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From Apollo LM to Altair: Design, Environments, Infrastructure, Missions, and Operations

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Abstract

This essay presents a comparison between the Apollo Lunar Module (LM) and the current concepts and requirements for the Altair Lunar Lander. The basis of comparison reflects the difference between the Apollo Program, pursuing a Cold War era "Flag and Footsteps" mission, and the Constellation Program creating a more expansive program of exploration leading to a permanent human presence on the moon. The specific areas of comparison derive largely from the changes in mission philosophy and exploration strategy – not from technology or engineering. These factors illuminate the differences in the current design drivers for the Altair compared to the Apollo LM.

Nomenclature

ALARA	As Low As Reasonably Achievable, refers to radiation exposure.
ALHAT	Autonomous Lander Hazard Avoidance Technology.
Altair	NASA's Lunar Lander to return crew and cargo to the moon.
Ascent Module	The Altair module with the flight crew station where the crew pilot the vehicle; the Ascent Module launches from the surface to return the crew to the Orion in LLO, leaving the DM behind.
Ascent Stage	The Apollo LM module with the flight crew station where the crew pilot the vehicle. The Ascent Stage launches from the surface to return the crew to the CSM in LLO, leaving the Descent Stage behind.
BFO	Blood forming organs.
CARD	Constellation Architecture Requirements Document, NASA CxP-70000.
CEV	Crew Exploration Vehicle.
CM	The Apollo Command Module, also the Orion Crew Module.
ConOps	Concept of Operations.
CSM	The Apollo Command and Service Module.
EDS	Earth Departure Stage.
EOR	Earth orbit rendezvous.
ESAS	Exploration Systems Architecture Study, December 2005.
EVA	Extra vehicular activity.
GCR	Galactic Cosmic Ray.
Gray	*Gray* (Gy) is the SI unit of absorbed [radiation] dose. One gray is equal to an absorbed dose of 1 Joule/kilogram (100 rads). US NRC § 20.1004 Units of radiation dose. An absorbed dose.
Gy-Eq	*Gray equivalent* – a [radiation] dose weighted for relative biological effectiveness (RBE). In the NCRP Report No. 132 (2000), dose limits for deterministic effects are expressed as the organ dose in gray multiplied by the relevant RBE for the specific organ and radiation.
HSIR	Human System Integration Requirements, NASA CxP-70024.
HZE	High Z (atomic number) and energy particles.
Inconel	A registered trademark of the Special Metals Corporation for a family of austentitic nickel-chromium-based "superalloys," used with great success for the pressure vessel of the Apollo LM crew cabin.
ISRU	In situ resource utilization.

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ISS	International Space Station.
IVA	Intra vehicular activity.
kPa	kilo Pascals, unit of atmospheric pressure.
LDAC	Lunar Development Analysis Cycle.
LEO	Low earth orbit.
LH_2	Liquid hydrogen.
LIDS	Low impact docking system.
LLDS	Lunar Lander Development Study, 2008.
LLO	Low lunar orbit.
LM	The Apollo Lunar Module.
LOI	Lunar orbit insertion.
LOR	Lunar orbit rendezvous.
LOX	Liquid oxygen.
MLI	Multi-layer insulation.
NAS	National Academy of Science.
NASM	National Air and Space Museum.
NCRP	National Council on Radiation Protection.
NRC	National Research Council.
Orion	NASA's forthcoming Crew Exploration Vehicle.
Outpost	Plan for a permanent base on the moon, the preferred location is Shackleton Crater at the South Pole.
PLSS	Portable Life Support System.
Rad	*Rad* is the special unit of absorbed [radiation] dose. One rad is equal to an absorbed dose of 100 ergs/gram or 0.01 joule/kilogram (0.01 gray). US NRC § 20.1004 Units of radiation dose. An absorbed dose.
Rem	*Rem* is the special unit of any of the quantities expressed as [radiation] dose equivalent. The dose equivalent in rems is equal to the absorbed dose in rads multiplied by the quality factor (1 rem=0.01 sievert). US NRC § 20.1004 Units of radiation dose. A biologically effective dose
Sortie	A mission in the Altair to any region on the lunar surface.
SPE	Solar Particle Event
Sv	*Sievert* is the SI unit of any of the quantities expressed as dose equivalent. The dose equivalent in sieverts is equal to the absorbed dose in grays multiplied by the quality factor (1 Sv=100 rems). US NRC § 20.1004 Units of radiation dose. A biologically effective dose.
TDL	Terminal descent and landing
TEI	Trans-earth injection
TLI	Trans-lunar injection
US NRC	United States Nuclear Regulatory Commission

I. Introduction

On 19 September 2005, Dr. Michael Griffin, the NASA Administrator, characterized NASA's exploration plans to return humans to the moon as "Apollo on Steroids" (Malik, 2005). However, although the Constellation lunar program does bear the outward appearance of similarity to the Apollo lunar program, there are profound differences between them, particularly for Constellation's Altair Lunar Lander. Understanding these distinctions is the first step to appreciating the development path from the Apollo LM to Altair, the logic that generates them, and their far-reaching implications.

This essay traces the development of the Altair beyond the heritage of the Apollo Lunar Module (LM) into this new era of crewed lunar and planetary exploration. It describes the much more challenging missions that the Altair will perform and the more difficult and hazardous lunar environments in which it will operate. These lunar environments consisting of radiation, micrometeoroids, thermal cycling, and lighting – and especially our improved comprehension of them -- constitute the primary design drivers for the new and enhanced performance requirements that the Altair must fulfill. Understanding these differences help to generate the planning philosophy and design strategies that shape the Altair and its Concept of Operations (ConOps).

Using contemporary materials, production methods, operations, structures, and technologies the Altair Program seeks to improve upon the LM's cost, mass, margins, and reliability. Northrop Grumman in-house studies indicate that it is feasible to achieve significant mass savings by using modern materials and technologies. These mass savings enable the Altair to meet more stringent requirements, to function safely in more hazardous environments, and to add new capabilities. In addition, the interface between the Altair and the Orion, although evoking the Apollo LM and the Apollo Command and Service Module (CSM), entails subtle differences with profound effects.

FIGURE 1 shows a Grumman Aircraft Engineering Corporation artist's rendering of the LM from 1969. The LM was the first crewed vehicle designed and engineered to operate exclusively in space, to survive the hazards of space, and the rigors of the dynamic flight environment. The probes extending down from the landing leg pads would give the signal for engine cut-off upon contact with the lunar surface.

