NASA/TP-2020-220517

The Flexible Lunar Architecture for Exploration (FLARE)

Designed for the Artemis-3 Moon 2024 mission and beyond

Dr. Michael E. Evans
Planetary Scientist
Astromaterials Research and Exploration Science (ARES) Division
NASA Johnson Space Center
michael.e.evans@nasa.gov
281-483-3276

Mr. Lee D. Graham
Senior Research Engineer
Astromaterials Research and Exploration Science (ARES) Division
NASA Johnson Space Center
lee.d.graham@nasa.gov
281-244-5192

National Aeronautics and Space Administration

Johnson Space Center Houston, Texas 77058

April 2020

NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TP-2020-220517

The Flexible Lunar Architecture for Exploration (FLARE)

Designed for the Artemis-3 Moon 2024 mission and beyond

Dr. Michael E. Evans
Planetary Scientist
Astromaterials Research and Exploration Science (ARES) Division
NASA Johnson Space Center
michael.e.evans@nasa.gov
281-483-3276

Mr. Lee D. Graham
Senior Research Engineer
Astromaterials Research and Exploration Science (ARES) Division
NASA Johnson Space Center
lee.d.graham@nasa.gov
281-244-5192

National Aeronautics and Space Administration

Johnson Space Center Houston, Texas 77058

April 2020

Available from:

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov

ABSTRACT

The Flexible Lunar Architecture for Exploration (FLARE) is a concept to deliver four crew to the lunar surface for 7 to 14 days and then return them safely to Earth by 2024. This meets NASA's internal 2024 lunar landing deadline directed by President Trump (Trump, 2017) and the "5-year" goal set forth by Vice President Pence (Pence, 2019). FLARE is an alternative to NASA's Human Landing System reference architecture from the Design Analysis Cycle (DAC) #2 (NASA, 2019b). The minimum FLARE concept uses one Space Launch System launch, one Orion, one European Service Module (ESM), and one human lander to deliver four crew to the Moon for a minimum surface duration of 7 days and return them to Earth. FLARE adds a new capability, called the SpaceTug, based upon the mature and successful United Launch Alliance "Common" Centaur Upper Stage vehicle, with modifications. In FLARE, the SpaceTug provides propulsion needed to return the Orion+ESM from the Moon to Earth. The SpaceTug also provides propulsion to deliver the human lander Descent Element (DE) and Ascent Element (AE) separately to lunar orbit. The Orion+ESM then completes a rendezvous with the mated DE+AE in lunar orbit. FLARE also offers optional phases to the Moon 2024 mission. The SpaceTug can also deliver components of the planned Gateway - including the Power and Propulsion Element and the Habitation and Logistics Outpost - to lunar orbit; however, the planned FLARE destination is a Low Lunar Frozen Polar Orbit unlike the NASA DAC2 plan for a Near Rectilinear Halo Orbit. FLARE also provides an option to deliver precursor equipment - including a habitation module, crew mobility devices and an In-Situ Resource Utilization demonstration - to the lunar surface for enhanced crew exploration and science with the extended 14-day surface mission.

CONTENTS

EXECUTIVE SUMMARY

BACKGROUND

The Flexible Lunar Architecture for Exploration (FLARE) is a concept to deliver four crew to the lunar surface for 7 to 14 days and then return them safely to Earth by 2024. This meets NASA's internal 2024 lunar landing deadline directed by President Trump (Trump, 2017) and the "5-year" goal set forth by Vice President Pence (Pence, 2019). FLARE is an alternative to NASA's Human Landing System (HLS) reference architecture from the Design Analysis Cycle (DAC) #2 (NASA, 2019b). The minimum FLARE concept uses one Space Launch System (SLS) launch, one Orion, one European Service Module (ESM), and one human lander to deliver four crew to the Moon for a minimum surface duration of 7 days and return them to Earth. FLARE adds a new capability, called the SpaceTug, based upon the mature and successful United Launch Alliance (ULA) "Common" Centaur Upper Stage vehicle, with modifications. In FLARE, the SpaceTug provides propulsion needed to return the Orion+ESM from the Moon to Earth. The SpaceTug also provides propulsion to deliver the human lander Descent Element (DE) and Ascent Element (AE) separately to from Low Earth Orbit (LEO) to lunar orbit. The Orion+ESM then completes a rendezvous with the mated DE+AE in lunar orbit. FLARE also offers optional phases to the Moon 2024 mission. The SpaceTug can also deliver components of the planned Gateway - including the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) - to lunar orbit; however, the planned FLARE destination is a Low Lunar Frozen Polar Orbit (LLFPO) unlike the NASA DAC2 plan for a Near Rectilinear Halo Orbit (NRHO). The LLFPO provides a stable orbit that overflies the south pole every 2 hours (Elipe et al., 2003), ensuring easy access to the lunar surface for surface aborts. FLARE also provides an option to deliver precursor equipment - including an inflatable habitation module, crew mobility devices, an In-Situ Resource Utilization (ISRU) demonstration, and science experiments - to the lunar surface for enhanced crew exploration and science with an extended 14-day surface mission.

FLARE CONCEPT

FLARE is built from a comprehensive technical analysis of multiple factors, including mass and change in velocity (ΔV) calculations for crew, cargo, and propulsion systems. FLARE develops a concept of operations for launch and rendezvous of necessary components in Earth and lunar orbit. FLARE provides a reference design for a human lander, including both the pressurized AE and a "common" DE capable of delivering either crew or cargo to the lunar surface. Payload volumetric evaluations are considered within existing launch vehicle fairings, and also for crew logistics on the lunar surface (within both the lander and in an optional inflatable habitation module). A lunar surface concept of operations provides for Extra-Vehicular Activity (EVA) traverses and crewed exploration activities for a 7- to 14-day campaign. FLARE also provides a reference design for an individual crew mobility device, called the "Lunar-ATV".

The FLARE utilizes launches on mature, proven Commercial Launch Vehicles (CLVs) to augment the single SLS Block I (SLS B1) lifting crew in the Orion+ESM to Trans-Lunar Injection (TLI). The FLARE launch schedule requires a 9-week period in 2024 that integrates ULA, SpaceX, and NASA launch pad availability with predicted boil-off rates for vehicle cryogenic propellants. FLARE places Orion+ESM with a human lander in a specific lunar orbit. **FLARE utilizes a LLFPO with inclination of 86.5° at an altitude of 100 km over the lunar surface. The key to FLARE is an added resource, called the SpaceTug (based on an existing upper-stage vehicle), that is launched on a CLV.** The SpaceTugs transfer assets between LEO and LLFPO. A dedicated Return SpaceTug (RST), waiting in LLFPO before the crew launches, provides the necessary propulsion for crew return to Earth in Orion+ESM.

Although not required, FLARE provides an option to transfer Gateway components from LEO to LLFPO with SpaceTugs (recognizing that Gateway vehicle modifications to existing NASA contracts may be required to operate in LLFPO rather than NRHO). FLARE also provides an optional precursor cargo mission (launched on a SpaceX Falcon Heavy (FH) rocket) to enhance lunar surface exploration with an inflatable habitation module, individual crew mobility devices, and science demonstrations and experiments.

The FLARE rejects the HLS NRHO for lunar exploration due to its high ΔV transfer requirement for surface operations, poor surface science support, and severe mission operations limitations due to its highly elliptical shape (varying 2000 km to 75,000 km from the Moon). During most of the NRHO 7-day period, the Orion is too far from the lunar surface for a contingency ascent abort (Whitley and Martinez, 2016). Compared to the NRHO, the LLFPO requires only 60% of the lander propellant to deliver the same dry mass to the lunar surface (see Appendix B: Calculations). A comparison of possible lunar orbits is shown in Figure EC-1 with approximate ΔV transfer requirements.

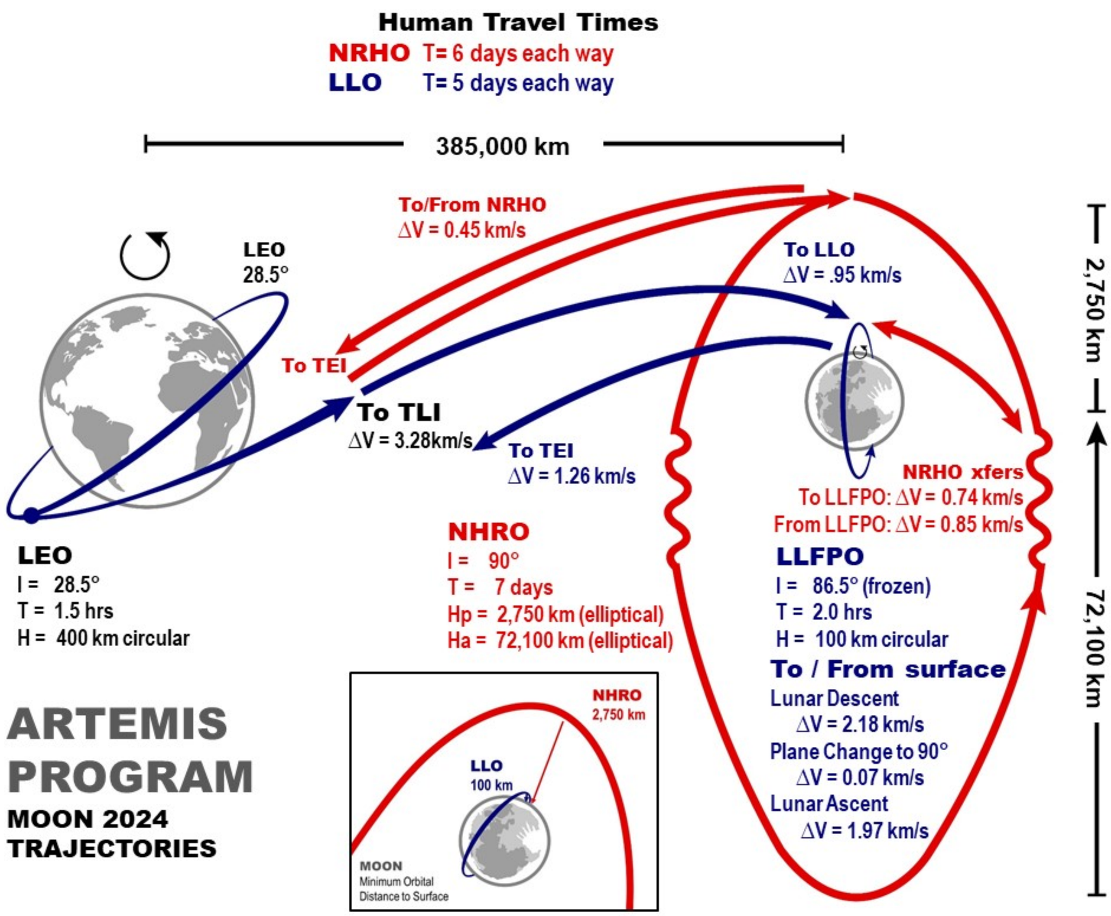

Figure EC-1: Comparison of lunar orbits.

<u>SPACETUG</u>

The FLARE SpaceTug is based upon a successful, mature flight-proven upper-stage developed by ULA. The “Common Centaur” (evolved from the Centaur-III) uses a standard RL-10 engine powered by Liquid Oxygen (LOX) and Liquid Hydrogen (LH_2) to deliver payloads to LEO atop an Atlas launch vehicle (Rudman and Austad, 2002). ULA has also developed the Integrated Vehicle Fluids (IVF) technology to limit cryogenic boil-off on their newer Advanced Cryogenic Evolved Stage (ACES) (Barr, 2015). The FLARE SpaceTug is created by mounting body solar arrays and a new Tug Adaptor (TA) to the Common Centaur upper-stage. The TA includes spacecraft electronics for Guidance, Navigation, and Control (GN&C), a cryogenic repressurization system (including IVF technology), retractable docking struts, and umbilical connections for power and fluid transfer with other vehicles (including other SpaceTugs). All of these adaptions are based upon existing mature spacecraft technologies. The SpaceTug is therefore an autonomous vehicle with independent power generation and command/control systems to deliver payloads from LEO to either Low Lunar Orbit (LLO) or the lunar surface (see Figure EC-2). Each SpaceTug can also operate independently or collaboratively when stacked with other SpaceTugs. The resulting SpaceTug dry mass is 2.75 metric tonnes (mt) (0.5 mt more than the Common Centaur) with a LOX/LH_2 propellant mass load of 20.05 mt (identical to the Common Centaur).

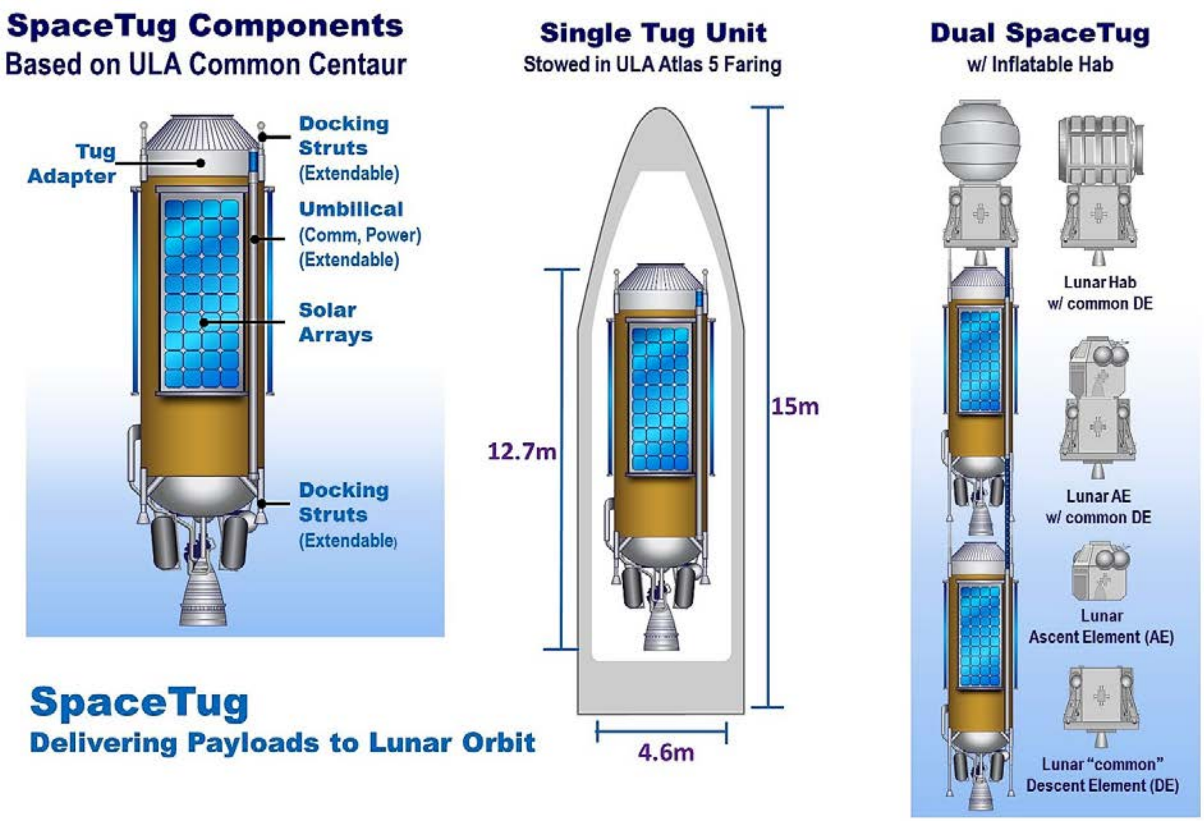

Figure EC-2: SpaceTug configurations.

FLARE requires a minimum of seven CLV launches to deliver five SpaceTugs and the human lander components to LEO, followed by one SLS launch carrying the crew in Orion+ESM to TLI. One SpaceTug pushes the lander AE from LEO to LLFPO. Two SpaceTugs stacked together push the lander DE from LEO to LLFPO. One SpaceTug pushes the RST from LEO to LLFPO where it waits to return Orion+ESM to Earth. Using IVF technology, the FLARE architecture assumes the cryogenic boil-off rate is < 0.5%/day. The launch schedule timing is therefore critical to ensure that on-orbit LOX/LH_2, used in both the SpaceTugs and the DE, is sufficient to provide the necessary ΔV when needed.

LUNAR LANDER

No existing launch vehicle provides the necessary performance to lift to TLI an integrated human lander capable of transfer from NRHO to/from the lunar surface. However, a SL B1 could lift to TLI an integrated lunar lander capable of transfer from LLFPO to the lunar surface. NASA's assumed ability to deliver only one SLS launch/year requires this dedicated launch for lifting the Orion+ESM to TLI. Thus, alternate architectures and concepts of operation need to be created for delivery of a human lander to lunar orbit. NASA is currently procuring commercial human lunar lander options (NASA, 2020c) but none have yet been chosen.

The FLARE has developed a representative lander for this effort to ensure an overall concept that can be launched on CLVs with adequate propellant margin, integrated launch schedules, and operations concepts. The FLARE lunar lander functions as the vehicle that places crew and supplies on the lunar surface. It consists of two major parts: the 4-person crewed AE, and the "common" DE. The common DE can either be attached to an AE (for crew) or to a payload as a cargo lander (see Figure EC-3). The common DE (2.5 mt dry mass, 9.0 mt LOX/LH_2 propellant mass) uses high specific impulse LOX and LH_2 feeding an RL-10 engine for the main propulsion system. The DE also includes four self-contained hydrazine monopropellant Reaction Control System (RCS) pods, with one connected to each leg.

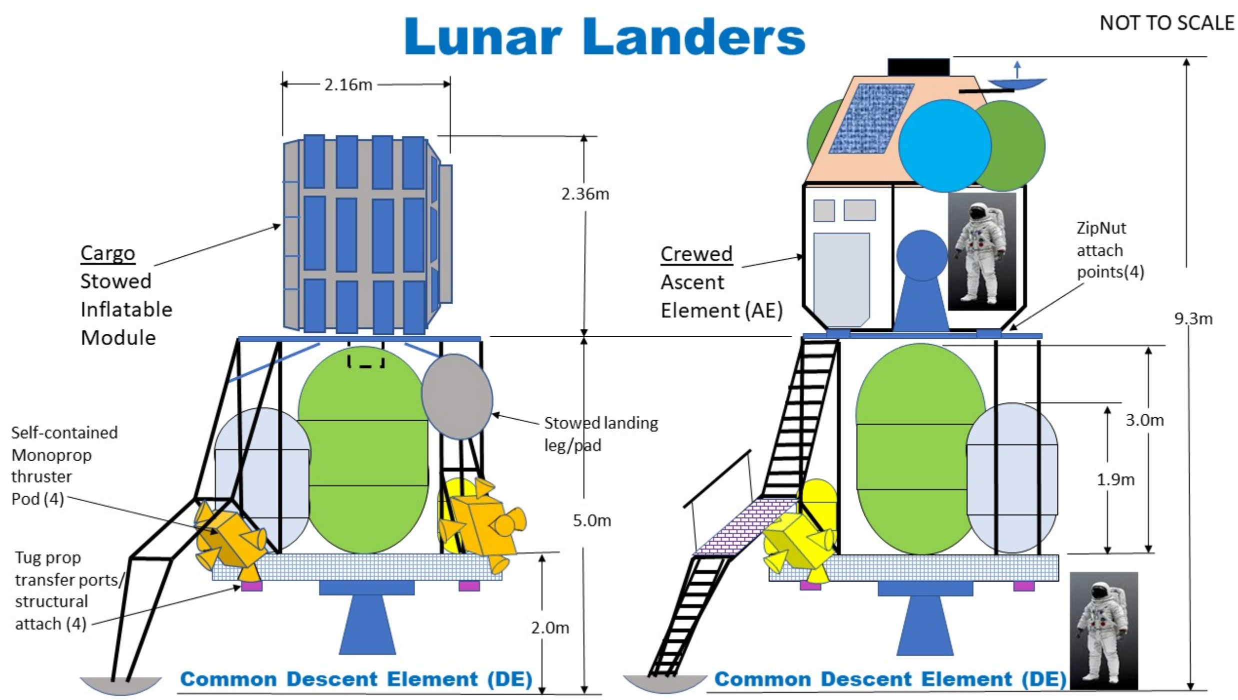

Figure EC-3: "Common" DE concept: with cargo payload (left) or attached AE (right).

The mass of the FLARE AE is the key architecture constraint that drives the entire concept. The AE has a dry mass of 4.0 mt with 8.4 m^3 of pressurized volume. This mass and volume is sufficient to support four crew on the lunar surface for 7 days. The AE holds 4.4 mt mass of storable monomethylhydrazine (MMH) with nitrogen tetroxide (N_2O_4) bipropellant in four tanks sufficient to deliver the vehicle from the lunar surface to LLFPO.

The FLARE human lander is transferred to lunar orbit with SpaceTugs. First, the uncrewed AE is launched on a CLV to LEO. It mates with a single SpaceTug (launched separated) in LEO, and they mate and transfer to LLFPO. Next, three launches occur in a 3-week period to lift individually one DE and two SpaceTugs to LEO (timing is critical to minimize LOX/LH_2 boil-off in each vehicle). They all rendezvous in LEO, and the first SpaceTug pushes the mated stack from LEO towards TLI and separates. The second SpaceTug then pushes the DE to TLI and into LLFPO. In LLFPO, the DE and AE rendezvous and mate to create the integrated human lander. Once this is accomplished, the crew launches on SLS aboard the Orion+ESM. After Orion+ESM rendezvous with the human lander in LLFPO, the crew transfers from Orion to the lander. The DE delivers the crew in the lander to the lunar surface, and the AE returns the crew to Orion+ESM in LLFPO.

OPTIONAL GATEWAY COMPONENTS

The NASA HLS DAC#2 assumed Gateway exists in NRHO. **FLARE does not require the Gateway PPE (Ticker et al., 2019) or the HALO (Foust, 2019b);** however, these elements are available as optional phases in FLARE. Note their existing NRHO designs would need modification to accommodate LLFPO. The PPE could provide a valuable communications relay for lunar surface operations, and HALO could provide unpressurized docking adaptors for SpaceTugs. Using FLARE, the PPE and HALO are each launched on a CLV to LEO, and then pushed to LLFPO by a single SpaceTug (launched separately to LEO).

OPTIONAL LUNAR SURFACE PRECURSOR EQUIPMENT

The FLARE "common" DE design provides a delivery vehicle for crew or cargo to the lunar surface. **With the additional launch of one SpaceX Falcon Heavy to TLI, a cargo DE can land 4.5 mt of precursor cargo payload mass directly to the lunar surface.** This option could be executed once, or multiple times, to build a sustainable lunar surface infrastructure. The first precursor payload could include a 2.0 mt inflatable habitation module (based upon the International Space Station (ISS) on-orbit BEAM module by Bigelow Aerospace) that provides 16 m^3 of additional crew living quarters (Valle and Wells, 2017) with an inflatable airlock. Solar arrays atop the inflated habitat (located at least 8 m above the surface) provide nearly continuous power generation for the field station (Mazarico et al., 2011). The first precursor payload also includes crew consumables for a 14-day surface mission, two additional Exploration Extravehicular Mobility Unit (xEMU) space suits, individual crew surface mobility device(s), and science experiments and demonstrations. Additionally, SmallSats carried onboard the DE can be deployed prior to descent to support lunar surface communications and navigation.

FLARE CONCEPT OF OPERATIONS

The FLARE concept of operations begins with the CLV launch of the RST, the AE, and the crew DE to LEO where each mates with SpaceTugs for transfer to LLFPO. Each then docks in LLFPO with Gateway (if it exists). Without Gateway, the AE and crew DE rendezvous and mate, while the RST maintains station keeping nearby. After these assets are safely in LLFPO, the crew launches to TLI in Orion+ESM on a SLS B1. The ESM then delivers Orion to a LLFPO. When Orion arrives, it will dock with either Gateway or the AE. All four crew will then transfer to the AE and descend with the fully integrated lander (AE+DE) to the lunar surface. After completion of the surface campaign, the crew will ascend in the AE and dock with either Orion or Gateway. The RST then docks with Orion+ESM and provides the needed ΔV to push the crew safely back to Earth.

The crewed lander descends to the lunar surface with all four members in the AE. Two crewmembers are donned in xEMU suits and two crewmembers are donned in Orion Launch and Entry Suits (LES) (NASA, 2019f). This is due entirely to DE mass constraints during landing. In the case of no precursor mission, crew pairs alternate days conducting EVA within walking distance of the AE using the two xEMU suits. The AE design includes 20 kg of stowage equipment (included in dry mass) supporting the return of 100 kg lunar surface and crew biological samples to Orion. Orion then delivers samples to Earth for curation and analysis at NASA Johnson Space Center (JSC).

If, however, the FLARE optional Phase B has delivered an inflatable habitation module and inflatable airlock to the lunar surface, the two xEMU-suited crewmembers can bring over the additional two xEMUs from the inflatable habitat after AE touchdown. All four crewmembers then reside in the habitat for 14 days while conducting surface EVAs. The landed precursor cargo also includes individual crew mobility device(s), science experiments, and an ISRU demonstration. This FLARE extended surface science campaign concept is based upon the 40-year successful “Antarctic Search for Meteorites” (ANSMET) program using individual mobility device(s) and coordinated traverses near a science field station (Institution, 2017). FLARE provides a reference design for a Lunar All-Terrain Vehicle (ATV) using the ANSMET model. Crew pair teams alternate EVA and AE interior activities each day, or all four crewmembers (divided in two-pair teams) can conduct EVAs to 10 km from the landing site using mobility vehicle(s). The extended surface campaign allows broad and far-ranging searches for interesting science samples and hydrated regoliths (including water ice) to feed the ISRU demonstration, thus providing proof of concept for sustainability.

CONCLUSION

The FLARE provides the opportunity to send four crew to the lunar surface for up to 14 days by 2024. FLARE requires a minimum of seven CLV launches to deliver five SpaceTugs and the human lander components to LEO, followed by one SLS launch carrying the crew in Orion+ESM to TLI. FLARE offers options to deliver Gateway to LLFPO, and to deliver precursor equipment to the lunar surface. FLARE uses existing, mature CLVs to launch SpaceTugs and lander components to LEO. The SpaceTug then transfers the components from LEO to LLFPO. The SpaceTug is derived from the ULA “Common Centaur” upper-stage (with over 20 years of successful launch history), but enhanced with existing technology modifications. FLARE includes a conceptual human lunar lander with a “common” DE and crewed AE. The common DE design provides either cargo or crew to the lunar surface. Future NASA selected commercial human and cargo landers, and lunar surface mobility vehicles, can also be integrated to FLARE. FLARE uses existing technologies and flight-proven launch systems, coupled with proven mission operations concepts based upon ISS LEO and Apollo LLO rendezvous, and the ANSMET field station science campaign, to lower development cost and program risk for Artemis. FLARE allows for inclusion of Gateway elements (PPE and HALO) and lunar surface precursor equipment to extend and sustain human surface operations. Components for on-orbit fluid transfer, ISRU propellant resupply, and deep space communications satellites are included in FLARE to enable expanded exploration of cislunar space then on to Mars.

