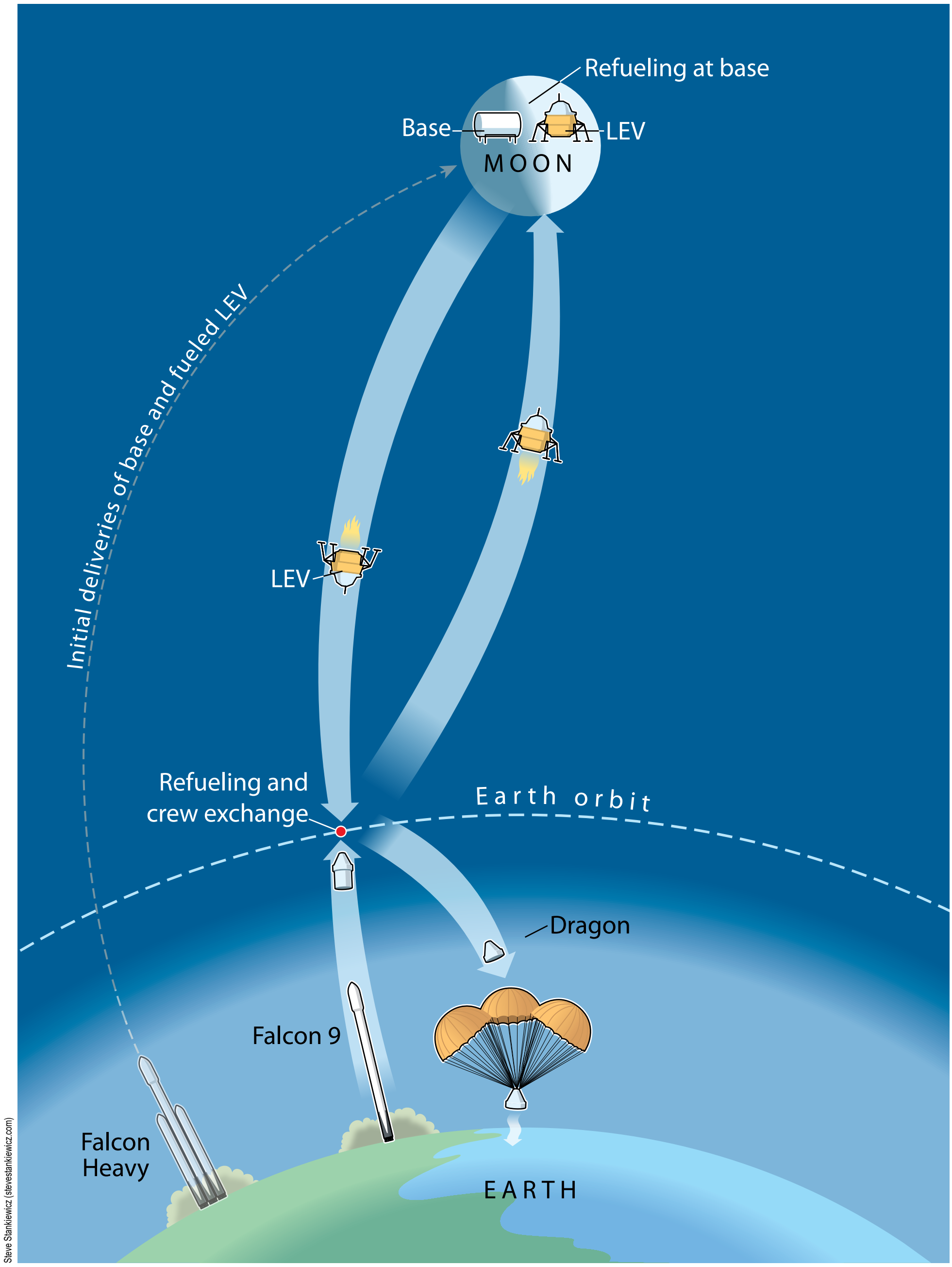
We can now also see the power of giving our LEV a 6.1 km/s delta-V capability: It will allow the spacecraft not only to do global-scale lunar exploration, but also to return from the lunar surface to low Earth orbit for crew exchange, and then refuel and take another crew back to the Moon.

And, as we will see, all of this can be done with rockets that are already commercially available—SpaceX's Falcon 9, with a likely launch cost of around $70 million with a full payload, and Falcon Heavy, with a launch cost of $150 million with a full payload.[4] Once lunar propellant production is online, each recurring mission could be done by means of a single Falcon 9 launch. If we include the cost of the propellant, cargo, and crew, the total cost of each recurring mission would probably be roughly double the launch cost, or about $140 million—low enough for a highly sustainable lunar exploration program.



Lunar Orbit Rendezvous as used by the Lunar Orbital Platform-Gateway

NASA's plan for returning humans to the Moon is to use lunar orbit as a staging point by building a space station there. This would require later development of a lander to explore the surface. While practical for Apollo's short trips, for long voyages, lunar orbit rendezvous increases launch mass, creates liabilities in lunar orbit, and wastes valuable crew time.



Direct Earth Orbit Return as used by Moon Direct

With Moon Direct, crews would live and work on the lunar surface. The same lightweight vehicle would allow long-range surface trips and direct return to Earth orbit. Launch mass would be low enough to use existing rockets. And the mission would have purpose: mining propellant and performing the first sustained, global human exploration of another world.

Three Phases of Moon Direct

A Moon base producing propellant for a lunar vehicle would enable global access, direct trips between the Moon and Earth orbit, and very low recurring costs. These are the prime requirements for a highly cost-effective lunar exploration program.

There are three phases required for establishing such a program:

- Phase 1: Unmanned missions deliver the materials for the lunar base to the Moon.

- Phase 2: Piloted missions make the base operational. A key objective of this phase is to bring propellant production online and make it continuously available.

- Phase 3: This is the long-term phase, with recurring piloted missions using propellant produced on site.

