Witness Statement for the Hearing

Returning to the Moon: Keeping Artemis on Track

U.S. House of Representatives
Committee on Science, Space and Technology
Space and Aeronautics Subcommittee

Rayburn House Office Building
Room 2318

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17 January 2024

NASA, as well as the nation on behalf of which it executes our civil space program, should modify the strategy, tactics, acquisition approach and programmatic structure of human lunar return as it is presently planned. To the topic of this hearing, the Artemis Program should not be "kept on track"; it should be fixed and then prosecuted with all deliberate speed.

Strategic issues first. The agency has awarded fixed-price contracts to SpaceX and Blue Origin to carry out lunar landings for, respectively, $2.9 and $3.4 billion dollars (https://www.nytimes.com/2021/04/16/science/spacex-moon-nasa.html, https://www.reuters.com/technology/space/nasa-name-second-company-build-astronaut-lunar-lander-2023-05-19/). The cost of the Apollo Program over the 14-year period from 1960-73 is estimated to have been $257 B in 2020 U.S. dollars (C. Dreier, *An Improved Cost Analysis of the Apollo Program*, Space Policy, https://doi.org/10.1016/j.spacepol.2022.101476). It is reasonable to believe that with the flight experience and space industrial infrastructure that exist today, human lunar missions could and should be executed for considerably less than Apollo. It is grossly unrealistic to suggest that they could be done for 1.5% of Apollo's cost. The award of these unrealistically low fixed-price contracts makes it clear that cost reasonableness was not a factor in ranking these contract awards. The further implication is that the United States is not yet serious about a program that should be regarded as a core national interest – returning U.S. and international partner astronauts to the Moon before our self-declared adversaries can do so.

As in the 1960s, we are again faced with near-term peer competition in space, this time with the Chinese Communist Party and, once again, potentially Russia: (https://www.newsweek.com/russia-approves-plan-establish-lunar-base-china-1848731). For the U.S. not to be able to put its own and partner astronauts on the Moon, to be watching on the internet while adversary powers do so, makes a statement about a shift of global power and preeminence that we ought not to allow. People and nations align themselves with leaders; for most of the last 80 years that has been the United States, in partnership with our European and

Western Pacific allies. Are we prepared to relinquish that leadership to China? If not, and if we view preeminence in space as part of that leadership and therefore an element of national security, then it is again necessary to prioritize urgency of execution.

Underlying the above is a key theme: we cannot separate civil space exploration from national security space. It's one national program, artificially separated at birth by President Eisenhower to demonstrate to the world, and especially to the Soviet Union, that we were a peaceful nation, exploring and developing space for peaceful purposes. But the reality is that the creation of NASA was a national security initiative from the start, a response to the Soviet Union's launch of Sputnik.

National security takes many forms beyond raw power projection. In exploring and developing the space domain we are pioneering the human frontier. Even a casual reading of history shows that every great nation was on the frontiers of its time; this is almost a defining characteristic of great powers. To quote from President Kennedy's "man, Moon, decade" speech, where mankind goes, free men must fully share. The point is that value systems matter. The United States mounted one of the most powerful yet non-aggressive responses in history to the Soviet Union's launch of Sputnik. Had the first satellite been launched by the United Kingdom, the United States might have been a bit chagrined that we weren't first, but the response would simply not have been the same. The values of the United Kingdom and our own are highly aligned; the values of the United States and the Soviet Union were about as antithetical as it was possible to be. This difference was critical to our response to Sputnik, as it should have been.

The reality is that decisions are made, standards are set and values are established on a frontier by the people who show up, not by those who stay home and watch. The society that sets those standards (as we have done for global air transportation since the end of World War II) and establishes the key infrastructure emerges as first among equals, the proper goal for the United States.