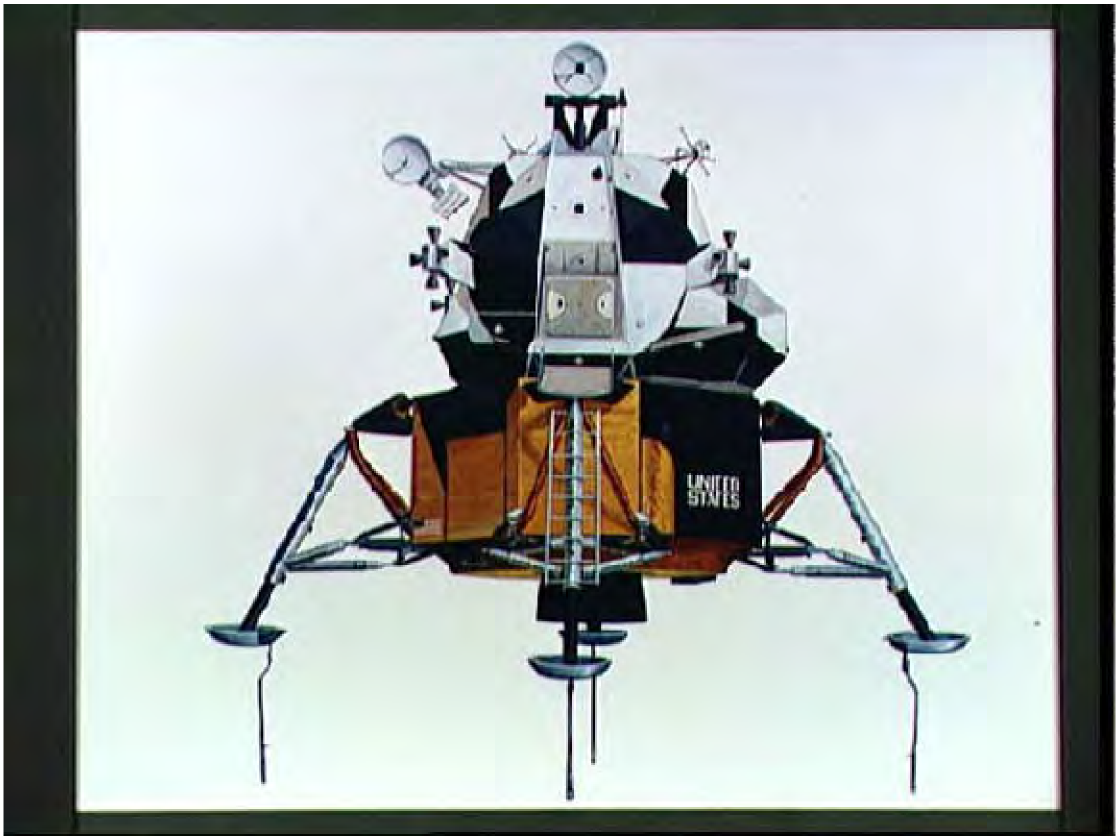

FIGURE 1. Grumman Aircraft Engineering Corporation artist's concept of the Lunar Module 5 March 1969. NASA image S69-25668.

Planning Philosophy

The LM performed short missions in the equatorial region at lunar dawn, when the sun angles were low and limited, and the temperatures were the coolest. The major philosophical changes from Apollo to the Constellation lunar mission derive from three parameters:

1. Land anywhere on the surface,
2. Return anytime from the surface, and
3. Longer mission durations.

Go-Anywhere Philosophy

The Go-Anywhere philosophy (also known as “global access”) means that the Altair must be able to land anywhere on the Moon. The LMs landed only in the equatorial and near-temperate zones on the near side. However, for the Altair, going anywhere means landing in the high temperate zone, the poles, and the entire far side. This expansion of landing sites means potentially more complex flight regimes requiring longer flight times with more engine burns, therefore requiring more propellant for operations and greater reserves of all consumables. In addition, go-anywhere means that the Altair will be exposed to significantly more challenging dust, lighting, micrometeoroid, radiation, and thermal environments than the LM.

Return Anytime Philosophy

A concomitant of the Go-Anywhere Philosophy is the Return Anytime from the Surface. Apollo applied the Return Anytime approach, but under emergency launch conditions the actual Ascent Stage rendezvous with the CSM could take up to 12 hours. The CSM carried sufficient reserve capacity to rescue the LM in low lunar orbit (LLO). For the Constellation Altair, NASA has a goal of making the Ascent flight time shorter, while retaining the 12-hour reserve capability.

Apollo satisfied the corresponding requirements by applying stringent limitations to mission duration and landing site locations. The combination of Go-Anywhere and Return Anytime will impose increased demands upon the Altair Ascent Module’s (AM) propulsion system to accommodate the greater Delta V requirements for ascent and rendezvous.

Longer Mission Durations

The longer Altair mission durations – seven days for sorties and 14 to 30 days for outpost-buildup plus six months for Outpost operations – pose greater demands on all lander systems for efficiency, reliability, and in-flight maintainability. The Outpost missions, especially, entail long-term environmental threats to lander systems, surface operations, and human health and performance.

Design Strategy

The four strategies that shape the Altair program and distinguish it from Apollo are:

1. Larger Crew,
2. Outpost-first lunar exploration strategy,
3. EOR-LOR Mission Architecture, and
4. LOI Burn on Lander

Larger Crew

The Apollo crew size was three, but the CSM pilot remained in LLO while the other two crewmembers descended to the lunar surface in the LM. The first strategy that NASA formulated after the announcement of the Vision for Space Exploration in 2004 was that the Constellation Program’s crew on the lunar surface should be larger than Apollo’s and so defined the crew size as four. This larger crew will provide a more robust capability in flight and on the lunar surface. Having four crewmembers in the Altair on the surface will enable much more extensive extravehicular activity (EVA); two crewmembers will suit up and go EVA while two remain in the Altair doing support tasks and scientific analysis. The next 24-hour cycle, the two inside crewmembers go EVA while the other pair spends the day inside resting from the exertions, providing EVA support and doing scientific analysis of lunar samples they may have collected.

Outpost-First Strategy

At the Second Exploration Conference in December 2006 in Houston, NASA announced the “Outpost-First” strategy of lunar exploration, which centers upon building a permanent base at the lunar South Pole before engaging in a wide campaign of sortie missions. Outpost-first means focusing upon engineering and construction missions before global-access science missions, and makes support of outpost construction a major purpose of the Altair. The most recent NASA launch manifests show a robotic landing, followed by an Altair cargo landing, followed by first crewed landing.