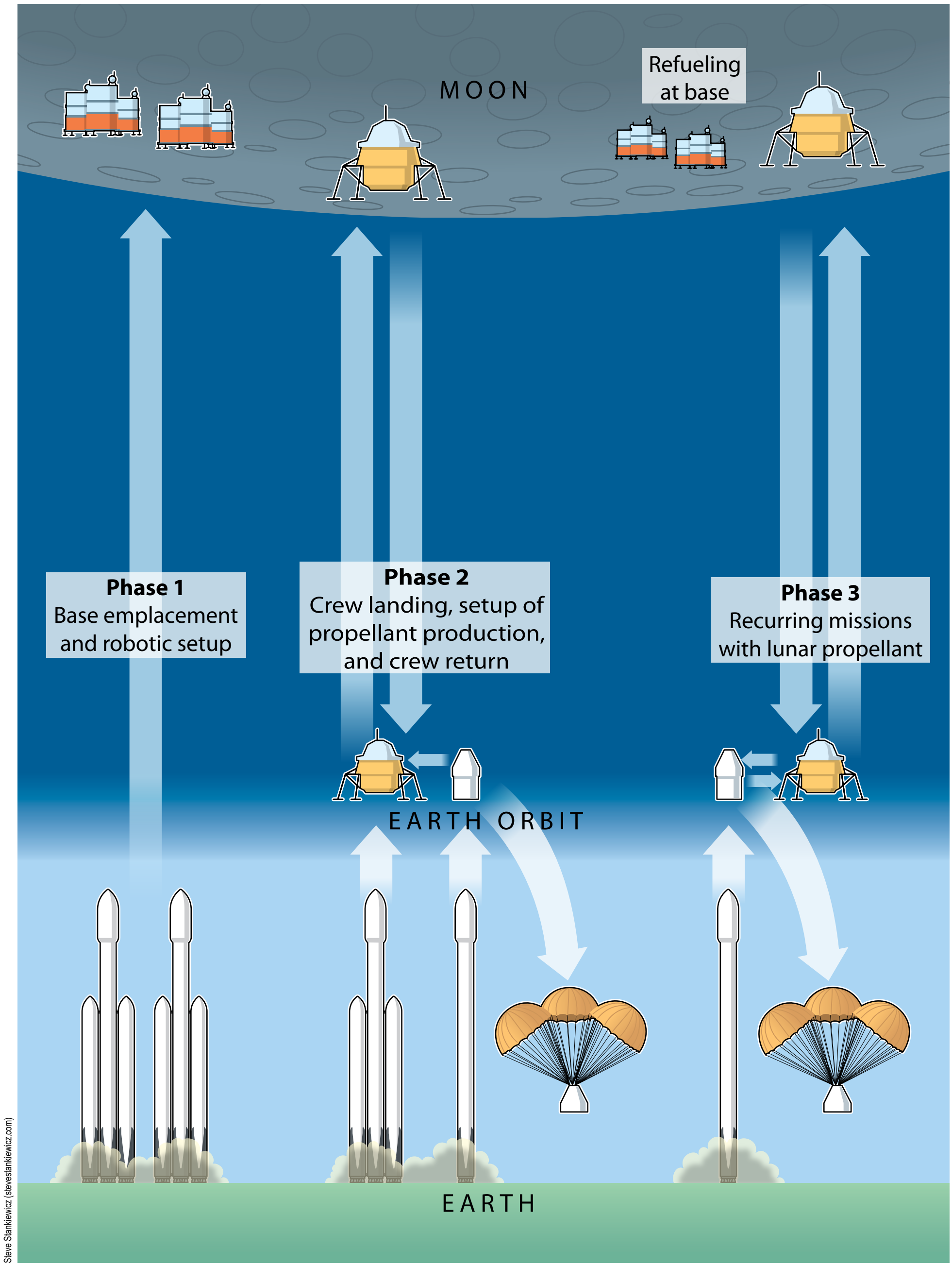
The diagram on the facing page shows the Moon Direct flight plan for each of the three phases:

Phase 1

For delivering the base modules to the Moon—both for habitation and for propellant production—we need a separate cargo lander system. In Table 1 (see page 39), we can see how much cargo could be delivered to the Moon with a single launch of a variety of launch vehicles, plus a cargo lander system. This lander takes the cargo from a staging orbit—where the lander separates from the launcher—to the lunar surface.

The Falcon Heavy rocket can deliver over 8 tons of cargo to the lunar surface with any of the four options considered. We know that we will eventually need a launcher that can deliver at least 8 tons so that we can deliver the fueled LEV. The New Glenn and the Vulcan cannot deliver 8 tons. New Glenn can come close, however, and its large fairing—the cargo compartment at the top of the rocket—could make it attractive for delivering high-volume, low-mass payloads. The SLS can deliver more than what is required, and the BFR much more. But SLS, BFR, New Glenn, and Vulcan are not yet available. We will therefore plan to use the Falcon Heavy, which has a launch cost of $150 million.

To establish our base near the Moon's south pole, we will deliver our initial cargo using two Falcon Heavy launches, which gives us a mass budget of 16 tons. The first cargo lander will deliver the equipment needed for setting up the propellant production site. This includes solar panels,



The Moon Direct program. *In Phase 1, two Falcon Heavy boosters are used to deliver the materials for the base and other cargo to the Moon. In Phase 2, one Falcon Heavy and one Falcon 9 are used to deliver the crew to the Moon in a fueled LEV. In Phase 3, only one Falcon 9 is used to deliver a new crew to orbit in a Dragon 2, exchange crews, and refuel the LEV. The new crew then flies to the Moon in the LEV, which refuels again at the lunar base, while the Dragon 2 returns to Earth with the previous crew.*

communications gear, equipment for microwave power-beaming, a unit for electrolysis and refrigeration (hydrogen and oxygen are cryogenics, requiring very low temperatures to liquefy), rovers for the crew, robotic rovers, and a trailer for hauling raw materials. The second cargo lander will deliver the habitation module in which the crew will live and work, and will include food, tools, research equipment, extra spacesuits, and so forth.

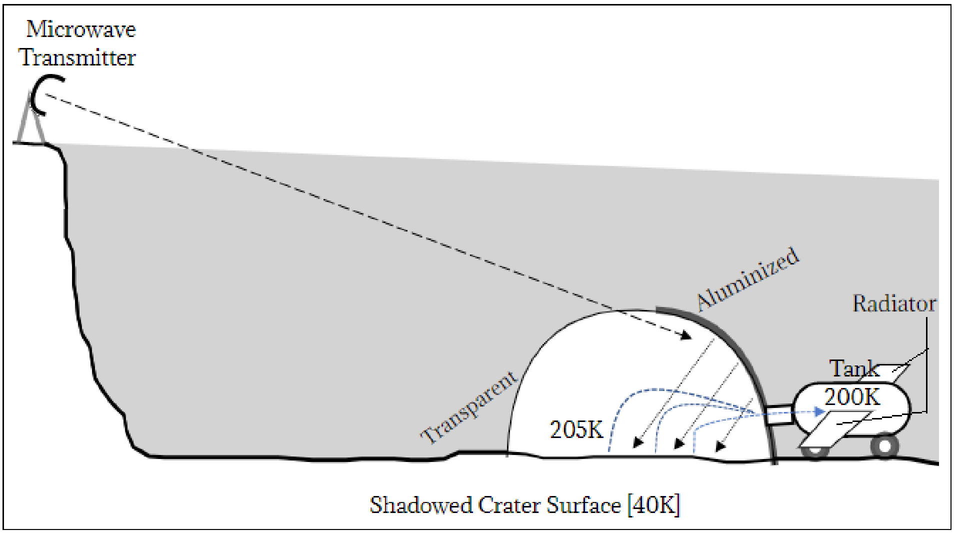
After the cargo lands, tele-operated rovers will set up the solar and communications systems, connect the solar array to equipment that needs power, and install radio beacons for later missions. They will then be sent out to survey the area, taking detailed photographs that mission planners, scientists, and engineers back on Earth will use to plan the crewed missions, and that can be used to create a virtual reality environment on Earth that will allow millions of citizens to participate in the program, exploring alongside the astronauts as "ghost assistants."

These two Falcon Heavy launches, costing $150 million each, will likely be all that is needed for transporting the base, as we will later show. But even if we have to add another launch or two, this only adds to the initial setup costs of Moon Direct and does not affect the recurring costs, which is where the overwhelming majority of an ongoing program's expenses are incurred.

Phase 2

Phase 2 will again require two launches. In the first launch, a Falcon Heavy takes another cargo lander, this time containing a fully fueled LEV, to low Earth orbit. In the second launch, a Falcon 9 delivers a crew to low Earth orbit in a Dragon 2 capsule to rendezvous with the LEV. The crew transfers into the LEV, and the cargo lander then takes the crew and the LEV to the Moon base. The Dragon 2 stays behind in low Earth orbit, and the LEV arrives on the Moon still fully fueled.

Once the crew arrives at the base, they finish setting it up and testing all its functions. The base relies on solar power, which needs to be beamed to the water mining site in a permanently shadowed crater (see illustration on facing page). The main mission is to establish this site, to begin the mining operation with the help of rovers, and to transport the water in a trailer back to the base. There the crew will use the electrolysis and refrigeration unit to separate the water into hydrogen and oxygen and to liquefy the gases, then store them in tanks. (The tanks of previously delivered cargo landers would provide ample storage capacity.) The hydrogen and oxygen will later be used for rocket propellant and to supply fuel cells and oxygen for breathing, while unelectrolyzed water can be used to support other life support functions.



