New Stars in NASA's Constellation

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The research described in this paper was conducted within the Constellation program at the National Aeronautics and Space Administration.

Image courtesy NASA/John Frassanito & Associates

Imagine waking up after eight hours and floating down off your bunk onto the floor. You bounce down the hallway to the food station where you make a hot cup of instant coffee and hydrate your pre-packaged breakfast before quickly showering and checking in with mission control. Passing by a small window in the corridor, you pause for a moment and take in the magnificent desolation surrounding the outpost. Lucky for you, your lunar base location also provides for a spectacular view of Earthrise out of a small window. You have been anxiously awaiting today because you are headed out on an enclosed, pressurized dune buggy to monitor the cargo offloading of a resupply lander that arrived a day ago. It brought not just logistics (food, water, supplies), but also a new and improved in-situ resource tool that should make helium-3 harvesting three times faster than what the outpost can process out of the lunar rocks and soil today.

Sound like science fiction? Exciting? By 2024 the United States, along with the help of international partners, plans to establish a permanent outpost on the moon where we master how to function and survive in a new and harsh environment far from home. The Constellation Program, NASA's implementation of the bold policy for American space exploration in the 21st century, is currently developing and testing new technologies to enable multiple astronauts to live and work on the moon, or places even further away such as Mars. The moon has no breathable atmosphere, temperatures that range from +100 to -173 °C on a daily basis, and gravity only 1/6 that of Earth's. Though we have sent humans to the moon before, we did so for a very limited amount of time and with limited capability to explore. By increasing requirements such as the number of astronauts we want to send simultaneously, the locations we want to visit, the amount of time we want to stay, and the goals we want to accomplish, there are many details and exciting technology challenges waiting to be solved in the next decade before we launch.

How do we get there?

Constellation's purpose is to execute a challenging space-faring plan that includes developing and operating spacecraft for transportation to and from the moon, and resources to sustain a semi-permanent human presence on the lunar surface. Two primary spacecraft, Orion and Altair, serve as the backbone of the program's transportation architecture. Orion, a dual-purpose vehicle for missions to the International Space Station (ISS) as well as lunar orbit, is responsible for the safe launch and return of the crew to Earth. Altair's primary purpose is to take the crew down to the moon's surface, as well as any cargo that needs to be transported, and then safely launch the crew back into low lunar orbit (LLO) to mate with Orion for the journey home. Each spacecraft utilizes a different launch vehicle to boost it into space: the Ares I for Orion and the Ares V for Altair.

Orion and Altair are designed to launch within 90 minutes of each other from the same launch pads currently in use by the Space Shuttle at the Kennedy Space Center in Florida. The two vehicles plan to mate in low Earth orbit (LEO) where the crew checks out both to verify proper operational functionality before setting course to intercept the moon.

Three days later, the crew is prepped and ready to transfer into Altair, the vehicle that lands on the surface, while Orion stays in orbit for the duration of their stay on the moon. In conjunction with many "go's" from mission control, the vehicles separate, and Altair positions itself to align with the desired landing site. A high-thrust engine burn slows the 45,000-kilogram vehicle down from orbital velocity to a comparably slow 1 meter per second at touchdown in approximately 14 minutes. The initial missions are expected to last for seven day on the surface, allowing the crew to explore scientifically interesting and challenging locations on the moon such as ice, geographic formations, and unique mineralogical terrain, while future missions are more focused on assembling and utilizing the outpost. Once established, mission durations may last for up to 210 days at a time.

The Exploration Systems Architecture Study performed by NASA identified ten preferred