END OF EXECUTIVE SUMMARY

(This page intentionally left blank.)

INTRODUCTION TO MOON 2024

The United States is planning to return humans to the Moon. President Trump signed Space Policy Directive 1 (SPD-1) on 12/11/2017 stating:

> "Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations (Trump, 2017)"

In 2019, Vice President Pence then directed NASA to return an astronaut crew, including at least one female, to the Moon within five years – hence, "Moon 2024". He stated:

> "…we have to demonstrate that we can live on the moon for months and even years. We have to learn how to make use of all available resources to sustain human life and all our activities in space, including by mining the vast quantities of life-sustaining water that's frozen in ice on our lunar poles" (Pence, 2019).

Since receiving the challenge, NASA has created the Artemis Program (Strickland, 2019) and directed analysis of mission options to accomplish "Moon 2024". The recently completed NASA Human Landing System (HLS) Design Analysis Cycle (DAC) #2 evaluated various architectures with a specific set of given constraints (NASA, 2019b). **The DAC2 constraints included**:

1. Launch four crew aboard the Orion Multi-Purpose Crew Vehicle (MPCV) connected to the European Space Module (ESM).
2. Launch Orion+ESM from the Kennedy Space Center (KSC) using NASA's Space Launch System (SLS) Block 1 and Interim Cryogenic Propulsion Stage (ICPS) Upper-Stage
3. Launch only one SLS mission per year, with first lunar surface crew launch in 2024.
4. No pre-positioned hardware elements are delivered to the lunar surface
5. All four crew travel to Gateway in a lunar Near Rectilinear Halo Orbit (NRHO)
6. Only two crew depart Gateway to visit the lunar surface, with the other two remaining on Gateway. Once the two surface crew return to Gateway, all four crew return to Earth in Orion using the propellant in the ESM.
7. The Gateway element is created by first launching the Power and Propulsion Element (PPE) (Ticker et al., 2019), then adding a small volume module. This module is called the Habitation and Logistics Outpost (HALO) (Foust, 2019a), and was formerly called the "minimal habitation module" aka "MiniHab" (MH) (Foust, 2019c). Both the PPE and the HALO are launched on Commercial Launch Vehicles (CLVs) for delivery to a lunar NRHO.

The DAC2 evaluation explicitly excluded architectures with single-stage elements, Earth-orbit rendezvous (with or without the International Space Station (ISS)), and lunar descent staging. The only viable options from the DAC2 assessment required additional vehicle(s), called the "Transfer Element" (TE), and/or on-orbit propellant transfer between elements for "closure", despite their recognition that this requires technology development and additional elements and launches not included in their assessment constraints. Although a follow-on DAC3 cycle was initiated, it terminated without a possible lunar architecture supporting Moon 2024.

FLARE DESIGN CONSTRAINTS

The Flexible Lunar Architecture for Exploration (FLARE), demonstrates a viable method to **deliver four crew to the Moon by 2024 with up to 2 weeks on the surface**. **F**LARE is an alternative to prior NASA HLS concepts. FLARE is an integrated near-term return-to-the-lunar-surface architecture that was developed based on multiple real-life constraints identified by the authors, including:

1) Use of the Orion capsule is required - *no other crewed spacecraft is currently planned or certified for lunar return*
2) Use of the existing European Service Module (ESM) is required - *the ESM is integral to the Orion capsule operation and is required for nominal in-space operation*
3) Use of the Space Launch System (SLS) is required - *no other launch vehicle (LV) is available that can launch an integrated Orion+ESM to a Trans-Lunar Injection (TLI) orbit to the Moon*
4) Use of existing, currently available Commercial Launch Vehicles (CLVs) – *CLVs launch the SpaceTug to LEO. While other potential HeavyLift Launch Vehicles (HLV) may become available before 2024, the FLARE is not bound to the shifting first-launch dates of these new rockets. FLARE can adjust to accommodate new HLV resources as they become available, and therefore reduce the required number of launches*
5) Use of realistic KSC launch schedules are utilized – *FLARE uses a launch schedule that considers pad turnaround time within an integrated master schedule that also includes calculation of orbital boil-off of LOX/LH_2*
6) All four crewmembers go to the lunar surface with a surface campaign from 7 to 14 days – *the existing NASA concept only supports 2 crew for up to 7 days on the lunar surface*
7) Use of a Low Lunar Frozen Polar Orbit (LLFPO) at 100 km altitude and 86.5° inclination is baselined - *use of a NRHO provides little to no surface science capability for the mission, and forces development of large lunar landers to support the necessary ΔV to access the lunar surface. NRHO is also a significant operations risk to the crew by being unavailable for abort or rescue during the majority of the lunar surface campaign*
8) Use of Gateway components is not required but is not precluded - *provides flexibility in the architecture while still meeting the 2024 deadline for human surface exploration*
9) Additional use of the International Space Station (ISS) is not precluded - *provides flexibility in the architecture and utilizes an existing international asset for future LEO assembly of larger vehicles*
10) Use of other existing space assets with modifications – *creating the SpaceTug from an existing upper-stage and using existing launch pads with modifications for LOX/LH_2 refill reduces the cost and schedule risk of developing completely new space assets. The crew uses the planned Orion Launch and Escapes Suits (LES) and the planned Exploration Extravehicular Mobility Unit (xEMU) for landing on the lunar surface. FLARE also plans on utilizing SmallSats for communications and navigation which can be easily adapted to support lunar surface operations*
11) Use of pre-positioned assets on the lunar surface are not precluded – *adding a lunar habitat with an inflatable airlock on a single precursor cargo mission supports longer and more scientifically robust lunar surface missions*
12) Science is part of the mission – *the crewed Ascent Element includes 100 kg of mass for lunar geological surface and crew biologic samples to be returned to Earth. The precursor hardware (PrC) includes science experiments and In-Situ Resource Utilization (ISRU) demonstration hardware for Moon 2024. Use of unpressurized crew surface rovers is not precluded; however, adding individual mobility device(s) based upon readily available terrestrial All-Terrain Vehicles (ATVs) technology enhances science during crew traverses for Moon 2024. Larger, more complex, unpressurized and pressurized rovers can be added to FLARE as they are developed*

13) Use of a Commercial Lunar Payload Services (CLPS) lander is not precluded - *this program provides a significant increase in possible lunar surface hardware delivery, but is not required. The FLARE reference "common" Descent Element (DE) also provides precursor resources for the 2024 target*
14) Use of new technology in key points of the architecture are minimized as stretch goals – *adding on-orbit propellant transfer capability to the SpaceTug provides the opportunity to demonstrate technology necessary for longer human missions to Mars and beyond*
15) Provision of multiple optional paths as technology develops – *FLARE allows maximum flexibility for addressing current known challenges and "unknown unknowns" variable impacts*

FLARE uses Orion and SLS as planned by the NASA HLS DAC, but adds a transfer element called the SpaceTug to provide necessary supplemental ΔV for crew and cargo transfers between Earth and the Moon. The SpaceTug is NOT a completely new vehicle, but a modification of a mature ULA upper-stage with a long and reliable flight history. The SpaceTug delivers human lander components to lunar orbit, and provides the propulsion necessary to return the Orion+ESM from the Moon to Earth. In 2024, the crew is launched aboard the Orion+ESM on an SLS B1. The presence of Gateway is optional. The lunar surface duration can be extended with an optional phase to deliver PrC (including a habitation module, crew mobility vehicles, and experiments). Future missions after 2024 might use other commercial Heavy-Lift Launch Vehicles (HLVs), landers, or crew transport vehicles as they become available. Thus, FLARE provides a pathway to sustainable lunar exploration with growth opportunities in technology evolution for human missions to Mars and other planetary bodies.

STUDY BACKGROUND

HLS DAC2 Development Methodology

The NASA HLS team published the DAC2 results in August 2019 (NASA, 2019b). They set guidelines for assessment of proposed missions to meet the Moon 2024 goal, including the use of SLS B1 for crew launch, the Orion MPCV with attached ESM (Orion+ESM) for crew transfer between Earth and Moon, and use of the NRHO for Gateway. Much well-researched documentation is available discussing the evolution of the SLS (Donahue, 2013, Calfee and Smith, 2014, Jackman, 2016, NASA, 2017, Smith, 2018, Donahue and Sigmon, 2019), the Orion MPCV (Berthe et al., 2013, GAO, 2016, Gutkowski et al., 2016), and the ESM (Berthe et al., 2013, Berthe et al., 2018, Thirkettle et al., 2018). Since the release of SPD-1, numerous papers document NASA's planned Gateway (Carpenter, 2018, Crusan et al., 2019, Berger, 2019a, Ticker et al., 2019) and Artemis program (Honeycutt et al., 2019, Smith et al., 2018). Development of each of the required vehicles, however, presents schedule and budget risks for meeting the Moon 2024 goal. A major hindrance to DAC2 was the requirement to use Gateway in a NRHO. After DAC2, HLS released the commercial crewed lander Request For Proposal, with optional use of NRHO Gateway for Moon 2024 (Gao, 2020, Clark, 2019).

FLARE Development Methodology

The evolution of FLARE is founded upon the mass of the crewed lunar Ascent Element (AE), which drivers the overall architecture. With this decision to design a pressurized surface lander that could accommodate four crew, all other elements were derived as follows:

1. Select the lunar module AE pressurized compartment dry mass. Compared to the dry mass of 2.2-2.4 mt for the Apollo Lunar Module (LM) Ascent stage (Orloff, 2000), the FLARE AE upsizes to a total dry mass of 4.0 mt to accommodate 4 crew.

2. Allocate a payload mass in the AE. The total payload AE mass is 0.5 mt for descent and ascent. Crew mass is considered payload, with a total of 0.1 mt/crewmember allocated (thus 0.4 mt for four crew). The 0.1 mt for science payload mass is allocated on lunar descent for EVA tools and surface science equipment, and on ascent is allocated for science support equipment, surface samples, and crew biological samples.
3. Select the propellant for the AE. Given the expectation that the AE will reside on the lunar surface for extended periods (up to a month or more, limited by crew consumables), the chosen propellant must not quickly boil away. The FLARE AE propellant chosen is the hypergolic monomethylhydrazine (MMH) and nitrogen tetroxide (N_2O_4), which are the same propellants used on the Space Shuttle Orbital Maneuvering System (OMS) and Reaction Control System (RCS) engines, and similar to the Apollo Lunar Excursion Module (LEM) ascent stage.
4. Calculate the required propellant mass of the AE to travel from the lunar surface to the desired lunar orbit. The FLARE uses the LLFPO with a 100 km altitude and 86.5° inclination as the target, so the required propellant is approximately 4.4 mt to accomplish the necessary change in velocity (ΔV) for ascent, and Rendezvous and Proximity Operations and Docking (RPOD). Thus, the total AE "wet" mass is 8.4 mt (4.0 mt dry and 4.4 mt propellant) with an additional 0.5 mt for crew mass and science payload.
5. Select the propellants for every other vehicle.
   A. The FLARE uses LOX/LH_2 to maximize thrust (Isp = 450.5 s) for the DE and the SpaceTug, recognizing that available advanced technology is required to limit the boil-off of the cyrogenic propellants on-orbit. FLARE assumes a LOX/LH_2 boil-off rate of ~ 0.5%/day (see discussion below).
   B. As stated previously, the Orion's ESM, based upon reuse of the Shuttle OMS engine, uses MMH and N2O4 storable propellants. The FLARE AE also uses this same propellant combination to ensure adequate propellant availability on the lunar surface for extended periods.
6. Calculate the required propellant mass for the DE to carry the AE to the lunar surface from LLFPO. The FLARE upsizes the Apollo LEM DE dry mass of 2.0 mt to 2.5 mt (for larger tanks), and thus requires at least 9.0 mt of propellant to deliver the AE and DE to the lunar surface with margin (including up to 2.5° descent plane change). Thus, the DE total mass is 11.50 mt (2.5 mt dry + 9.0 mt propellant). This DE "common" design is used for both cargo PrC placement on the surface (replacing the AE with uncrewed payload) and also for the mission that places the crewed AE on the lunar surface.
7. Design the launch schedule and delivery sequence to minimize on-orbit LOX/LH_2 boil-off time, within reasonable launch pad preparation and other ground turnaround requirements.
8. Provide flexibility in the launch schedule and delivery sequence to use Gateway in LLFPO, or not. Without Gateway, only the AE+DE mated to the Orion+ESM with a Return SpaceTug (RST) reside in LLFPO.
9. Provide flexibility in the sequence for prepositioned lunar hardware on the lunar surface, including a lunar habitation module, crew mobility devices, and a ISRU demonstration or other science equipment.
10. Provide flexibility in the launch schedule and delivery sequence for commercial HLV or commercial crew transport vehicles (such as SpaceX Dragon), if and when they are available.

FLARE Results

The calculated mass of each vehicle and payload for FLARE is shown in Table 1.

Table 1: FLARE Vehicle Mass Summary

Item	Dry (mt)	Prop (mt)	Tot (mt)	ISP
SpaceTug	2.75	20.05	22.80	450.50
PPE (Gateway)	8.00	0.00	8.00	
HALO (Gateway)	8.00	0.00	8.00	
Common DE	2.50	9.00	11.50	450.50
AE	4.00	4.40	8.40	320.00
Precursor Surface	4.50	0.00	4.50	
Crew	0.40	0.00	0.40	
EVATools (Descent)	0.10	0.00	0.10	
Samples (Ascent)	0.10	0.00	0.10	
CM	9.30	1.10	10.40	320.00
ESM	6.90	8.60	15.50	320.00

The change in velocity, delta-V (ΔV), values for each major FLARE target is given in Table 2.

Table 2: ΔV Values for FLARE (Mueller, 2012, NASA, 2019)

From	To	ΔV (km/s)	Xfer (days)	Reference
LEO (407km)	TLI	3.276	<1	Mueller (2012)*
**TLI	Lunar Surface	2.900	5	Copernicus SW **
TLI	LLO (100 km)	0.952	5	Mueller (2012)*
TLI	NRHO	0.450	5	DAC2
NRHO	LLO (100 km)	0.740	<1	DAC2
LLO (100 km)	Lunar Surface	2.180	<1	Mueller (2012)*
RPOD	Any	0.045	<1	DAC2
LLO 2.5° Plane Change	Lunar Surface	0.071	0	Calculated ***
Lunar Surface	LLO (100 km)	1.968	<1	Mueller (2012)*
LLO (100 km)	TEI	1.256	<1	Mueller (2012)*
LLO (100 km)	NRHO	0.850	<1	DAC2
NRHO	TEI	0.450	<1	DAC2
TEI	Splashdown	0.011	5	Mueller (2012)*

* Includes 5% reserve

** NASA software simulation, COPERNICUS program

*** See Appendix B for Calcuations

The FLARE sequence is divided into five Phases A-E (with each subdivided into subphases a-b):

A. Deliver equipment to create the Gateway in LLFPO (Optional, see Table 4)
B. Deliver lunar surface precursor equipment (Optional, see Table 4)
C. Deliver vehicles to LLFPO for crewed mission support (Required, see Table 3)
D. Deliver crew to LLFPO, then lunar surface, then to LLFPO (Required, see Table 3)
E. Return crew to Earth (Required, see Table 3)

FLARE sequence naming convention is XXY, where the XX identifies the vehicle element (see Appendix A: Acronyms), and Y is an incrementing counter for those vehicle elements. For SpaceTugs, the naming convention is repeated, e.g. Tug1DE1 (which identifies the first SpaceTug that pushes the first DE from LEO to LLFPO). Generic vehicle discussion uses their acronym only without a counter (Y). When discussing the launch vehicle for each element (see Table 3 and Table 4), the designated CLV is listed first, e.g. A5_AE1 (identifies the ULA Atlas V that lifts the AE1 to LEO).

The minimum sequence of detailed steps for the FLARE crewed mission is shown in Table 3, with a graphical description provided in Appendix C. All launches for these phases occur in a 9-week period (see Figure 1). The optional sequence of steps for the FLARE is shown in Table 4, with a graphical description provided in Appendix D. Launches for optional phases occur before the 9-week launch sequence of required phases (see Figure 1). All calculations are provided in Appendix B.

Minimum Required FLARE Phases

A few points merit discussion:

- Sequence #18 is an optional stretch goal to provide a flight demonstration of on-orbit LOX/LH_2 transfer between SpaceTugs and/or a DE2
- Sequence #19 assumes the DE2 for crew delivery to the lunar surface provides the entire ΔV for the lunar descent and landing, but an option exists to use a SpaceTug (Tug2DE2). Initially, Tug2DE2 pushes the DE2 from TLI to LLFPO and has residual propellant available when the crew arrives to LLFPO. Although not included in these calculations, the Tug2DE2 could conduct a perigee adjust maneuver for the crewed lander (AE1+DE2) to decrease the deorbit propellant needed by DE2 for the lunar landing
- Phases C1a to C4a must occur in a 9-week period to account for boil-off of LOX/LH_2 in SpaceTugs and pre-positioned DE2 (see Figure 1 for the launch schedule)
- Phases C4b to E1a occur over a period from 3 to 4 weeks (depending upon the duration of the lunar surface campaign and if Optional Phase B is implemented)

Table 3: FLARE Required Crew Phases (C, D & E)

Crew Phases (C,D,E)

USE A5, F9, FH & SLS. ASSEMBLY LEO & LLFPO

Seq	Phase	Vehicle	Payload	Description	ΔV (km/s)	Margin (mt)
1	C1a: AE1 to LEO	A5_AE1	AE1	Launch AE1 to LEO		
2	C1a: AE1 to LEO	F9_Tug1AE1	Tug1AE1	Launch Tug1AE1 to LEO		
3	C1a: AE1 to LEO			Assemble AE1 to Tug1AE1 in LEO		
4	C1b: AE1 to LLFPO	Tug1AE1	AE1	Push AE1 w/TugAE1 to LLFPO	4.23	0.80
5	C2a: RST to LEO	F9_Tug1RST		Launch Tug1RST to LEO		
6	C2a: RST to LEO	F9_RST		Launch RST to LEO		
7	C2a: RST to LEO			Assemble RST to Tug1RST in LEO		
8	C2b: RST to LLFPO	Tug1RST	RST	Push RST w/Tug1RST to TLI, D/O Earth	2.40	0.15
9	C2b: RST to LLFPO	RST	RST	Push RST w/RST to LLFPO	1.88	12.15
10	C3a: DE2 to LEO	F9_Tug1DE2	Tug1DE2	Launch Tug1DE2 to LEO		
11	C3a: DE2 to LEO	A5_DE2	DE2	Launch DE2 to LEO		
12	C3a: DE2 to LEO	F9_Tug2DE2	Tug2DE2	Launch Tug2DE2 to LEO		
13	C3a: DE2 to LEO			Assemble DE2, Tug1DE2, Tug2DE2 in LEO		
14	C3b: DE2 to LLFPO	Tug1DE2	DE2	Push DE2+Tug2DE2 w/Tug1DE2 to TLI	1.80	0.15
15	C3b: DE2 to LLFPO	Tug2DE2	DE2	Push DE2 w/Tug2DE2 to LLFPO. Mate AE1 with DE2 in LLFPO	2.48	4.05
16	C4a: Crew to TLI	SLS	OrionESM	SLS to TLI (4 crew in Orion+ESM)		
17	C4b: Crew to LLFPO	2 wks after DE2	OrionESM	Push w/ESM to LLFPO	1.00	1.50
18	D1a: Refuel demo			Transfer LOX/LH2 between vehicle(s)*		
19	D1b: Crew to surface	DE2	AE1	Crew (4) push w/DE2 to LS	2.25	0.26
20	D2: Surface Campaign			Crew(4) on surface of Moon 7d		
21	D3a: Crew from surface	AE1	AE1	Crew (4) push w/AE1 to LLFPO	2.01	0.18
22	E1a: Crew in LLFPO	RST	OrionESM	Assemble RST to Orion+ESM, Push w/RST to TEI, RST deorbit Earth	1.13	0.14
23	E1b: Crew to Earth	ESM	Orion	Push to EI with Orion+ESM, all descend Earth	0.14	0.70

* stretch goal based upon SpaceTug capability

Optional FLARE Phases

Optional Phase A assembles Gateway in LLFPO. NASA has existing contracts for commercial launch of the PPE and HALO - former known as Mini-Hab (MH) - elements in NRHO (Ticker et al., 2019, Foust, 2019c). By moving the Gateway elements from NRHO to LLFPO, vehicle thermal and power systems may need to be modified (based on the assumed stack attitude timeline in the lower lunar orbit). Without Phase A, Orion+ESM must dock directly to the AE1 of the human lander (composed of AE1+DE2). This is exactly the Apollo program approach, and requires compatible docking adaptors on each vehicle (which are different from the current requirements for each vehicle docking to Gateway). Each Gateway element is launched to LEO on an Atlas V (A5). Each SpaceTug is launched to LEO on a Falcon (F9). Each SpaceTug conducts an autonomous RPOD with the Gateway element in LEO and then transfers the element to LLFPO (see Appendix D).

Optional Phase B provides PrC to the lunar surface, including an inflatable surface habitat and inflatable airlock (for a 14-day surface duration). The PrC also includes consumables, EVA support, communication/navigation satellite(s), human mobility vehicle(s), an ISRU demonstration and science experiments. Phase B is necessary for developing lunar surface sustainability as a human “field station”. Phase B requires one Falcon Heavy (FH) launch to deliver a “common” DE (named DE1) and the cargo payload of PrC to TLI. The DE1 then deploys the comm/nav satellite(s) and carries the payload directly to the lunar surface (see Appendix D).

Table 4: FLARE Optional Phases (A & B)

Optional Phases (A, B)

USE A5, F9, FH & SLS. ASSEMBLY LEO & LLFPO

Seq	Phase	Vehicle	Payload	Description	ΔV (km/s)	Margin (mt)
1	A1a: PPE to LEO	A5_PPE	PPE	Launch PPE to LEO		
2	A1a: PPE to LEO	F9_Tug1PPE	Tug1PPE	Launch Tug1PPE to LEO		
3	A1a: PPE to LEO			Assemble PPE & Tug1PPE in LEO		
4	A1b: PPE to LLFPO	Tug1AE1	PPE	Push PPE w/Tug1PPE to LLFPO	4.23	1.05
5	A2a: HALO to LEO	F9_Tug1HALO	Tug1HALO	Launch HALO to LEO		
6	A2a: HALO to LEO	A5_HALO	HALO	Launch Tug1HALO to LEO		
7	A2a: HALO to LEO			Assemble HALO to Tug1HALO at LEO		
8	A2b: HALO to LLFPO	Tug1HALO	HALO	Push HALO w/Tug1HALO to LLFPO (GW)	4.27	0.95
9	B1a: DE1+PC1 to TLI	FH_DE1+PC1	DE1+PC1	Launch DE1+PC1 to TLI		
10	B1b: DE1+PC1 to LS	DE1	0.00	Push DE1+PC1 to lunar surface	2.90	1.18

The FLARE minimum mission for Moon 2024 provides a 7-day surface stay with all four crew living in the AE. This is similar to one HLS DAC option for a 6.5-day surface mission, but dramatically longer than an alternate DAC option for a “grab and go” mission with a lunar surface duration of less than 12 hours. For all DAC2 missions, two crew traveled to/from the lunar surface, and two crew remained in NRHO aboard Orion docked to Gateway (NASA, 2019b). FLARE could support either of these DAC2 missions (but with four crew instead of two on the lunar surface); however, with the optional Phase B FLARE offers enhanced human exploration and science investigation on the lunar surface for 14 days.

The FLARE Launch and Mission Schedule

The minimum crewed mission (FLARE Phases C, D, E) to the lunar surface requires the launch of five Falcon 9 (F9), two Atlas V (A5) and one SLS within a 9-week period (see Figure 1). The launch timing of these phases is critical since the SpaceTug and DE vehicles use LOX/LH_2 as propellant that boils away in orbit. FLARE calculates the required timing and sequence of launches to provide necessary margin in ΔV calculations including the loss of LOX/LH_2 from “boil-off” in orbit (see Appendix B for these calculations). This fleet of orbital vehicles for the minimum required mission is composed of one Orion, one ESM, one human lander (composed of components identified as AE1 and DE2) and five SpaceTugs (four SpaceTugs for pushing other vehicles from LEO, and one returning the Orion+ESM from LLFPO). The crewed phase consists of a 3- or 4-week period commencing with the SLS launch and ending with the Orion splash-down on Earth. Without optional Phase B, all four crew spend 7 days on the lunar surface living in the AE1 (see Appendix C). With optional Phase B, all four crew live for 14 days in the inflatable habitat provided by the precursor cargo mission (see Appendix D).

The SLS launches Orion+ESM to TLI, and the ESM then provides the required 1.0 km/s ΔV for LLO insertion and RPOD to the AE1 waiting in LLFPO (or to Gateway if Option A is implemented). This consumes most of the ESM propellant. The FLARE provides a SpaceTug in LLFPO, named the RST, with sufficient propellant to push the Orion+ESM and crew back to Earth (including boil-off margin). The RST is launched 1.5 months before SLS. After delivery to LLFPO, the RST experiences 56 days of propellant boil-off yet retains sufficient ΔV to return the crew to Earth (including a 14-day surface duration with Optional Phase B). All of the necessary elements for lunar descent, ascent, and return are therefore in place before the crew launches in Orion.

The SLS launch window must include considerations for lunar polar plane rotation in LLFPO to minimize ΔV for Trans-Earth Injection (TEI) return, and also lunar surface lighting during the crew lunar surface campaign.

Recognizing the risk of reliance on a SpaceTug in LLFPO for crew return **to Earth**, FLARE considered a possible alternative of this crewed sequence using a SpaceTug to push the Orion+ESM **to LLFPO**. This allows the Orion+ESM in LLFPO to provide the ΔV for crew return to Earth (no RST required). Preliminary analysis suggests this approach is viable but requires assembly of an unreasonably large, multi-stage vehicle in LEO composed of three SpaceTugs and the Orion+ESM to conduct TLI and Low Orbit Insertion (LOI) (see Appendix B for calculations using multiple SpaceTugs from LEO). Another alternative is to assemble two SpaceTugs and their payloads in a High Earth Orbit (HEO). The risk of these alternatives outweighed the initial FLARE risk assessment of employing one pre-positioned RST in LLFPO. The proposed schedule and sequence could be adapted, however, with further risk and design assessments (perhaps a larger SpaceTug).