Lunar Ice Mining. *Microwaves, powered by solar arrays, are beamed from the top of the crater on the left through the transparent side of a half-aluminized tent at the bottom of the crater. The crater is permanently shadowed, and contains frozen water deposits in the soil. The microwaves are reflected into the soil, the microwaves heat up the soil, the water evaporates, and the vapor is extracted into a tank on a trailer, where it freezes.*

After a few months of initial mining, exploring, and resource prospecting, the crew boards the LEV, still fueled from when it was delivered by the cargo lander, and returns to low Earth orbit, where it will rendezvous with a Dragon 2. This can either be the Dragon that took the crew to Earth orbit, or it can be another one that has been launched with a Falcon 9 to bring a replacement crew. Either way, the returning crew will transfer into the Dragon 2, which will serve as their re-entry capsule for the final leg of the journey back home.

The launch cost of each Phase 2 mission, requiring one Falcon 9 and one Falcon Heavy, will be $220 million. We will assume that two of these Phase 2 missions will be required to resolve the technical issues with getting lunar propellant production fully online. But we could easily plan for additional Phase 2 missions as needed.

Phase 3

Once propellant production on the Moon is operational, the LEV can be reused. When a crew returns in the LEV to low Earth orbit, they can refuel the LEV and exchange with a new crew, which can use the LEV for the trip back to the Moon. Because refueling will now be available on the Moon, we will no longer need to launch fuel for the LEV to travel from the lunar surface to Earth, or a cargo lander system to deliver the LEV. The only mass that will need to be launched from Earth will be the crew in their capsule, and a tank to refuel the LEV just for the trip back to the Moon. Moreover, with propellant now available on the Moon, the LEV can be used not only to take crews back to Earth, but to explore the lunar surface itself.

Recall that the LEV requires 6 tons of propellant to perform its 6.1 km/s delta-V. SpaceX's Falcon 9 launcher is capable of lifting 23 tons to low Earth orbit. This is more than enough to deliver a tank with enough propellant to refuel the LEV, plus a Dragon 2 capsule with a replacement crew. Thus, the recurring Moon mission could be done by means of a single Falcon 9 launch, which costs only about $70 million.

Furthermore, once the base is well established, there will be little reason not to extend lunar stays to four months or more. Again, if we use a common planning assumption that our mission's total costs aside from the launcher—that is, the cost of the refueling tank, crew, cargo, and so on—will be roughly equal to the launch cost, we should be able to sustain a permanently occupied lunar base with just three $140-million missions annually. This is an ongoing yearly cost of around $420 million, or two percent of NASA's current budget of about $20 billion.

We have focused on the Falcon 9 and Dragon 2 capsule, as these are the cheapest equipment and are already available or likely to be so soon. However, we should keep in mind that for recurring missions, if the Falcon 9 were to become unavailable, we could use the Atlas V, the Delta IV (not to be confused with delta-V), or the soon-to-be-built New Glenn or Vulcan. Also, if the Dragon needs to stand down, it could be replaced with the soon-to-be-built Orion (which would probably require a more powerful launcher than the Falcon 9), Boeing Starliner, or Sierra Nevada Dream Chaser. The architecture of our Moon transportation system is thus extremely versatile and robust.

Production Requirements

We will next consider the crucial question of whether a crew could produce enough propellant, oxygen, and electricity on the Moon at a fast enough rate to sustain the recurring Phase 3 missions. We need to produce liquid hydrogen and oxygen for propellant; oxygen for crew consumption; and power for extracting water from lunar soil, splitting it into hydrogen and oxygen, and cooling these gases into liquids. Additional water can be used for life support, supplementing water recycled from consumables.

First we will consider propellant production. Each Moon Direct mission requires 6 metric tons of propellant to be made on the Moon for the LEV's flight back to Earth orbit. It also requires 6 tons of propellant for each long-distance surface sortie from the base to a distant location on the Moon and back. For purposes of analysis, we will assume that once the base is operational, every fourth month there will be a round-trip mission from the Moon to Earth to exchange crew, and in each other month there will be one long-range exploration flight. The propellant manufacturing requirement will therefore be 6 tons per month, or 200 kilograms per day.

Engines running on liquid hydrogen and liquid oxygen use a higher ratio of hydrogen to oxygen than what is found in water. To get our 200 kilograms of propellant, we would need to electrolyze around 260 kilograms of water (about 70 gallons) per day. The happy side effect is that this would leave about 60 kg of leftover oxygen every day, which could be used for crew breathing supply.[5]

The dominant power requirement will be for vaporizing and electrolyzing the water. To electrolyze 260 kg of water per day will require 56 kilowatts of power.[6] We can estimate that water could be vaporized at the same rate using beamed microwaves with about 26 kilowatts of power.[7] Cryogenic liquefaction of the hydrogen and oxygen products—aided by the extremely cold temperatures on the Moon—will add about 25 kilowatts, and life support and other equipment will also add another 13 kilowatts to the power needs, so we can estimate 120 kilowatts for our total power requirement. This could be supplied by either a solar array or a nuclear reactor; for either alternative we estimate a mass of around 4 tons using proposed technologies.[8]

Learning about how easily we can harvest resources on the Moon is a central reason for creating a human exploration program in the first place. It will be the task of the first crew members on the Moon to discover some of the details about water extraction and electrolysis that we don't yet fully know—especially the precise concentrations of water present in the soil of the permanently shadowed craters.

But we already know that water is fairly plentiful in lunar craters, enough so to make propellant production feasible. A 2015 study in *Icarus* estimates that water ice is present in concentrations of 0.1 to 1 percent in the visible surface layer (the first few millimeters of soil) of craters near the south pole. Higher concentrations may also be available beneath the surface. When NASA's 2009 LCROSS mission crashed a projectile into a crater near the south pole, spectral analysis on the resulting dust plume found water ice concentrations of 3 to 9 percent in soil just a few meters below the surface. Most strikingly, in August, just as this article went to publication, a study published in the *Proceedings of the National Academy of Sciences* offered the most reliable evidence to date by using measurement techniques definitively able to distinguish water from similar molecules. The study, which measured the visible surface of polar craters, found that in some areas water concentration reaches 30 percent by weight.

There are uncertainties in the total mass required for operating lunar ice harvesting end to end. But we won't know until we go. Perfecting the techniques for finding, extracting, and electrolyzing ice to produce fuel and oxygen will be a significant but surmountable challenge for the first lunar explorers. Although there are already promising schemes for lunar resource utilization, some trial and error under the actual conditions will inevitably be needed to work out the kinks. This is the reason to send human explorers and not robots. The water is there. The light from the Sun is there to power the transformation of water into breathable oxygen and usable rocket fuel. What isn't there yet is the most valuable resource of all: human ingenuity.

Comparison of Mission Modes

Now that we know that Moon Direct is possible and sustainable, we can compare it to alternative plans for a lunar base. We have already discussed some of the advantages of Moon Direct over NASA's Lunar Orbital Platform-Gateway, and we can now look at the numbers to confirm this, assuming the gateway were used as a base for lunar exploration. We will consider five different mission modes, including Moon Direct. For the sake of getting an overall sense of our program, we will assume that each mode, after bringing propellant production online, will include twenty recurring crewed missions—about seven years' worth. The most important points of comparison are the total mass that has to be lifted into low Earth orbit—a good indicator of a program's overall costs—and the portion of the lunar surface we can explore with round trips of a lunar lander once propellant production is operational (see Table 2, page 45).

Our first option is an applied version of the current NASA program of record. It requires setting up the Lunar Orbital Platform-Gateway prior to any human-piloted missions to the surface of the Moon. Since the gateway actually serves no useful function, it is not surprising that this bizarre plan turns out to be the worst for sustaining a lunar base. The total mass to be lifted into low Earth orbit would be 2,750 tons, and only about 3 percent of the Moon's surface would be available in a round trip mission of a lunar lander.