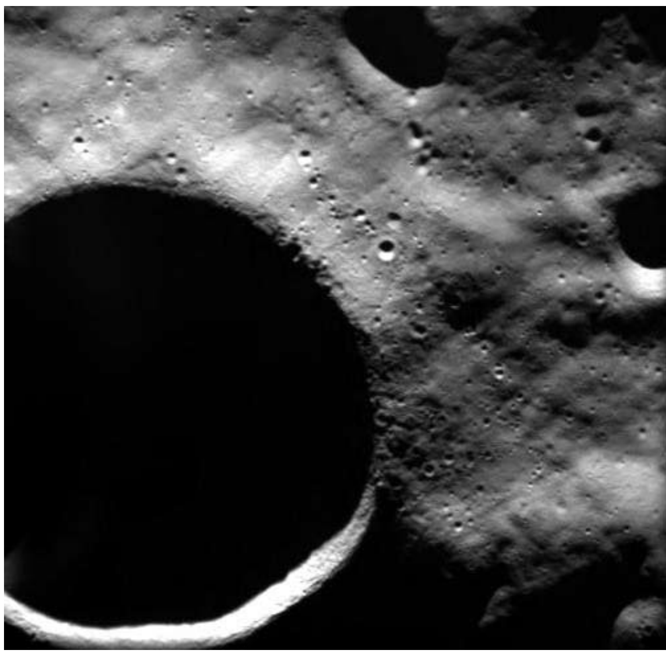
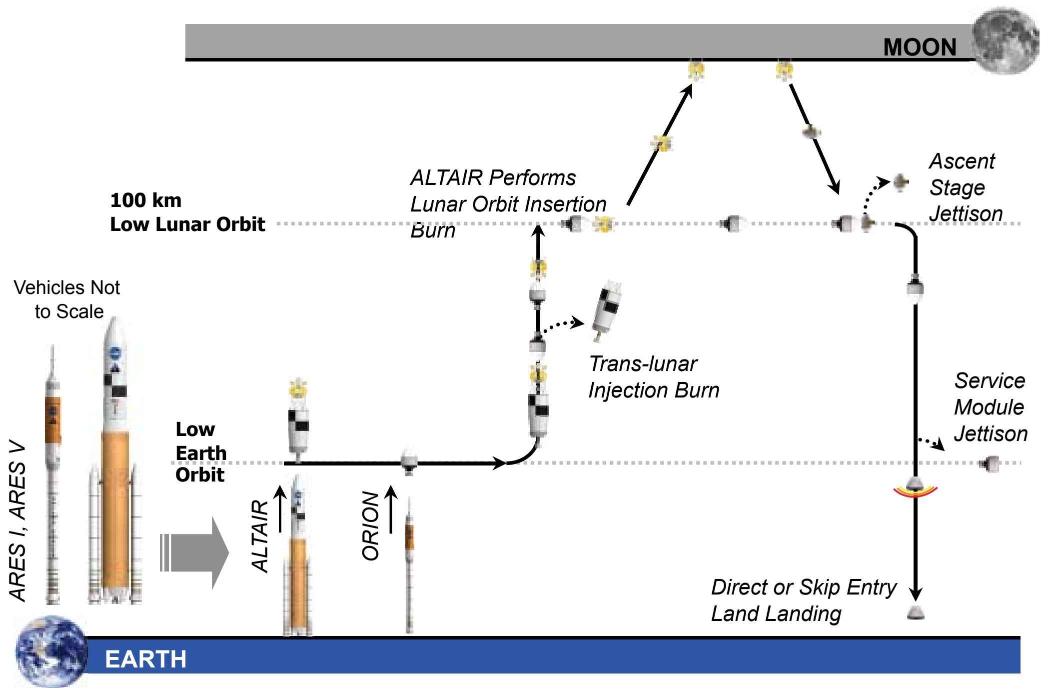


Figure 2: Shackleton Crater taken by the European Space Agency's SMART-1 spacecraft in January of 2006.
ESA/Space-X (Space Exploration Institute)



locations of interest on the moon based on either scientific rationale such as geomorphology, or for exploration to seek out elements available for resource utilization. The Aitken Basin at the lunar south pole is one of these locations. It is the largest and oldest basin known on the moon, and the primary conceptual destination for an outpost. Shackleton Crater is a point of interest internal to the Basin. Its center is completely shadowed year round resulting in temperatures near -170 °C, while its raised edges see almost perpetual sunlight, a noteworthy feature due to the feasibility of using solar cells for power generation. At 19 kilometers across, relatively small for a lunar crater, it is one of many difficult places to land, but is an exciting destination due to the potential presence of ice in the crater that could provide life-sustaining resources for an outpost.

Orion

Orion, currently being developed by Lockheed Martin for NASA, has the responsibility for not only transporting four astronauts to the moon and home again, but also taking over the Space Shuttle's role of ferrying six crewmembers to the ISS. Because of the relative difficulty in executing a lunar mission, Orion is being developed in two phases known as "Block 1" and "Block 2." This two-phase development scheme allows the design to quickly reach initial operating capability for Shuttle replacement by 2015, but incorporate the more technically challenging upgrades for lunar missions a few years later. The major difference impacting vehicle design for the lunar upgrade is the duration for which the system must remain functional. The short-duration lunar stays where astronauts operate in a science-gathering mode last for seven days on the surface, resulting in a total Orion mission duration of approximately 16 days. For the long-duration mission where astronauts spend up to 210 days at a lunar outpost, Orion must remain in orbit around the moon that much longer before returning the crew home.