Flare Schedule for Crewed Phases

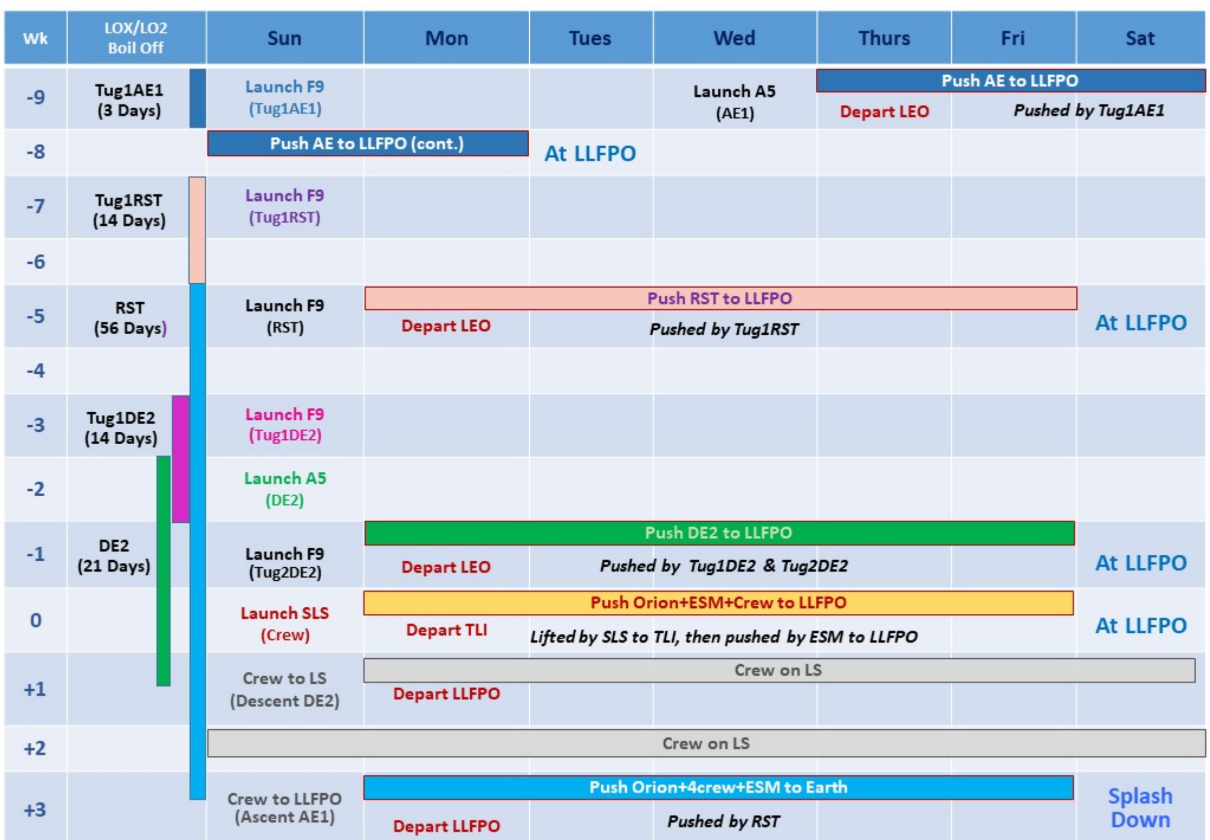

Figure 1: FLARE launch schedule for required phases.

LUNAR ORBITS

Near Rectilinear Halo Orbit (NRHO)

The NASA DAC2 cycle mandated the NRHO for the Artemis Program (NASA, 2019b), but this orbit is not optimal for lunar exploration.

NRHO Mission Operations Limitations

The HLS DAC2 evaluation guidelines required Gateway in a NRHO (NASA, 2019b). The NRHO is highly elliptical lunar orbit with a period of 6 to 8 days. It has been well studied as a potential staging orbit for deep space exploration using the Earth-Moon-Sun L1 and L2 Lagrange Points (Mendell and Hoffman, 1993). Altitudes above the lunar surface can vary from 2,000 to 75,000 km during each NRHO period (Whitley and Martinez, 2016). A specific NRHO with a 9:2 lunar synodic resonant, chosen for the NASA HLS DAC2, places apolune over the lunar south pole. This orbit is favored for its low orbital maintenance maneuver requirement and infrequent eclipse by the Earth and Moon (Williams et al., 2017).

In a representative 6.5-day period, southern NRHO, a spacecraft spends the bulk of every week at the far end of the orbit (relative to the Moon) with only 1 to 2 days near the lunar surface. For a brief time the orbiting vehicle is difficult to reach from the lunar surface (passing at high velocity nearly 2000 km above the surface) and for the majority of the week the orbiting vehicle is impossible to access (>30,000 km away). This forces human mission designers into one of two difficult choices. First, a short-duration "grab and go" mission to descend to the lunar surface from Orion+ESM in NRHO, consisting of a very brief surface exploration campaign (< 12 hours), and then ascend to the Orion+ESM. This short mission provides little surface science opportunity or surface infrastructure development, and requires an extremely long crew wake period (>24 hours to prepare in orbit for descent, descend, explore, ascend, and dock with Orion). The second option is a weeklong mission on the lunar surface; however, the crew has no ability to rapidly abort to Orion+ESM once they are on the surface for > 4 hours (since Orion+ESM are too far away and moving rapidly further from the Moon). A few interim abort opportunities exist, but the crew must survive in the ascent vehicle for 2 to 3 days while conducting a rendezvous with the distant Orion+ESM. The Orion+ESM then overflies the landing site 6.5 days after landing, and the crew can ascend and rendezvous in NRHO. Adding a surface habitation module and pre-positioned infrastructure components (e.g. crew mobility devices, EVA tools, and contingency consumables) increases safety and reduces risk for the longer surface missions while Orion+ESM is unavailable for rendezvous.

NRHO Science Limitations

Science opportunities from the NRHO include Earth observations (outside the Earth's magnetosphere), heliophysics, fundamental physics, and microgravity or radiation studies of biological and physical systems (Crusan et al., 2019, Brown et al., 2000). The first instruments selected for Gateway observe space weather and monitor the Sun's radiation environment (NASA, 2020a). With an orbiting spacecraft in NRHO, however, the vehicle is so distant from the lunar surface that telescope observations from Earth exceed resolutions possible from likely equipment available viewing from a window, or externally attached to HALO (if HALO can even support such telescopes). Additionally, the current HALO concept provides little volume for internal or additional external science instrumentation and experiments. For example, without an external robotic arm to grapple a robotic ascent vehicle and transfer a sample container to a science airlock, the Gateway cannot support unmanned lunar surface sample return. Additionally, Orion has no unpressurized external storage. Thus, the crew must bring any Artemis lunar sample from the lunar surface into Orion or Gateway for stowage in Orion's pressurized volume for delivery to Earth.

NRHO ΔV Limitations

The SLS B1 vehicle with the ICPS can deliver the 26 mt Orion+ESM to TLI (Smith et al., 2018), but the 8.6 mt of propellant and oxidizer in the ESM (Berthe et al., 2013) delivers a maximum total ΔV of only 1.25 km/s (Whitley and Martinez, 2016)). This ESM therefore provides insufficient delta-V (ΔV) to both insert the Orion+ESM into a 100 km circular Low Lunar Orbit (LLO), requiring a ΔV = 0.952 km/s, and return it to Earth from LLO, requiring a ΔV = 1.256 km/s (Mueller, 2012). It might be possible for Orion+ESM to return from LLO to Earth alone (with little excess margin). The NRHO is an elegant mathematical solution to the ΔV limitations of Orion+ESM and the SLS B1. The NRHO significantly reduces the total ΔV cost for a near-lunar orbiting spacecraft, requiring a total Orion+ESM ΔV=0.850 km/s for insertion and exit in a 21-day mission (Whitley and Martinez, 2016). This reduction in ΔV for access to NRHO from TLI, however, forces any lunar lander to increase their ΔV lunar ascent propellant budget by 0.85 km/s to achieve the higher orbit from lunar surface (NASA, 2019b). This requirement for increased lunar ascent propellant mass ripples through every possible architecture with impacts on lunar descent propellant, lander dry mass, and ultimately launch mass for the components (see Appendix B for comparison study of lander mass for NRHO and LLO). Additionally, the transfer from lunar surface to NRHO can take up to 3.5 days (which also impacts surface aborts to a distant Orion+ESM).

NRHO Required Additional Vehicles

The NASA HLS DAC2 presented a new vehicle, labeled the Transfer Element (TE), to ferry cargo elements individually from launch to NRHO, or from NRHO to LLO. The DAC2 provided cases with a single TE or a double-stacked TE. This additional element was required to create viable architecture scenarios, but violated the DAC2 guidelines. Since DAC2 proposed a TE, this FLARE employs a similar vehicle (called the SpaceTug) but enhanced as a robust transfer stage between LEO and LLO, not NRHO.

Low Lunar Frozen Polar Orbit (LLFPO)

In the past, NASA has embraced novel concepts that differed dramatically from then-current internal study baselines. The Apollo program placed the Command Module (CM), Service Module (SM), and Lunar Module (LM) in LLO for efficient access to the lunar surface, although it required the radical use of a Lunar Orbit Rendezvous (LOR). This approach differed greatly from the original NASA plans using Earth Orbit Rendezvous (EOR) (Reeves et al., 2006). Initially disapproved by NASA management, LOR proved essential (credited largely to the persistence of NASA engineer Mr. John Houbolt) to minimizing Earth-delivered mass for human lunar surface access (Hansen, 1995). FLARE's novel concept chooses a specific LLO at 86.5° inclination, called the LLFPO, for placement of vehicles involved in the lunar surface campaign of Moon 2024. The FLARE does not require any Gateway components, but can accommodate them if desired by NASA. A comparison of NRHO and LLO is shown in Figure 2.

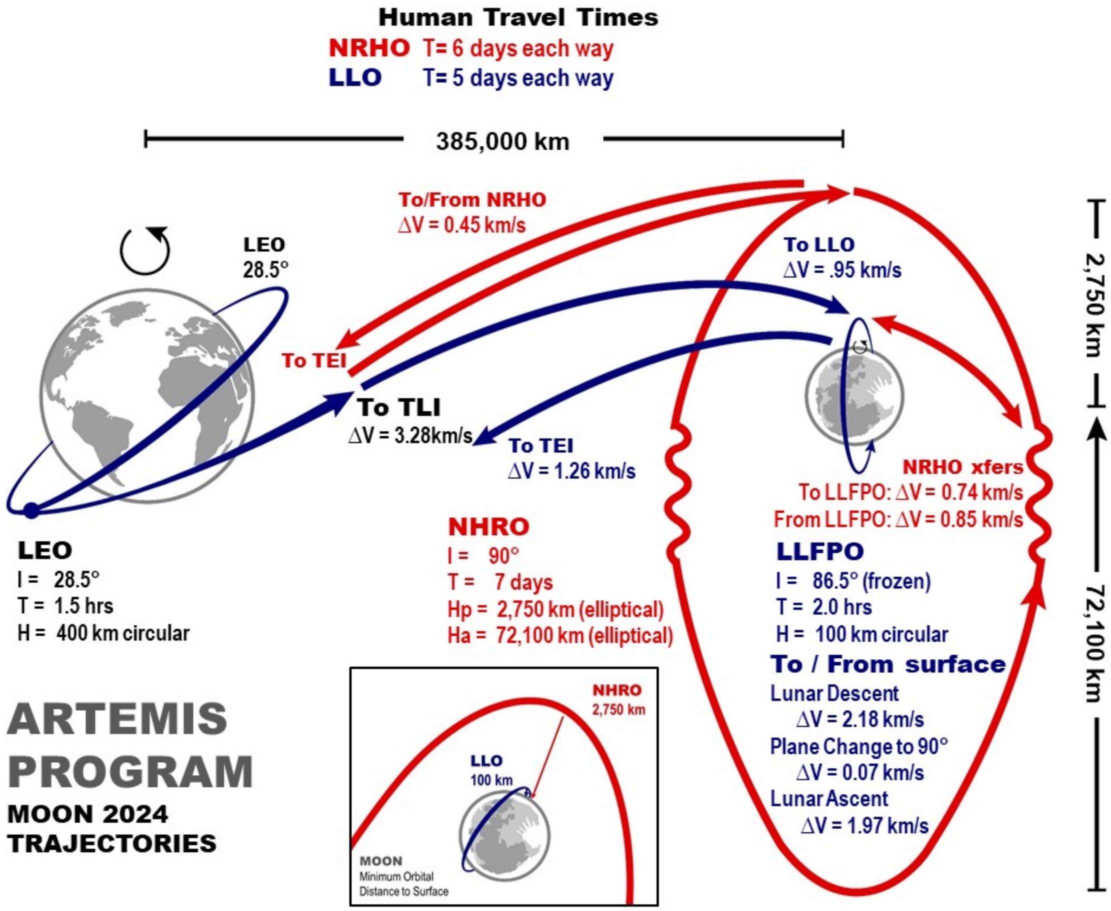

Figure 2: Comparison of lunar orbits.

Lunar Orbit Maintenance

FLARE places the Orion in a LLO with an altitude of 100 km and inclination of 86.5°, with a period of approximately 2 hours. This orbit provides frequent overflight of the landing site by the orbital vehicle. Additionally, the FLARE orbit is at a nearly polar inclination. This makes the entire lunar surface available for observation and mission access at some point during a lunar month. Lessons learned from Apollo teach that LLOs do not all have the same propellant budget to maintain the LLO. For example, the Apollo 16 mission released an orbital scientific satellite to study charged particles and magnetics fields around the Moon. The vehicle crashed into the moon after only 35 days due to unknown subsurface gravity mass concentrations (“mascons”) that altered the satellite orbit with each revolution, thus causing it to deorbit much sooner than planned. Subsequent lunar missions have mapped the locations of these mascons and identified their gravity impact on lunar orbits (Konopliv et al., 2001). A few special LLOs are less affected by these mascons. These “frozen orbits” have “constant mean eccentricity, mean inclination and mean argument of perigee” (Nie and Gurfil, 2018), and provide multi-year stability requiring no corrective maneuvers (Whitley and Martinez, 2016).

Frozen orbits ensure a constant altitude while minimizing the station keeping propellant budget, and are thus favored for orbiting reconnaissance spacecraft (Elipe et al., 2003). **To support a lunar south polar landing site, a LLFPO with I=86.5° and e=0.153 is selected for FLARE** (Elipe et al., 2003). From this inclination, a small 2.5° plane change during descent provides access to likely landing sites on flat areas near the Persistently Illuminated Regions (PIRs) of the south pole (Mazarico et al., 2011, Gläser et al., 2014). The ΔV cost for this 2.5° plane change maneuver is calculated, based upon orbital velocity for a 100 km lunar altitude, to be 71 m/s (see Appendix B). This is additional to the landing propellant budget of 2.180 km/s (Mueller, 2012). During ascent (when the vehicle velocity is low) the 2.5° plane change is not budgeted with additional propellant to the required 1.968 km/s (Mueller, 2012) for ascent to the 100 km altitude.

Earth Communications and Lunar Surface Navigation

The average Earth visibility from possible landing sites at the lunar south pole vary from 30%-70% during a typical month, and no likely site has 100% coverage (Mazarico et al., 2011). This limitation can easily be included as a constraint in launch window development for Moon 2024, with the short mission of 7 to 14 days planned to occur when communications with Earth is in direct line-of-site. For a sustained, long-term human presence at the south pole, the Earth visibility becomes problematic. To ensure continuous Earth communications, additional equipment needs to be placed either on lunar surface topographic features (e.g. atop a tall nearby mountain such as the rim of Malapert crater) that provide continuous visibility to the landing site and either Earth or an orbiting vehicle. The surface solution could be implemented with a communications tower using a CLPS lander prior to the Artemis-3 Moon 2024 launch. FLARE, however, chooses to place a satellite in orbit for continuous communications between Earth and the lunar landing site. Co-manifested with various elements of FLARE (possibly with PPE, HALO, DE1, AE, or DE2), the satellite(s) could be deployed after the payload stack achieves sufficient ΔV for TLI.

THE SPACETUG

The NASA HLS DAC2 Case 3 (single TE) and Case 4 (multi-stage TE) recognized the need for an orbital TE vehicle to deliver mass to the Moon. Rather than following the DAC2 cases for transfer between LEO, NRHO, and the lunar surface, FLARE employs a transfer vehicle only between LEO and LLO. The chosen design, known as a SpaceTug, is based on the ULA single-engine "Common Centaur" (see Figure 3), which evolved from the Centaur-III (Rudman and Austad, 2002). The SpaceTug is essential to FLARE as a propulsive vehicle to push payloads from LEO to LLFPO (required for AE1, DE2, and RST, and optional for PPE and HALO), and from LLFPO to Earth (crew in Orion+ESM). The ULA Common Centaur is a proven, reliable vehicle; however, modifications are required to morph it into a robust, independent SpaceTug. The FLARE goal is to create a SpaceTug vehicle that is capable of autonomous RPOD. It can then transfer payloads, reboost platforms, and potentially store and transfer propellants to other vehicles (see Figure 4).

The Centaur program has a long and successful history of flying upper stages since 1958. The Common Centaur was developed to support the Atlas IIIA program during the early 2000s, and has evolved to offer a double-engine variant (Rudman and Austad, 2002). Both versions are available on the current Atlas V rocket. The new ULA Vulcan rocket, planned for first launch in 2021 (Alliance, 2019)), uses a larger and more powerful upper-stage called the Advanced Cryogenic Evolved Stage (ACES). The Common Centaur, although smaller than ACES, is a more flexible upper-stage since it could be flown on both ULA and SpaceX CLVs (with modifications to the F9 to accept a longer fairing). The SpaceTug requires the ULA Integrated Vehicle Fluids (IVF) technology on ACES to re-pressurize the system and provide power to the vehicle (Barr, 2015). This also removes the need for hydrazine or helium as tank pressurizers. Additional electrical power is provided to the SpaceTug with solar arrays affixed on each side, which cover Multi-Layer-Insulation (MLI) blankets to reduce solar heating into the propellant tanks.

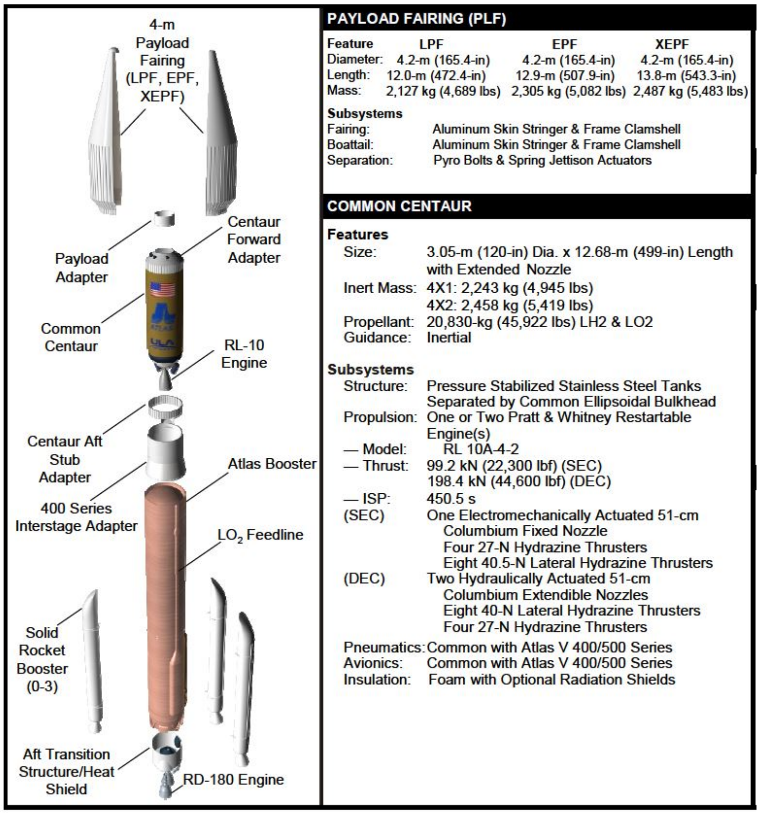

Figure 3: ULA common Centaur components.

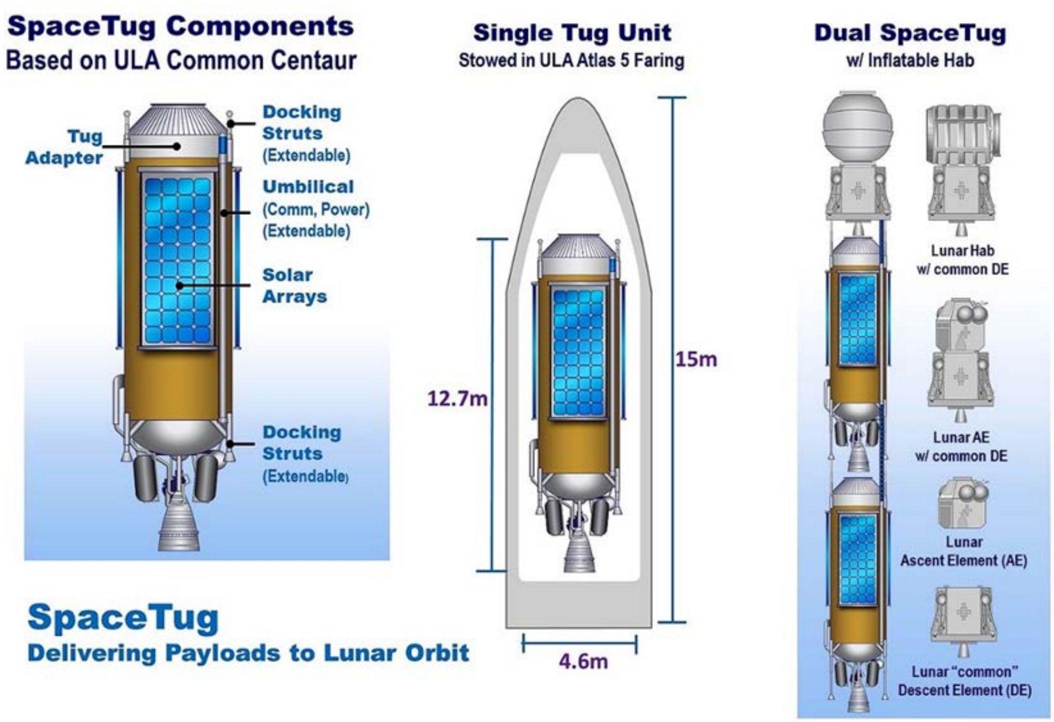

Figure 4: SpaceTug configurations.

A new Tug Adaptor (TA), replacing the Common Centaur Payload Adaptor atop the LH_2 tank, provides the electronics, batteries, and re-pressurization system components for the SpaceTug. The TA also houses the retractable docking struts and umbilical connections for mating the SpaceTug to other vehicles (including other SpaceTugs).

The dry mass for the SpaceTug is 2.75 mt (including 0.5 mt for the above modifications) with a propellant load of 20.05 mt (slightly reduced from the Centaur-III to keep the total mass within the expected SpaceX F9 28.5° LEO capability). The SpaceTug can be stacked together to become a 2-stage vehicle for pushing heavy payloads from LEO to TLI, NRHO, or LLO (see Figure 4). A single SpaceTug has the ability to deliver nearly as much mass from LEO to TLI as a SpaceX Falcon Heavy. A double SpaceTug can deliver significantly more mass from LEO to TLI than a SLS B1 with ICPS (see Table 5 for a summary of SpaceTug single and double-stage transfers, see Table 6 for a comparison to launch vehicle capabilities).

Table 5: SpaceTug Transport Capability from LEO

SpaceTug original orbit:	28.5° LEO, 400 km		
Mass Delivery from LEO to:	TLI	NRHO	LLO
Required Total ΔV (km/s):	3.276	3.796	4.265
One Stage (mt):	15.5	12.0	9.5
Two Stages (mt):	32.9	25.9	21.2

FLARE calculations use the documented ΔV required for a burn from LEO (407 km) to TLI is 3.276 km/s (see Table 2) including a 5% reserve margin (Mueller, 2012). An ESA study suggests the TLI burn from a 300km x 384 km LEO requires only 3.1 km/s (Biesbroek and Janin, 2000). Thus, the FLARE calculations (see Appendix B) for the SpaceTug delivering payloads from LEO to TLI are expected to be conservative.

To support Moon 2024, the boil-off of cryogenic LOX/LH_2 must be minimized. This propellant is employed both the SpaceTug and the human lander concept for the DE. The original Titan/Centaur was designed to support an eight-hour mission with a boil-off of 2%/day (Kutter, 2015). ULA has developed and patented numerous concepts to store propellant on-orbit (Kutter et al., 2012, Zegler, 2017). A new design, using the Centaur upper-stage as a secondary tank, called the CRYogenic Orbital Test (CRYOTE) concept, conceives of up to 1 year of storage of cryogenic propellants on-orbit (McLean et al., 2011, Gravlee et al., 2012). Building on CRYOTE tests, the next ULA concept uses a “Drop Tank” which waits in LEO for “days, weeks, or even months” to refill a Centaur upper-stage launched on a subsequent mission (Kutter, 2015). The Drop Tank remains attached to its depleted upper-stage and spins slowly (1°/sec) to provide centrifugal acceleration that settles the cryogenic fluids. The Drop Tank design includes features to minimize boil-off with insulated blankets, lightweight materials, a vacuum insulated common bulkhead and low conductivity struts. The expected boil-off is under 0.1%/day of the total propellant load.

NASA has investigated cryogenic fuel transfer and fuel depot concepts using the Centaur, with a goal of reducing boil-off to 0.1%/day (Bergin, 2011). Studies with “Zero-Boil-Off” systems show that spacecraft with proper insulation, and/or small cryo-cooling systems, could provide for months of liquid hydrogen storage without evaporation (Sun et al., 2015, Plachta et al., 2016). **FLARE assumes a higher Technology Readiness Level on the SpaceTug design to achieve an average LOX/LH_2 boil-off rate of 0.5%/day (based on a full cryogenic propellant tank).** This boil-off rate is also assumed for the lander DE (see the human lander discussion, below).