The Outpost construction necessitates that the Altair provides a substantial cargo-carrying capacity that the LM did not have. This cargo capacity takes two forms. According to NASA’s Constellation Architecture Requirements Document (CARD, 2009, p. 195), the Altair should provide a minimum of 500 kg of cargo capacity. In addition, the deployment of major outpost elements implies a cargo variant of the Altair that flies without the ascent stage or airlock, carrying cargo such as the surface power system, rovers, and habitat. The 2007 Lunar Design and Analysis Cycle 1 (LDAC-1) and the 2008 Lunar Lander Development Study recapitulated the 500 kg minimum down cargo.

TABLE 1. Down payload mass for three Altair variants (NASA (2009, March 5, CARD).

Altair Configuration	Altair Minimum Down Cargo Mass in kg	Altair Desired Down Cargo Mass in kg
Sortie Mission	500	500
Crewed Outpost Mission	1800 (cargo replaces airlock)	1800
Uncrewed Cargo Mission	14,000	17,500

EOR-LOR Architecture

On the Apollo missions, the architecture included one rendezvous – after the LM Ascent Stage launched from the surface to low lunar orbit (LLO), it performed a lunar orbit rendezvous (LOR) and docking with the CSM to return *from* the moon. The Constellation lunar architecture retains this same LOR, and adds an Earth Orbit Rendezvous (EOR) on the way *to* the moon. Because the Orion CEV and the Altair will launch on separate rockets, they must rendezvous and dock in LEO before trans-lunar injection (TLI).

The addition of EOR to the mission architecture poses a new burden on the docking mechanism and structure that connects the Orion and the Altair. In the Apollo ensemble, during the trans-lunar injection (TLI) burn, the CSM was mounted on top of the LM fairing, which was 3.9 m in diameter. That meant that the length of the resisting moment arm -- against the bending moment from launch loads and vibration -- was 3.9 m at the connection between the Service Module and the top of the LM fairing. The CSM separated from the LM fairing only *after* TLI, when the CSM performed the mission-critical maneuver of turning around and docking with the LM. However, EOR dictates that the Orion and the Altair dock *before* TLI. That means the Orion and CSM connect through the low impact docking system (LIDS) (Lewis, Carroll, Morales, Le Thang, 1999) during TLI, which provides a resisting moment arm of only about 1.5 m across the 0.75 m hatch. The dynamics and mode will behave like a configuration of two bodies connected by a short spring. This configuration and all it implies will impose much greater bending moments upon the Orion/Altair docking mechanism than the Apollo mechanism experienced. These loads may also pose potential challenges for the elastomeric seals in the LIDS docking hatch.

EOR requires the Altair to loiter in LEO from four to 14 days to accommodate Orion launch contingencies. This wait-time drives the cryogenic propellant storage requirements for the Descent Module. It requires the spacecraft design to take micrometeoroid and orbital debris protection under greater consideration.

Lander Performs the LOI Burn

On the Apollo spacecraft, the Service Module carried sufficient propellant to perform both the Lunar Orbit Insertion (LOI) burn and the Trans Earth Injection (TEI) burn. The moon-bound Orion will launch on the envisioned Ares I that is much smaller than the Saturn V; its Service Module cannot carry sufficient propellant to perform both the LOI and TEI burns. To compensate for this difference, the Constellation lunar architecture puts the LOI burn on the Altair. One reason for this design decision is that there will not be an Orion with a Service Module present for Altair Cargo missions, so the Altair will need to do its own LOI burn in all mission scenarios. Also, the use of the Earth Departure Stage (EDS) would require additional long duration cryogenic storage to ensure successful TLI or LOI.

Use of Cryogenic Propellants on the Descent Module

To minimize the TLI mass and to perform the LOI and descent phases efficiently, Altair uses cryogenic (LOX/LH2) rocket propulsion in its descent stage. This design decision saves propellant mass per kg of landed mass compared to using storable hypergolic propulsion as Apollo did. This selection is a critical difference from Apollo that drives the need for improvements in the technology for long duration cryo storage, highly reliable in-space LOX/LH2 propulsion systems, and deep-throttling cryogenic engines. The large volume required by this low density propellant also drives up the diameter and the height of the Altair.

Interface with the Orion Crew Exploration Vehicle

The CARD articulates three missions for the Orion, two of which relate to the Altair.

1. Orion crew or cargo missions to ISS
2. Orion and Altair lunar outpost mission, which may be:
    a. Crew “sortie” to the Outpost site,
    b. Outpost Crew and cargo, or
    c. Just cargo.
3. Orion and Altair crewed lunar sortie “Go Anywhere” mission.

The Outpost and Sortie missions involve the Altair for each of the four variants. The ISS missions do not involve the Altair. For the 7-day Sortie, 14 to 30 day Outpost Construction, and 180 to 210 day Outpost missions, the Orion will remain in low lunar orbit for the Altair’s return. Keeping the Orion uncrewed in standby mode for such a long duration in lunar orbit and then expecting it to perform flawlessly will pose new challenges to reliability.

In the “Outpost-First” strategy, the Altair landers begin building the Outpost at the lunar South Pole as a higher priority than the “Go Anywhere” sortie missions. The Outpost missions lead to two variants of the Altair: the Crew Lander and the Cargo Lander. The Crew lander carries four astronauts to the surface, although it is possible that on the first mission, that one crewmember will remain in the Orion as a safety precaution as in the Apollo program to ensure a successful LOR.

II. Constellation Systems Infrastructure [1]

The Apollo LM was designed to perform the one function of the lunar landing. Serving as a lifeboat for the CSM, as in the Apollo 13 flight, was pre-planned as a contingency beyond nominal operations.[2] In contrast, the Altair will serve multiple planned functions and operations across the three different missions: Outpost crew, Outpost cargo, and Sortie. This greater complexity in mission requirements and operations translates into important differences in the demands of the Constellation Systems overheads, notably: telecommunications, interfaces for subsystems; and the Constellation Common Support Services, as defined in several documents. These Common Support Services apply equally to the Orion and the communications and telemetry aspects of the Ares launchers.

Multi-Use

Under some scenarios, the Altair can become a building block for the Outpost, especially if the cargo lander/Descent Module with “cargo habitat” can be incorporated intact into the Outpost. While Apollo's LM did essentially one job, once the Altair is on the surface, it will perform several jobs: long-term habitat, payload delivery system, and basis for power systems, communications relay, recharge rovers, and probably more. The design of the Altair subsystems will probably allow the scavenging of consumables, subsystems, and components for reuse in the Outpost or to repair other vehicles.