For a crewed lunar mission, the astronauts launch from Earth to LEO in the Orion vehicle. Once in LEO, the crew performs a precision docking maneuver to mate Orion with Altair prior to heading for the moon. In today's concept, the crew has access to Altair via a docking tunnel, but inhabits Orion until reaching low lunar orbit (LLO). Once in LLO, the crew places Orion into a quiescent state and enters Altair for the descent to the lunar surface. Orion continues orbiting the moon, passing over the landing location of Altair approximately every two hours, for the duration of the lunar surface stay. During this time, Orion generally serves as a communication relay for Altair if the Earth is out of view from the surface, and also performs regular rocket burns to maintain a stable orbit. Once the crew's stay reaches duration, they ascend into orbit with Altair, rendezvous, re-dock with and enter Orion, and then jettison the Altair ascent vehicle before returning home.

~~For the reentry, descent and landing phase of the mission, one of the most critical and intense phases even compared to the landing on the moon, Orion utilizes one of the largest thermal protection systems (heatshield) ever designed at five meters in diameter.~~ Much of the heatshield material ablates away due to extremely high temperatures of 2,600 °C during the time Orion decelerates through the atmosphere from an initial entry speed of nearly 11 kilometers per second. Unlike the Shuttle, Orion does not utilize wings and therefore does not perform runway landings. Instead, a sequence of two drogue parachutes triggers the deployment of three giant main chutes to slow the spacecraft to a cushy splashdown of 7 meters per second in the ocean.

Orion's command module resembles the Apollo command module in that the shape is a blunt-body cone capable of withstanding the extremely high heating experienced during Earth reentry. It is the habitable portion of the Orion vehicle. The service module provides capabilities necessary during the mission, such as the engine used to return from LLO to Earth and consumables like water, and is jettisoned prior to reentry. The vehicle configuration at launch also incorporates a launch abort rocket system to rapidly whisk the capsule away from the launch vehicle in the unlikely event of a rocket mishap on the launch pad or during ascent. For electrical power, Orion relies on two radial solar arrays that each span five meters across. Therefore, Orion's orientation with respect to the sun at any given time is extremely critical for the health of the vehicle. Exposure to micrometeoroids, orbital debris, and radiation also increases with longer mission durations, subsequently increasing the robustness required of the array design.

Orion's internal space, known as "habitable volume," is extremely limited due to limitations on the weight and dimensions the Ares 1 design is capable of launching. The spacecraft interior contains 2.5 times the amount of space as compared to the Apollo capsule, but for twice

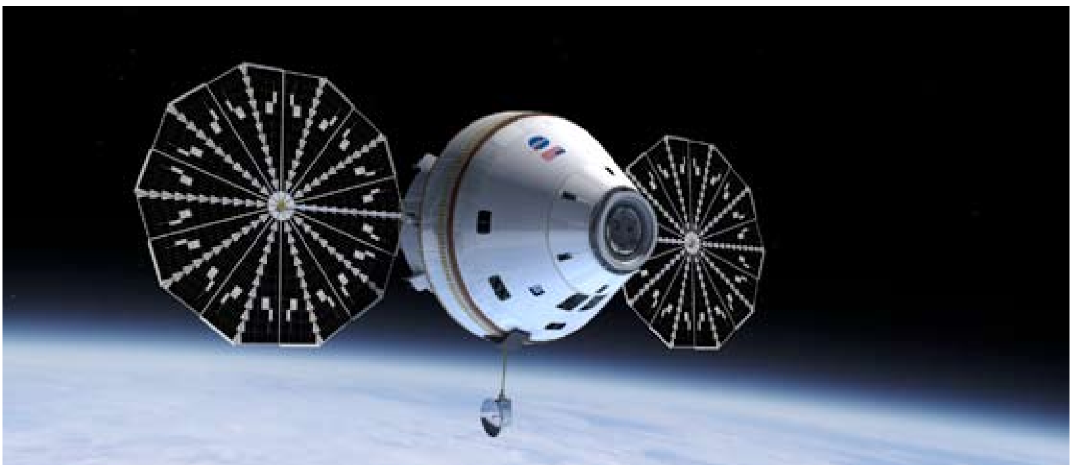


Figure 3: Orion vehicle in low earth orbit with solar arrays deployed.
NASA/John Frassanito & Associates