Although FLARE does not require on-orbit fluid transfer of LOX/LH_2, it provides an opportunity to demonstrate this capability in LLFPO (see Sequence #18 in Table 3, above). A SpaceTug in LLFPO could transfer residual propellant to the human lander DE or another SpaceTug. NASA considered the transfer of LOX between vehicles in Earth Orbit Rendezvous (EOR) as one of four architectures for lunar exploration. The Apollo plan required transfer of oxidizer from a tanker S-IVB upper-stage to a Trans-Lunar Injection Stage containing the CM, SM, Lunar Touchdown Module and Lunar Braking Module in order to achieve TLI (Reeves et al., 2006).

A challenge of cryogenic fluid transfer on-orbit is evolved gas release during the fill process. "No-vent-fill" designs, tested by NASA in the 1990s (Taylor, 1992, Chato et al., 2002), use cold liquid thermodynamic properties to condense the vapor in the tank (Kutter, 2015). In 2019, a company built an experiment "Furphy" on the ISS that successfully demonstrated the transfer of water on-orbit (Foust, 2019d). NASA and Yetispace have conducted tests on Earth demonstrating successful liquid nitrogen transfer under flight-like conditions (Stephens et al., 2019). The Shuttle program demonstrated an astronaut-controlled remote transfer of hydrazine between two tanks mounted in the payload bay of STS-41G (NASA, 2019a). Originally planned as a water transfer, Astronaut Dave Leestma convinced NASA management to allow the transfer of toxic hydrazine in order to better simulate refueling of spacecraft on-orbit (Hitt and Smith, 2014). Similarly, the Apollo 14 crew demonstrated liquid transfer of an inert fluorochemical, perfluorotributylamine, from one container to another using a hand pump operated by an astronaut (Abdalla et al., 1971). The propellant transfer technology gap must be closed to support long-term harvesting of planetary resources to fuel space vehicles. On-orbit transfer of LOX/LH_2 enables future Mars exploration and lunar commercialization.

The FLARE minimum required crew phases requires five SpaceTugs, of which three (Tug1AE1, Tug1RST, Tug2DE2) ultimately crash on the lunar surface. Adding an auxiliary Electric Propulsion (EP) system to the SpaceTugs would allow the depleted LOX/LH_2 vehicles to remain on-orbit and be repurposed as communications, navigation, or science experiment satellites. NASA has employed EP on three science missions: Deep Space 1, Dawn, and Space Technology 7 (Schmidt et al., 2018). Current NASA Solar Electric Propulsion (SEP) plans employ a 100 kw system with a 13.3 kw Hall thruster system for the PPE (Jackson et al., 2018). Development of a low power SEP, perhaps using the SpaceTug solar arrays (anticipated power in the 100s watt range), has previously been studied (Patterson et al., 1998). Eventually, clustered SpaceTugs in orbital tank farms might be filled from a robust lunar ISRU program. Numerous lunar fuel depot studies have been published detailing the necessary technology and infrastructure requirements for this capability (NASA, 1988, Eckart and Aldrin, 1999, Oeftering, 2011, Spudis, 2016). Future versions of the SpaceTug could also be landed on the lunar surface for collection and transport of ISRU products. ULA has developed a concept to transform an ACES into a horizontal lander. Called XEUS, it provides a novel design to deliver crew and cargo to the lunar surface (Barr, 2015). Similarly, since the LOX/LH_2 harvested from insitu regolith or ice needs to be stored, the SpaceTug could provide both the storage system and the transportation engine to deliver the propellants from the lunar surface to LLO (or beyond).

For FLARE, a vertical "lander" SpaceTug is estimated to require an additional 1.25 mt (dry mass = 4.0 mt) of hardware modifications for structural components (legs, pads, tanks) and surface refilling equipment. FLARE calculations predict that a modified SpaceTug could deliver ~11.25 mt of propellant to orbit from a full (~20 mt) propellant load on the lunar surface (see Appendix B). The lander vehicle attitude control systems would control descent, hover, and touch-down. Conceptually, the lander SpaceTug is launched on a FH towards TLI, and the vehicle then completes the burns necessary for TLI and direct descent to the lunar surface.

An additional future concept for future SpaceTug design is aerocapture. Rather than have a propellant depleted vehicle de-orbit to Earth after pushing components from LEO towards TLI, necessary decelleration could be performed with an inflatable shield that would slow the SpaceTug again to LEO velocities for RPOD with ISS (Oeftering, 2011). The SpaceTug could then be refilled and reused from LEO.

THE LANDER

NASA has issued calls to industry to help develop both unmanned science landers, and also crewed landers for the Moon. NASA selected nine companies to provide unmanned landers for lunar exploration with the Commercial Lunar Payload Services (CLPS) announcement on Nov. 29, 2018 (Voosen, 2018). An additional 12 NASA payloads and experiments were selected on Feb. 21, 2019 (NASA, 2019e), with another 12 selected on July 1, 2019 (NASA, 2019d). Beginning in 2021 with payloads of at least 10 kg, the landers are expected to grow to support future payloads of up to 500 kg or larger (Voosen, 2018). A human lander solicitation was issued by NASA on Sept. 30, 2019, with an anticipated award in March or April 2020 (NASA, 2020c).

The FLARE concept can accommodate any commercial lander for humans or cargo that falls within the mass, diameter, and height constraints of available CLVs. The FLARE concept provides a “common” lunar lander DE to be multi-purposed as either an uncrewed payload platform (called DE1 in the FLARE sequence) or a crewed AE platform (called DE2 in the FLARE sequence) to the lunar surface.

Ascent Element (AE)

The Ascent Element (AE) of the Apollo LEM, carrying two crew for a few days to the lunar surface, weighed 2.4 mt dry. To support four crew on the lunar surface for FLARE’s “Moon 2024” for 7 days, the Apollo dry mass is scaled up to 4.0 mt (see Table 1). This mass is the key design driver for FLARE, for it forces the ascent propellant quantity. The AE supports the crew as they descend from LLFPO, land, and live on the lunar surface for 7 days. The AE volume is 8.4 m^3 (or approximately 2 m^3 per person) and has a pentagon-shaped outer mold line. It has a dry mass of 4.0 mt, a propellant mass of 4.4 mt (total of 8.4 mt), and is designed such that the crewmembers stand during descent and ascent (see concept in Figure 5).

The AE supports crew use of either full xEMU spacesuits or Orion LES. The crew has sufficient volume to don/doff their xEMU and/or LES two-at-a-time, and also supports crew sleep periods (by use of hammocks) inside the pressurized volume. The AE is designed to carry 100 kg of lunar surface and crew biological samples (allocated as payload). The AE dry mass includes 20 kg of additional science supporting equipment such as containment boxes within the pressurized volume.

The AE propulsion system uses a single Shuttle AJ10-190 Orbital Maneuvering Engine (OME) internal to the crew volume, similar to the Apollo-era LEM. The AE uses the hypergolic bipropellants of MMH and N_2O_4 fed under helium pressurization and ignited in the OME with an oxidizer-to-fuel ratio of 1.65:1. It has two N_2O_4 and two MMH Composite Overwrap Pressure Vessels (COPV) tanks, both with 5% ullage volume and the same 1.6m diameter. If loaded to full capacity, the four tanks contain approximately 1734 kg of MMH and 2667 kg N_2O_4 for a total ΔV capability of 2.3 km/s for ascent to the 86.5° inclination 100 km LLFPO. The AE also has four RCS thruster quads fed from the same propellant and pressurant tanks as the OME (see Figure 6).

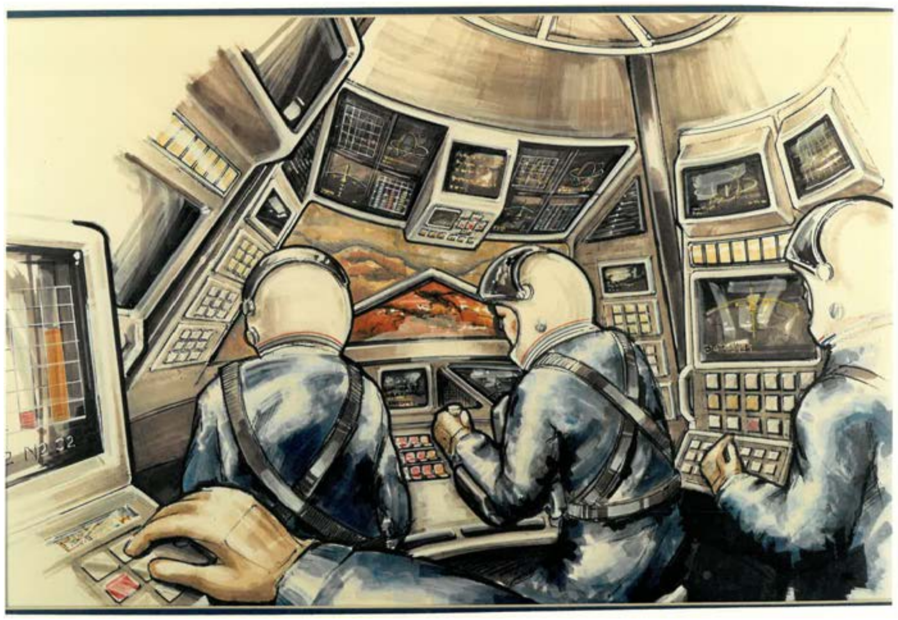

Figure 5: Concept for 4 crew descending to the Moon (Kitmacher, 1989).

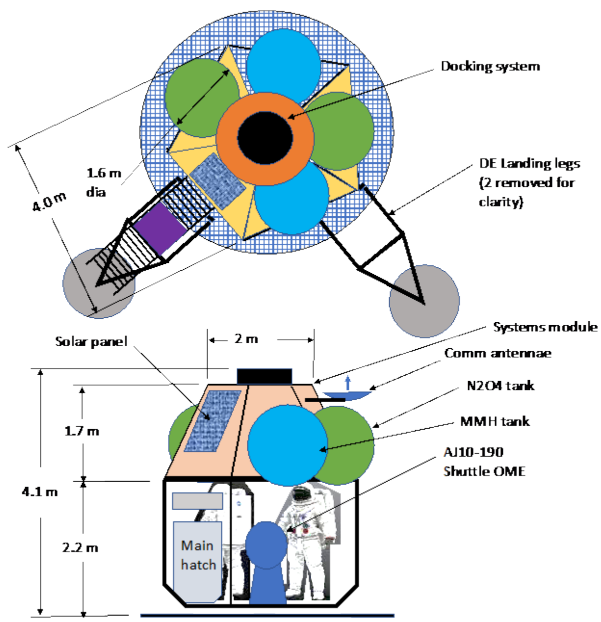

Figure 6: AE conceptual design.

The main pressure wall material of the AE habitable volume uses the common 0.040” aluminum 6061-T6 material (slightly thicker than the Apollo LEM 0.012” thick pressure wall). Similar to the DE, it has external MLI interleaved with additional sheets of inexpensive fiberglass fabric for micro-meteoroid protection (Briefs, 2014), and polyethylene sheets for radiation protection (Harrison et al., 2008) The entire AE module itself is structurally attached to the DE-based support structure using (4) pyrotechnic bolts with ZipNuts. These pyrotechnically-modified Snap-On © ZipNuts (Fastorq, 2013) mate the 2 elements (AE and DE) on-orbit and only require a straight push to fully engage. They therefore do not require any turning of the nut to ensure proper torqueing. These also have the advantage that the greater the tension the better the split nut threads grip the bolt shaft. The bolts themselves have been modified to fragment the bolt head upon the separation firing command. The AE will fire the four pyrotechnic bolts to separate from the DE immediately prior to liftoff from the lunar surface.

The FLARE AE is designed for an atmospheric pressure of 8.2 psi to 14.7 psi. The AE is able to support multiple depress/repress cycles for EVA, including the optional Phase B extended surface mission. With the optional surface habitation module in Phase B, the crew depress the AE to vacuum, power down the AE, traverse to the inflatable habitation module, complete the surface mission, return to the AE, repress the AE, power up the AE, liftoff and ascend to the Orion+ESM.

The AE has a single large Ingress/egress hatch for individual crew access in and out of the module while on the lunar surface. This allows a single crewmember to quickly traverse across the sill while only stooping slightly. A second hatch exists for crew entrance/exit on-orbit when docked to either the Orion or Gateway. The AE has two windows, each of which is a triple pane system to protect the pressure pane from inadvertent impact from the crew or impact from micro-meteoroids in lunar orbit or on the surface. After the AE returns to Orion in LLFPO, it may be repurposed as an additional pressurized volume or as an airlock for Gateway (if present).

Descent Element (DE)

The FLARE "common" DE concept is shown in Figure 7. It includes a lightweight composite truss structure with a dry mass of 2.5 mt and a total mass of 11.5 mt consisting of:

a) two LOX and two LH_2 tanks carrying a total of 9.0 mt propellant (7.714 mt LOX, 1.286 mt LH_2)
b) four helium pressurant tanks at pressure of 2.0684E7 Pascals (3000psi)
c) four small self-contained monopropellant RCS thruster pods each containing 40 kg hydrazine
d) a single gimbaled RL-10A-4-2 engine (specific impulse of 450.5 s)
e) four landing legs that are launched folded up (to fit inside the FH CLV fairing), then deploy and lock into place after the TLI burn is completed
f) a overhead composite support structure for a maximum 8.4 mt payload mass. Within FLARE the "common" DE is utilized in two modes: DE1 (optional cargo mission to deliver precursor equipment to the lunar surface), and DE2 (crewed AE1 to the lunar surface). Using CLVs and SpaceTugs to deliver the AE1 and DE2 from LEO to LLFPO, the DE2 supports its maximum payload weight with the crewed AE1. Using a FH to launch the integrated DE1 and precursor cargo to TLI, the payload mass of 4.5 mt is limited by the CLV ascent performance (not the DE support structure). DE1 then delivers the precursor cargo payload directly to the lunar surface from TLI.
g) a base composite support structure for the Main Propulsion System (MPS) tanks, leg attachment and main engine
h) two composite thrust deflection ramps to redirect the AE module ascent plume away from the DE propellant and pressurant tanks during AE ascent.

The MPS of the DE must provide 2.251 km/s total Δ-V to perform the lunar descent, requiring 2.18 km/s from 100 km LLO to lunar surface (Mueller, 2012), and 0.071 km/s for the plane change from 86.5^{o} to 90^{o} south pole (see Appendix B). The MPS consists of two cylindrical, dome-capped 2.75m long LH_2 fuel tanks (1.286 mt at a density of 70.8 kg/m^3) and two cylindrical, dome capped 1.9m long LOX oxidizer tanks (7.714 mt at a density of 1141 kg/m^3). This provides a total of 9.0 mt of propellant. Ullage volume was assumed to be 10% for both the LOX and LH_2 tanks. The DE employs a single gimbaled RL-10A-4-2 deep throttle-able engine mounted on the base thrust structure burning an oxidizer-to-fuel ratio of 6:1. As stated previously, FLARE assumes a cryogenic LOX/LH_2 boil-off rate of 0.5%/day (for both SpaceTugs and DE).

The DE has four landing legs which are launched stowed so as to fit within the 4.6m dynamic envelop of the FH fairing. The legs are deployed immediately following the completion of the TLI burn. Each leg is deployed using small electrical motors and the legs lock in place when fully extended. Internal to each leg is a crushable aluminum honeycomb structure which absorbs a portion of the touchdown loads. One leg has the crew surface access ladder attached to it. The ladder is in segments so as to "fold" when the landing leg compresses from the touchdown loads. This prevents the buckled ladder from blocking the crew access to the surface. Approximately 2 m above the landing pad is a small open-grated "porch" which also functions as a station for dust removal from the xEMU, as well as a storage location for tools and other equipment.

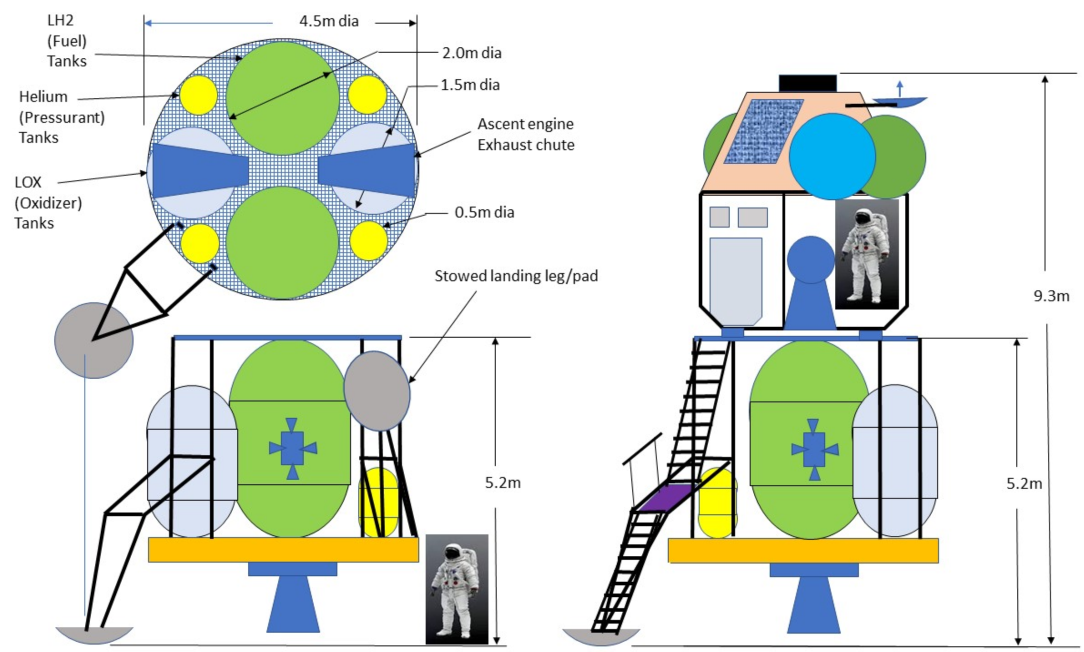

Figure 7: "Common" DE concept: with cargo payload (left) or attached AE (right).

DE attitude control is maintained by a combination of reaction wheels, RCS thrusters and main engine gimbaling. The DE uses a reaction wheel module mounted on the support structure that torques the DE when slower rate movements are required. When faster rates are required, the four 40 kg RCS thruster pods are also utilized. These are mounted on the four landing legs of the DE and are self-contained monopropellant (hydrazine) systems. As mentioned previously, one leg has the crew surface access ladder attached to it. The "up" firing thruster on the RCS thruster pod on that leg is normally inhibited from firing, but can be commanded to fire through the open-grated porch platform. The opposite leg, opposite thruster is normally used to accomplish this "pitch down" motion. When faster rates are required, a combination of reaction wheel operation, RCS thruster firings, and main engine gimbaling are used to accomplish the movement.

The AE support structure on the DE is a composite frame attached to the base thrust structure and is intended to support the loads induced from a fully loaded AE during lunar orbit maneuvering and landing on the lunar surface. It is not flown during any precursor supply mission. The top of the AE structural support structure on the DE is located 5.0 meters above the lunar surface and consists of an open web platform with the four attach points for the AE. Also attached to this structure are two ascent engine exhaust "chutes". These are placed to redirect the AE OME liftoff exhaust plume such that it doesn't impinge on the DE LOX/LH_2 tanks and potentially cause an explosion. These main LH_2/LOX propulsion system components are mounted inside this support structure and, with the chutes in place, are able to withstand the brief pressure and temperature spikes seen during AE liftoff.

The DE does not have a "hard" shell around its moldline. Surrounding DE propulsion components are "soft side" sheets of MLI interleaved with additional sheets of inexpensive fiberglass fabric. This provides a viable short-term Micro-Meteoroid and Orbital Debris (MMOD) shield similar to what is used to protect the SpaceX Dragon commercial cargo vehicles (Briefs, 2014).

The "common" DE is designed for flight with a crewed AE, or with an uncrewed payload. The DE uses two flight control computers for command and control when an AE is not attached. When an AE is attached, the AE flight computers control the integrated stack. Employing the optional Phase B, the "common" DE is fully tested and demonstrated prior to its required service for landing the crew.

A FLARE stretch goal is to have the DE capable of on-orbit refueling from a SpaceTug (see Sequence Step #18 in Table 3, above). Mounted on the underside of the base thrust structure are four propellant transfer/structural attach points for the SpaceTug extendable docking struts. These ports provide pressurized fluid transfer as well as structural attach points for the SpaceTug. In addition, there are also two ports on the underside for power/data umbilical attachments. These redundant ports provide communication and power transfer to/from other SpaceTugs when they are attached.

LAUNCH VEHICLES

The FLARE utilizes LEO in a circular altitude of 400 km, which is a common (but not universal) altitude for CLV vendors to publish mass delivery values for LEO. The FLARE reference CLV for component delivery (e.g. the required AE1 and DE2, or the optional PPE and HALO) to a 400km 28.5° LEO is the ULA Atlas V (A5) 551 rocket. The FLARE reference CLV for SpaceTug (including the RST) delivery to a 400km 28.5° LEO is the SpaceX Falcon 9 (F9) Block 5 rocket. The F9 Block 5 delivers 22.8 mt to a 28.5° LEO orbit (SpaceX, 2019) for an unspecified altitude. Prior SpaceX documentation reveals approximately a 5% reduction in payload delivery with a F9 Block 2 between a circular 200 km orbit (delivery = 10.454 mt) and a circular 400 km (delivery = 9.953 mt) orbit (SpaceX, 2009). The F9 Block 5 is thus expected to incur the same Performance Fraction (PF) for similar LEO altitudes. It is unknown how much reserve SpaceX maintains for the F9 Block 5 capacity. FLARE thus assumes the F9 Block 5 can deliver 22.8 mt to a 400km circular orbit of 28.5° inclination.

A comparison of past, present, and future vehicle payload mass delivery to LEO and TLI is provided in Table 6 (FAA, 2018, Jenkins, 1996, ESA, 2016, Smith, 2018, NASA, 2017, SpaceX, 2009, SpaceX, 2019, SpaceX, 2020, ULA, 2010). Mass fractions are used to equalize delivery mass to LEO and TLI across vendors. The 0.94 mass fraction for performance reduction from LEO 28.5° to LEO 51.6° is based upon published values for the SpaceX F9 Block 2 (SpaceX, 2009). The 0.27 mass fraction for performance reduction from LEO 28.5° to TLI is based upon published values for SLS (Donahue and Sigmon, 2019, NASA, 2017). Note the Space Shuttle (retired) is an entirely different architecture from CLVs that does not follow the mass fraction for 51.6°, and it was not capable of delivering payloads to TLI. Also included in Table 6 is the predicted performance of a ULA SpaceTug (FLARE concept) in either a single or double-stacked configuration.

Table 6: Comparison of Launch Vehicle Performance

PAYLOAD MASS DELIVERY (Past, Present & Future Vehicles)

	From KSC (ETR)	Launch to 28.5° LEO	Launch to 51.6° LEO	Launch to TLI
	Mass Fraction*	1.00	0.94*	0.27**
Vendor	Launcher	(mt)	(mt)	(mt)
SpaceX	Falcon 9 Block2	10.0	9.4	2.7
ULA	Atlas V 551	18.5	17.7	5.1
SpaceX	Falcon 9 Block5	22.8	21.4	6.2
ESA	Ariane 5	20.2	19.0	5.5
ULA	Delta IV Heavy	28.8	27.1	7.9
ULA	Vulcan Heavy	32.62	30.7	8.9
Blue Origin	New Glenn	45.0	42.3	12.3
ULA	SpaceTug (1 only)			15.5
SpaceX	Falcon Heavy	63.8	60.0	17.5
NASA	SLS Block I	95	89.3	26.1
ULA	SpaceTug (2 stacked)			32.9
NASA	SLS Block 1b	105	98.7	37.0
NASA	SLS Block II	130	122.2	45.0
NASA	Space Shuttle	27.5	16.1	

* Mass fraction for 51.6° from SpaceX F9 Block 2

** Mass fraction for TLI from NASA SLS Block 1

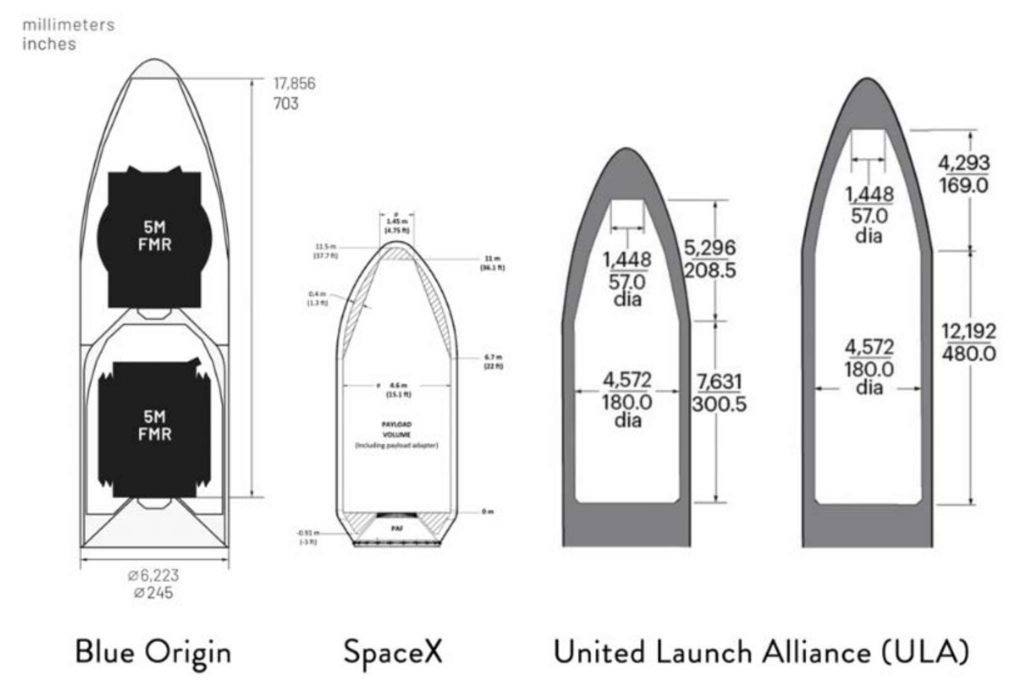

Figure 8: Fairing comparisons (Ralph, 2019).