Operability and Autonomy

Uncrewed cargo Altairs will require autonomous landing and teleoperated operations. NASA also envisions more on-board control than Apollo. The astronauts will have more situational awareness and do more planning on board. At the same time, Altair will incorporate an advanced Vehicle Health Monitoring System (HVMS). These improvements will require more processing capability. More autonomy and operability will allow the reduction of ground staffing, facilities, and their associated costs. The addition of autonomy will change the role of the LM astronauts’ human-in-loop control to supervisory control of layered complex autonomous systems. During the descent phase of landing astronauts will have to switch between several autonomous control modes and in emergencies quickly response in a timely fashion from the switch of supervisory control to direct human-in-loop control. Decades of aircraft accident investigations suggest that the switch from supervisory control to human-in-the-loop control can become a high-risk element of flight as more and more automation is added to systems. These findings indicate the need for careful human factors design with extensive simulation and testing to reduce this potential risk.

Interfaces

The interfaces between Altair and the other components of Constellation will be much more sophisticated. They includes both space and ground systems. The main medium for these interfaces with Constellation Systems will be the “Common Support

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[1] Thanks to Stewart Moses, Northrop Grumman Aerospace Systems, Redondo Beach, CA, for suggesting and outlining this section on system infrastructure.

[2] Personal conversation with Carl Meade, NASA astronaut, retired, and Director of Space Systems, Advanced Programs and Technologies Division, Northrop Grumman Aerospace Systems, El Segundo, CA, 15 August 2009.

Services” that include command and control, communications and data processing, telemetry, text and graphics, tracking, video, and voice communications. For example, these “services” mean that the Altair will need to interface with many more processors than the LM. The Altair will interface with a wide variety of payloads and potentially with commercial systems. As the Outpost build-up proceeds, there will be more interfaces to the Altair systems.

Telecommunication

Telecommunications is a special case of system infrastructure. The Altair will probably need to provide vastly higher data rates back to the Earth than Apollo's LM. The public will want increased media access to the missions through HDTV and other high throughput links that will require substantially greater bandwidth.

III. Environments

The environments that Altair will see differ from those of the Apollo LM, insofar as the Altair will land in more locations away from the equatorial zone and because the missions are longer, experiencing a wider range of conditions in the lunar day. The principal environments of interest include the extreme thermal cycle, radiation, micrometeoroid fluxes, lighting and dust conditions. FIGURE 2 illustrates some of these environmental effects from a recent Lunar Reconnaissance Orbiter photograph.

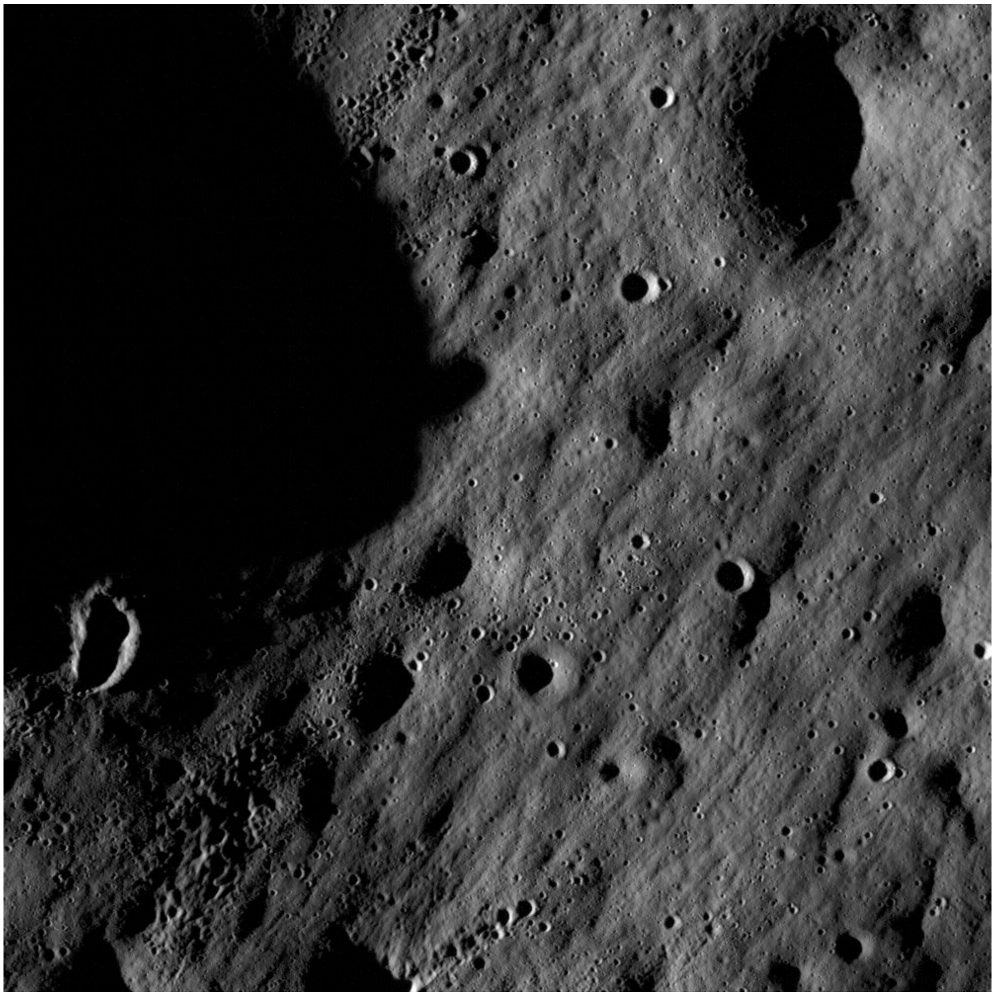

FIGURE 2. Lunar Reconnaissance Orbiter image, 2 July 2009 of the lunar surface near Hell E crater in the lunar highlands south of Mare Nubium, or Sea of Clouds, showing environmental effects. Courtesy of NASA-Goddard Space Flight Center.

Most prominent in FIGURE 2 is the constant gardening by meteoroids, creating a rich distribution of impact craters large and small. The newer craters are quite sharp-edged, but the older ones are smoother, worn by space weathering and the regular extreme temperature cycles, which grind the top layer of regolith to dust. Inside the craters is the deep shadow so black that the camera does not see into them. The sunward edges of the craters are blindingly illuminated. Not only can these environments become much more severe than what the LM and Apollo crews experienced, but our understanding of their properties and hazards have improved greatly since Apollo, largely based on the knowledge gained from the Apollo missions. Over the same time, our tolerance for such risks has become more conservative.

Radiation[3]

Radiation in Space was a concern for the Apollo program. Jack Miller of Lawrence Berkeley National Lab explains the Apollo Program attitude toward radiation hazards in recounting the literature of the time (Geertz, 1965).