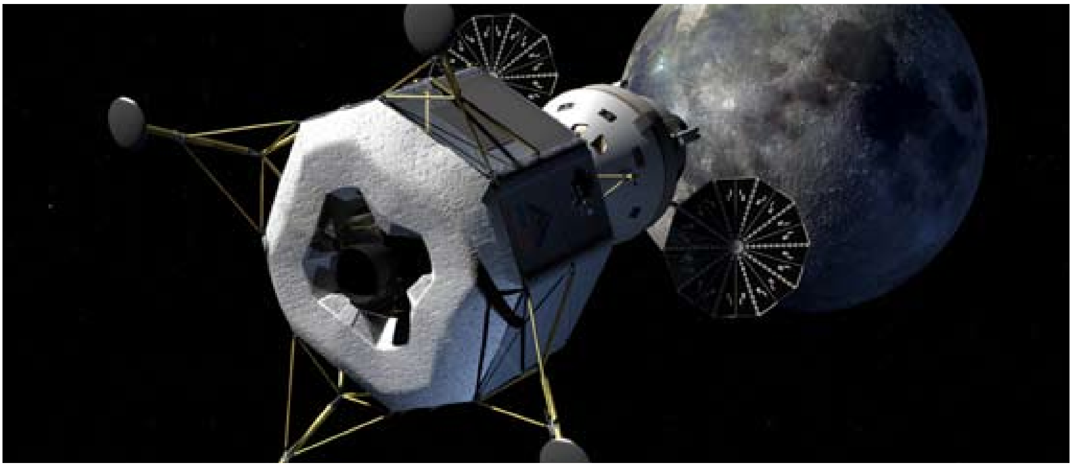


Figure 4: Orion and Altair in a mated configuration on the way to the moon prior to lunar orbit insertion. *NASA/John Frassanito & Associates*

as many astronauts. With a volume of 11 cubic meters, each crewmember has limited personal space to eat and drink, let alone take a shower. (Imagine a room three meters long and two meters square, about the size of a large sport utility vehicle.) The Space Shuttle might seem luxurious comparatively where the astronauts currently enjoy a private bathroom, as opposed to Orion's solution of using a small curtain to separate the toilet area from the rest of the crew. Tomorrow's astronauts must be prepared for close quarters, albeit for only a few days!

Altair

Altair, also known simply as the "lunar lander," provides the capability to take four astronauts and any necessary payload from LLO down to almost any location on the moon's surface. Unfortunately, Altair contains limited capacity for payloads due to the space required to house the crew and other life support logistics such as breathing systems, water, and space suits. In order to build an outpost on the moon requiring living and working quarters, as well as large mobility robots, it is necessary to have a way to carry much heavier payloads than normally possible in the presence of crew. Therefore, Altair is being designed with three possible configuration variants:

1. short-duration crewed variant – a seven-day exploratory mission where Altair provides all life support logistics necessary
2. long-duration outpost variant – an extended mission of up to 210 days where Altair provides the way down to the surface and back into orbit, and an outpost is expected to sustain the crew for the duration
3. cargo-only variant – crew quarters and life support are stripped out to maximize the amount of cargo (over 14 metric tons) that can be delivered

For a crewed mission, Altair launches from Earth on an Ares V, mates with the Orion in LEO, and then undergoes a functional check-out by the crew to verify proper operations of critical systems such as life support, power, and guidance. Following the three-day journey to the moon, Altair is responsible for providing the propulsion for it and Orion on at least three major rocket burns resulting in close to 4,200 meters per second of total velocity change or "delta V." The first burn takes the Orion and Altair vehicles out of the trans-lunar trajectory and places them in an orbit around the moon approximately 100 kilometers in altitude. At this point, the crew transfers out of their cramped Orion home into a more cramped Altair home to prepare for their final hours before landing. Prior to descent, a short burn to adjust the orbit plane may be necessary to fine-tune the targeting to the landing site, and final system checks are completed before committing to the final powered descent burn.

Over 60% of Altair's mass consists of propellant to carry out the mission.

The current Altair design is equipped with a large cryogenic liquid oxygen and hydrogen (LOX/LH_2) main descent propulsion system, and a smaller hypergolic reaction control system that burns monomethyl hydrazine and nitrogen textroxide (MMH/NTO) propellant. These small thrusters provide thrust for minor attitude corrections to the Altair and Orion when mated, as well as small, planned burns that are inefficient for the main engine.

The significant difficulty of using cryogenic propellant for the main engine lies in the mission duration and the propellant's low saturation temperature for the designated tank pressure. Current launch systems utilizing cryogenic fuels typically perform a single burn almost immediately after lift-off that is completed in less than 20 minutes. In contrast, Altair's trip to the moon takes a minimum of 4 days from the time of lift-off, and extreme challenges exist in keeping the propellant sufficiently cold to prevent loss due to boil off. After landing on the moon, residual propellants feed a fuel cell, Altair's primary power source. That need for power, and possibly water as a fuel cell reaction by-product, is expected to last up to 210 days.