A comparison of launch vehicle fairings is provided in Figure 8. The 2019 Falcon 9 fairing is 5.2m in outer diameter and 13.2m high overall and it can accommodate payloads of 4.6m diameter and 11m tall (barrel volume). A longer fairing is needed for the SpaceX Falcon 9 (F9) to hold the 12.7m tall SpaceTug derived from the ULA Common Centaur for Moon 2024. There are longer fairings available for the SpaceX vehicles, developed by RUAG for the ULA Atlas V, that have previously been discussed to support Department of Defense (DoD) payloads (Ralph, 2019).

FLARE assumes only one SLS B1 launch is available for Moon 2024, and that rocket is dedicated to lifting the crew in Orion+ESM to TLI. A second SLS B1 could assist a LLO architecture (like FLARE), but not a NRHO architecture (like HLS DAC2). This assumes two SLS B1 launches could be accomplished in a two-week period. The SLS B1 has sufficient performance to carry an integrated human lander (AE1+DE2 of mass 26.1 mt) to TLI for access to the lunar surface from LLO. The DE2 performs the LLO insertion burn. The lander would then loiter in LLO for 2 weeks (with LOX/LH_2 boil-off) until the crew arrives. This is NOT the FLARE sequence provided in Table 3 (or graphically in Appendix C) with lander components and SpaceTugs launched on CLVs, delivered to TLI, and inserted in LLFPO by the SpaceTugs. A SLS B1 does NOT have sufficient performance to deliver an integrated human lander (AE1 to DE2) to TLI for access to the lunar surface from NRHO. Compared to LLO, the use of NRHO requires an additional 2.95 mt of ascent propellant and 4.7 mt of descent propellant to deliver four crew in a AE (4.0 mt dry mass) to/from the lunar surface (see Appendix B for calculations). The NRHO integrated human lander (AE1+DE2 of mass 34.05 mt) would require a SLS Block 1b for delivery to TLI (see Table 6). This comparison highlights the impact of NRHO on lunar lander mass. Using NRHO forces separate launches on CLVs of a 4-crew (4.0 mt dry mass) AE1 and DE2 with orbit rendezvous for mating to create the integrated human lander. To reduce this lander weight on NASA’s planned Artemis-3 mission, the HLS plans to only send two of the four astronauts from Orion to the lunar surface and back to NRHO. Two other crew will remain aboard Gateway in NRHO (Honeycutt et al., 2019). Additionally, Artemis-3 payload mass and crew support equipment in the AE has been reduced to lighten the vehicle.

LUNAR SURFACE PRECURSOR MISSION (OPTIONAL)

FLARE optional Phase B provides lunar surface precursor equipment for human exploration infrastructure. Phase B, if implemented, is launched from Earth using a single FH launch to TLI, carrying DE1 (a common DE) and a 4.5 mt payload. The DE1 deploys a communications and navigation satellite after TLI as it travels towards the moon. DE1 then conducts a direct descent to the lunar surface and lands very near the planned human location (see Appendix D). The components of the 4.5 mt payload for DE1 are given in Table 7.

Table 7: DE1 PreCursor Payload Components

FLARE PreCursor Mission (PrC) - Phase B (optional), DE1 vehicle		
Mass (mt)	Component	Reference Concept
0.15	Comm/Nav satellite	York spacecraft (65kg), payload (85 kg, 100w)
2.00	Inflatable Hab & airlock	BEAM on ISS
0.35	Logistics (air/water)	4 crew for 14 days on lunar surface
0.38	xEMU suits (2)	2 icarried in AE, 2 in hab
0.30	Science Experiments	Trailer and stationary experiments
0.40	ISRU pilot plant	Proposed in NASA 2005 ESAS report
0.92	Mobility vehicle(s)	3 ATVs and solar charging station
4.50	Total	

Communications/Navigation Satellite(s)

With the FLARE optional precursor mission, one SmallSat is deployed after completion of the TLI burn. The SmallSat contains the necessary power and propulsion systems for its own transfer to Earth-Moon L1 (EML1), which is a location that provides continuous coverage for the lunar landing site. It also functions as a navigational target to allow surface assets to precisely determine their locations. One commercially available candidate is the S-Class spacecraft (allocated 85 kg mass and 100w power) built by Firefly Aerospace and York Space Systems (Foust, 2018) using readily available Radio Frequency (RF) transmitter and receiver equipment coupled to a GPS transponder.

An alternate orbital destination is to place a small relay satellite(s) at Earth-Moon L2 (EML2), which could provide continuous Earth communications support for both orbiting and surface equipment (Whitley and Martinez, 2016). Many space-rated communications SmallSat and CubeSat systems are readily available for this function, including MarCO (Laboratory, 2018) coupled with a Commercial Off the Shelf (COTS) SmallSat propulsion systems by Aerojet-Rocketdyne (Aerojet_Rocketdyne, 2019).

Satellite operations commences once the desire orbital destination is achieved and the vehicle completes onboard systems checks and communications tests with Earth and the lunar surface. This satellite then provides continuous communications and navigation support for the forthcoming human surface mission.

Inflatable Habitation Module

This lunar surface facility provides the four crew additional pressurized volume for living on the Moon during the planned 2-week extended mission. Based upon the proven design of the ISS Bigelow Expandable Activity Module (BEAM), the 3.6m^3 packed volume expands to 16m^3 when inflated (Valle and Wells, 2017), which exceeds the pressurized AE volume of 8.4 m^3. The ISS BEAM dry mass of 1.4 mt is increased to 2.0 mt for FLARE to include surface components for crew sleep stations, toilet, galley, and an inflatable airlock. The assumed internal pressure is 14.7 psi, although detailed design may lower the desired pressure to 8.2 psi to accommodate EVA preparations. An additional mass of 0.35 mt is also included in the DE1 payload for crew logistics to support a 14-day surface mission for 4 crew (water/air/food), which is 6.25 kg/person/day. Similar to the AE, the inflatable habitation module has external MLI interleaved with additional sheets of inexpensive fiberglass fabric for micro-meteoroid protection, and polyethylene sheets for radiation protection (Harrison et al., 2008).

The DE1 payload also includes two xEMU suits (mass 189 kg/each, total = 0.38 mt) (NASA, 2019c) that are stored in the habitat. When the human lander delivers all four crew to the lunar surface, two crew will be wearing xEMU suits and two crew will be wearing the Orion LES. After depressurizing the AE1, the two wearing xEMU suits will traverse to the habitat and retrieve the two xEMU suits in the habitat, then return to AE1. All four crew then relocate to the habitat for the remainder of the surface mission. EVAs from the habitation module will be conducted via the attached inflatable airlock. Stowed solar arrays atop the habitat are deployed after landing. With the chosen south polar region landing site, the surface is illuminated at a relatively constant, low, sun angle for more than 88% of the lunar year (Mazarico et al., 2011). Since the base of the DE1 platform sits at approximately 5 m above the surface, and the inflated habitat diameter is approximately 3.2 m (Valle and Wells, 2017), the solar arrays atop the stack are >8 m above the surface. At this elevation, the solar arrays would be illuminated for 95% of the lunar year (Mazarico et al., 2011). These arrays power both the habitat and the surface recharging station (used by mobility devices and science equipment). Additional solar arrays could be deployed on the surface, but they would experience eclipse periods ranging from days to weeks depending on the landing site location.

Science Experiments

The science experiments delivered on DE1 are a combination of mobile and static instruments. They are initially installed and tested by the crew, but then can be operated remotely from Earth after the crew departs.

a. Mobile Experiments: These instruments are designed to be moved about on the surface by crewed or robotic vehicles, and include examples such as a robotic arm with a sample capture system, a Mass Spectrometer, an Inertial Measurement Unit, or geophones. A trailer incorporating these instruments is delivered to the surface with DE1. The trailer also includes a solar panel for power generation and batteries for energy storage, communications, and navigation equipment.

b. Fixed Experiments: These instruments are designed to be emplaced in a single location, and include examples such as seismometers, solar wind and dust collectors, laser reflectors, or mass spectrometers. These instruments also require stationary solar arrays for power, batteries for energy storage, and communications equipment.

c. Communications: While RF communication to the crewed elements is a well-proven flight system, optical communications can also be used. Bidirectional optical communications at lunar distances were successfully shown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) (Cornwell, 2014) and demonstrated an error-free data upload rate of 20 Mb/s across the 400,000 km distance from the Earth to the Moon. If a 0.5 W infrared (laser at 1.55 micron wavelength is used (similar to LADEE), it is eye-safe as well as invisible to the eye so crew health and safety are not at risk. This approach therefore allows for dissimilar communication redundancy (RF and optical) as well as less dependence on the NASA Deep Space Network and it is heavily subscribed resources. These alternate communication systems are well suited for science surface experiments. For example, a modulating retroreflector (Goetz et al., 2012) can be used to transmit science data from either mobile or fixed science platforms and experiments. Between Earth-initiated laser transmissions and data transfers, the lunar surface science platform can store the data on radiation-resistant internal solid-state data storage units. For extremely long-term operation or operation during the lunar "night", a self-powered modulating retroreflector can also be employed (Chun and Theofylaktos, 2006).

d. Precision Navigation: The delivery of resources to specific lunar surface landing sites requires detailed navigation during descent and landing. Use of a pre-placed navigation surface beacon would significantly reduce landing error risk. Similarly, a terrain navigation system is required when planning and executing surface traverses with either crew or mobile robots. CLPS landers could provide demonstration opportunities for these precision navigation systems prior to the launch of DE1. DE1 itself can become a surface asset for relative navigation providing a transponder on the lander that feeds into triangulation calculations using a network of other surface transponders. The science payload of DE1 could include other surface assets to use in relative navigation, such as passive Radio Frequency Identification (RFID) Surface Acoustic Wave (SAW) semiconductor chips that respond to electromagnetic energy with a transmission. These semiconductors can also detect environmental parameters such as temperature or gas concentrations to characterize the environment with a wide network of inexpensively deployed sensors (Evans and Graham, 2019).

e. Star Tracker instruments can also be utilized for lunar precision navigation, especially when incorporated with other navigation instruments (Shaver, 2018, Dwyer-Cianciolo et al., 2019). The precursor mission small communications satellite at EML1, deployed by DE1, can have a GPS-type transponder that provides a node in a future network of satellites to provide precise navigation on the surface. Use of the PPE (in either NRHO or LLO) or FLARE SpaceTug(s) outfitted with GPS-type transponders could also augment the network in the timeframe of the human landing. In addition, NASA is developing a lunar receiver to use signals from Earth-orbiting GPS satellites for precision navigation on the lunar surface and in orbit around the Moon. Based upon improvements to the existing high Earth altitude Magnetospheric Multiscale Mission (MMS), this lunar system will require improved electronics, antenna and clock technology (Howell, 2019, Winternitz et al., 2019).

ISRU Demonstration

With FLARE, the crew will have time on the lunar surface to explore different regions and acquire lunar regolith samples. The Phase B payload includes 0.40 mt for development of an experimental process to demonstrate extraction of in-situ resources. This seeks to meet a key SPD-1 goal for sustainability (Trump, 2017). Several possible technologies are available for this demonstration payload.

The European Space Agency (ESA) is planning to deliver an ISRU demonstration to the south lunar polar region in 2023. The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial Exploitation and Transportation (PROSPECT) experiment is designed to prepare technologies for extraction of lunar volatiles, and is part of the Russian-led planned Luna-27 mission (ESA, 2019). The goal is to extract 50 mg of water from the lunar surface using ilmenite reduction (Sargeant et al., 2019). The overall PROSPECT mass is < 35 kg, and the experiment is designed to operate for one terrestrial year at a high latitude southern site (Laneve, 2018).

NASA has studied possible techniques for resource extraction from the lunar regolith, and several different technologies are feasible (Sanders, 2018, Linne et al., 2019). NASA has awarded 10 companies contracts with a combined valued estimated at $10 million for work extending through 2021 to investigate space resource collection (NASA, 2018). A past 2005 NASA proposal for a lunar O_2 pilot plant weighted ~800 kg (Stanley, 2005). The most favorable of these concepts that fits within the mass limitations of this FLARE payload would be chosen for the ISRU demonstration experiment.

Crew Mobility Vehicle(s) and Solar Charging Station

NASA released Requests for Information (RFIs) on 2/6/2020 for industry approaches to develop robotic mobility systems and human-class lunar rovers. The Lunar Terrain Vehicle (LTV) RFI specifically requests a vehicle capable of carrying ~500 kg including two EVA suited astronauts with science and exploration equipment for a distance >2 km from the lander (NASA, 2020b).

The FLARE concept categorizes mobility devices for each mission based on the maximum distance the crew explores from the landing site. If less than 1 km, then the crew does not need a mobility device (walking in the xEMU suit is sufficient). If EVA traverses are from 1 to 20 km, the crew requires a personal mobility device. If 20 to 50 km, the crew needs an unpressurized multi-person rover device with enhanced carrying capacity (“buggy” or “truck” style). If >50 km, the crew requires a pressurized rover so the crew can live in the vehicle and not return to the landing site each day. Crew mobility requirements also depend upon the topology of the desired exploration region, with rough terrain or vertical slopes requiring more mobility vehicle assistance than flat, smooth terrains.

Given the SPD-1 direction to send crew to the south polar region (Trump, 2017), the Moon 2024 mission will likely land on a region with:

1. a flat landing site (for safe descent and landing on the Moon)
2. nearby high illumination zones (for solar array energy production)
3. nearby interesting geologic features (for science experiments)
4. nearby Permanently Shadowed Regions that contain frozen volatiles (for ISRU)

A candidate landing region meeting this criteria exists near Shackleton crater (see Figure 9).

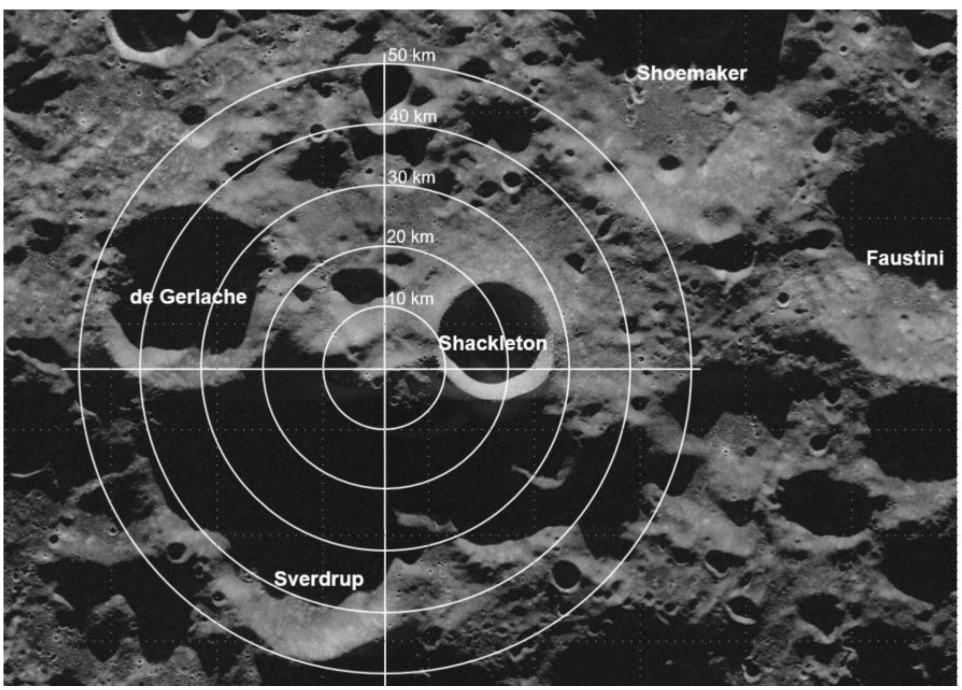

Figure 9: Candidate south pole landing site.

Major factors in lunar vehicle design are regolith properties and propulsion energy requirements. For the Artemis program, lunar regolith properties are much better understood than with the Apollo program. Apollo sample analysis, lunar rover projects, and robotic missions on Mars have contributed great experience to design and operation of vehicles on planetary surfaces. For propulsion, current electric battery technology and materials science enhancements facilitate design alternatives that were not possible during the 1970s. Existing COTS vehicles may be modifiable for Moon 2024, thus alleviating the need for an entirely new design as called for in the NASA RFI. The FLARE lunar surface concept of operations can support the NASA LTV when it is developed and delivered to the Moon on future missions; however, the FLARE reference design selects smaller, individual mobility devices for Moon 2024 to explore within 10 km of the landing site.

FLARE Reference Crew Mobility Device: The Lunar ATV

For Moon 2024, FLARE plans to load small vehicles inside (or perhaps alongside) the deflated habitation module atop DE1. The crew then unpacks them from the cargo lander and assembles them on the lunar surface. Options for individual crew devices were considered prior to NASA astronauts driving the first Lunar Rover Vehicle (LRV-1) on 7/31/71 during Apollo 15. NASA tested a “lunar motorcycle” (see Figure 10) as an alternative to the selected LRV-1 designed by Boeing (Riley, 2012).

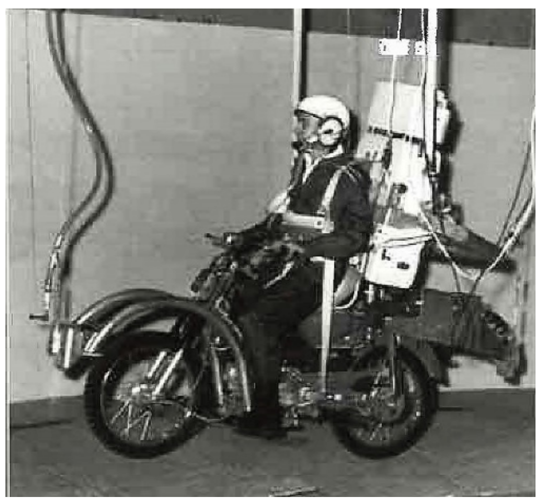

Figure 10: Apollo concept for a lunar motorcycle.

The FLARE lunar surface traverses are modeled after the successful Antarctic Search for Meteorites (ANSMET) program. The ANSMET program, sponsored by the National Science Foundation (NSF), has recovered more than 22,000 meteorites from the ice of Antarctica since 1976 (Institution, 2017). A small team of scientists is deployed each year to a scientific “field station” in the remote Antarctic mountains for 4 to 8 weeks of research and sample recovery (see Figure 11). The teams conduct exploration traverses by walking and using individual mobility devices.

Figure 11: ANSMET science team on snowmobiles (Bennett, 2015).

The ANSMET site is extremely isolated in hostile environmental conditions, and provides a human training analog to conditions on the Moon or Mars (Marvin et al., 2015). The ANSMET science team uses individual mobility devices (specifically, Ski-Doo snowmobiles) to daily traverse kilometers of region in the Transantarctic Mountains, then return each night to their "tent city" field camp. This technique has demonstrated great flexibility, redundancy, safety, and efficiency in meeting program goals.

For the Moon 2024 mission, FLARE selects individual Lunar ATVs rather than Apollo LRV-style "buggy' unpressurized rovers. The FLARE optional Phase B precursor mission has limited mass and volume that precludes an unpressurized rover, but could accommodate a smaller ATV design. Terrestrial electric propulsion ATVs have either 3- or 4-wheel options, and many are capable of functioning in extreme environments and difficult surface terrains. A reference COTS design by Doohan (Doohan, 2017) provides an example of a 3-wheeled design with an Earth weight of 160 kg that is capable of carrying two passengers up steep terrain in a variety of surface conditions (See Figure 12).

Figure 12: FLARE Reference Concept for a Lunar ATV.

Following are considerations for selecting a lunar ATV for the Moon 2024 crew mobility vehicle.

Commercially Available Designs:
Many vendors provide "hardened" ATV designs for use on off-road, sand, snow, or ice conditions with electric propulsion systems using removable batteries (which allows for rapid replacement of depleted batteries for fully charged replacements). Modification of an existing commercial design is likely much faster and cheaper than developing a new vehicle, which supports the aggressive schedule for Moon 2024. Commercial companies may also contribute "in-kind" development resources for a lunar ATV for the publicity and market attraction of participating with NASA.

Weight:
A typical ATV weighs from 100-300 kg on Earth, which is 50 kg (approximately 110 pounds) on the Moon with 1/6th Earth's gravity. A single astronaut can partially or completely lift, rotate, or push this mass on the Moon. If the ATV is stuck in soft regolith, the crew could lift the wheel or pull the vehicle towards a more solid surface.

UnPacking, Stowage, and Spare Parts:
The individual mobility device(s) can be designed to easily assemble/disassemble into large pieces, so that they could perhaps be initially unloaded from the hatch in the deflated surface habitation module (FLARE optional Phase B) or from volume-constrained CLPS missions. The crew then rapidly assembles the components into a functional vehicle on the lunar surface. Reversing the process allows long term storage of the vehicles in the habitat or in lunar surface sheds that protect them from solar wind and micro-meteoroid exposure while providing warmth and power to survive lunar nights.

ANSMET teams in Antarctica have often cannibalized parts from one snowmobile to keep other vehicles functional. Having multiple identical vehicles on the surface similarly provides an inventory of spare parts in the event of unforeseen failures.

Rechargeable Batteries:
The mobility system needs solar array(s) with recharging capability for the ATV batteries. As previously discussed, solar arrays from the inflatable habitat could be used for recharging the ATV batteries, or a separate ground station could be installed. Multiple excess batteries should also be charged and ready for rapid replacement once an ATV has depleted the energy in its current battery. The recharging of each battery can be done inductively with the battery remaining on the vehicle (necessary for telerobotic operations), or the battery can be removed by the crew and attached to the recharging terminal (either outside or inside a pressurized volume).

EVA Requirements:
On the first mission to return humans to the lunar surface, there is little existing infrastructure to support long traverses. It is extremely unlikely an unpressurized rover will be developed and available before 2024, without which the crew would return to the landing site after each EVA to live in the inflatable habitat (with FLARE optional Phase B) or the AE (without FLARE optional Phase B). Using these modified lunar ATVs, however, could enable crew exploration of the immediate region near the candidate landing site (perhaps near the illuminated ridge adjacent to Shackleton Crater shown in Figure 10) within a 10 km range. The lunar ATV must survive the cold conditions, the dusty regolith, and provide batteries that can be easily recharged. The vehicle must also be compatible with the lunar xEMU suit design so that astronauts can sit and ride on the vehicle comfortably. Preliminary assessment of the xEMU design,

including joint movement and range of motion, indicates the astronaut can mount, unmount, ride, and control an upright ATV with the xEMU.

Traverse Flexibility:
With each EVA team of 2 crew on individual mobility devices allows multiple surface objectives to be conducted simultaneously. Pairs of astronauts could work collaboratively or independently on tasks. This increases the efficiency of astronaut EVA time and enhances the flexibility in executing traverses.

Crew Rescue:
Each ATV is capable of carrying two astronauts each in the xEMU suit. A rescue ATV could be driven to a stranded astronaut by crew, or an empty ATV could be telerobotically (using a remote operator) driven to the disabled crew location.

Telerobotic Capability:
NASA and many terrestrial industries have developed the capability to robotically drive a vehicle using a remote operator. For remote operations, the vehicle must be designed to recharge the electrical battery directly with easy connectors to a charging station or through inductive field charging. Telerobotics on a lunar-ATV adds multiple capabilities to the entire mission. First, the ATV is an able platform for pulling the science instrument trailer when the crew is not present. Long term science experiments could thus be conducted from Earth during surface crew absence. Secondly, the ATV could be teleoperated by the surface crew to explore areas which are precluded from humans (due to slopes, temperatures, or surface roughness/softness). The astronaut could watch the ATV directly and manipulate the vehicle in conducting operations in these more difficult terrains. Third, the ATV could be telerobotically operated as a rescue vehicle to recover a stranded astronaut at a distant location.

LUNAR SURFACE CREWED CONCEPT OF OPERATIONS

After a successful launch and transit to the Moon, the Orion+ESM docks with the assets in LLFPO, which is, at a minimum, the human lander (AE1 + DE2) and the RST. The PPE and HALO may also be present (as Gateway) but are not required. On Crew Flight Day 8 (see the FLARE Master Schedule in Figure 1) all four Orion crew board the AE1 and seal the hatch. They then descend to the lunar surface and land at the designated site. After safely landing on the lunar surface, the operations concept depends upon the available surface assets. If Phase B is NOT implemented, the four crew will conduct limited walking EVAs alternating pair teams using the 2 xEMU suits in the AE. The surface duration may be brief (up to one week) before the crew returns to Orion.

The FLARE extended 14-day surface mission with longer science traverses required the prepositioned assets from Optional Phase B. All four Orion crew descend to the lunar surface inside the pressurized AE1. Two of the crew are dressed in xEMU suits, and two are dressed in the Orion LES. Once the DE2 has landed safely on the Moon, the AE1 is depressurized and the two crew dressed in xEMU suits depart. The two crew remaining in the AE1 - dressed in the LES that can keep the astronauts alive for up to 6 days (NASA, 2019f) - then repressurize the AE1 and wait for the return of their crewmates. The two crew in xEMU suits walk to the deflated habitation module and unload the crew mobility vehicles and two xEMU suits inside. They then inflate the habitation module and attached inflatable airlock, then return to the AE1. The AE1 is again depressurized to allow the xEMU crew to enter, then the AE1 is pressurized and the two crew left inside doff the LES and don the xEMU. The AE1 is again depressurized and all 4 crew depart to the DE1 landing site. The crew ingress/egress the habitation module via the inflatable airlock. Science, ISRU, EVA tools, and solar array mobility equipment are unloaded and deployed. The crew sleeps in the habitat for the next 14 nights. Each day, one team conducts traverses using the lunar ATVs, and one team remains at the habitat landing site (either inside the habitat or conducting walking EVAs). Each traverse pair includes one crewmember on an ATV, and the other one on an ATV pulling the science trailer. A third ATV (if available) can be pulled behind the non-science trailer pulling the ATV, driven telerobotically, or left behind at the habitat site (for rescue). Each team of two crew will alternate days as an ATV traverse team or local habitat team. Upon completion of the 2-week campaign, the crew will reconfigure the site for remote science operations by enabling telerobotic equipment and stowing equipment and configuring the habitat module for human absence. The crew then reverse the sequence of walking between the AE1 site and habitat site returning two xEMU suits to the habitat and bringing two xEMU suits into the AE. On Flight Day 22 (see Master Schedule in Figure 1), all four crew in the AE1 return from the lunar surface to Orion in LLFPO.

COST CONSIDERATIONS

The Federal Aviation Administration (FAA) publishes an annual report on the estimated launch costs for commercial vendors (FAA, 2018), and frequent website announcements provide general industry details on price modifications. Tables 8-10 provide a summary of required vehicles and transportation costs for all phases of FLARE. The selected CLVs (F9, FH, and A5) are for reference only and could be replaced with different rockets as they become available before 2024. Estimated transportation costs for each phase are provided, using published launch vehicle costs (SpaceX, 2020, ULA, 2010, Qiu, 2018, FAA, 2018); however, these costs are difficult to estimate for future NASA missions and are intended for broad discussion only.