The next two options are progressively more rational, if less imaginative. Essentially, they duplicate the lunar orbit rendezvous mission plan that provided the basis of the Apollo program, but they execute it mostly with current hardware. The only difference between these two plans is that, to stay in lunar orbit, one plan uses the massively overweight Orion capsule to take the place of the Apollo Command and Service Module or the lunar gateway, while the other plan employs the much lighter Dragon. (NASA designed the Orion too heavy to launch to orbit on an Atlas V, thereby creating the need for its hoped-for Ares I launch vehicle. This was not a good idea. It resulted in a wildly suboptimal Orion, and President Obama canceled the Ares I anyway.)

So, if you wish to copy Apollo's lunar orbit rendezvous plan, using a Dragon is the way to go. But, as noted earlier, while lunar orbit rendezvous is quite serviceable for Apollo sortie missions, it has issues when applied to the operation of a permanent lunar base. The Orion-based plan requires lifting over 2,300 tons to low Earth orbit, an improvement over using the gateway, but still unattractive. The Dragon-based plan requires just under 1,000 tons. Both options still give you access to only 3 percent of the Moon's surface on round-trip sorties.

For supporting a Moon base, a mission mode based on direct return from the surface to Earth would be preferable. There are two ways this could be done. The simplest, which is our fourth option, would be to take off from the lunar surface in a capsule, fly straight back to Earth, directly enter the atmosphere, pop a parachute, and land. The problem with this plan, however—and the reason it was not employed in Apollo—is that it requires taking a heavy capsule all the way to the Moon, landing it there, and then lifting it again to shoot it back home. Attempting this with an ultra-heavy Orion would be absurd. Even doing it with a much lighter Dragon, as presented in our fourth option, requires 1,600 tons, significantly more than using the Dragon for lunar orbit rendezvous—although the difference becomes modest for the recurring mission. It would also make less than 1 percent of the lunar surface available for exploration.

But there is, of course, another way to do a direct-return mission. Our final option is Moon Direct, in which we leave the Dragon capsule in low Earth orbit and only go to the Moon and back in a much lighter Lunar Excursion Vehicle. Because it has no heat shield and can't use the atmosphere as a brake, the LEV needs to use its propulsion system to slow it down to enter into low Earth orbit, so its return delta-V is 6.1 km/s instead of the 3 km/s required for the other mission modes. But because its dry mass is just a quarter of the Dragon's, total mass requirements for this mode turn out to be much lower than a Dragon direct return or any other mode—a little over 500 tons.

Furthermore, the LEV's delta-V provides an entirely new capability that all the other mission options lack: global mobility on the Moon. To put this in perspective, if you land at the North Pole on Earth and can travel to a quarter of the global surface, you could get to Houston, Shanghai, or Cairo and back. At three or one percent of the surface, you'd only make it part of the way to the Arctic circle.

Moon Direct

We can see that the Moon Direct approach is decisively the best option. It has by far the greatest exploration capability—a quarter of the surface compared to a scant few percent for the other plans. It has no need for the complications and hazards of lunar orbit rendezvous. It has the lowest total program launch mass—half that of the next closest alternative, a fifth that of NASA's current plan. And it has by far the lowest recurring launch mass—less than half that of the closest alternative.

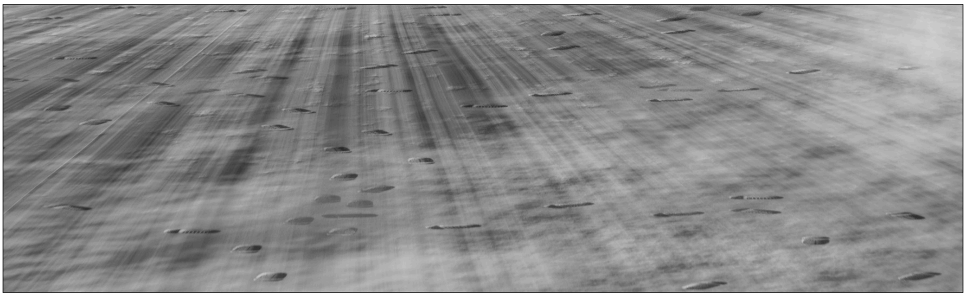
Moon Direct also has the marked advantage of using systems that are either already available or could be readily adapted from existing technologies. Instead of waiting on launch vehicles like the SLS that have already been delayed for years and are likely to be delayed again, it uses rockets that are commercially available now. Instead of adding the needless complexity of designing a new space station, it uses an Earth orbit crew capsule slated for its first crewed launch later this year, and a lunar lander that would require little more than updating the blueprints for the Apollo lander. Propellant production on the lunar surface has already been extensively studied and modeled. No fundamental breakthroughs are required to make it work, only adaptation from established industrial technologies to suit the unique conditions of the Moon.

Because Moon Direct requires relatively little launch mass and largely uses existing technologies, we can also expect it to be implemented on the cheap. Following our assumption that launch costs and non-launch costs will be roughly equal, we could execute our setup missions (two flights for Phase 1 and two Phase 2 missions) for about $1.5 billion, and our recurring missions for $420 million per year—again, about two percent of NASA's current budget. This is very inexpensive by the standards of human space programs. For comparison, NASA's human spaceflight program total budget is currently around $10 billion per year with little clear purpose.

The promise of perfecting systems for creating propellant from water on other worlds has become even greater with a landmark pair of scientific findings announced just this summer. The first is the study, published in August, finally proving beyond a reasonable doubt that there is water ice in permanently shadowed craters on the Moon—and at concentrations much higher than previously demonstrated. The second is the discovery, announced in July, of a persistent body of water on Mars—a lake, a meter deep and twenty kilometers long, under the southern polar ice cap. Creating a site on the Moon for harvesting water and turning it into propellant would not only be of tremendous value in itself, but would provide a clear demonstration of the value of using local resources in space—which will ultimately be the key to opening up the Martian frontier as well. These findings offer dramatic proof that it is time to stop talking about creating propellant on other worlds as a merely theoretical possibility, and to start carrying out plans.

There is also good reason to think that having a human presence on the Moon might lead to the discovery that water is even more widely abundant there than we presently realize. A new analysis of a lunar meteorite found on Earth, published in May in the journal *Science Advances*, argued that water is present in the lunar soil not only in polar craters but across the entire planet, at depths of a few millimeters to a few hundred meters and at a concentration of at least 0.6 percent, far higher than previous estimates. Who knows what treasures human prospectors—if they are allowed to stay not for the few days granted to Apollo astronauts but for months or years, and to travel not a few kilometers from their landing site but two thousand—might discover on the Moon?

The Moon itself, not lunar orbit, is where we can *do* things. It is the potential site for human ingenuity and achievement, the place where resources and discoveries await. Moon Direct would give NASA, for the first time in decades, a human space program with a clear purpose. It would not only provide valuable experience and insight for an eventual Mars mission, but would give a badly needed boost to public confidence that America can and will remain a nation of pioneers. If NASA wants to return to the Moon, then a Moon base is what we need, not a tollbooth in lunar orbit. There is no point in going to other worlds unless we can do something useful when we get there. The resourceful will inherit the stars.