If managing the cryogenic propellants for an extended period of time presents technical challenges, one might wonder why we use them. For a quick transit to the moon, cryogenics provide an extremely high specific impulse. The consequence is that the propellant is extremely efficient in terms of energy release potential per unit mass. Other types, including choices with easier thermal management requirements, would be less mass efficient and therefore result in the need to carry more propellant to perform the same job. Such a mass increase would potentially result in a vehicle prohibitively heavy to fly.

For a cargo mission, Altair launches from Earth and transits directly to the moon without docking with an Orion capsule. By not requiring time in orbit to transfer crew and supplies, a cargo Altair can execute a simpler orbit initiation sequence to position itself for a direct landing and avoid orbiting the moon altogether. In order to accomplish this autonomous landing, Altair relies on intelligent sensors and/

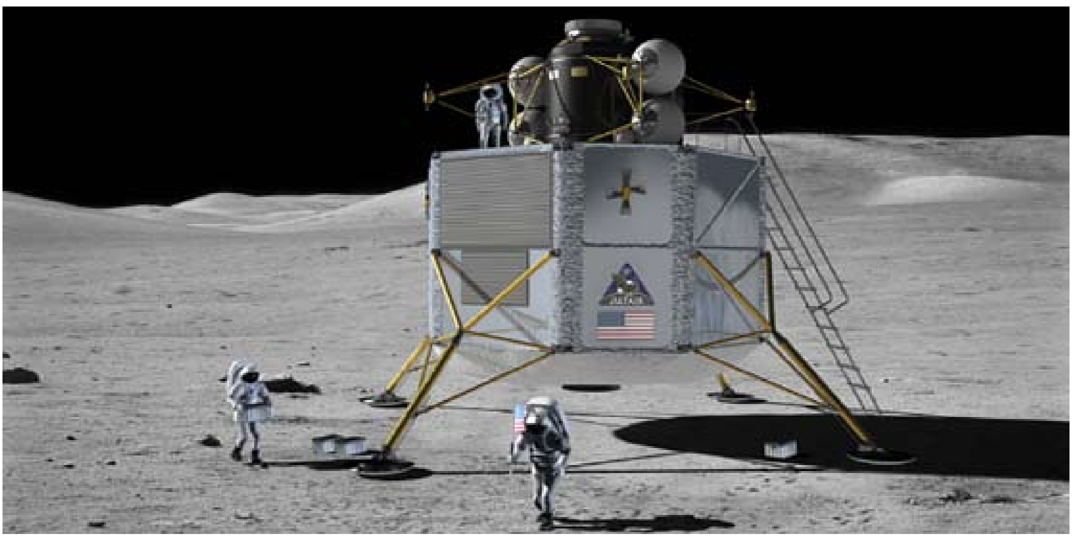


Figure 5: Altair accompanied by three crewmembers in an artist's conception of what a ~~sortie~~ mission might look like on the l`un[illegible]rface.

Image courtesy NASA/John Frassanito & Associates

or pre-placed beacons in order to touch down on the lunar surface, while avoiding major rocks, craters, and other hazardous obstacles placed in its path. This capability becomes extremely critical when trying to land multiple Altairs within a kilometer or less of one another during the outpost construction campaign.

The Apollo landings all took place during lunar "noon" and in the equatorial region. The lighting allowed them to see rocks and craters during descent easier than if they had encountered long shadows caused by landing at a time with the sun near the moon's horizon. Apollo missions also landed in relatively smooth terrain known as "Mare." These locations allowed the astronauts to aim for relatively large landing zones with low probabilities of steep craters or large rocks. Due to the Constellation goal of exploring a more diverse set of regions on the moon, Altair will face situations that may put it in darkly lit, or rough regions known as hummocky ~~u~~plands, with craters as wide as 295 kilometers (crater "Bailly") and as deep as 8.8 kilometers (Newton).

There are several potential technologies that Altair and the crew might employ for safe landing. ~~One specific solution might be in design conflict with another;~~ so determining the right combination of those solutions is challenging. A stronger structure may withstand impact from hazards or higher loads at landing, but can add prohibitive amounts of mass. A softer landing, or one that allows the vehicle to maneuver away from hazards in real-time, typically results in carrying more fuel and requiring tightly constrained control of the vehicle. Better sensors result in easier detection of hazards, but rely on more costly computer processing hardware and algorithm development. There are many different sensor options currently under consideration that could aid Altair and its crew in knowing its position relative to landmarks, helping it to line up with maps of the surface generated by orbiting satellites, or

Figure 6: Exploded view of the Ares I vehicle ~~with~~ Orion ~~in its position~~ at launch.
Image courtesy NASA/John Frassanito & Associates

identifying and avoiding hazards in real-time once within a few kilometers of the surface.