The unit cost (after development) of a SpaceTug is expected to be similar to the existing ULA Common Centaur. The SpaceTug assumed cost is $80M each (~1/2 the cost of an Atlas V 551 launch).

The unit cost of a SLS B1 is difficult to assess. Recent announcements indicate the costs are much higher than previously predicted (Berger, 2019b). For this analysis, the assumed price of one SLS launch is $2 billion to carry the Orion+ESM to the Moon. Adding a second SLS B1 to launch an integrated human lander would reduce the requirements for CLVs launches to LEO carrying individual component (DE and AE). The two SLS B1 launches would need to be within 2 weeks of each other to accommodate LOX/LH_2 boil-off in the DE. However, two SLS B1 launches in 2 weeks in 2024, from the same launch pad, is not considered as a viable alternative in FLARE.

Development costs are not included in this analysis. The FLARE philosophy is to rely on existing, proven resources (to the maximum extent possible) that could be modified with less expense and risk than developing new vehicles for Moon 2024. The SpaceTug modifications to the existing Common Centaur require a new Docking Adaptor, Solar Arrays, Power and Electrical umbilicals fore and aft, Retractable docking struts, cryogenic fluid connections, computer system with GN&C for independent and collaborative flight and RPOD, and communication and command system upgrades. Launch pads require modifications necessary to refill LOX/LH_2 to the SpaceTug within the fairing of a CLV prior to launch. Note that a longer fairing is required to accommodate the SpaceTug on the SpaceX rockets.

It is generally noted that delivery of mass to the Moon is much less expensive when using SpaceTug(s) to provide the necessary ΔV from LEO to TLI compared to a single SLS B1 launch. Launching two CLVs (each carrying a SpaceTug) to LEO to mate with a lunar payload launched on a third CLV to LEO provides more

ΔV than one SLS launching the same payload to TLI at profoundly less cost. This less-expensive approach, however, requires LEO rendezvous to mate the SpaceTugs and payload.

The Transportation Costs (not including development) for FLARE phases is given in Table 8 for Optional Gateway Components, Table 9 for Optional Phase B Lunar Surface Precursor Equipment, and Table 10 for Required Crewed Phase Vehicles.

Table 8: Transportation Costs for Optional Gateway Components

Optional Gateway Components						
Phase A (Gateway)	F9	FH	A5	SLS	Tugs	Notes
A1a: PPE to LEO	1		1			Deliver to LEO
A1b: PPE to LLO					1	Tug pushes to LLO
A2a: HALO to LEO	1		1			Deliver to LEO
A2b: HALO to LLO					1	Tug pushes to LLO
Cost ($M) per vehicle	$62	$90	$153	$2,000	$80	
Phase A (PPE & HALO)	2	0	2	0	2	Total ($M)
Total	$124	$0	$306	$0	$160	$590

Table 9: Transportation Costs for Optional Lunar Surface Precursor Equipment

Optional LS Precursor Hardware						
Phase B (LS Precursor Hardware)	F9	FH	A5	SLS	Tugs	Notes
B1a: DE1+PC1 to TLI		1				Deliver to TLI
B1b: DE1+PC1 to LS						DE1 pushes to LS
Cost ($M) per vehicle	$62	$90	$153	$2,000	$80	
Phase B (LS Precursor Hardware)	0	1	0	0	0	Total ($M)
Total	$0	$90	$0	$0	$0	$90

Table 10: Transportation Costs for Required Crewed Phase Vehicles

Required Crew Vehicles						
Crewed Phases (C, D, E)	F9	FH	A5	SLS	Tugs	Notes
C1a: AE1 to LEO	1		1		1	AE1 and Tug1AE1
C1b: AE1 to LLO						Tug1 pushes AE1
C2a: RST to LEO	2				2	Tug1 and RST
C2b: RST to LLO						Tug1 pushes RST
C3a: DE2 to LEO	2		1		2	DE2 amd 2 Tugs
C3b: DE2 to LLO						2 Tugs push DE2
C4a: Crew to TLI				1		Orion+ESM to TLI
C4b: Crew to LLO						ESM push to LLO
D1a: Refuel demo						Between Tugs/DE2
D1b: Crew to LS						DE2 pushes to LS
D2: Surface Campaign						
D3a: Crew from LS						AE1 pushes to LLO
E1a: Crew at Gateway						RST pushes to TEI
E1b: Crew to Earth						ESM push to Entry
Cost ($M) per vehicle	$62	$90	$153	$2,000	$80	
Vehicles	5	0	2	1	5	Total ($M)
Crewed Phase Costs	$310	$0	$306	$2,000	$400	$3,016

In summary, the SLS launch costs overwhelm all other costs for CLV launches or SpaceTugs. The FLARE provides for future CLV and commercial crew vehicles that could provide human transportation to the Moon without reliance solely on the SLS or Orion+ESM.

ANTICIPATED FLARE CHALLENGES AND OPPORTUNITIES

The FLARE concept attempts to use existing vehicles and technology as much as possible to limit development cost and schedule risk; however, there are several areas of concern that require further analysis. These issues must be balanced against similar risks in other architectures to determine which approach is most appropriate for NASA's lunar exploration campaign.

SpaceTug

- The SpaceTug must be human rated to dock with Orion+ESM and deliver them with crew back to Earth from LLFPO
- The SpaceTug propellant (LOX/LH_2) boil-off rate must be reduced to < 0.5%/day implementing some technologies developed and some technologies proposed by ULA
- Numerous autonomous RPOD between SpaceTugs and payloads in LEO and LLFPO is required
- For future missions to the Moon and Mars, the SpaceTug could demonstrate propellant transfer between other SpaceTugs and landers on-orbit
- For future missions to the Moon and Mars, the SpaceTug could demonstrate surface landing and refill of propellants from ISRU equipment for return to orbit
- For future missions to the Moon and Mars, the SpaceTug could demonstrate aerocapture in LEO following transfer of crew from LLFPO

Human Lander

- The common DE propellant (LOX/LH_2) boil-off rate must be reduced to < 0.5%/day implementing technologies developed and proposed by ULA
- The lander AE docking adaptor could be different designs for direct docking of each crewed vehicle (Orion, AE) in LLFPO instead to Gateway components (crew ingress/egress)
- The lander AE can be designed so that it can be reconfigured as a crew airlock or additional crew quarters on Gateway (if it exists) after the four crew return from the lunar surface
- Precision human landing using a surface navigation beacon is required to place the crew near the precursor equipment (Optional Phase B)
- Continuous communication is required with a SmallSat deployed from orbit, or with a predeployed surface tower on a CLPS mission

Launcher

- The SpaceX Falcon 9 fairing must be long enough to accommodate the SpaceTug
- The ULA Atlas V fairing must be long enough to accommodate the SpaceTug
- The SpaceX launchpad must provide for LOX/LH_2 refill of the SpaceTug prior to launch
- The ULA launchpad must provide for LOX/LH_2 refill of the SpaceTug prior to launch
- In future missions, the SpaceX, Blue Origin, or ULA new HLS rockets might be evaluated as an alternative to the SLS for launch of Orion and the ESM

Capsules

- The Orion needs to be evaluated to ensure all systems can operate in a LLFPO, or if modifications to the ESM or Gateway components (if they exist) can assist Orion functionality in LLFPO
- The Orion docking adaptor could be different designs if directly docked to Orion or AE rather than a Gateway HALO (for crew ingress/egress)
- For future missions, consider replacing the ESM with a larger SM to provide sufficient ΔV for Orion transfer to/from LLFPO without SpaceTugs. However, an integrated Orion with a larger SM would exceed the launch capability of SLS B1 to TLI, and would thus require SLS Block Ib or Block II development
- Commercial crewed capsules launched on CLVs to TLI could augment FLARE in the future if they are rated for lunar missions

PPE (Gateway)

- The PPE mission was conceived for NRHO and analysis must determine whether the vehicle can be modified to fly a LLFPO
- The PPE attitude control system must accommodate docked SpaceTug(s), and perhaps allow SpaceTug(s) to perform reboost maneuvers in LLFPO
- The PPE must add a SpaceTug docking adaptor (unpressurized)
- The PPE could provide orbital navigation for surface operations with the addition of a GPS-type transponder

HALO (Gateway)

- The HALO - formerly known as “Mini-Hab” (MH) - was conceived for NRHO and analysis must determine whether the vehicle can be modified to fly a LLFPO

- For future missions to the Moon and Mars, the HALO could demonstrate propellant storage with transfer from SpaceTugs and landers on-orbit
- The docking adaptor for HALO must accommodate the lander AE and Orion docking system for crew ingress/egress

SUMMARY

The FLARE provides a reasonable, practical sequence to deliver four Americans to the Moon in 2024, and then return them safely to Earth. The underlying FLARE concept is to maximize available commercial technology for the mission, and limit development of entirely new systems or vehicles. As new technology or vehicles become available, FLARE provides multiple growth opportunities for their integration. Transportation costs are minimized using existing CLVs for delivery of components to LEO, and the SpaceTug (which is a modification of mature, successful technology combined with newer, proven innovations) provides the necessary propulsion for transfer between LEO and LLFPO (which is the optimal lunar orbit for sustained lunar surface operations). A new human lander is required, but commercial contracts provided by NASA are underway for its further definition and development. FLARE allows for inclusion of Gateway elements (PPE and HALO) and lunar surface precursor equipment to extend and enhance human surface operations. Crew lunar surface mobility devices being investigated by NASA can be added, and FLARE provides a reference concept for an individual vehicle (called the lunar ATV) for Moon 2024. Advanced technology demonstrations for on-orbit fluid transfer, ISRU propellant resupply, and deep space communications satellites are included in FLARE to enable enhanced exploration of cislunar space, then on to Mars.

REFERENCES

Abdalla, K. L., Otto, E. W., Symons, E. P. & Petrash, D. 1971. Liquid transfer demonstration on board Apollo 14 during transearth coast.

Aerojet_Rocketdyne. 2019. *Modular Propulsion Systems for CubeSats and SmallSats* [Online]. Available: https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop-2sided.pdf.

Alliance, U. L. 2019. *SNC Selects ULA for Dram Chaser Spacecraft Launches* [Online]. Available: https://www.ulalaunch.com/about/news/2019/08/14/snc-selects-ula-for-dream-chaser-spacecraft-launches.

Barr, J. The ACES Stage Concept: Higher Performance, New Capabilities, at Lower Recurring Cost. AIAA SPACE 2015 Conference and Exposition, 2015. 4495

Bennett, J. 2015. Space Rock Hunters Are About to Invade Antarctica. *Smithsonian.com*.https://www.smithsonianmag.com/science-nature/space-rock-hunters-are-about-invade-antarctica-180956777/

Berger, E. 2019a. *Some NASA Contractors appear to be trying to kill the Lunar Gateway* [Online]. arsTechnica. Available: https://arstechnica.com/science/2019/09/some-nasa-contractors-appear-to-be-trying-to-kill-the-lunar-gateway/ [Accessed 09/19/2019.

Berger, E. 2019b. *The White House Puts a Price on the SLS Rocket* [Online]. Available: https://arstechnica.com/science/2019/11/the-white-house-puts-a-price-on-the-sls-rocket-and-its-a-lot/ 2019].

Bergin, C. 2011. NASA interest in an interplanetary highway supported by Propellant Depots. *NASA Spacelight*.https://www.nasaspaceflight.com/2011/08/nasa-interest-interplanetary-highway-supported-propellant-depots/

Berthe, P., Over, A. P., Gronowski, M. & Richard, B. Orion European Service Module (ESM) development, integration and qualification status. 2018 AIAA SPACE and Astronautics Forum and Exposition, 2018. 5146

Berthe, P., Schubert, K., Grantier, J. A., Pietsch, K., Angelillo, P. & Price, L. A. The multi-purpose crew vehicle European service module: a European contribution to human Exploration. AIAA SPACE 2013 Conference and Exposition, 2013. 5477

Biesbroek, R. & Janin, G. 2000. Ways to the Moon. *ESA bulletin,* 103**,** 92-99

Briefs, T. 2014. *Low-Cost, High-Performance MMOD Shielding* [Online]. Available: https://www.techbriefs.com/component/content/article/tb/techbriefs/materials/19909#close-olyticsmodal.

Brown, P. G., Hildebrand, A. R., Zolensky, M. E., Grady, M., Clayton, R. N., Mayeda, T. K., Tagliaferri, E., Spalding, R., Macrae, N. D., Hoffman, E. L., Mittlefehldt, D. W., Wacker, J. F., Bird, J. A., Campbell, M. D., Carpenter, R., Gingerich, H., Glatiotis, M., Greiner, E., Mazur, M. J., Mccausland, P. J. A., Plotkin, H. & Mazur, T. R. 2000. The fall, recovery, orbit, and composition of the Tagish Lake meteorite: A new type of carbonaceous chondrite. *Science,* 290**,** 320-325

Calfee, C. & Smith, D. A. 2014. SLS Mission Planners Guide (MPG) Overview.

Carpenter, J. N., Rumi; Crawford, Ian 2018. Research ideas in solar-system, lunar, and earth-sciences with Deep Space gateway. *EPSC Abstracts,* 12**,** 1151.https://sci.esa.int/s/8ZklqoA

Chato, D. J., Plachta, D. W., Gaby Jr, J. D., Tucker, S. P., Harrison, R. A. & Hastings, L. J. 2002. Cryogenic Fluid Management Technologies for the Space Launch Initiative. *IAC-02 V,* 5

Chun, K. & Theofylaktos, N. 2006. Applications of Self-Powered Modulating Retroreflectors.

Clark, S. 2019. NASA opens competition to build human-rated lunar landers. *SPACEFLIGHT NOW*.https://spaceflightnow.com/2019/10/07/nasa-opens-competition-to-build-human-rated-lunar-landers/

Cornwell, D. 2014. *Laser communication from the Moon at 622Mb/s* [Online]. SPIE. Available: https://spie.org/news/5368-laser-communication-from-the-moon-at-622mb/s?SSO=1.

Crusan, J., Bleacher, J., Caram, J., Craig, D., Goodliff, K., Herrmann, N., Mahoney, E. & Smith, M. NASA's Gateway: An Update on Progress and Plans for Extending Human Presence to Cislunar Space. 2019 IEEE Aerospace Conference, 2019. IEEE, 1-19

Donahue, B. & Sigmon, S. The NASA SLS Upper Stage Development and Mission Opportunities. 2019 IEEE Aerospace Conference, 2019. IEEE, 1-17

Donahue, B. B. Space Launch System Capabilities with a New Large Upper Stage. AIAA SPACE 2013 Conference and Exposition, 2013. 5421

Doohan. 2017. *iTank 2.0 2017 3-Wheeled Electric Scooter* [Online]. XOffRoad. Available: https://x-offroad.com/doohan-itank-2-0-2017-3-wheeled-electric-scooter.html?gclid=EAIaIQobChMIgd_hh4WJ5gIVHoVaBR0XxwqiEAkYASABEgLnIvD_BwE 2017].

Dwyer-Cianciolo, A. M., Karlgaard, C. D., Woffinden, D., Lugo, R. A., Tynis, J., Sostaric, R. R., Striepe, S., Powell, R. & Carson, J. M. Defining Navigation Requirements for Future Missions. AIAA Scitech 2019 Forum, 2019. 0661

Eckart, P. & Aldrin, B. 1999. The Lunar Base Handbook, An Introduction to Lunar Base Design. *Development, and Operations (US: McGraw-Hill, 2006),*

Elipe, A., Mart-Egrave & Lara, N. 2003. Frozen orbits about the moon. *Journal of Guidance, Control, and Dynamics,* 26**,** 238-243

ESA 2016. Ariane 5 User's Guide. *In:* ESA (ed.).https://www.arianespace.com/vehicle/ariane-5/#

ESA 2019. *About PROSPECT* [Online]. European Space Agency. Available: https://exploration.esa.int/web/moon/-/59102-about-prospect [Accessed 11/26/19.

Evans, M. E. & Graham, L. D. Lunar Lighthouse: RFID Technology for Inexpensive Science Sensors and Relative Navigation. AGU Fall Meeting 2019, 2019. AGU,

FAA 2018. *The Annual Compendium of Commercial Space Transportation* [Online]. Available: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf 2020].

Fastorq. 2013. *Zip Technology: ZipNut and ZipCONNECTOR* [Online]. Available: http://www.fastorq.com/wp-content/uploads/Zip-Technology1.pdf.

Foust, J. 2018. *Firefly Aerospace and York Space Systems partner to provide integrated sattelite solutions* [Online]. SpaceNews. Available: https://spacenews.com/firefly-aerospace-and-york-space-systems-partner-to-provide-integrated-satellite-solutions/.

Foust, J. 2019a. *Gateway development remains on track* [Online]. 2019. Available: https://spacenews.com/gateway-development-remains-on-track/.

Foust, J. 2019b. *ISS Partners endorse modified Gateway plans* [Online]. Available: https://spacenews.com/iss-partners-endorse-modified-gateway-plans/ [Accessed 8/30/19 2019].

Foust, J. 2019c. *NASA to sole source Gateway habitation module to Northop Grumman* [Online]. SPACENEWS. Available: https://spacenews.com/nasa-to-sole-source-gateway-habitation-module-to-northrop-grumman/ [Accessed 07/23/2019.

Foust, J. 2019d. *Orbit Fab demonstrates satellite refueling technology on ISS* [Online]. Available: https://spacenews.com/orbit-fab-demonstrates-satellite-refueling-technology-on-iss/.

Gao. 2016. *Orion Multi-Purpose Crew Vehicle Action Needed to Improve Visbility ito Cost, Schedule, and Capacity to Resolve Technical Challenges* [Online]. Available: https://www.gao.gov/products/gao-16-620.

Gao 2020. NASA LUNAR PROGRAMS: Opportunities Exist to Strengthen Analyses and Plans for Moon Landing.

Gläser, P., Scholten, F., De Rosa, D., Figuera, R. M., Oberst, J., Mazarico, E., Neumann, G. & Robinson, M. 2014. Illumination conditions at the lunar south pole using high resolution digital terrain models from LOLA. *Icarus,* 243**,** 78-90

Goetz, P. G., Rabinovich, W. S., Mahon, R., Murphy, J. L., Ferraro, M. S., Suite, M. R., Smith, W. R., Burris, H. R., Moore, C. I. & Schultz, W. W. 2012. Modulating retro-reflector lasercom systems for small unmanned vehicles. *IEEE Journal on Selected Areas in Communications,* 30**,** 986-992

Gravlee, M., Kutter, B., Mclean, C. & Marquardt, J. 2012. Cryogenic Orbital Testbed (CRYOTE) Development Status. *Cryogenics,* 52**,** 231-235

Gutkowski, J. P., Dawn, T. F. & Jedrey, R. M. 2016. Evolution of Orion mission design for exploration mission 1 and 2.

Hansen, J. R. 1995. *Enchanted rendezvous: John C. Houbolt and the genesis of the lunar-orbit rendezvous concept*, NASA History Office, NASA Headquarters.

Harrison, C., Weaver, S., Bertelsen, C., Burgett, E., Hertel, N. & Grulke, E. 2008. Polyethylene/boron nitride composites for space radiation shielding. *Journal of applied polymer science,* 109**,** 2529-2538

Hitt, D. & Smith, H. R. 2014. *Bold They Rise: The Space Shuttle Early Years, 1972-1986*, U of Nebraska Press.

Honeycutt, J., Cianciola, C. & Wooten, L. 2019. NASA's Space Launch System: Artemis 1 Vehicle Nears Completion. *AIAA Propulsion and Energy Forum.* Indianapolis, IN: NTRS.https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190030450.pdf

Howell, E. 2019. *Lunar GPS? NASA Knows How to Help Astronauts Havigate* [Online]. Space.Com. Available: https://www.space.com/nasa-developing-lunar-gps-capability.html [Accessed 7/9/19 2019].

Institution, S. 2017. *ANSMET, the Antarctic Search for Meteorites* [Online]. Available: http://mineralsciences.si.edu/research/meteorites/antarctica/.

Jackman, A. 2016. Space Launch System-A New Capability for Space Exploration.

Jackson, J., Cassady, J., Allen, M., Myers, R., Tofil, T. A., Herman, D. A. & Pencil, E. J. 2018. Development of High Power Hall Thruster Systems to Enable the NASA Exploration Vision.https://ntrs.nasa.gov/

Jenkins, D. R. 1996. *Space shuttle: The history of developing the national space transportation system*, Walsworth Publishing Company Melbourne Beach.

Kitmacher, G. C., J. 1989. *Future Lander* [Online]. Available: https://io.jsc.nasa.gov/app/info.cfm?pid=6524400.

Konopliv, A., Asmar, S., Carranza, E., Sjogren, W. & Yuan, D. 2001. Recent gravity models as a result of the Lunar Prospector mission. *Icarus,* 150**,** 1-18

Kutter, B. F. Distributed Launch-Enabling Beyond LEO Missions. AIAA SPACE 2015 Conference and Exposition, 2015. 4593

Kutter, B. F., Zegler, F. C. & Ragab, M. R. 2012. Cryogenic propellant depot and integral sunshield. Google Patents

Laboratory, J. P. 2018. Mars Cube One (MarCO).https://www.jpl.nasa.gov/cubesat/missions/marco.php

Laneve, V. R., H.; Hager, P.;Trautner, R.; Risackerly, R. 2018. *PROSPECT - Thermal Design Challenges for Lunar Volatile Extraction* [Online]. Boulder, CO. Available: https://www.colorado.edu/event/ippw2018/sites/default/files/attached-files/lunarsmallbody_5_hager_presid572_presslides_docid1184.pdf [Accessed 6/14/18.

Linne, D., Sanders, G., Kleinhenz, J. & Moore, L. 2019. Current NASA In-Situ Resource Utilization (ISRU) Strategic Vision.

Marvin, U. B., Harvey, R. P., Schutt, J., Karner, J., Righter, K., Satterwhite, C. E., Mcbride, K. M., Corrigan, C. M., Welzenbach, L. C. & Weisberg, M. K. 2015. The Origin and Early History of the US Antarctic Search for Meteorites Program (ANSMET). *35 Seasons of US Antarctic Meteorites (1976–2010)***,** 1-22.https://doi.org/10.1002/9781118798478.ch1

Mazarico, E., Neumann, G., Smith, D., Zuber, M. & Torrence, M. 2011. Illumination conditions of the lunar polar regions using LOLA topography. *Icarus,* 211**,** 1066-1081

Mclean, C., Mustafi, S., Walls, L., Pitchford, B., Wollen, M. & Schmidt, J. Simple, robust cryogenic propellant depot for near term applications. 2011 Aerospace Conference, 2011. IEEE, 1-24

Mendell, W. W. & Hoffman, S. Strategic considerations for cislunar space infrastructure. IAF, International Astronautical Congress, 44 th, Graz, Austria, 1993.

Mueller, R. P. 2012. NASA human spaceflight architecture team: Lunar surface exploration strategies.http://hdl.handle.net/2060/20120008182

NASA The Second Conference on Lunar Bases and Space Activities of the 21st Century. *In:* MENDELL, W. W., ed. The Second Conference on Lunar Bases and Space Activities of the 21st Century, 4/7/1988 1988 Houston, Tx.: LPI, 1.https://space.nss.org/the-second-conference-on-lunar-bases-and-space-activities-of-the-21st-century/

NASA 2017. *Space Launch System (SLS) Mission Planner's Guide* [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170005323.pdf [Accessed 4/12/17.

NASA 2018. *NASA Selects US Companies to Advance Space Resource Collection* [Online]. Available: https://www.nasa.gov/press-release/nasa-selects-us-companies-to-advance-space-resource-collection [Accessed 5/31/18.

NASA 2019a. *35 Years Ago: STS-41G - A Flight of Many Firsts* [Online]. Available: https://www.nasa.gov/feature/35-years-ago-sts-41g-a-flight-of-many-firsts.

NASA 2019b. *Human Landing System (HLS) Architecture Analyses of Alternatives, Design Analysis Cycle (DAC) 2* [Online]. Available: https://beta.sam.gov/opp/d5460a204ab23cc0035c088dcc580d17/view.

NASA 2019c. *NASA Human Landing System Requirements Amendment 3* [Online]. NASA. Available: https://beta.sam.gov/opp/d5460a204ab23cc0035c088dcc580d17/view 2019].

NASA 2019d. *NASA Selects 12 New Lunar Science, Technology Investigations* [Online]. Available: https://www.nasa.gov/press-release/nasa-selects-12-new-lunar-science-technology-investigations.

NASA 2019e. *NASA Selects Experiments for Possible Lunar Flights in 2019* [Online]. Available: https://www.nasa.gov/press-release/nasa-selects-experiments-for-possible-lunar-flights-in-2019.

NASA 2019f. *Orion Suit Equipped to Expect the Unexpected on Artemis Missions* [Online]. NASA. Available: https://www.nasa.gov/feature/orion-suit-equipped-to-expect-the-unexpected-on-artemis-missions [Accessed 10/15/19 2019].

NASA 2020a. *NASA Selects First Science Instruments to Send to Gateway* [Online]. Available: https://www.nasa.gov/feature/nasa-selects-first-science-instruments-to-send-to-gateway.

NASA 2020b. *NASA to Industry: Send Ideas for Lunar Rovers* [Online]. Available: https://www.nasa.gov/feature/nasa-to-industry-send-ideas-for-lunar-rovers.

NASA 2020c. *NextSTEP H: Human Landing System* [Online]. Available: https://www.nasa.gov/nextstep/humanlander2.

Nie, T. & Gurfil, P. 2018. Lunar frozen orbits revisited. *Celestial Mechanics and Dynamical Astronomy,* 130**,** 61

Oeftering, R. A Cis-Lunar Propellant Infrastructure for Flexible Path Exploration and Space Commerce. AIAA SPACE 2011 Conference & Exposition, 2011. 7113

Orloff, R. W. 2000. *Apollo by the numbers: a statistical reference*, National Aeronautics and Space Administration.

Patterson, M. J., Grisnik, S. P. & Soulas, G. C. 1998. Scaling of Ion Thrusters to Low Power.

Pence, M. 2019. *Moon 2024 Announcement* [Online]. National Space Council. Available: https://www.nasa.gov/press-release/nasa-administrator-statement-on-return-to-moon-in-next-five-years.