APPENDIX

Range and Fraction of Moon Accessible with LEV

If we assume, as is typically the case, that there are 10% delta-V losses incurred fighting gravity during takeoff or landing on each burn,[9] the real velocity V per burn achievable for a LEV with a total delta-V capability D that is divided among four burns is given by:

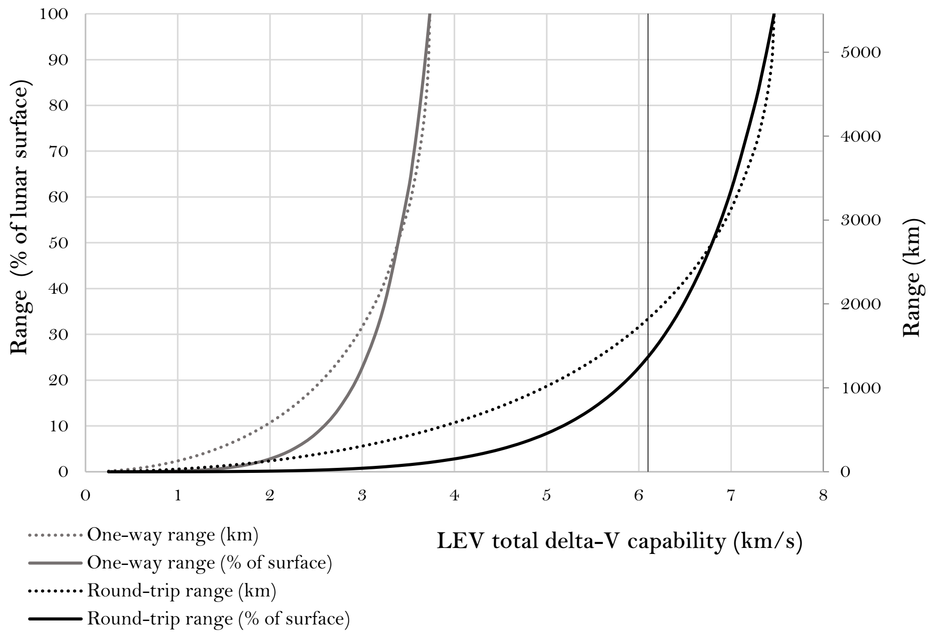
$$V = 0.9\, D / 4$$

The maximum range of a projectile fired with velocity V, on a spherical airless planet with radius R, where the velocity of a zero-altitude orbit around that planet is W, is given by:[10]

$$\text{Maximum range} = 2R \sin^{-1} \left[(V^2/W^2) / (2 - V^2/W^2) \right]$$

On the Moon, W = 1680 m/s and R = 1737 km.[11] Combining the two equations, the range of the LEV used as an excursion vehicle is shown in Figure 1. We can see that a LEV with a delta-V capability of 6.1 km/s provides substantial global access on round trip missions—a range of 1,823 km, or 25% of the surface. And it provides 100% global access on one-way missions, with substantial fuel to spare.[12] One-way trips would allow the LEV to, for example, go from one polar base to another base on the opposite pole.

Figure 1. Range of LEV on the Moon as a Function of Delta-V Capability



The portion of the total lunar surface made accessible to the LEV on round-trip excursions is shown with the solid black line. The absolute range in kilometers is shown with the dotted black line. Similar values for one-way trips are shown with the gray lines. It is assumed that round trips require four equal burns, while one-way trips require only two burns. A vertical line marks the 6.1 km/s performance point.

Mass and Payload of LEV

In Figure 2 we show the LEV's required wet mass (or total mass), propellant mass, and inert mass (tanks, engines, and other propulsion structures), and the available payload mass, as a function of its total delta-V capability.

The LEV's liquid oxygen/hydrogen (LOX/H_2) propulsion system is assumed to have a specific impulse of 450 seconds. Informally, specific impulse is a measure of a propulsion system's efficiency—its "gas mileage." Formally, the specific impulse measures how much change in momentum (or how much impulse) a rocket system can attain for a given amount of propellant, usually calibrated assuming the rocket is operating in a vacuum. For example, a rocket system that required 2,500 pounds of propellant to deliver 10,000 pounds-force of thrust for 100 seconds would have a specific impulse of 10,000 pounds-force * 100 seconds / 2,500 pounds = 400 seconds. (A pound-force is the amount of force exerted by Earth's gravity on a pound of mass.) One way of understanding why the unit of specific impulse is seconds is that it measures for how many seconds the rocket system can use a pound of propellant to deliver a pound-force of thrust.

As shown by Russian space pioneer Konstantin Tsiolkovsky in 1903, we can derive a rocket's required wet mass (M_{wet}) from its dry mass (M_{dry}), its specific impulse (I_{sp}), its delta-V capability, and standard gravity (g_0, a constant value required for unit conversion, calibrated by using Earth's gravitational constant, 9.8 m/s^2, as standard). The equation is as follows:

$$M_{wet} = M_{dry} \exp\left(\text{delta-V} / I_{sp}\, g_0 \right)$$

The dry mass of the LEV, which we have assumed will be 2 metric tons, will be divided between the payload and the various structures directly required for propulsion—the engines, fuel tanks, rocket structure, and various other supporting equipment. These latter structures are collectively called the *inert mass*, since they are neither propellant nor payload, but must come along for the ride. The required inert mass will increase as we need to carry more propellant. We will assume that the inert mass will increase proportionally to the mass of the propellant, requiring a mass equal to 11% of the propellant mass. With a denser propellant such as LOX/CH_4, the ratio might be about 7%.[13]

Here is an example of how we'd calculate our required wet mass, propellant mass, and inert mass, and finally our available payload mass, at a delta-V of 6.1 km/s:

First, we use Tsiolkovsky's equation to calculate our required wet mass:

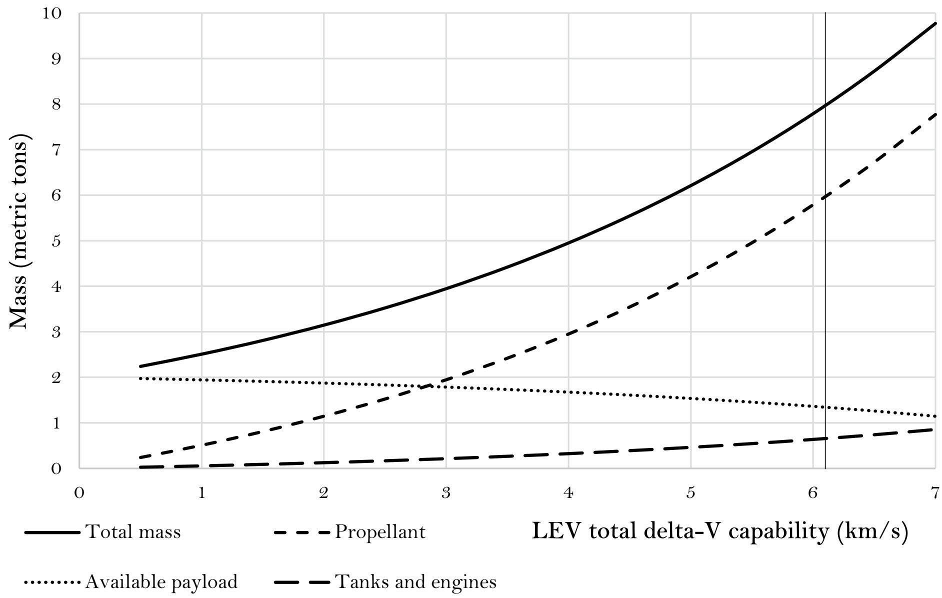
$$M_{wet} = (2{,}000\ \text{kg}) * \exp\left(6100\ \text{m/s} \ / \ (450\ \text{s} * 9.80665\ \text{m/s}^2) \right)$$
$$= 2{,}000\ \text{kg} * 3.984 = 7{,}968\ \text{kg}$$

Of this total mass, we have assumed that 2 tons will be dry mass, leaving 5,968 kg of required propellant.

If we assume the tanks, engines, and other propulsion structures have a combined mass equal to 11 percent of the propellant, then 656 kg of the 2,000-kg dry mass must be employed for such purposes, leaving us 1,344 kg for the crew compartment and cabin payload.

Examining Figure 2, we see that the critical 6.1 km/s delta-V performance point, needed to achieve either direct return from the Moon to LEO or global mobility on the Moon, is readily achievable with 8 tons of total mass.

Figure 2. Mass and Payload of LEV as a Function of Delta-V Capability



A vertical line marks the 6.1 km/s delta-V performance point. To achieve this, our LEV will need to use about a third of its 2-ton dry mass on tanks and engines, leaving about two-thirds for payload. It will need about 6 tons of propellant, for a total mass of 8 tons.