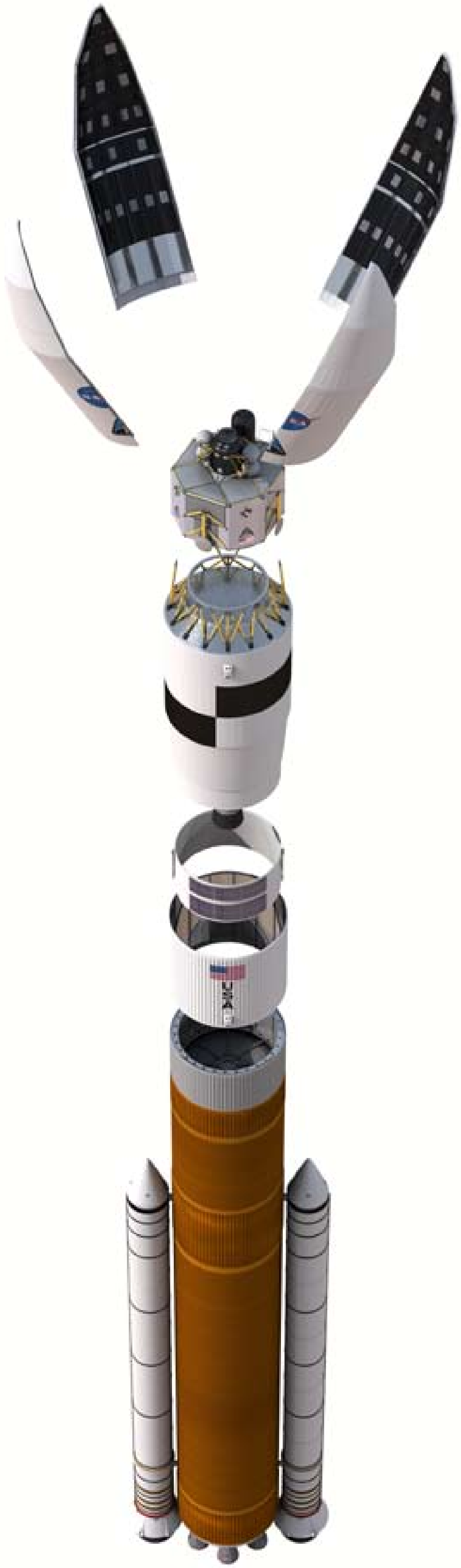
NASA's Lunar Reconnaissance Orbiter (LRO) and India's first mission to the moon, Chandrayaan-1, are among two of the robotic lunar orbiter missions that are providing topological data to assist the Constellation program in choosing landing sites for Altair. The quality of the data and amount of coverage help determine the robustness of Altair's landing capability required to safely touch down at the selected sites. Chandrayaan-1 will also focus on performing high resolution mineralogical and chemical imaging in shadowed polar regions as well as searching for surface or sub-surface water-ice. This data will inform scientists as to the highly desired landing locations based on scientific merit versus vehicle capability to land in challenging terrain.

Once on the surface, Altair either provides life support and habitat functions as mentioned previously, or sits dormant during the crew's stay at the outpost. At the conclusion of the surface mission, Altair's ascent vehicle, the same module utilized by the crew during descent, will blast off and head for low lunar orbit. The bottom portion of the vehicle, consisting of the descent engine, empty fuel tanks, and landing gear, serves as a launch pad for the ascent vehicle and is left behind on the lunar surface. For this part of the mission, Altair utilizes an engine and propulsion system designed specifically for the ascent to lunar orbit and rendezvous with Orion. After rendezvous and docking, the crew then transfers back into Orion through the hatch and prepares for return to Earth. Prior to the trip home, the crew commands Orion to jettison Altair and places it on a trajectory to minimize interference with future missions.

Ares I and Ares V

Because a combined launch of both vehicles is mass prohibitive for a single rocket, and Altair weighs almost twice as much as Orion, each spacecraft warrants its own launch vehicle. Both Orion's and Altair's boosters draw from existing technologies where feasible, but new capabilities are also being developed. Orion utilizes a design called the Ares I. This rocket, currently under development at the Marshall Space Flight Center in Huntsville, Alabama, is a thin, 99-meter tall vehicle capable of lifting 25 metric tons to LEO. The Ares I first stage is a single, five-segment, reusable solid rocket booster derived from the Space Shuttle program's reusable solid rocket motor. It separates 133 seconds after launch and is recovered from the Atlantic Ocean and reused. The upper stage employs a liquid fueled engine derived from the original Saturn V's J-2, and burns for 495 seconds to take Orion to an altitude of 134

Figure 7: The Ares V approximately 6 seconds after ignition as it lifts from the launch pad at Cape Kennedy. *Image courtesy NASA/John Frassanito & Associates*



kilometers. After separation from the upper stage, Orion boosts itself into a circular orbit while the upper stage reenters the atmosphere and plunges into the Indian Ocean.