Finally, when a society can do things that others cannot it commands a degree of respect that is by itself a valuable national security asset, possibly more so than in many instances of the exercise of "hard power". Quite simply, the very best people want to come to the place where the very best things are being done. It is quite instructive to observe how many key figures in the Manhattan and Apollo programs were immigrants, a number that was hugely out of proportion to the rest of the population. To quote an observation by former Deputy Under Secretary of Defense for Research and Engineering Dr. Lisa Porter, the United States is a country where a six-sigma individual can flourish. They are the people who create, in the words of another quote attributed to JFK, the rising tide that lifts all boats. Space exploration attracts such people. That is something in which we should take pride and is an asset to be nourished.

These are the forms of national security that NASA enables, and that we should take to heart in crafting our national space exploration strategy.

Tactically, the selected mission architectures pose significant concerns. SpaceX's approach requires an impractically large number of orbital refueling operations for even a single lunar mission (Space News, 17 Nov 2023; https://spacenews.com/starship-lunar-lander-missions-to-require-nearly-20-launches-nasa-says/), while Blue Origin's mission design depends on the development of one of the most difficult enabling technologies for long-duration space flight, zero-boiloff cryogenic fuel storage (https://en.m.wikipedia.org/wiki/Blue_Moon_(spacecraft)). These architectures feature concepts – cryogenic propellant storage, likely in large depots with low, controllable boiloff – that are critical to long-term, sustainable human space exploration. But while important, their development is unlikely to be completed easily or quickly, and over the last half-century we have used up the time that could have been devoted to the evolution of Apollo-era systems to a more sustainable architecture. Like it or not, we are engaged in a competition with others who do not wish us well; timeliness matters.

There are other concerns as well.

Crew Safety

The present Artemis mission architecture requires staging operations at a Gateway based in a lunar polar near-rectilinear halo orbit (NRHO) with a 6.5-day period and dimensions of 3,000 km x 70,000 km altitude above the lunar surface. This approach is said to offer two significant advantages: the Orion spacecraft, which as discussed below has limited ΔV capability, can get into and back out of this orbit on the way to and from the Moon, and any point on the lunar surface can be accessed from the staging area. The first of these issues can be addressed by far simpler means, discussed below, and the second is not unique to NRHO – it is a characteristic of any polar orbit.

However, these points are trivial in comparison to the major disadvantage of staging from NRHO, which is that immediate return to the Gateway from the lunar surface is possible only on 6.5-day centers. If a lunar crew encounters a problem on the surface that mandates a return to the comparative safety of the Gateway, then depending upon when that problem occurs, a multi-day wait may be required. It is possible in some scenarios to wait in low lunar orbit (LLO), but access to the Gateway is only possible at periodic intervals.

With present technology, flying in space is just barely possible; even in Earth orbit it is both difficult and dangerous. Expeditions to the Moon will be even more demanding. From a safety perspective, no early human lunar mission should knowingly accept the risk of stranding a crew, whether on the surface or in lunar orbit, for days at a time. No mission architecture should be contemplated without, as in Apollo, the capability to leave the surface and rendezvous with a safer habitat within a few hours. Somewhat like the first experience of "wintering over" in Antarctica, when enough lunar surface infrastructure has been emplaced to allow a viable long-term shelter-in-place option to be implemented, the crew abort strategy can be reconsidered. Such is not the case for early human lunar return. The Artemis program has not been designed with this consideration in mind.