Cargo Lander Mission

Launchers will deliver payloads to various possible staging orbits; from there, cargo landing systems will then deliver the payloads to the lunar surface. These payloads could be either the base modules delivered in Phase 1 or the fully fueled LEV delivered in Phase 2. Note that, although the eventual purpose of the LEV is to use its own propulsion system when traveling between LEO and the lunar surface, until lunar propellant production is online in Phase 3, it will need to be delivered to the Moon fully fueled using a cargo lander, so that it can be used to return to Earth.

We use delta-V values of 6.1 km/s for LEO to the lunar surface (LS), 3.7 km/s for geosynchronous transfer orbit (GTO) to LS, and 1.6 km/s for low lunar orbit (LLO) to LS. For the cargo lander propulsion system, we consider both LOX/CH_4 propellant with 375 s specific impulse, 7% inert mass / propellant ratio, and 800 kg/m^3 bulk density; and LOX/H_2 with 450 s specific impulse, 11% inert mass / propellant ratio, and 360 kg/m^3

bulk density.[14] Note that while LOX/H_2 propulsion systems are already widely used, LOX/CH_4 propulsion is in an advanced state of development at SpaceX and Blue Origin, with the first firing of their Raptor and BE-4 engines done in 2016 and 2017, respectively.

We use several simplifying assumptions for the purposes of estimation. First, we assume that all available payload mass from the Earth launcher will be used, delivering the maximum possible mass to the lunar surface. Second, we model payload fairings (that is, the compartment where the LEV and the cargo landing system will reside) as cylinders, and where inner dimensions are not known, we conservatively use figures slightly lower than available specifications for outer dimensions. Third, we calculate the propellant mass and inert mass (tanks, engines, and so forth) required for the cargo landing system. The "payload delivered" value is the remainder of the available payload mass—the usable payload delivered to the lunar surface. We also calculate the volume of the propellant needed by the cargo landing system, and the equivalent length of the payload fairing cylinder taken up by this propellant. Table 1 lists the remaining length and volume of the payload fairing that will be available for "cargo," encompassing the deliverable payload as well as the engines, tanks, and inert structures of the cargo landing system.

We can observe various trends, including that LOX/CH_4, because of its higher density, offers an advantage in available payload volume, while LOX/H_2, because of its higher specific impulse, offers an advantage in available payload mass.

Flight systems considered include:

- Falcon Heavy (SpaceX): 63.8 tons of available payload to LEO, or 26.7 tons to GTO; payload fairing with inner dimensions of 4.6 meters diameter by 11 meters long. (Note that the current Falcon fairing is not perfectly cylindrical, as modeled here, but tapers toward the top.)

- New Glenn (Blue Origin): 45 tons to LEO, fairing diameter 7 m, length 15 m.

- Vulcan Centaur Heavy (United Launch Alliance): 34.9 tons to LEO, fairing diameter 5 m, length 20 m.

- SLS Block 1 (NASA): 90 tons to LEO, fairing diameter 5 m, length 12 m.

• Big Falcon Rocket (SpaceX): 150 tons to LEO. Alternately, if the configuration is used in which "tankers" are also launched to fully refuel the first BFR, the same 150 tons can be brought at least as far as LLO. In both cases we estimate fairing diameter 8 m, length 40 m.

Table 1. Cargo Lander Mission

Launcher	*Date available*[15]	*Staging orbit*	*Cargo lander propellant*	*Fairing length used by propellant*	*Fairing length available for cargo*	*Fairing volume available for cargo*	*Payload mass deliverable to lunar surface*
Falcon H.	2018	LEO	LOX/CH_4	3.9 m	7.1 m	118 m^3	8.5 tons
Falcon H.	2018	GTO	LOX/CH_4	1.3	9.7	162	8.6
Falcon H.	2018	LEO	LOX/H_2	8.0	3.0	50	10.8
Falcon H.	2018	GTO	LOX/H_2	2.5	8.5	141	9.9
New Glenn	2020	LEO	LOX/CH_4	1.2	13.8	532	6.0
New Glenn	2020	LEO	LOX/H_2	2.4	12.6	484	7.6
Vulcan	2023	LEO	LOX/CH_4	1.8	18.2	357	4.7
Vulcan	2023	LEO	LOX/H_2	3.7	16.3	320	5.9
SLS	2020	LEO	LOX/CH_4	4.6	7.4	145	12.0
SLS	2020	LEO	LOX/H_2	9.5	2.5	48	15.2
BFR	2022	LEO	LOX/CH_4	3.0	37.0	1859	20.1
BFR	2022	LLO	LOX/CH_4	1.6	38.4	1932	82.7

The column labeled "Fairing length used by propellant," again, refers to the length of the tankage required by the cargo lander's propellant, if it is stored as a cylinder, ignoring hemispherical end caps. The lander propulsion system would also need additional length for engines and other equipment. In addition, the booster fairing would also have to accommodate not only the lander, but its payload. So as much as 8 meters (2 m for end caps, 2 m for engines, and 4 m 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, while the option of using a LOX/H_2 lander to take cargo from LEO to the lunar surface theoretically delivers the most mass, it would not fit into the current fairing. One solution to this problem would be to extend or expand the fairing, a modification that would appear modest compared to the other developments SpaceX has achieved. If this is not done, however, any of the other Falcon Heavy options would be feasible.

Mission Comparison Details

We will consider five options for a sustained lunar exploration and ice mining program, each making use of different staging orbits and ships for crew transport and exploration. Each option has essentially the same three phases as Moon Direct: Phase 1, in which necessary cargo is robotically emplaced; Phase 2, in which initial crewed missions establish *in situ* propellant production (that is, propellant production on the lunar surface); and Phase 3, in which recurring crewed missions occur to, from, and around the lunar surface, making use of the propellant produced on site.

Our mission options are:

A. *NASA Program of Record* (modified lunar orbit rendezvous, plus LOP-G): NASA's program of record, though far from finalized, calls for using the Lunar Orbital Platform-Gateway (LOP-G) in lunar orbit as an outpost for lunar exploration. Orion ships are used to shuttle crew back and forth between Earth's surface and the LOP-G, while a vehicle similar to the LEV is used to shuttle crew back and forth between the LOP-G and the lunar surface, and to explore on the surface. We can slightly expand upon this architecture to enable propellant production on the Moon by adding automated flights to deliver cargo directly from Earth's surface to the lunar surface in Phase 1.

B. *Lunar Orbit Rendezvous with Orion*: This is similar to option A, except no LOP-G is used. Low lunar orbit is used as a rendezvous point between an Orion ship, which shuttles crew back and forth to Earth's surface, and a LEV-type vehicle, which shuttles crew back and forth to the lunar surface and is used to explore the lunar surface.

C. *Lunar Orbit Rendezvous with Dragon*: Same as option B, except a Dragon 2 capsule is used instead of an Orion.

D. *Direct Return*: A Dragon 2 delivers crew directly from Earth's surface to the lunar surface, is used to explore the lunar surface, and then returns directly to trans-Earth injection and re-entry to Earth's atmosphere.

E. <u>*Moon Direct*</u> (direct Earth orbit return): As outlined in this article, low Earth orbit is used as a rendezvous point between a Dragon 2 capsule, which shuttles crew back and forth to Earth's surface, and a LEV, which shuttles crew back and forth to the lunar surface, and is also used to explore the lunar surface.

For each of these mission modes, we can now estimate their relative costs in terms of Initial Mass in Low Earth Orbit (IMLEO)—that is, the amount of mass that has to be launched into low Earth Orbit—as well as their benefits in terms of available range of the exploring vehicle on the lunar surface. For the sake of estimation, we will make the following assumptions:

- We will look only at requirements for launching major cargo and fuel, ignoring any other deliveries of food and consumables, which we can expect will be roughly similar across the options.