In contrast to Orion, Altair utilizes the giant Ares V booster. Prior to the Constellation effort, the largest and most powerful rocket ever built was the Saturn V for the Apollo Program. The three-stage Saturn, an engineering marvel of the 1960's, stood 111 meters high and utilized five F-1 engines to produce greater than 33 million Newtons of thrust for the first stage. It boasted a LEO payload capability of 344 metric tons. The Ares V is a two-stage liquid-fueled rocket that stands two meters shorter than the Saturn V, but is still taller than the length of a soccer field. This rocket is capable of boosting 414 metric tons to LEO. It relies on two reusable solid rocket boosters, similar in design to the Ares I first stage, which strap onto the sides to assist a first stage powered by six RS-68B engines. The second stage, referred to as the Earth Departure Stage (EDS), performs the trans-lunar insertion burn for the mated Orion-Altair vehicle. This maneuver transitions the spacecraft from an Earth orbit to a path that will intersect the M

In looking ahead at a Mars capability, the Ares V is being designed such that additional solid rocket boosters can be adjoined providing additional lift capacity for heavier spacecraft.

Surface Systems

The technologies to sustain life on the moon and beyond are in the earliest stages of development, but already have some very exciting prototypes ~~under test~~ in exotic locales such as the Mojave Desert and Antarctica. One element of living on the moon is mobility, both for people and objects such as science experiments and living quarters. The moon, while much smaller than the Earth, is still a large place to

Figure 8: An exploded view of the Ares V ~~with~~ Altair in its launch position. The Earth Departure Stage (EDS) can be seen below Altair.

Image courtesy NASA/John Frassanito & Associates

Figure 9: An evening test run of the NASA-prototyped "chariot" concept in the Arizona desert.

Image courtesy NASA Desert RATS team

Figure 10: The enclosed rover concept being tested in the Arizona desert. The rover shares the ~~shared~~ chassis of the "chariot" concept.

Image courtesy NASA Desert RATS team

explore. The Apollo astronauts walked around in spacesuits, and used their "open air" lunar rover to explore up to a few kilometers from the landing site. Constellation astronauts can also perform walking excursions near the landing location, but a small enclosed rover is being designed to provide a shirt-sleeve environment for two crew to live for days at a time while driving 20 to 30 kilometers away from the habitat location. Today's rover concept is a six-legged vehicle with 12 wheels. The prototype was recently taken out to the Arizona desert where engineers tested it to understand its maneuverability, obstacle avoidance capability, and ease of controllability.

Similar to the enclosed rover, the design of the habitats and workspaces is challenging due the constraint of landing them on a limited-size vehicle such as Altair. They require packaging that occupies as little space and mass as possible. Engineers are currently working on designs that collapse around a central, rigid core and inflate or expand once on the surface. Multiple modules can be connected together through common airlock doors, including a hatch to pull up and park the enclosed rover when not in use. The scalability of designs is a key factor due to the flexibility of designing either one module to meet all needs, or the luxury of utilizing several specific modules. Radiation and micrometeoroid hazard robustness also affect habitat design, providing an opportunity for material specialists to develop unique, lightweight methods to provide protection.

These large modules dictate the need for the ability to unload large, heavy objects down from the top of Altair's deck, a height equivalent to a three-story ledge. Once removed from the deck, astronauts will need to transport the modules over rocks, craters, and other pieces of unloaded hardware before reaching the final destination. ATHLETE, the All-Terrain Hex-Legged Extra-Terrestrial Explorer, is another lunar surface concept being designed to do just that. It utilizes jointed, six-degree-of-freedom limbs to help it crawl on and off of the Altair, maneuver next to an Altair to help with repairs or resource retrieval, or align two habitats for proper connection to increase living and work space. Both remote control and autonomous operations are currently being tested to allow a crewmember to operate it while remaining within the relatively safe confines of an established outpost, or perform other work while the ATHLETE accomplishes its tasks.

Human suit design is also a large part of the Constellation effort. Engineers are working to design astronaut surface suits less bulky than the Apollo units, while more adept at providing a healthy, safe environment, and capable of reporting diagnostics of the crew member's health. Certain aspects of the suit may assist an astronaut in performing strenuous tasks such as lifting heavy objects, or facilitating exercise by providing muscular resistance. Another team is looking at the types of ancillary telemetry to collect, and efficient display techniques such as using a heads-up display when an astronaut is out working. For example, if a crewmember is out exploring and their rover encounters a problem, the presence of an internal guidance and map capability could help them get home.