> It's important because it shows the thinking in the Apollo design era. The take-home message seems to be: yes, they were concerned about radiation, but not enough to measurably impact vehicle design; the emphasis was rather on estimating doses in various scenarios and reassuring themselves that the likelihood of a disabling or lethal radiation event was very small (personal e-mail from Jack Miller, 24 AUG 2009).

For the Constellation Systems, especially missions that leave the protective cocoon of the Earth's magnetosphere, the need to provide positive countermeasures against radiation is much more prominent. The Committee on the Evaluation of Radiation Shielding of the National Research Council (on which this author served as a committee member) summarized the hazards of radiation in their 2008 study, Managing Space Radiation Risk in the New Era of Space Exploration:

> Space is a harsh environment. Nevertheless, engineering technology is capable of protecting astronauts against vacuum, extreme thermal conditions, and micrometeoroid environments. Protection from radiation, however, is much less straightforward. . . .
>
> While the general climate of galactic cosmic radiation (GCR) varies fairly predictably on an 11-year cycle, solar particle events (SPEs) are unpredictable, both in timing and character. Whereas the radiation hazard posed by episodic SPEs can be managed by providing sufficient shielding, GCRs pose a radiation hazard that is distinctly different: (1) GCRs are always present, and (2) their energy spectra extend to very high energies with sufficient intensity that the hazard cannot be eliminated by shielding. Moreover, both SPEs and GCR contain not only protons but also heavier nuclei (also known as HZE particles, for "high Z [atomic number] and energy"). Not enough is currently known about the biological effects of HZE particles. . . . (NRC, 2008, p. 7).

In the first sentence of the above paragraph, the Committee refers to the phenomenon that the intensity of GCRs varies *inversely* with the intensity of the sunspot cycle. At *solar maximum*, when sunspots are the most active the heavier flux of solar particles – the solar wind – counteracts and reduces the GCR flux. Conversely, at *solar minimum*, when sunspots are the least active, the weaker solar wind allows a heavier GCR flux. The Committee on the Evaluation of Radiation Risk continues:

> The health risks to be considered are of two kinds: risks to mission success and risks to health following a successful mission. The success of a mission is jeopardized whenever a crewmember is unable to perform his or her functions properly, if at all. In such cases, one or more of the mission objectives may be compromised; in extreme cases, the mission may be lost. In terms of radiation, the mission could be compromised by these short-term consequences or "acute effects," which may include headaches, dizziness, nausea, fatigue, and illness ranging from mild to fatal (NRC, 2008, p. 7).

James Michener makes this threat -- as the Solar Particle Event (SPE) of August 1972 might have triggered it -- a plot device of his novel Space about the imaginary Apollo 18 mission in which the surface crew dies from the intense radiation's "prompt effects." Since 1972, the radiation research community has amassed a vastly greater knowledge of space radiation and its risks for humans and electronics. In that time, standards for allowable radiation exposure have developed much greater sophistication and conservatism than the minimal standards available in the 1960s. The Committee continues:

> Risks incurred during a mission may also extend beyond its successful completion. . . . Radiation risks are of even greater concern, these risks—in particular the increased risk of fatal cancer—last for the entire life of the crewmember. Astronauts may also face other dangers, including cataracts, skin damage, central nervous

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[3] Thanks to Jack Miller, Lawrence Berkeley National Laboratory, for his guidance and mentorship on radiation.

> system damage, and impaired immune systems. Although these effects are not immediate enough to be classified as acute, they have the potential to impact very long missions or an astronaut’s future missions. . . .
>
> Radiation protection must become a matter of constant vigilance . . . (p 7-8).

In response to this severe threat environment, the Human Systems Integration Requirements, CxP-70024 states unequivocally in section 3.2.7.1.1, Radiation Design Requirements, Rationale that radiation exposure should be kept As Low As Reasonably Achievable (ALARA):

> Rationale: The radiation design requirement is imposed to prevent clinically significant deterministic health effects, including performance degradation, sickness, or death in flight and to ensure crew career exposure limits are not exceeded with 95% confidence. The ALARA principle is a legal requirement intended to ensure astronaut safety. An important function of ALARA is to ensure astronauts do not approach radiation limits and that such limits are not considered "tolerance values".

Solar Particle Events (SPEs)

SPEs are generally tied to the sunspot cycle (peaking each eleven years), when the sun puts out huge flares that release particle events consisting mainly of protons and some helium nuclei. However, individual SPEs -- and the solar flares that produce them -- are unpredictable and can occur at any time. These flare particles radiate from the sun in a wave front, but when they arrive at the moon or LEO, they behave locally like an omnidirectional swarm. The SPEs can be very intense, with the peak flux reaching five Sievert/day (500 Rem equivalent), which is sufficient to give an LD-50 lethal dose to the average human. For the lunar crew on the early short duration sortie and outpost assembly missions of 30 days or less, the SPE poses the greater risk compared to GCRs. The ESAS Report (NASA, 2005, pp. 109-112) proposed a dose of 4x the 1972 SPE as the maximum credible event for Constellation missions. The occurrence of such large flares is unpredictable; the NASA approach is to prepare for what they anticipate as the worst.

Galactic Cosmic Rays (GCRs)

The GCR flux is relatively constant, and constitutes a potential long-term threat to the health of insufficiently shielded astronauts. For this reason, GCRs pose a more certain risk of radiobiological damage to the crew in a long duration stay such as the 180-day outpost mission than the unpredictable threat of an SPE particles. One of the ubiquitous effects of GCRs is the experience some astronauts had were light flashes from charged particles when their eyes are closed. Hoffman, Pinsky, Osborne, and Bailey recounted that “The observation of light flashes was first reported by the Apollo 11 Lunar Module pilot, Edwin Aldrin, with subsequent observations made on all Apollo missions” (1977, p. 127).

Edward Gibson wrote about it vividly after his experiences on Skylab 4:

> After some major flares on the Sun during one night, we saw a high number of flashes. Most of them appeared as a white, double-elongated flash, perhaps double in some cases as other people have described, and Bill Pogue and I also saw the ones that looked like a whole multitude of pollywogs; very short ones, many of them of low intensity. For us, the latter kind occurred on the second orbit after we saw the very bright ones, suggesting they are of lower energy but of many more particles. Also, I saw one green flash. Not a slightly green flash, but a good old St. Patrick's Day green flash, and exceptionally bright (Gibson, 1977, p. 25).

There is some basis for concern that these transmitted particles could cause damage to the optic nerve or other parts of the central nervous system.