Reliability and Mission Risk

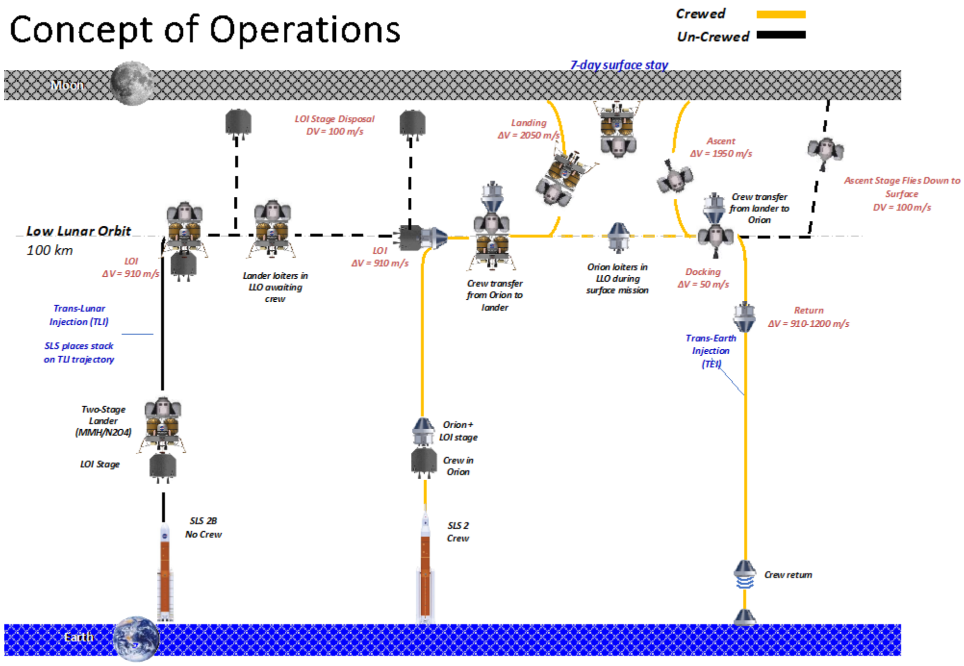
Leaving safety aside, mission architectures requiring multiple complex operations in series, such as propellant supply launches and cryogenic fuel transfer, are inherently less reliable than those requiring fewer. The table below makes this point; the left side of the table specifies a postulated reliability for each launch and propellant transfer operation, while across the top is shown a varying number of such operations.

Reliability of One Operation	**Number of Operations**			
	5	**10**	**15**	**20**
99%	0.95	0.90	0.86	0.82
98%	0.90	0.82	0.74	0.67
97%	0.86	0.74	0.63	0.54
96%	0.82	0.67	0.54	0.44
95%	0.77	0.60	0.46	0.36

The results speak for themselves. Even if (for example) it is assumed that each single operation, e.g., launch plus propellant transfer, can be performed successfully 98% of the time, i.e., with a 1-in-50 failure rate, a mission requiring ten such operations in a specified campaign window will fail to be completed within that window 18% of the time. As a practical matter, mission architectures requiring multiple launch and propellant transfer operations will be very difficult to complete with a reasonable likelihood of overall success. Congress should question whether this is a gamble that, from either the fiscal or national prestige perspective, it wishes to support.

<u>A Lower-Risk Approach: A Two-Launch Solution for Human Lunar Landing</u>

Early lunar return missions that meet NASA's basic requirements – four people on the surface for a week at any location – can be achieved using technology and systems that are largely available today. One straightforward approach is discussed below. It requires two SLS Block 2 heavy lift launches, each carrying a Centaur III upper stage; an Orion command and service module; and a two-stage storable-propellant lunar lander, yet to be designed. A schematic view of this approach is shown below:



Mission Sequence

1) A payload stack consisting of a partially fueled Centaur III upper stage and the fully fueled but uncrewed Lander is launched as cargo on the SLS Block 2B cargo variant with the capability to put about 45 metric tons (mT) into a trans-lunar insertion (TLI) trajectory.

2) The Centaur III is fueled with sufficient propellant (including allowance for boiloff) to provide a ΔV of about 1 km/s for the payload stack and is used as a lunar orbit insertion (LOI) stage to deliver the Lander to LLO to await the crew.

3) At a later time, the crew is launched on an SLS Block 2 crew variant (41 mT to TLI) to LLO in Orion using the same Centaur III LOI stage as for the Lander. As the fully fueled Orion has a mass of 27 mT, there are potentially several tons of margin for this launch.

4) The Orion crew rendezvous with the Lander in LLO and transfers crew and possibly additional equipment and provisions enabled by the mass margin for the Orion launch.

5) The lander descends and lands out of LLO. The crew executes its surface mission, launches back to LLO in the ascent stage, rendezvous with Orion, transfers crew, and deploys the ascent stage into a controlled lunar surface disposal.