In addition to the habitat, suit, and mobility technologies, there exist other surface capabilities under development to facilitate communications, to extract natural resources found on the moon, and to increase the autonomy desired of robots. It is also important that aspects of the spacecraft design employ the concept of reusability because of the difficulty in landing material on the moon. For example, potential components include power sources, water and fuel processing and storage hardware, and avionics boxes suitable for both Altair and reuse at the outpost after the conclusion of the Altair mission.

In addition to all of the scientific and engineering discovery, it is desired that as many of us here on Earth share in the experiences of the astronauts on the moon. In order to accomplish this goal, NASA plans to beam back high-definition video so that we can be involved with the work of the astronauts, and explore alongside them!

What's so exciting about the moon?

In 1969, when our first Apollo mission landed two astronauts on the moon, it was an engineering feat of a lifetime. After the upset of losing the race to the Soviet Union for the first satellite in orbit, and the first human to orbit and return to Earth, the United States placed humans on another celestial body. Unfortunately, the scientific enlightenment and excitement of exploring a heavenly locale that was all but an impossible dream for many millennia of human history, was cut short after only six short missions.

Our reasons for going to the moon in 1969 were very different from what they are today. There is no longer a "space race," no Cold War, no need to be the first to accomplish putting a human on the moon. However, what has not changed is our desire to continue learning about and exploring the universe that waits outside of our comfortable, earthly bubble. Many nations have spent substantial time, effort, and resources exploring our solar system, including Venus, Mars, and the moons of Saturn and Jupiter. We have telescopes that see far beyond what many of us ever thought existed, searching for Earth-like planets or gravitational waves beyond our solar system to provide an understanding of our universe's origins.

We continue to be excited and intrigued by tales told via Star Trek and 2001: A Space Odyssey, which says something about our capacity and yearning for exploration. In addition, the Moon provides a unique place to study our universe's origins due to the lack of exposure to planetary changes as compared to Earth and the other planets. The lunar surface has been much less affected than the Earth by forces of erosion such as plate tectonics, volcanism, and wind and water. Consequently, much of the original formation is more intact than any other known body we can currently study.

Learning how to survive and be productive on the moon, a short 363,000 kilometers away, places us one step closer to traveling to more distant bodies such as Mars. We can experiment with different concepts of transport, logistics, construction, in-situ resource utilization, and different communication schemes that may require inhabitants to operate independent from Earth for a period of time, or advance our technology solutions that simply enable us to survive in a non-earthlike environment. For example, we have learned a significant amount about how microgravity affects humans physiologically. Mars gravity is slightly stronger than the moon's at 3/8 that of the Earth. By understanding the effects of ~~1/6 Earth~~ lunar gravity on humans over extended periods of time, we can better prepare the proper training, exercise regimens, and diet to mitigate the effects of Mars gravity.

Conclusion

Sending robotic missions to far away places is significant to learning a great deal about the basics of a planet or comet, but in order to perform more in-depth science that requires real-time decision making and adaptation, we need the capability to explore first hand. To accomplish this imperative, we must invest in and establish our knowledge of how to live and operate safely in harsh environments. The moon provides an excellent opportunity by being relatively close to home, but still posing challenging problems in all aspects of the mission. Can you imagine producing your own oxygen for breathing, out of soil? How can we create or bring resources that are reusable or recyclable into something useful again? What kind of telescope is best for placement in a shadowed crater such that it can accomplish radio astronomy without interference from the Earth?

While the Constellation program has established a plan to fulfill the American space policy of going to the moon and beyond, it has not done so in a vacuum. The effort required for developing and sustaining the capability to function in a permanent way beyond our Earth home is promoting numerous international partnerships between both old space-faring foes such as the United States and Russia, and newcomers just getting started. Those such as Japan and the European Union are increasing contributors to our knowledge and understanding of the universe. This exploration effort also draws on many different groups of people as we consider how to build a thriving community that ultimately needs teachers, doctors, engineers, scientists and other citizens. Thanks to the efforts of independent enterprises such as Scaled Composites, almost anyone will have the opportunity to personally participate in exploration of the moon during this lifetime.

NASA's effort to renew and establish a capability for human exploration on the moon is an exciting frontier for many reasons. Constellation's success depends on national and international support, as well as the success of its many projects such as Orion and Altair to fulfill their missions. And, back to the moon we go, but not just for the moon's sake; for the sake of the moon, Mars, and beyond.

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