Plachta, D. W., Johnson, W. L. & Feller, J. R. 2016. Zero boil-off system testing. *Cryogenics,* 74**,** 88-94

Qiu, A. T. Y. 2018. *The New Rockets Racing to Make Space Affordable* [Online]. Available: https://www.bloomberg.com/graphics/2018-rocket-cost/.

Ralph, E. 2019. *SpaceX may have signed a fairing agreement with ULA supplier RUAG (Update: no agreement)* [Online]. Available: https://www.teslarati.com/spacex-agreement-ruag-bigger-falcon-fairings/ [Accessed 8/14/19.

Reeves, D. M., Scher, M. D., Wilhite, A. W. & Stanley, D. O. 2006. Apollo lunar orbit rendezvous architecture decision revisited. *Journal of spacecraft and rockets,* 43**,** 910-915

Riley, C. W., D.; Dolling, P. 2012. *Lunar Rover Owner's Workshop Manual,* Somerset, UK, Haynes Publishing.

Rudman, T. J. & Austad, K. L. 2002. The Centaur Upper Stage Vehicle. *4th IAC on Launcher Technology,*

Sanders, G. B. 2018. Overview of Past Lunar In Situ Resource Utilization (ISRU) Development by NASA.

Sargeant, H., Abernethy, F., Anand, M., Barber, S., Sheridan, S., Wright, I. & Morse, A. 2019. Experimental Development and Testing of the Ilmenite Reduction Reaction for a Lunar ISRU Demonstration with ProSPA.

Schmidt, G., Jacobson, D., Patterson, M., Ganapathi, G., Brophy, J. & Hofer, R. 2018. Electric propulsion research and development at nasa.

Shaver, M. D. 2018. *Comparison of Nonlinear Filters for an Autonomous Lunar Mission using Existing Navigation Techniques.*

Smith, D. A. 2018. Space Launch System: SLS Payload Delivery Capability Overview.

Smith, R. M., Gates, M., Cassady, A. & Krezel, J. An overview of NASA's exploration mission 2 (EM-2). 2018 IEEE Aerospace Conference, 2018. IEEE, 1-11

SpaceX 2009. *Falcon 9 Launch Vehicle Payload User's Guide Rev 1* [Online]. Available: https://web.archive.org/web/20110429015952/http://www.spacex.com/Falcon9UsersGuide_2009.pdf 2009].

SpaceX 2019. *Falcon User's Guide 2019* [Online]. Available: https://www.spacex.com/sites/spacex/files/falcon_users_guide_0619.pdf.

SpaceX 2020. *SpaceX Capablities and Services* [Online]. Available: https://www.spacex.com/about/capabilities [Accessed 2/15/2020.

Spudis, P. D. 2016. *The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources*, Smithsonian Institution.

Stanley, D. O. 2005. NASA's Exploration Architecture.

Stephens, J., Valenzuela, J., Smith, J., Rhys, N., Hauser, D., Plachta, D. & Johnson, W. 2019. Liquid Nitrogen Testing of ISRU Liquefaction Methods in Unsteady Applications.https://ntrs.nasa.gov/search.jsp?R=20190030399

Strickland, A. 2019. *NASA details Artemis moon missions, named after Apollo's twin sister* [Online]. CNN. Available: https://www.cnn.com/2019/07/24/us/nasa-artemis-program-scn/index.html [Accessed 7/24/19.

Sun, X.-W., Guo, Z.-Y. & Huang, W. 2015. Passive zero-boil-off storage of liquid hydrogen for long-time space missions. *international journal of hydrogen energy,* 40**,** 9347-9351

Taylor, W. C., D. Comparing the results of an analytical model of the no-vent fill process with no-vent fill test results for a 4.96 cu m (175 cu ft) tank. 28th Joint Propulsion Conference and Exhibit, 1992. 3078

Thirkettle, A., Hartwell, W., Schulze-Varnholt, D., Monien, G., Huermann, B., Poornachandran, S. & Rauen, L. 2018. The Second European Service Module (ESM-2) Evolutions, Production and Challenges.

Ticker, R. L., Gates, M., Manzella, D., Biaggi-Labiosa, A. & Lee, T. The Gateway Power and Propulsion Element: Setting the Foundation for Exploration and Commerce. AIAA Propulsion and Energy 2019 Forum, 2019. 3811

Trump, D. 2017. *Space Policy Directive 1* [Online]. Washington, D.C. Available: https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/.

ULA 2010. *Atlas V Launch Services User's Guide* [Online]. Available: http://www.ulalaunch.com/uploads/docs/AtlasVUsersGuide2010.pdf.

Valle, G. & Wells, N. 2017. Bigelow Expandable Activity Module (BEAM) ISS Year-One.https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006506.pdf

Voosen, P. 2018. NASA to pay private space companies for moon rides. American Association for the Advancement of Science

Whitley, R. & Martinez, R. Options for staging orbits in cislunar space. Aerospace Conference, 2016 IEEE, 2016. IEEE, 1-9

Williams, J., Lee, D. E., Whitley, R. J., Bokelmann, K. A., Davis, D. C. & Berry, C. F. 2017. Targeting cislunar near rectilinear halo orbits for human space exploration. *In:* NASA (ed.) *27th AAS/AIAA Space Flight Mechanics Meeting.* San Antonio, Tx: NASA Technical Reports Server.https://ntrs.nasa.gov/search.jsp?R=20170001352

Winternitz, L. B., Bamford, W. A., Long, A. C. & Hassouneh, M. 2019. GPS Based Autonomous Navigation Study for the Lunar Gateway.

Zegler, F. C. 2017. Integrated vehicle fluids. Google Patents

APPENDIX A: ACRONYMS

A5	Atlas V rocket built by ULA
ACES	Advanced Cryogenic Evolved Stage, the ULA new Upper Stage for Vulcan rocket
AE	Ascent Element (HLS terminology)
ANSMET	Antarctic Search for Meteorites (NSF funded program in the Unitec States of Americal)
ARES	Astromaterials Research and Exploration Science Division at NASA JSC
ATV	All-Terrain Vehicle (FLARE terminology) or Automated Transfer Vehicle (basis of ESM)
CLPS	Commercial Lunar Payload Services
CLV	Commercial Launch Vehicle delivering up to 15t at TLI (HLS terminology)
CM	Apollo Command Module
COTS	Commercial Off-The-Shelf
CV	Centaur V upper-stage built by ULA for Vulcan rocket
DAC	Design Analysis Cycle, NASA evaluation of architectures for Artemis program
DE	Descent Element (HLS terminology)
DoD	Department of Defense
EML1	Earth-Moon L1 point
EML2	Earth-Moon L2 point
EOR	Earth Orbit Rendezvous, a concept considered for Apollo stages before TLI
ESA	European Space Agency
ESM	European Service Module (based on Automated Transfer Vehicle, ATV) provides the ΔV for Orion to/from NRHO or lunar orbits (max ~ 1.25 km/s per Whitley & Martinez, 2016)
EVA	Extravehicular Activity
FAA	Federal Aviation Administration
F9	Falcon 9 built by SpaceX
FH	Falcon Heavy built by SpaceX
FLARE	Flexible Lunar Architecture for Exploration, a concept to achieve Moon 2024 goal with future growth and sustainability objectives
GN&C	Guidance, Navigation, & Control
HALO	Habitation and Logistics Outpost (former "Mini-Hab" planned for Gateway
HEO	High Earth Orbit
HLS	Human Landing System (HLS), NASA approach to deliver humans to the Moon with guidelines provided on the NextSTEP website
HLV	Heavy Lift Vehicle (delivery of >18 mt to TLI)

ICPS	Interim Cryogenic Propulsion Stage (ICPS), upper-stage for SLS Block I to achieve TLI for Orion+ESM on the planned Artemis 3 mission
ISRU	In-Situ Resource Utilization
ISS	International Space Station, NASA vehicle located in Earth's LLO at 51.6° inclination
IVF	Integrated Vehicle Fluids
JSC	Johnson Space Center
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEM	Lunar Excursion Module (LEM), later Lunar Module (LM) from the NASA Apollo program
LEO	Low Earth Orbit, for FLARE altitude = 400 km circular, inclination = or 28.5°
LES	Orion Launch and Entry Suit
LH_2	Liquid Hydrogen
LLFPO	Low Lunar Frozen Polar Orbit (LLFPO), for FLARE altitude = 100 km, inclination = 86.45°
LLO	Low Lunar Orbit, typically a 100-500 km circular orbit above the lunar surface
LM	Lunar Module (aka Lunar Excursion Module)
LOI	Low Orbit Insertion burn to place a vehicle in orbit around the Moon
LOR	Lunar Orbit Rendezvous
LOX	Liquid Oxygen
LRV	Lunar Roving Vehicle from Apollo program
LTV	Lunar Terrain Vehicle
LV	Launch Vehicle
MH	MiniHab platform (derived from the Cygnus vehicle built by Northrop Grumman) for Gateway (optional phase in FLARE), renamed HALO
MLI	Multi-Layer Insulation
MMH	Monomethylhydrazine
MMOD	Micro-Meteoroid and Orbital Debris
MMS	Magnetosphere Multiscale Mission
MPCV	Multi-Purpose Crew Vehicle, another name for NASA's Orion capsule
MPS	Main Propulsion System (HLS terminology)
mt	Metric Tonnes
NextSTEP	Next Space Technologies for Exploration Partnerships: NASA public-private partnership to develop human exploration missions (see www.nasa.gov/nextstep)
NRHO	Near Rectilinear Halo Orbit (rp = 3300 km, ra = 65,000 km in HLS terminology)
NSF	National Science Foundation

N_2O_4	Nitrogen Tetroxide
OME	Orbital Maneuvering Engine, part of the ESM and lunar lander AE
PF	Performance Fraction (FLARE terminology), a method to estimate delivery of mass to certain ΔV targets based upon published LEO delivery values
PIR	Persistently Illuminated Regions of the Moon (near the poles)
PPE	Power and Propulsion Element of Gateway (optional phase in FLARE)
PrC	Precursor hardware, Phase B (optional) of FLARE to deliver LS resources before the human lander arrives
PROSPECT	Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (ESA mission planned for Lunar-27)
PSR	Permanently Shadowed Region on the Moon (near poles)
OMS	Orbital Maneuvering System
RCS	Reaction Control System
RF	Radio Frequency
RFI	Request for Information
RFID	Radio Frequency Identification
RPOD	Rendezvous, Proximity Operations and Docking
RST	Return SpaceTug in FLARE
SAW	Surface Acoustic Wave
SLS	Space Launch System is a proposed family of rockets being developed by NASA during the 2010s
SLS B1	SLS Block I delivers up to 26t to TLI and is the human launch vehicle for the planned NASA Artemis 3 mission (HLS terminology)
SM	Apollo Service Module
SPD-1	Space Policy Directive !
TA	Tug Adaptor (FLARE terminology), includes solar arrays, support struts, electrical umbilical, GN&C RPO system
TE	Transfer Element (HLS terminology)
TE1	TE for AE/DAE for orbit to orbit transfer or initial braking (HLS terminology)
TE2	TE for TE1 and provides orbit to orbit transfer and/or initial deorbit (HLS terminology)
TEI	Trans-Earth Injection burn to send a vehicle into the Earth's gravity field
TLI	Trans-Lunar Injection burn to send a vehicle into the Moon's gravity field
ULA	United Launch Alliance formed in 2006
xEMU	NASA's Exploration Extravehicular Mobility Unit for lunar surface exploration

APPENDIX B: CALCULATIONS

1. These are the rocket equation calculations for each orbit transfer within FLARE.
Assumed SpaceTug Boiloff rate: 0.5%/day, 0.10 mt/day (Total Prop = 20.05 mt full).
Assumed Descent Element (DE) Boiloff rate: 0.5%/day, 0.05 mt/day (Total Prop = 9.0 mt full).

A1: PPE	Step1	Step2
Vehicle	Tug1PPE	n/a
Init Mass (mt)	30.80	n/a
Final Mass (mt)	11.80	n/a
Prop (mt)	19.00	n/a
Isp (s)	450.50	n/a
ΔV (km/s)*	4.23	n/a
Margin (mt)	1.05	n/a
Margin (boil-off days)	10.5	n/a

* TLI (3.28 km/s) + LOI (0.95 km/s)

To LEO: PPE is launched on an A5, Tug1PPE launched on a F9
Vehicle Initial mass = Tug1PPE (22.8 mt) and PPE (8.0 mt)
Vehicle final mass = Tug1 PPE (3.8 mt) and PPE (8.0 mt)
To LLFPO: SpaceTug pushes PPE (1.05 mt margin, or 10.5 boil-off days)

A2: HALO	Step1	Step2
Vehicle	Tug1HALO	n/a
Init Mass (mt)	30.80	n/a
Final Mass (mt)	11.70	n/a
Prop (mt)	19.10	n/a
Isp (s)	450.50	n/a
ΔV (km/s)*	4.27	n/a
Margin (mt)	0.95	n/a
Margin (boil-off days)	9.5	n/a

* TLI (3.28 km/s) + LOI (0.95 km/s) + RPOD (0.05 km/s)

To LEO: HALO is launched on A5, Tug1HALO launched on a F9
Vehicle Initial mass = Tug1HALO (22.8 mt) and HALO (8.0 mt)
Vehicle final mass = Tug1 HALO (3.7 mt) and HALO (8.0 mt)
To LLFPO: SpaceTug pushes HALO and conducts RPOD with PPE
SpaceTug final propellant = 0.95 mt margin, or 9.5 boil-off days

B: LS Precursor Hardware	Step1	Step2
Vehicle	DE1	n/a
Init Mass (mt)	15.78	n/a
Final Mass (mt)	8.18	n/a
Prop (mt)	7.60	n/a
Isp (s)	450.50	n/a
ΔV (km/s)*	2.90	n/a
Margin (mt)	1.18	n/a
Margin (boil-off days)	26.1	n/a

*Direct Lunar Surface (2.90 km/s)

To TLI: DE1+Payload launched on a FH
DE1 is the "common" lander configured for cargo to LS
DE1 Initial mass = 11.28 mt after 5 days LOX/LH_2 boil-off
DE1 Payload mass = 4.5 mt

0.15	Comm/Nav satellites
2.00	Inflatable Hab & airlock
0.35	Logistics (air/water)
0.38	xEMU suits (2)
0.30	Science Experiments
0.40	ISRU pilot plant
0.92	Mobility Vehicles
4.50	Total

To LS: DE1 pushes payload from TEI directly to landing (0.88 mt margin, or 19.4 boil-off days)

C1: AE	Step1	Step2
Vehicle	Tug1AE1	n/a
Init Mass (mt)	31.20	n/a
Final Mass (mt)	11.95	n/a
Prop (mt)	19.25	n/a
Isp (s)	450.50	n/a
ΔV (km/s)*	4.23	n/a
Margin (mt)	0.80	n/a
Margin (boil-off days)	8.0	n/a

* TLI (3.28 km/s) + LOI (0.95 km/s) with margin for RPOD w/Gateway

To LEO: AE1 launched on an A5, Tug1AE1 launched on a F9
Vehicle Initial mass = Tug1AE1 (22.80 mt) and AE1 (8.4 mt)
Vehicle final mass = Tug1AE1 (3.45 mt) and AE1 (8.4 mt)
To LLFPO: SpaceTug pushes AE1 and conducts RPOD with Gateway (if present)
SpaceTug final propellant = 0.70 mt, or 7.0 boil-off days

C2: RST (Return SpaceTug)	Step1	Step2
Vehicle	Tug1RST	RST
Init Mass (mt)	44.20	22.80
Final Mass (mt)	25.70	14.90
Prop (mt)	18.50	7.90
Isp (s)	450.50	450.50
ΔV (km/s)*	2.40	1.88
Margin (mt)	0.15	12.15
Margin (boil-off days)	1.5	121.2

* TLI (3.28 km/s) + LOI (0.95 km/s) + RPOD (0.05 km/s)

Total ΔV = 4.27 km/s in two burns

To LEO: Tug1RST launched on F9, 2 weeks later RST launched on a F9

Tug1RST Initial Mass = 21.40 mt after 14 days LOX/LH_2 boil-off

RST Initial Mass = 22.80 mt (full propellant load of 20.05 mt)

To LLFPO:

Step1: Tug1RST pushes RST towards TLI and then separates and deorbits to Earth

Step2: RST pushes itself to TLI, then to LLFPO and RPOD with Gateway (if present)

RST final propellant = 12.15 mt, or 121.2 boil-off days

C3: DE2	Step1	Step2
Vehicle	Tug1DE2	Tug2DE2
Init Mass (mt)	55.38	33.99
Final Mass (mt)	36.88	19.39
Prop (mt)	18.50	14.60
Isp (s)	450.50	450.50
ΔV (km/s)*	1.80	2.48
Margin (mt)	0.15	4.05
Margin (boil-off days)	1.5	40.4

* TLI (3.28 km/s)+LOI (0.95 km/s)+RPOD (0.05 m/s)

Total ΔV = 4.27 km/s in two burns

To LEO: Tug1DE2 launched on a F9, then 1 week later DE2 launched on a A5, then 1 week later Tug2DE2 launched on a F9 (Tug2DE2 launched 2 weeks after Tug1DE2)

DE2 is the “common” lander to deliver the crewed AE1 to the lunar surface

Tug1DE2 Initial Mass = 21.40 mt after 14 days LOX/LH_2 boil-off

Tug2DE2 Initial Mass = 22.80 mt (full propellant load of 20.05 mt)

To LLFPO:

Step1: Tug1DE2 pushes stack towards TLI and then separates and deorbits to Earth

Step2: Tug2DE2 pushes DE2 to TLI, then to LLFPO and RPOD with either AE1 or Gateway

Note: Tug2DE2 could be used to help DE2 deorbit AE1 in Phase D1 (lower perilune)

C4: Crew	Step1	Step2
Vehicle	ESM	n/a
Init Mass (mt)	25.90	n/a
Final Mass (mt)	18.80	n/a
Prop (mt)	7.10	n/a
Isp (s)	320.00	n/a
ΔV (km/s)*	1.00	n/a
Margin (mt)	1.50	n/a
Margin (boil-off days)	n/a	n/a

* LOI (0.95km/s)+RPOD (0.05 m/s)

To TLI: Crew inside Orion+ESM launched on SLS Block 1

Vehicle Initial Mass = Orion (10.4 mt) and ESM (15.5 mt)

To LLFPO:

ESM pushes Orion to LLFPO and RPOD with AE1+DE2, or Gateway (if present)

ESM final propellant = 1.5 mt (no boil-off for storable propellant)

D1: Crew to LS	Step1	Step2
Vehicle	DE2	n/a
Init Mass (mt)	19.46	n/a
Final Mass (mt)	11.66	n/a
Prop (mt)	7.80	n/a
Isp (s)	450.50	n/a
ΔV (km/s)*	2.25	n/a
Margin (mt)	0.26	n/a
Margin (boil-off days)	5.7	n/a

*Descent/Landing (2.18km/s)+2.5° plane change (0.071 km/s)

To LS: Crew in AE1 descends to LS, DE2 controls descent and landing

DE2 Prop available in LLFPO = 8.06 mt after 21 days boil-off LOX/LH_2 (loss = 0.95 mt)

Initial Vehicle Mass = AE1 (8.4 mt), DE2 (10.56 mt), and Payload (crew = 0.4 mt, science equipment and EVA tools 0.1 mt)

AE1 dry mass (4.0 mt) includes 2 xEMU suits (0.38 mt): additional 2 xEMU suits in DE1 payload

DE2 final propellant after descent to LS = 0.26 mt, or 5.7 LOX/LH_2 boil-off days

Note: Tug2DE2 could be used to help DE2 deorbit DE1 (requires Tug2DE2 RPOD with AE1+DE2, then Tug2DE2 pushes to lower lunar orbit and separates, then DE2 completes landing). This option is not evaluated in the calculations

D3: Crew from LS	Step1	Step2
Vehicle	AE1	n/a
Init Mass (mt)	8.90	n/a
Final Mass (mt)	4.68	n/a
Prop (mt)	4.22	n/a
Isp (s)	320.00	n/a
ΔV (km/s)*	2.01	n/a
Margin (mt)	0.18	n/a
Margin (boil-off days)	n/a	n/a

* Ascent (1.97 km/s) + RPOD (0.05 km/s)

To LLFPO: Crew in AE1 ascends to RPOD with Orion+ESM (no boil-off for storable propellant)
Initial Vehicle Mass on LS = AE1 (8.4 mt) and Payload (crew = 0.4 mt, science = 0.1 mt)
AE1 final propellant in LLFPO = 0.18 mt

E: Crew to Earth	Step1	Step2
Vehicle	RST	ESM
Init Mass (mt)	27.99	18.80
Final Mass (mt)	21.69	18.00
Prop (mt)	6.30	0.80
Isp (s)	450.50	320.00
ΔV (km/s)*	1.13	0.14
Margin (mt)	0.14	0.70
Margin (boil-off days)	1.4	n/a

* TEI (1.256 km/s)+EI (0.011 km/s)

Total ΔV = 1.27 for 2 burns

In LLFPO: Crew transfer from AE1 to Orion+ESM. If no Gateway exists, jettison AE1 and conduct RPOD with RST
RST Prop Available = 6.44 mt after 57 days of LOX/LH_2 boil-off (loss = 5.71 mt)

To Earth:
Step1: RST pushes Orion+ESM to Earth
RST final propellant = 0.04 mt when it separates from Orion+ESM and deorbits to Earth

Entry:
ESM controls Orion Entry-Interface then separates from Orion and deorbits to Earth
ESM final propellant = 0.80 mt (margin)

2. This is the summary of calculations to compare crewed lander mass (4.0 mt AE + DE) for LLO and NRHO

LANDER DESIGN	Orion in LLO	Margin (mt)	Orion in NRHO	Margin (mt)	% Increase from LLO	% decrease from NRHO
AE prop type	N2O4+MMH		N2O4+MMH			
AE dry	4.00		4.00		0.0%	0.0%
AE prop	4.40	0.19	7.35	0.25	67.0%	40.1%
AE payload*	0.50		0.50		0.0%	0.0%
AE total (mt)	**8.90**		**11.85**		33.1%	24.9%
DE prop type	LOX/LH2		LOX/LH2			
DE dry	2.50		2.80		12.0%	10.7%
DE prop	14.70	0.80	19.40	0.70	32.0%	24.2%
DE total (mt)	**17.20**		**22.20**		29.1%	22.5%
AE+DE total (mt)	**26.10**		**34.05**		30.5%	23.3%
SLS Launch Vehicle	Block 1		Block 1b			

* includes 4 crew (0.4 mt) and 0.1 mt for tools (descent) or samples (ascent)

<u>SEQUENCE</u>

A SLS launches an integrated lander (combined AE1+DE2) to TLI

The DE2 performs orbit insertion (no RPOD)

The lander loiters 14 days (LOX/LH2 boil-off included) until crew in Orion+ESM performs RPOD

The DE2 performs deorbit burn and lands crew in AE1 on lunar surface

The AE1 lifts crew from lunar surface, and performs RPOD with Orion+ESM

2A. Lander burn calculations to/from Low Lunar Orbit (LLO)

LLO Insert	Step1	Step2
Vehicle	DE2	
Init Mass (mt)	26.10	
Final Mass	20.80	
Prop (mt)	5.30	
Isp (s)	450.00	
ΔV (km/s)	1.00	

LLO D/O	Step1	Step2
Vehicle	DE2	
Init Mass (mt)	20.10	
Final Mass (mt)	12.20	
Prop (mt)	7.90	
Isp (s)	450.00	
ΔV (km/s)	2.20	

LS to LLO	Step1	Step2
Vehicle	AE1	
Init Mass (mt)	4.90	
Final Mass (mt)	0.69	
Prop (mt)	4.21	
Isp (s)	320.00	
ΔV (km/s)	6.15	

2B. Lander burn calculations to/from Near Rectilinear Halo Orbit (NRHO)

NRHO Insert	Step1	Step2
Vehicle	DE2	
Init Mass (mt)	34.05	
Final Mass	30.45	
Prop (mt)	3.60	
Isp (s)	450.00	
ΔV (km/s)	0.49	

NRHO D/O	Step1	Step2
Vehicle	DE2	
Init Mass (mt)	22.95	
Final Mass (mt)	8.55	
Prop (mt)	14.40	
Isp (s)	450.00	
ΔV (km/s)	4.36	

LS to NRHO	Step1	Step2
Vehicle	AE	
Init Mass (mt)	11.85	
Final Mass (mt)	4.75	
Prop (mt)	7.10	
Isp (s)	320.00	
ΔV (km/s)	2.87	

3. These are the calculations for how much one SpaceTug can push from LEO 28.5°

SPACETUG
Dry mass = 2.75 mt
Prop = 20.05 mt
Total = 22.80 mt (max lift capacity of a F9 to LEO 28.5°)

Using one SpaceTug to TLI

SpaceTug + Payload to TLI	Step1	Step2
Vehicle	SpaceTug	n/a
Init Mass (mt)	38.30	n/a
Final Mass (mt)	18.25	n/a
Prop (mt)	20.05	n/a
Isp (s)	450.50	n/a
ΔV (km/s)	3.28	n/a
Payload:	15.50	

Using one SpaceTug to NRHO

SpaceTug+Payload to NRHO	Step1	Step2
Vehicle	SpaceTug	n/a
Init Mass (mt)	34.80	n/a
Final Mass (mt)	14.75	n/a
Prop (mt)	20.05	n/a
Isp (s)	450.50	n/a
ΔV (km/s)	3.79	n/a
Payload:	12.00	

Using one SpaceTug to LLO

SpaceTug+Payload to LLO	Step1	Step2
Vehicle	SpaceTug	n/a
Init Mass (mt)	32.30	n/a
Final Mass (mt)	12.25	n/a
Prop (mt)	20.05	n/a
Isp (s)	450.50	n/a
ΔV (km/s)	4.28	n/a
Payload:	9.50	

4. These are the calculations for how much two SpaceTugs can push from LEO 28.5°
Using two SpaceTugs to TLI

SpaceTugs+Payload to TLI	Step1	Step2
Vehicle	Tug1	Tug2
Init Mass (mt)	78.50	55.70
Final Mass (mt)	58.45	35.65
Prop (mt)	20.05	20.05
Isp (s)	450.50	450.50
ΔV (km/s)	1.30	1.97
Payload:	32.90	32.90