6) The crew returns to Earth from LLO in Orion. The Orion ΔV capability of 1.25 km/s is more than sufficient for the trans-Earth insertion (TEI) maneuver.

LOI Stage

This stage is needed because the presently existing Orion service module ΔV capability of 1.25 km/s is sufficient for either insertion into or return to Earth from LLO, but not both. If developed for this purpose, it is likely to be advantageous to use the LOI stage also for insertion of the Lander into LLO. However, depending upon the efficiency of the Lander descent propulsion engine, it can be reasonable to consider making the Lander descent stage large enough to accommodate the additional, less-efficient, storable propellant necessary for insertion into LLO.

The present analysis does not incorporate this assumption. It is conservatively assumed here that the LOI stage will be used for both tasks and hence is sized for the more difficult requirement, Lander insertion into LLO. To this point, the fully fueled Centaur III with a single RL10C-1 engine (presently used as an upper stage for Atlas V) has the following parameters:

Specific Impulse (Isp)	–	450 s
Dry Mass	–	2.25 mT
Propellant Mass	–	20.83 mT
Gross Mass	–	23.08 mT
Diameter	–	3.05 m
Length	–	12.7 m

The required insertion ΔV from a three-day trans-lunar coast trajectory to LLO is approximately 1 km/s, depending in detail on a variety of factors including the choice of landing site. Assuming a required ΔV of 1 km/s for this analysis, the mass of propellant required for the Centaur III to insert the initial payload stack (M_i = 45 mT) into LLO is

$$M_p = M_i \left(1 - e^{-\Delta V/gIsp}\right) = 9.2 \text{ mT}$$

and consists of about 8 mT of liquid oxygen and 1 mT of liquid hydrogen.

Propellant boiloff, primarily of the liquid hydrogen fuel, must be included in the cargo launch. For the production Centaur III, flown-vehicle data shows the loss rate to be 13-17% per day; with a few layers of insulation this can be reduced to 5% or less. (https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj2hPPF5t-DAxWdF1kFHbJOBywQFnoECBMQAQ&url=https%3A%2F%2Fwww.ulalaunch.com%2Fdocs%2Fdefault-source%2Fextended-duration%2Fcentaur-extensibility-for-long-duration-2006-7270.pdf&usg=AOvVaw1Vzv5kb-HhwZlszEs8dilI&opi=89978449). With this, the Centaur will lose less than 200 kg of propellant during a three-day trans-lunar coast. Including an allocation for a docking mechanism and other airborne support equipment for the Lander/Centaur cargo stack yields an allowable Lander mass of 32 mT, as shown:

SLS Block 2B TLI Payload	–		45 mT
Less			
Dry Mass, Centaur III	–	2.3 mT	
LLO Insertion Propellant Mass	–	9.2 mT	
Fuel Boiloff Allowance (5%/day)	–	0.2 mT	
Airborne Support Equipment Allocation	–	1.3 mT	
Subtotal for LOI Requirements	–		13 mT
Maximum Allowable Lander Mass	–		32 mT

The mass of the required LOI stage itself, slightly less than 12 mT, is about half the size of the Centaur III. For a lunar return mission, the stage could be flown as-is with a reduced propellant load, or a modified version with shorter tanks developed if desired. Also, the RL10C-1-1 engine variant for the Centaur V, the upper stage of Vulcan Centaur, offers an improved specific impulse of over 453 seconds. Given the time available before a lunar return mission will be executed, it may be feasible to incorporate this engine into a modified Centaur III LOI stage, thus gaining about 130 kg performance improvement.

Lunar Lander

To establish a baseline, the J-Series Apollo lunar landers (Apollo 15-17) had masses of less than 16.5 mT, including the 210 kg lunar rovers carried on each of these missions, and sustained two crewmembers for three days. Scaling of this experience would suggest that a four-person, 32 mT vehicle capable of supporting a 7-day mission is well within conservative design limits.