- Where not otherwise specified, cargo, spacecraft, and other payloads will be transported using additional LOX/H_2 propulsion stages under the same specifications used in Table 1.[16]

- We will use the following delta-V values: 5.1 km/s for round trips from Earth's surface to low lunar orbit (LLO), assuming aerobraking at Earth re-entry, and excluding the delta-V to reach low Earth orbit from Earth's surface, which comes "priced in" with launch to LEO; 4.0 km/s for round trips from LLO to the lunar surface; 4.1 km/s for one-way trips from LEO to LLO; 6.1 km/s for one-way trips from low Earth orbit to the lunar surface or vice-versa; 3.0 km/s for one-way trips from the lunar surface to re-entry in Earth's atmosphere.

- We will ignore the extra total round-trip delta-V that would be imposed on Option A missions, if they were forced to actually use the LOP-G, by the unusual egg-shaped Near-Rectilinear Halo Orbit that NASA plans to use for the LOP-G. Instead we will assume they can ignore it and use the more efficient trajectories that go through low lunar orbit, as all the other options will.

- For the first three options, the LEV-type vehicle will follow the same specifications as for the LEV in the Moon Direct plan. However, for the lunar orbit rendezvous modes, the LEV will need a delta-V capability of only 4.0 km/s to make the round trip from LLO to LS, meaning that slightly less of their 2-ton dry mass will be used on tanks and engines. (See Figure 2, page 37.)

We will consider a total program consisting of Phase 1, two Phase 2 missions, and twenty Phase 3 missions. We can now consider the total Initial Mass in Low Earth Orbit requirements for each option:

A. NASA Program of Record

Phase 1: 520 tons.

Lunar Orbital Platform-Gateway emplacement: There is little reliable information on the final mass of the LOP-G, as the gateway is still in the early development phases. (While initial plans outlined a four-module space station, the latest plan, unveiled by NASA in May, shows international partners joining to eventually expand the gateway into a much larger, ten-module station.) Current launch plans show four SLS Block 1B launchers being used to place the LOP-G into its Near-Rectilinear Halo Orbit near the Moon. This is the equivalent of about 400 tons IMLEO.

Cargo emplacement: The requirements are the same as for Moon Direct: two automated cargo flights from Earth's surface to the lunar surface, each delivering about 8 tons of habitation modules and other equipment. We have shown already that this can be accomplished with 120 tons IMLEO.

Phase 2: 115 tons.

Orion round trip from Earth's surface to low lunar orbit: We will estimate 100 tons IMLEO. Assuming a single additional LOX/H_2 propulsion stage, this allows for an Orion with a wet mass of 24 tons. (Available estimates range from 22 to 25 tons.[17])

LEV emplacement in low lunar orbit plus round trip to the lunar surface: For a LEV with sufficient fuel for the round trip from LLO to LS, we will need a wet mass of 5 tons (see Figure 2). To deliver this payload from LEO to LLO requires 15 tons IMLEO.

Phase 3: 100 tons.

Orion round trip from Earth's surface to low lunar orbit: 100 tons.

LEV round trip from low lunar orbit to the lunar surface: 0 tons. With *in situ* propellant production available, these trips can be made without launching any additional mass from Earth.

Total program IMLEO for Phase 1, Phase 2 (two missions), and Phase 3 (twenty missions): 2,750 tons.

B. Lunar Orbit Rendezvous with Orion

This configuration is the same as the applied NASA Program of Record, except without the Lunar Orbital Platform-Gateway.

Phase 1: Cargo emplacement: 120 tons.

Phase 2: 115 tons.

Phase 3: 100 tons.

Total Program IMLEO: 2,350 tons.

C. Lunar Orbit Rendezvous with Dragon

Phase 1: Cargo emplacement: 120 tons.

Phase 2: 53 tons.

Dragon round trip from Earth's surface to low lunar orbit: 38 tons IMLEO, assuming a wet mass of 9 tons.

LEV emplacement in low lunar orbit plus round trip to the lunar surface: 15 tons.

Phase 3: 38 tons.

Dragon round trip from Earth's surface to low lunar orbit: 38 tons.

LEV round trips between low lunar orbit and the lunar surface using *in situ* propellant production: 0 tons.

Total Program IMLEO: 986 tons.

D. Direct Return with Dragon

Phase 1: Cargo emplacement: 120 tons.

Phase 2: Dragon round trip from Earth's surface to lunar surface and back to Earth's surface with aeroentry: 118 tons. (See discussion in the text of "Earth–Moon Transportation," page 19.)

Phase 3: Unfueled Dragon delivered to the lunar surface, then refueled on Moon with *in situ* propellant production: 60 tons.[18]

Total Program IMLEO: 1,556 tons.

E. Moon Direct

Phase 1: Cargo emplacement: 120 tons.

Phase 2: 56 tons.

Dragon flies to low Earth orbit for crew transfer to LEV: 9 tons.

LEV round-trip from low Earth orbit to lunar surface: 47 tons.

Phase 3: 15 tons.

Dragon flies to low Earth orbit for crew transfer to LEV: 9 tons.

For trip from LEO to the lunar surface, LEV is refueled in low Earth orbit: 6 tons.

For trip from the lunar surface to LEO, LEV is refueled on the Moon using *in situ* propellant production: 0 tons.

Total Program IMLEO: 532 tons.

Finally, we will consider the round-trip range on the surface of the Moon that each option will provide its lunar lander once *in situ* propellant production is available. For Moon Direct, as noted, this figure is 25 percent of the lunar surface. For all three lunar orbit rendezvous plans, however, the LEV will require a delta-V of only 4.0 km/s to shuttle crew from the surface to the orbiting space station or ship. This figure would give the LEV access to only 3 percent of the surface for round-trip missions (see Figure 1, page 35). For the Direct Return with Dragon option, the Dragon would be delivered with a lander system capable of a 3.0 km/s delta-V burn for the trip from the lunar surface to Earth aeroentry. This would give a range of less than 1 percent of the lunar surface.

The results of the above analysis are shown in Table 2, showing Initial Mass in Low Earth Orbit per mission for each phase. Again, total program IMLEO assumes Phase 1, two Phase 2 missions, twenty Phase 3 missions.

Table 2. Comparison of Lunar Mission Options

	A. NASA Program of Record	*B. Lunar Orbit Rendezvous with Orion*	*C. Lunar Orbit Rendezvous with Dragon*	*D. Direct Return with Dragon*	*E. Moon Direct*
Phase 1 IMLEO	520 tons	120	120	120	120
Phase 2 IMLEO (per mission)	115 tons	115	53	118	56
Phase 3 IMLEO (per mission)	100 tons	100	38	60	15
Total Program IMLEO	2,750 tons	2,350	986	1,556	532
LEV Range (% of Surface)	3%	3	3	1	25

Notes

1. See my criticisms in Eric Berger, "NASA says it's building a gateway to the Moon—critics say it's just a gate," *Ars Technica*, Sep. 6, 2018, https://arstechnica.com/science/2018/09/nasa-says-its-building-a-gateway-to-the-moon-critics-say-its-just-a-gate/.