Radiation Exposure Limits

Since the Apollo era, the allowable radiation exposure limits have been decreasing steadily, with no stopping point in sight. These decreases in allowable exposures mean greater requirements to shield and otherwise protect the crew from ionizing radiation. TABLE 2 shows the historic changes in allowable exposure limits to the benchmark Blood Forming Organs (BFO) from the Apollo era to the present decade (Townsend, Fry; 2002). The BFO are the bone marrow principally in the femurs and pelvis, and secondarily in the ribs and other bones. Severe exposure to the BFO can cause radiation-poisoning leading to death. Exposure to the BFO and nearly all other organs can cause increased risk of cancer. (Note that the SI unit of one Sievert = 100 Rem of absorbed dose.) From 1989, the National Council on Radiation Protection (NCRP) rates career exposure limits by age and sex. The newest NASA standard, the Human System Integration Requirements (NASA CxP 70024) adopts the NCRP increment for 35 years of age as its metric, so that is the one used here. The "3% excess risk of cancer" is a commonly cited metric for increased cancer risk in space crews. In the 2000 NCRP limits, "Gray Equivalent (Gy-Eq) is used instead of Sievert as the unit to express dose limits for deterministic effects . . ." (Townsend, Fry; 2002, p. 962).

These radiation exposure and dose units are somewhat of a moving target, having been changed at least three times since the Apollo era. NCRP Report No. 153 (2006, p. 100) establishes Gy-Eq as the current unit of measure, and NASA is now applying it to all its radiation studies and precautions.

TABLE 2 shows that the 30-day allowable exposure limits have been reduced only 40 percent (from 0.25 to 0.15 Sv for a 35 year old) since the 1970 NAS/NRC study for Apollo. Meanwhile, the ***career limit*** has shrunk more substantially, by approximately 80 percent (from 4.0 Sv for any astronaut to 1.0 for a 35-year-old male or 0.60 for a 35-year-old female). In addition, the same numerical value for Gy-Eq units for incident radiation *exposure* generally means a lower radiobiological dose than the *absorbed* dose in Sv.

TABLE 2. Historic changes in Allowable Radiation Exposure Limits for the Bone Marrow (Blood Forming Organs / BFO) in Sieverts (Sv) except as noted otherwise. [4]

Standard or Guideline	30 Day Limit	Annual Limit	Career Limit
NASA SP-71, 2nd Symposium on Protection Against Radiations in Space, 1965	200 Rad (2 Gray) from one acute exposure from an SPE	55 Rad (0.55 Gray)	-
Apollo Maximum Operational Dose (English et al, 1973, p.3)	0.50 from an SPE	-	-
NAS/NRC, 1970	0.25	0.75	4.0
NCRP, Rpt. 98, 1989, 35 years of age.	0.25	0.50	1.75 female, 2.5 male
NCRP, Symposium Proceedings No. 3, 1997, 35 years of age: 3% excess risk of cancer.	-	-	0.9 female, 1.4 male
NCRP Rpt. 132, 2000, 35 years of age.	0.25 Gy-Eq.	0.50 Gy-Eq.	0.6 Gy-Eq. female, 1.0 Gy-Eq. male
NASA HSIR CxP 70024C, 3.2.7.1, 2009, p. 75. Effective (Integrated Body) Dose	0.15 from an SPE	-	-

Radiation Countermeasures

One solution for SPE exposure is for the crewmembers to wear a 35 kg polyethylene "diaper" that covers the blood-forming organs (femur and pelvis) and the reproductive organs. The intent of this countermeasure is to protect the crew from injury or death due to a solar flare and to reduce longer-term carcinogenic or other systemic effects. (Wilson et al., 1999 pp. 361-382) specifically discusses estimated exposures from the Aug. 1972 event, as well as 2x and 4x that exposure, and concludes that while potentially lethal, it depends on shielding. This countermeasure may not apply to GCRs because the crew cannot wear it all the time, which would be necessary to provide effective long-term protection.

The lunar outpost crew will need a different solution. This solution will most likely entail a build-up of shielding material or structure around the surface habitat and other living modules. Whether it is more cost- and mass-effective to incorporate the shielding into the Altair and associated systems, to land it separately and then attach it, or to fabricate it from regolith on the moon is a topic for further study. Northrop Grumman is pursuing research to understand the shielding properties of regolith. (Miller, et al, 2009, Feb, pp. 263-267).

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[4] Unfortunately, Sv and Gy-Eq are not directly convertible from one to the other without knowing the radiobiological effects and radiation measurements used to compute the dose.

Micrometeoroids

The LM paid rudimentary attention to micrometeoroids, depending on thin aluminum sheets over the multilayer insulation (MLI) -- similar to the material in spacesuits -- to afford a modicum of protection to the vehicle and its crew. This approach was successful during the small number of short duration missions. The LM design team paid particular attention to lightweight micrometeoroid protection based upon the current state of the art. In LEO, MMOD protection was less of a concern for the LM than it will be for Altair. The LM stayed in LEO for only one to two orbits; there was much less accumulation of orbital debris than there is today. The space community now knows a great deal more about micrometeoroids than in the 1960s, including the role they play in shaping the lunar environment.

Micrometeoroid Flux

The continuous bombardment of particles from space has shaped the entire surface of the moon. These particles range from the frequent micron to millimeter-sized meteoroids that contribute to the “constant gardening” of the regolith to objects of a meter or larger that make craters upon impact. The challenge to protecting against micrometeoroids is to determine the range of sizes that pose the primary credible threat and to develop the appropriate probabilistic risk assessment. The outcome of this assessment will necessarily identify the range of particle sizes against which NASA will want to protect the Altair and the Outpost.

The Space Studies Board of the National Research Council addressed micrometeoroids in their landmark 1997 study The Human Exploration of Space, pointing out the many unknowns of the micrometeoroid environment on the moon.

> The use of average collisional fluxes may give a false sense of security as excursion times outside protective habitats increase. . . . Recent reanalysis of lunar seismic data reveals that lunar impacts are neither temporally nor spatially random. Moreover, not all observed meteoroid showers on the Moon correlate with known terrestrial meteor showers.
>
> The potential dangers meteoroids pose to a long-duration presence on the Moon are two-fold. First, there is an increased risk of direct hits during peak activity. Second, there is a risk of high-velocity impacts from secondary and ricocheting debris. The potential for lethal damage depends on the actual flux, the size distribution of the impactors, and the effect of spatially clustered impacts. These unknowns need to be studied over a sufficiently long period not only to assess the short-term risks (day to month), but also to recognize annual events and possible catastrophic swarms during orbital passage of newly discovered comets. (NRC, 1997, p. 38).