Improvements are possible, for example the incorporation of storable, low toxicity "green propellants" rather than the legacy, highly toxic, difficult to handle nitrogen tetroxide/hydrazine storable propellant combination. However, in the interest of offering a low schedule risk approach, the present analysis does not presume such advances.

Acquisition Strategy

The fundamental flaw in the Artemis acquisition approach is the assumption that the U.S. government can and should leverage so-called "commercial space" for national purposes, and that this paradigm is applicable to human spaceflight. It is debatable whether, in general, "commercial space" is other than a catchphrase intended to differentiate traditional prime contractors from newer firms aspiring to obtain government contracts without the excessive and stifling regulatory framework surrounding traditional government acquisition. However, it should be clear that no significant fiscal return on investment in human lunar missions can be expected in the foreseeable future without significant government subsidy.

It is thus NASA's responsibility to acknowledge that it is the only significant customer for human missions to the Moon and that it must therefore establish and direct a credible mission design to which contractors can bid, and to develop an equally credible cost estimate to implement that design, rather than agreeing to unrealistic firm fixed price (FFP) bids for complex development programs. Government FFP contracts that are underbid leave both sides stuck in a bad deal with only a few possible but unsatisfactory outcomes: the contractor demands additional money to finish the program and the government pays it, the program is ultimately canceled because the government doesn't want to pay, or performance is reduced in a compromise between the amount of money the contractor wants and that which the government is willing to pay. There is a long and depressing history of such efforts: (https://www.defensenews.com/industry/2024/01/09/cautionary-tale-how-boeing-won-a-us-air-force-program-and-lost-7b/). We should not add human lunar return to the list.

If our nation is serious about returning to the Moon, this time to stay, then it properly requires an investment by the Congress on behalf of the public it serves. Congress and the public should expect that investment to be expertly managed by Executive Branch officials who are responsible and accountable for the quality of their decisions and the direction they provide to industry to implement those decisions. NASA's acquisition approach should reflect that fundamental principle.

Programmatic Considerations

The Artemis lunar landing missions as presently planned significantly compromise crew safety, carry high mission execution risk, are highly unlikely to remain on schedule, and are being executed via an inappropriate acquisition approach with grossly unrealistic fixed-price cost assumptions. These facts require hard decisions to be made if success is to be attained in the end. Congress must use its power of the purse to direct the Executive Branch to implement these decisions.

Or, we can just kick the can down the road, as we have been doing for more than five decades now.

Specifically, the existing contracts should be terminated for the convenience of the government and a new program initiated along the lines described above. Those who object will observe that termination for convenience will not allow significant funding to be recaptured from the existing fixed-price contracts, and this is correct. But to continue programs that we know will not achieve our goals distracts us from what must be done and damages NASA's and the nation's reputation, even if they are being executed for free. We need to focus our efforts on an approach that we know will work in a timely manner with the lowest mission risk and the greatest crew safety we can provide. To this point, while the analysis presented here offers a point design to illustrate concept feasibility, a sensitivity study should be conducted to establish the parametric feasibility space within which the two-launch mission design can be optimized.

Sustainability of our future space architecture does matter. Efforts to develop systems that expend fuel rather than hardware are important to that future. Because it is at the far end of the lunar ΔV gear train, a single-stage reusable crew lander is the most important of these developments. Thus, the development of cryogenic propellant transfer and zero-boiloff storage technologies should be pursued. But the development of these technologies will not be quick or easy, and timeliness is presently the more important feature for our nation's human lunar return program. Similarly, while NRHO and the Gateway as presently conceived are irrelevant to human lunar return, a transportation node or nodes like the Gateway will be valuable components of a sustainable future lunar architecture if placed in a more useful staging orbit than planned today.

But regardless of these finer points, the straightforward approach outlined here could put U.S.-led expeditions on the Moon beginning in 2029, given bold action by Congress and expeditious decision making and firm contractor direction by NASA. This is not the path being pursued at present and the existing Artemis contractual and programmatic structure will not support it. A new program, architected and managed by people who are clearly qualified for the job, should be initiated and executed with funding adequate to carry out this urgent and important national mission.