2. Available estimates for Dragon 2's mass vary. A 2014 FAA filing for the DragonFly reusable launch vehicle, a test Dragon 2 vehicle that included landing legs and represents the most plausible model for using Dragon 2 as a lunar landing vehicle, lists the dry weight as 14,000 pounds (6.4 metric tons), which would not include a crew or consumables. See Federal Aviation Administration, "Final Environmental Assessment for Issuing an Experimental Permit to SpaceX for Operation of the DragonFly Vehicle at the McGregor Test Site, McGregor Texas" (Washington, D.C., August 8, 2014), 2-2, https://www.faa.gov/about/office_org/headquarters_offices/ast/media/DragonFly_Final_EA_sm.pdf. Estimates for maximum propellant weight vary from 1.3 to 1.4 metric tons. See Erik Seedhouse, *SpaceX's Dragon: America's Next Generation Spacecraft* (Cham, Switzerland: Springer International Publishing, 2016), 37; Federal Aviation Administration, "Finding of No Significant Impact (FONSI) and Record of Decision (ROD)" for "Environmental Assessment for Crew Dragon Pad Abort Test at LC-40, Cape Canaveral Air Force Station, Florida" (Washington, D.C., March 5, 2014), 8, https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/media/fonsi_dragon_pad_abort.pdf. A 9-ton wet mass would allow for a payload of 1.2 to 1.3 tons, similar to our budget for the LEV.

3. The estimates here are based on using two additional LOX/H_2 propulsion stages, following the same assumptions and methods cited in Table 1; LEO to lunar surface delta-V of 6.1 km/s; and lunar surface to Earth atmosphere re-entry delta-V of 3.0 km/s.

4. SpaceX has published prices only for the partially reusable configurations, requiring less than a full payload mass—$62 million for Falcon 9, $90 million for Falcon Heavy. CEO Elon Musk has tweeted that the fully expendable (full-payload) Falcon Heavy will cost $150 million; a reasonable guess for a fully expendable Falcon 9 launch is $70 million.

5. A typical mass ratio for oxygen to hydrogen in rocket engines is about 6:1. As the mass ratio of oxygen to hydrogen in water is 7.94:1, to create 200 kg of propellant will therefore require 255 kg of water. That will leave 55 kg of leftover oxygen.

6. This assumes 85% efficiency for the water electrolysis unit.

7. This figure assumes 63 kilojoules per mole to heat ice from 40 K in a lunar crater to vaporization at 100 C (derived using the specific heat of water and ice and the enthalpies of vaporization and fusion) and about 40% overall efficiency in microwave generation to water vaporization.

8. This would require a specific mass for the power generation equipment of 33 kg per kilowatt of electric capacity (kg/kWe), which is within the range of proposed nuclear reactors and anticipated advances in solar array efficiency. (See Elisa Cliquet *et al.*, "Study of space reactors for exploration missions," 2013 International Nuclear Atlantic Conference (Recife, Brazil, November 2013), https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/107/45107386.pdf; Michael W. Obal, "Reenergizing U.S. Space Nuclear Power Generation," Institute for Defense Analyses Document NS D-4327 (2011), https://www.ida.org/idamedia/Corporate/Files/Publications/IDA_Documents/STD/2017/D-4327.pdf.)

9. For Apollo descents, NASA budgeted 8.7% delta-V gravity losses. Actual losses were 6% on Apollo 11 and less on subsequent landings. See Tables 1 and 2 in Alan Wilhite *et al.*, "Lunar Module Descent Mission Design," AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Guidance, Navigation, and Control and Co-located Conferences (Honolulu, August 2008), 5, https://doi.org/10.2514/6.2008-6939.

10. See Equation 9 in Leon Blitzer and Albert D. Wheelon, "Maximum Range of a Projectile in Vacuum on a Spherical Earth," *American Journal of Physics* 25, no. 21 (1957), https://doi.org/10.1119/1.1996071; or Equations 5 and 6 in Joseph Amato, "Using Elementary Mechanics to Estimate the Maximum Range of ICBMs," *The Physics Teacher* 56, no. 210 (2018), https://doi.org/10.1119/1.5028232.

11. $W = \sqrt{(GM/R)}$, where M is the planet's mass, R is the planet's radius, and G is the universal gravitational constant. Equivalently, $W = V_e/\sqrt{2}$, where V_e is the escape velocity. For M, R, and V_e values for the Moon, see David R. Williams, "Moon Fact Sheet," *NASA Goddard Space Flight Center* (2017), https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html.

12. One-way trips assume two burns. To achieve these values, for the first equation, substitute $V = 0.9\ D / 2$.

13. The ratio of inert to propellant mass can be approximated as constant over narrow ranges of propellant mass, such as the range of less than 20 tons of propellant under consideration here. Example ratio values for LOX/H_2 rocket stages in this range: 12% for Centaur I and Centaur II; 11% for Centaur 3A; 15% for Ariane-42L H10+.

(See Table 1 in Steven S. Pietrobon, "Analysis of Propellant Tank Masses," submitted to review of U.S. Human Space Flight Plans Committee, July 6, 2009, https://www.nasa.gov/pdf/382034main_018%20-%2020090706.05.Analysis_of_Propellant_Tank_Masses.pdf.) Engines using LOX/CH_4 are currently under development by SpaceX, but ratio values of liquid propulsion systems, according to one survey of existing systems, range from 7% to 24%. (See Fernando de Souza Costa and Ricardo Vieira, "Preliminary analysis of hybrid rockets for launching nanosats into LEO," *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 32, no. 4 (2010), http://dx.doi.org/10.1590/S1678-58782010000400012.) Note that for the sake of simplifying these approximations, the ratio used in the present article is similar to but slightly different from the more commonly used *inert mass fraction*, which is the ratio of inert mass to the sum of inert mass *and* propellant mass (the just-cited article by Costa and Vieira, for example, refers to inert mass fraction; the ratio values offered here are thus calculated from the inert and propellant masses).

14. For specific impulse values in a vacuum: Bruce Dunn calculates the theoretical maximum for LOX/CH_4 as 386 s and for LOX/H_2 as 469 s (see Bruce Dunn, "Alternate Propellants for SSTO Launchers," presented at Space Access 96 (April 1996), https://web.archive.org/web/20120201111637/http:/www.dunnspace.com/alternate_ssto_propellants.htm). For actual values, the Space Shuttle Main Engines achieved 452 s with LOX/H_2 (see "RS-25 Engine," Aerojet Rocketdyne, https://www.rocket.com/rs-25-engine). LOX/CH_4 engines have not yet been flown, but SpaceX is developing the Raptor engine to use this combination, with a projected specific impulse of 375 s (see Elon Musk, "Making Life Multi-Planetary," *New Space* 6, no. 1 (2018), 6, https://doi.org/10.1089/space.2018.29013.emu). *Bulk density* measures the combined density of propellant and oxidizer. For values, see Hilda Vernin and Pascal Pempie, "LOX/CH4 and LOX/LH2 Heavy Launch Vehicle Comparison," 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit (August 2009), http://dx.doi.org/10.2514/6.2009-5133. For inert mass / propellant ratio values, see Note 13 above.

15. Availability dates refer to the first successful or earliest projected test launch. Only Falcon Heavy is already available, first launched on February 6, 2018.

16. Heavy-lift launchers can typically lift cargo to higher orbits than LEO, albeit at a cost to payload capability. But treating LEO as the first staging orbit for each mission allows for launcher-agnostic, like-to-like comparison, and the differences in inert mass are very small relative to the IMLEO totals.

17. "Orion Quick Facts," NASA (2014), https://www.nasa.gov/sites/default/files/fs-2014-08-004-jsc-orion_quickfacts-web.pdf; Ryan Whitley and Roland Martinez, "Options for staging orbits in cislunar space," *2016 IEEE Aerospace Conference* (June 2016), http://dx.doi.org/10.1109/AERO.2016.7500635. Note that the Orion's own delta-V capacity is only 1.25 km/s, which, as Whitley and Martinez note, is insufficient even for transferring from a trans-lunar trajectory to low lunar orbit. We therefore assume that the Orion will be fully fueled, but its delta-V budget will be reserved entirely for maneuvering in LLO and LEO.

18. This assumes that a 10.1-ton Dragon 2 is delivered to the lunar surface: 9 tons as assumed in other mission modes, plus an additional inert mass of 1.1 tons capable of receiving the propellant on the lunar surface to allow for the 3.0 km/s delta-V return.