In addition to the micrometeoroid threat, Eric L. Christiansen describes the unique lunar threat of secondary ejecta:

> Lunar secondary ejecta are particles of the moon that are ejected during meteoroid impacts on the lunar surface and follow ballistic trajectories to rain back on the surrounding surface. Due to high impact velocity, each primary meteoroid impactor can excavate 100 times its own mass in secondary ejecta particles. These fall back to the surface at 10s to 100s of meters per second, and represent a low-velocity impact hazard to the lunar lander, extravehicular activity (EVA) crew, and surface systems (Christiansen, 2009, p. 16).

Christiansen describes the potentially devastating consequences of a micrometeoroid impact that penetrates a pressurized module with the crew inside:

> For crewed spacecraft, failure of protective shielding allows debris to penetrate through the pressure shell and into the crew cabin volume. Penetrations endanger crew survivability from several standpoints. First, if the hole and cracks in the pressure shell exceed the critical crack length, crack growth will not arrest and can lead to module unzip. Second, the pressure loss may be so fast that the crewmembers are unable to isolate the leak or evacuate successfully. Third, the internal fragments and other effects of a penetration (heat, light, blast/overpressure) can cause crew injury or loss, fail internal pressurized tanks resulting in additional secondary fragment release, or fail internal critical equipment/hardware necessary for vehicle/crew survival (Guidance, Navigation and Control, Environmental Control and Life Support System, etc)(Christiansen et al, 2009, p. 21).

Micrometeoroid Countermeasures

Christiansen (2009) summarizes the history and status of micrometeoroid and orbital debris (MMOD) protective systems:

> Providing effective and efficient MMOD protection is essential for ensuring safe and successful operations of spacecraft and satellites. A variety of shields protects crew modules, external pressurized vessels, and critical equipment from MMOD on the ISS. Certain Space Shuttle Orbiter vehicle systems are hardened from MMOD impact, and operational rules are established to reduce the risk from MMOD (i.e., flight attitudes are selected and late inspection of sensitive thermal protection surfaces are conducted to reduce MMOD impacts). . . . The development of low-weight, effective MMOD protection has enabled these spacecraft missions to be performed successfully. This handbook describes these shielding techniques. For future exploration activities to the moon and Mars, implementing high-performance MMOD shielding will be necessary to meet protection requirements with minimum mass penalty.

Christiansen concludes by asserting the importance of detecting micrometeoroid damage promptly, identifying the location, and applying leak-sealing repairs.

Protection against micrometeoroids consists of two main properties: the strength of the shielding material breaking or resisting the impact and the stand-off depth of the protection. When a particle traveling at several kilometers per second hits the outer layer of sacrificial material known as a bumper or Whipple shield, it breaks up into smaller secondary pieces that continue traveling but spread out behind the “exit wound.” The strength of the protective material helps to determine the size reduction and number of these secondary particles. The depth of the protective shield until the particles hit the next material determines how widely they spread out, reducing the areal density of the kinetic energy release and damage in any one location, in accordance with the inverse square law. The conventional MLI absorbed the energy of the dispersed secondary particles by spreading out the secondary particles to disperse the impact over a much wider area (Christiansen, 2004, p. 17).

Protection against micrometeoroids on the moon will involve both aspects of these countermeasures. For the Altair, it is possible that a conventional MLI approach may suffice, but there are new technologies involving other lightweight materials available such as aramide, aerogel, and carbon foams. The longer a habitat resides on the lunar surface, the greater the risk of being hit by a larger particle that could penetrate the pressure vessel and cause damage and danger to life and mission. The larger the particle, the less practical it is to increase shield strength in a flight vehicle (applying regolith as shielding on the lunar surface is suitable only for a module that does not need to fly again). The more practical solution is to increase the “bumper” stand-off distance. The best solution will incorporate an optimization of shielding mass and structure for standoff distance. One option is to erect or assemble a structure over the outpost, which could also add a measure of radiation protection and thermal attenuation Such a structure would be part of the Outpost, indeed a main point of the Outpost infrastructure.

Dust Conditions

Based on data from the precursor Surveyor program, NASA knew a little about the lunar dust – mainly that it was not so deep that the LM and astronauts would sink into it beyond recovery. There was no anticipation of the problems and hazards that the dust posed, even from short missions of two to three days. Several of the Apollo crewmembers experienced direct health effects of dust exposure including respiratory and skin irritation, and expressed concern that the dust may pose a serious threat to health on future missions, especially longer missions. For the Altair missions, the dust raises a threat that the space community understands much better now than during the Apollo era.

Dust Environment and Science

The depressurized LM opened directly to the vacuum of the lunar environment, so that the crew tracked dust back into the ascent stage cabin. Dust fouled the seals of the Apollo sample boxes, and clogged at least one of the life support system ventilation filters. The challenge of the dust is that even 40 years after the Eagle landed, the scientific and engineering methods of handling dust have advanced very little.

Apollo 17 encountered a larger variety of lunar dust problems because of their longest-ever stay on the lunar surface of 75 hours and their three EVAs lasting a record 22 hours. FIGURE 3 shows the dust accumulation on the crewmembers Harrison Schmitt and Eugene Cernan.

FIGURE 3a. Apollo 17 Astronaut Harrison Schmitt coated in lunar dust during his field investigations. NASA photo.

FIGURE 3b. Apollo 17 Astronaut Eugene Cernan after returning from an EVA in the LM cabin, with dust on his suit and face. NASA photo.

The Apollo 17 crew reported a distinct gunpowder-like odor and respiratory irritation from the intrusive dust. There is increasing evidence to suggest that the inhalation of dust can pose serious medical problems and deposition on the skin or in the eyes can be highly irritating.

One of the most challenging aspects of handling lunar dust and mitigating its effects is that there multiple ways that it can adhere or cling to a surface. Otis R. Walton (2007, p. 1) enumerates these various means of dust adhesion as:

- Mechanical forces due to mechanical attachment,
- Static-electric effects from:
    - UV photo-ionization, or
    - Triboelectric charging from contact transfer of a charge.
- Surface energy-related (Van der Waals) forces, and
- Static-electric-image forces (similar to the xerographic printing process).

Brian O’Brian (2009, abstract), one of the Apollo Program geologists states that with regard to the electrostatic cling:

> Analyses imply this adhesive force weakens as solar angle of incidence decreases. If valid, future lunar astronauts may have greater problems with dust adhesion in the middle half of the day than faced by Apollo missions in early morning. A sun proof shed may provide dust-free working environments on the Moon.