Using two SpaceTugs to NRHO

SpaceTugs+Payload to NRHO	Step1	Step2
Vehicle	Tug1	Tug2
Init Mass (mt)	71.50	48.70
Final Mass (mt)	51.45	28.65
Prop (mt)	20.05	20.05
Isp (s)	450.50	450.50
ΔV (km/s)	1.45	2.34
Payload:	25.90	25.90

Using two SpaceTugs to LLO

SpaceTug+Payload to LLO	Step1	Step2
Vehicle	Tug1	Tug2
Init Mass (mt)	66.80	44.00
Final Mass (mt)	46.75	23.95
Prop (mt)	20.05	20.05
Isp (s)	450.50	450.50
ΔV (km/s)	1.58	2.69
Payload:	21.20	21.20

Note that two SpaceTugs can not deliver Orion+ESM (total = 25.90 mt) from LEO to LLO (would need a 3rd SpaceTug)

5. This is the calculation for how much one SpaceTug can deliver to LLO after refilling on the lunar surface

<u>SPACETUG</u>

Dry mass = 4.0 mt (extra 1.25 mt from SpaceTug for landing gear and surface refill equip)

Prop = 20.05 mt (same as for SpaceTug)

Total = 24.05 mt (conceptually lifted from Earth on a dedicated FH towards TLI)

SpaceTug from LS to LLO	Step1
Vehicle	Tug1
Init Mass (mt)	24.05
Final Mass (mt)	15.25
Prop (mt)	8.80
Isp (s)	450.50
ΔV (km/s)	2.01
Payload:	0.00
Residual Prop:	11.25

6. This is the EXCEL calculation for a plane change during lunar descent from LLFPO

<u>Calculate Plane Change</u>				<u>ENTER</u>				
	ΔV = 2*v*sin(Δi/2)		ΔI (deg)	2.5		ΔV (km/s)	0.071	<====
	convert deg to radian		ΔI (rad)	0.0436	<== converted			
							<u>Moon</u>	<u>Units</u>
					Universal Constant of Gravitation	G	6.6743E-11	m3*kg-1*s-2
					Gravity	g	1.62	m*s-2
					Mass	M	7.347E+22	kg
				calculated	GM		4.9036E+12	m3s-2
					Published Planet Gravitational Constant (GM)	μ	4.9049E+12	m3s-2
					Density	ρ		g/cc
					Mean	Radius	1737.1	km
					Equatorial	Radius	1738	km
					Polar	Radius	1736	km
					Select a radius here ==>		1737.1	km

APPENDIX C: MINIMUM REQUIRED CREW PHASES (GRAPHICAL DISPLAY)

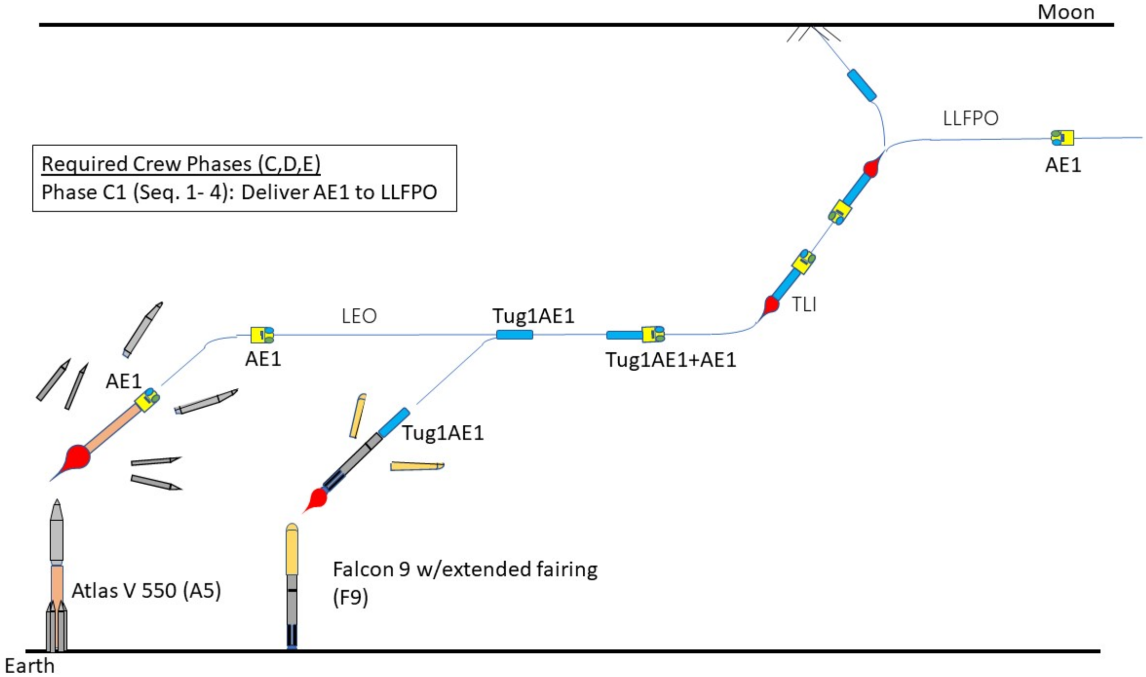

Figure C1: Launching the human Ascent Element (AE1) to LEO and transfer to LLFPO with Tug1AE1.

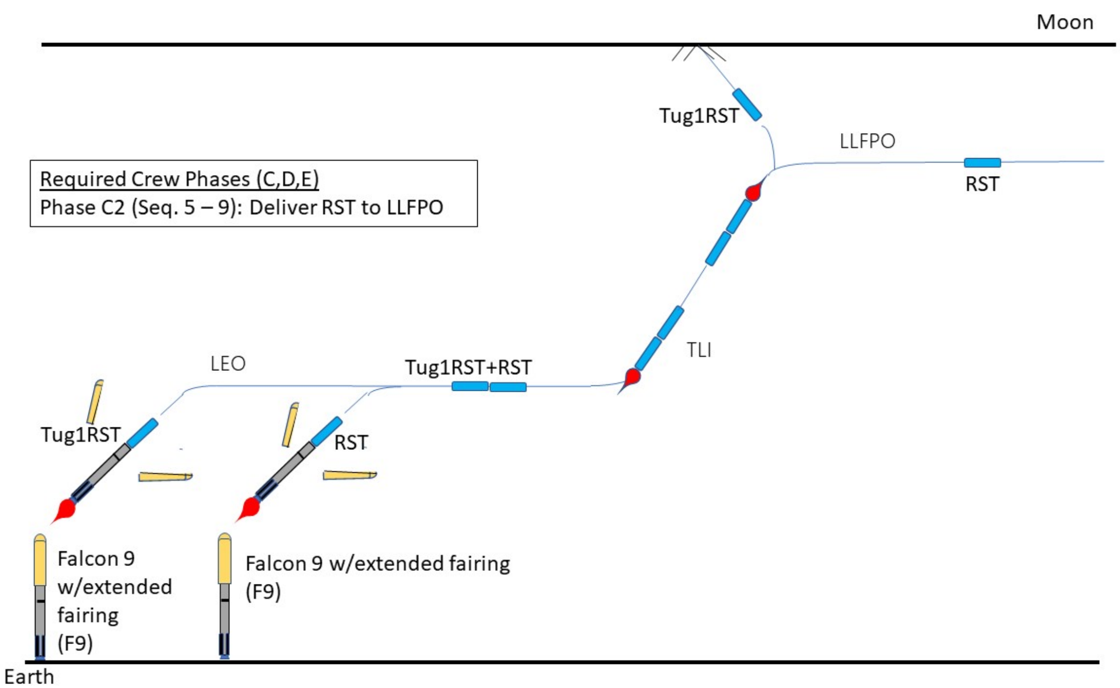

Figure C2: Launching the Return SpaceTug (RST) to LEO and transfer to LLFPO with Tug1RST.

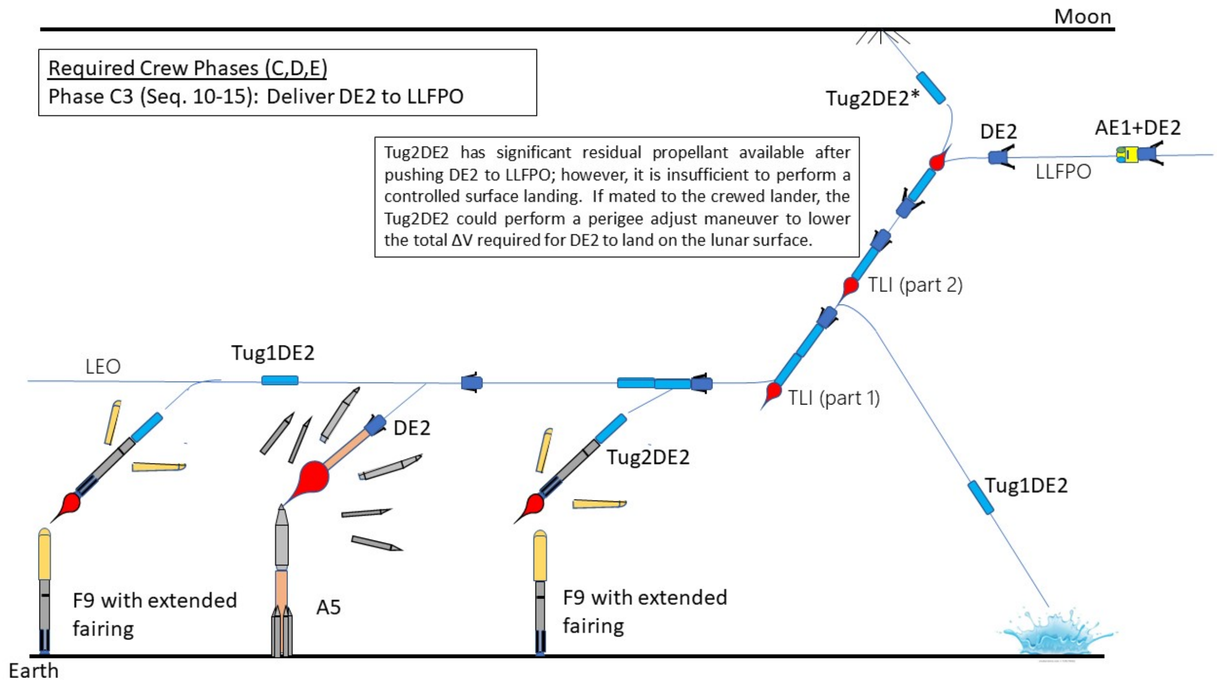

Figure C3: Launching the human Descent Element (DE2) to LEO and transfer to LLFPO with Tug1DE2 and Tug2DE2.

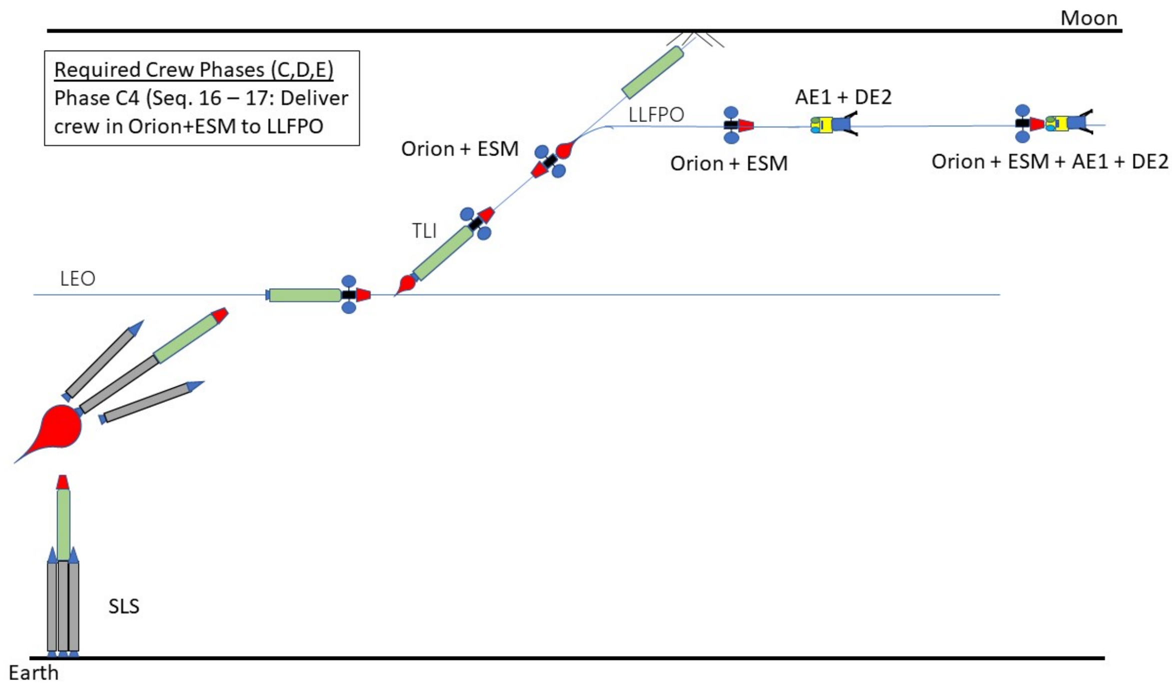

Figure C4: Launching the Crew in Orion+ESM and delivery to TLI and transfer to LLFPO with ESM.

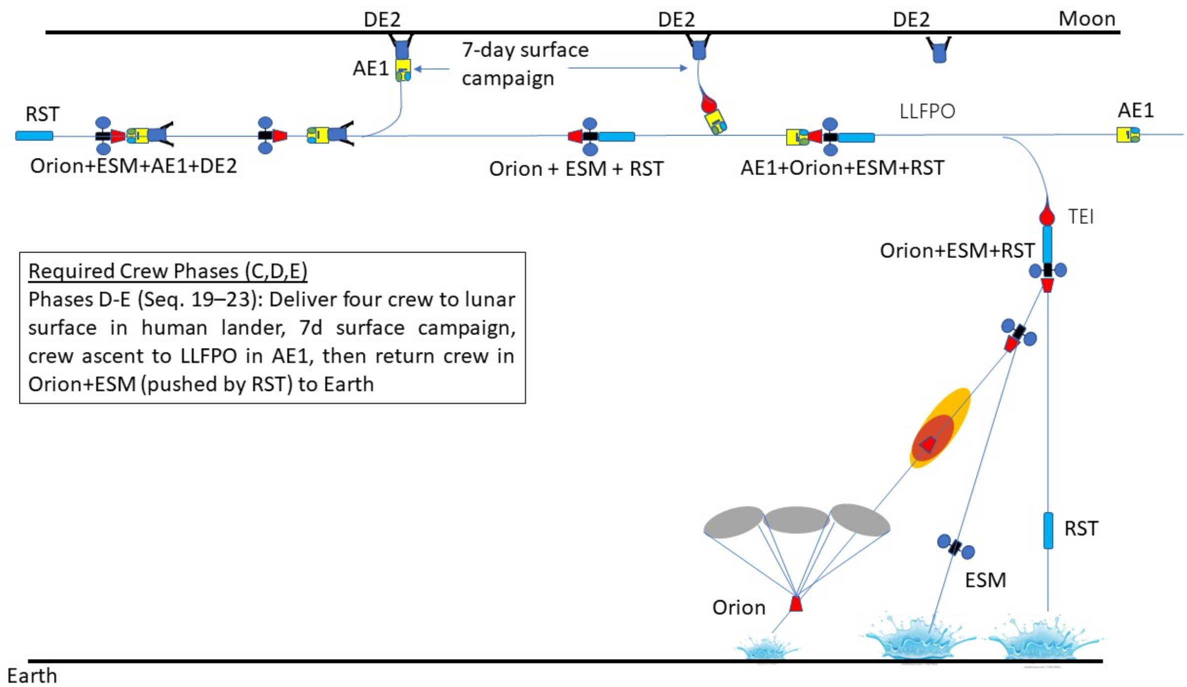

Figure C5: Crew lunar landing in human lander, surface campaign (7d), and crew return to Earth.

APPENDIX D: OPTIONAL FLARE PHASES (GRAPHICAL DISPLAY)

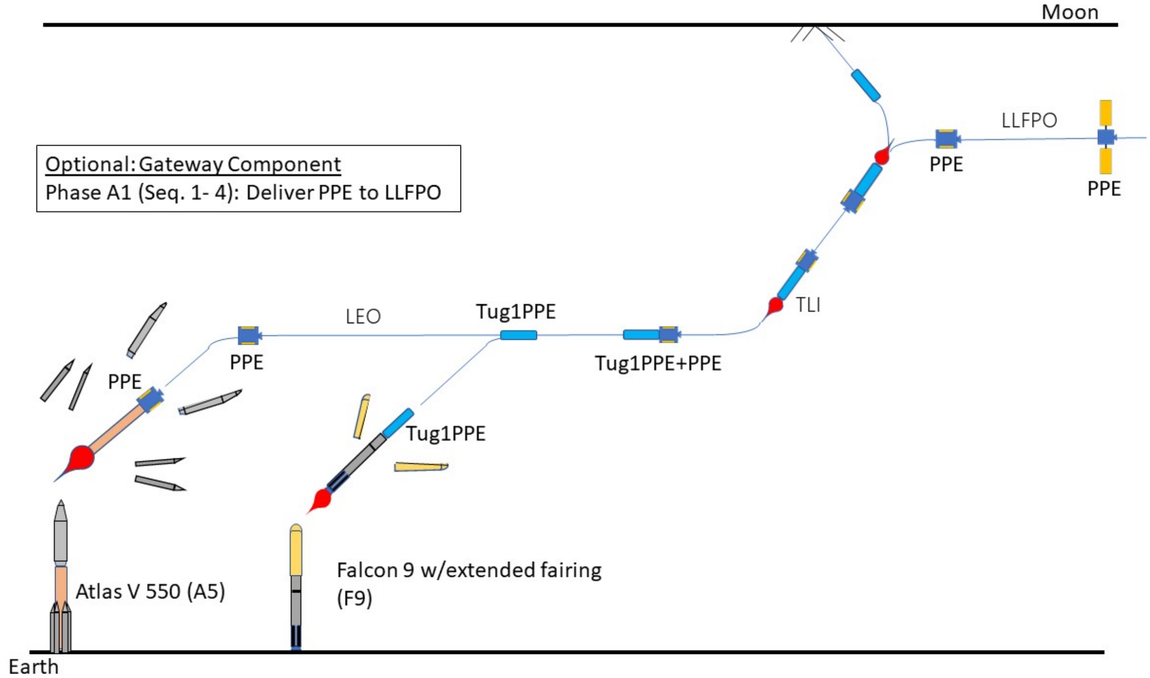

Figure D1: Launching the PPE to LEO and transfer to LLFPO with Tug1PPE.

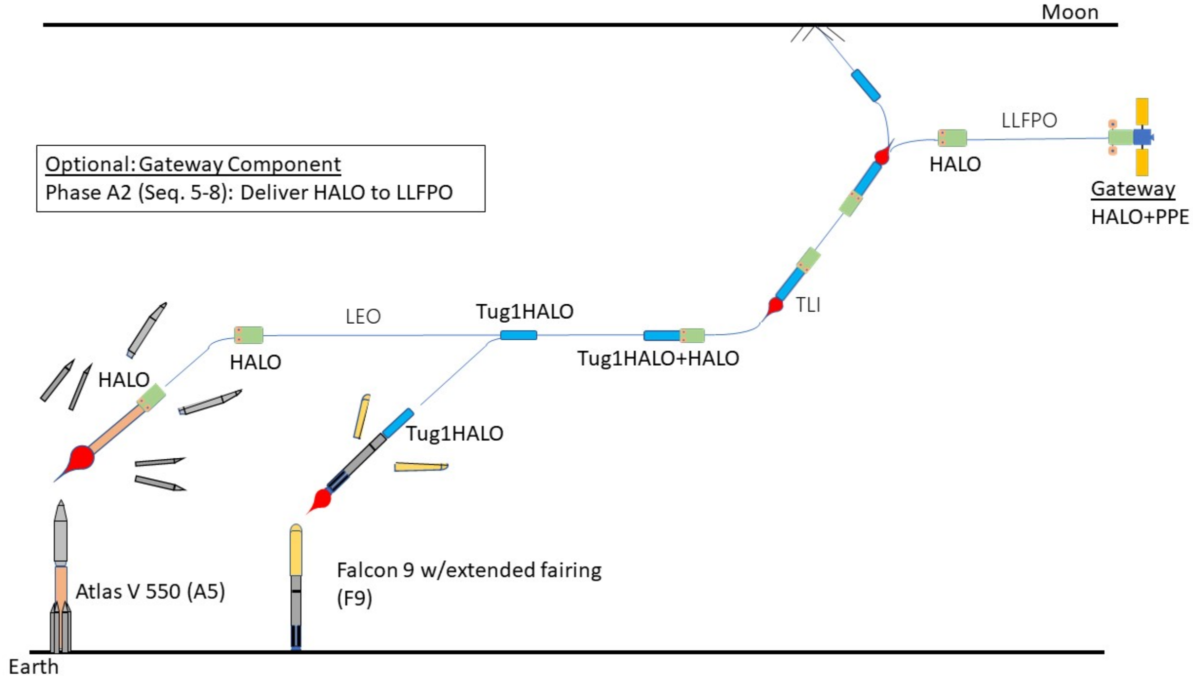

Figure D2: Launching the HALO to LEO and transfer to LLFPO with Tug1HALO.

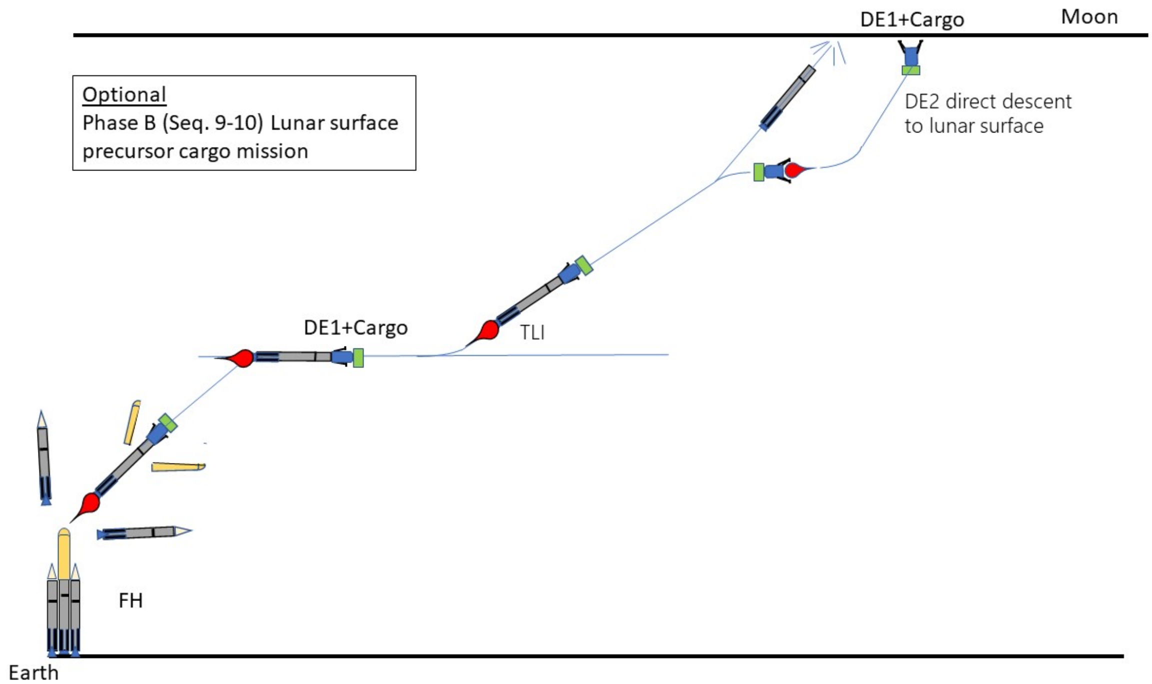

Figure D3: Launching DE1 and cargo payload to TLI and direct transfer to lunar surface with DE1.

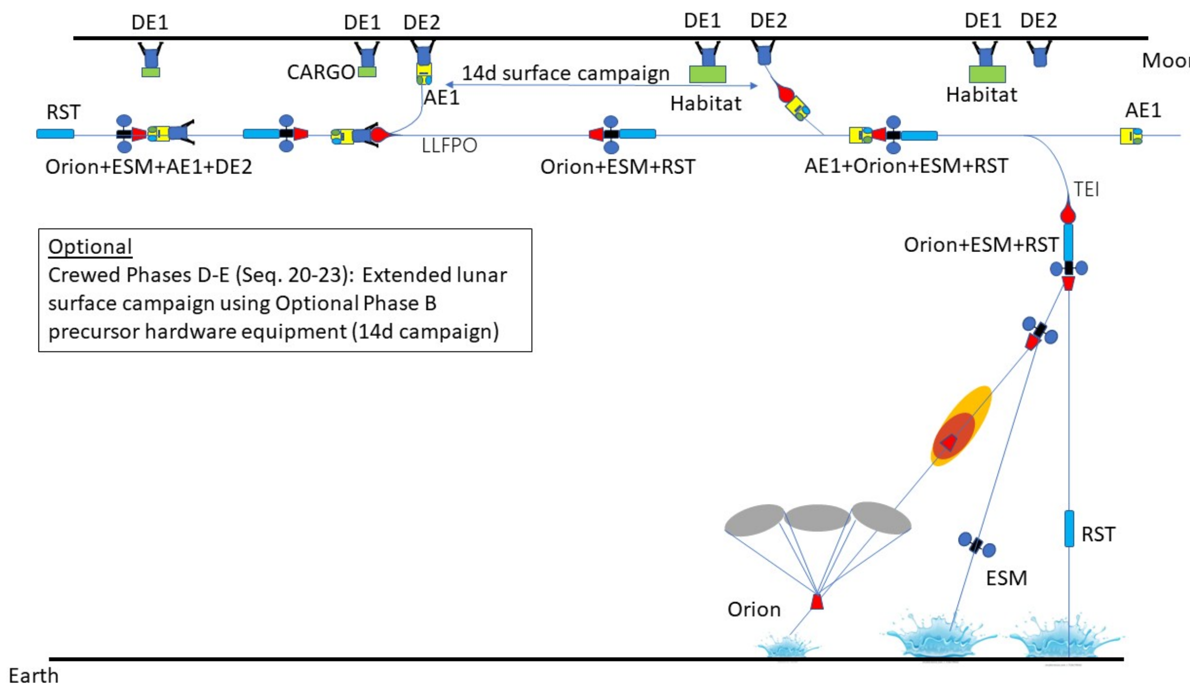

Figure D4: Crew lunar landing in human lander, surface campaign (14d), and crew return to Earth.