FIGURE 4 shows how Schmitt and Cernan needed to repair one of their lunar rover's fenders in an effort to keep the "rooster tails" of dust away from themselves and their gear. This picture reveals the wheel and improvised fender of their dust-covered rover (NASA, 2004, http://apod.nasa.gov/apod/ap040417.html, accessed 31 July 2009).

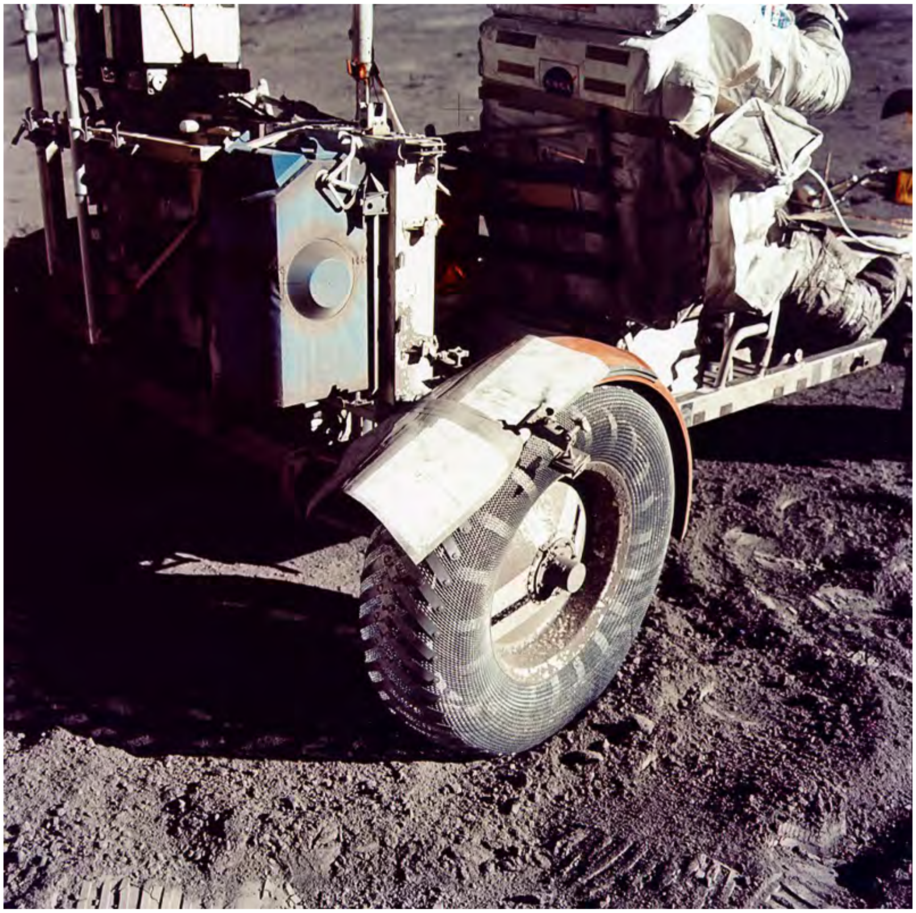

FIGURE 4. Rear wheel fender jury-rigged on the moon by astronauts of Apollo 17 from a plastic notebook parts, maps, and duct tape to prevent the abrasive lunar dust from hitting them while they drove and from damaging the rover.

The known and potential dust effects encompass a wide range of spacecraft and lunar surface systems. In addition to the ventilation system, there is the threat of the dust infiltrating the air revitalization system, including the CO_2 and contaminant removal subsystems. The finer dust particles can invade all kinds of mechanisms and mechanical systems, increasing friction and degrading lubricants. The dust can also affect external surfaces such as windows, radiators, and photovoltaic collectors. Katzan and Edwards (1991, p. 23) reported:

> Though these preliminary calculations bear experimental confirmation, they predict a rather serious threat to radiator performance by the presence of lunar dust, particularly in light of the particle fluences estimated in the previous section. The same types of performance degradation can be expected for photovoltaic surfaces as well.

To these findings, Pirich, Weir, and Leyble (2009, pp. 1-2) add:

> In addition, devices that require transparency to light for maximum efficiency such as solar photovoltaic power systems, video cameras, optical or infrared detectors, and windshields [sic] for various types of vehicles will suffer from the dust accumulation.

Within the space science community there is a new understanding of how the dust conditions appear to vary across the lunar topography. The area of new concern is the Polar Regions, where NASA is expressing interest for the Outpost site. The new research shows that the poles are probably the most active locations for the raising of the dusty plasma atmosphere. These data show:

1. Crew or equipment moving on the surface lofts the dust several meters,
2. The solar day/night terminator lofts the dust electrostatically from 30m to perhaps 100s of meters, and
3. The Earth's electromagnetic wake during lunar eclipses lofts the dust up to 100 km (Stubbs, Vondrak, Farrell, 2005).

The dust flies upward at up to 1000 m/second when activated by the electrostatic or electromagnetic forces, and most of it settles back to the surface. The challenge about the Polar Regions is that the electrostatic terminator continuously affects them, thus the dusty plasma is probably a chronic problem. The four major areas of concern manifested at the 2007 NASA Lunar Dust Workshop (Winterhalter, 2007) held can be summarized:

1. Basic science: characterize and understand dust properties
2. Effects on human health and performance, protection, and mitigation
3. Effects on life support and EVA systems, protection, mitigation, and cleaning, and
4. Effects on mechanisms, including seals and lubrication, and how to protect and maintain them.

Dust Countermeasures

Like the science, the study of dust countermeasures is still in its infancy. The major countermeasure on the table to help protect human health and the life support system is to provide an airlock that will afford a separation zone between the dusty exterior and the clean interior of the Altair and outpost. This airlock appears as part of the Altair in the ESAS Study in two forms: the conventional airlock and the alternate Suitport. There are NASA studies ongoing on a dust-sealing interface between the anticipated EVA suit and the airlock, called the Suitport. However, excluding dust from the cabin interior is only a small part of the challenge. Technologies that may help protect the Altair and outpost against dust include (but are not limited to):

1. Anti-contamination coatings,
2. Electrostatic or electromagnetic repulsion of dust particles,
3. Robotic cleaning of seals, hatches, and mechanisms,
4. Isolation of dust outside the airlock, and
5. Microwave sintering of dust in the vicinity of the outpost.

All of these technologies have a long path ahead to test them and prepare them for application. The design of the Altair will need to take the most mass-effective of these solutions into consideration. Northrop Grumman is investigating one of the most promising technologies are anti-contamination coatings that can prevent dust cling (Pirich, Weir, Leyble, 2009).

Thermal Environment

The extreme thermal cycling during the moon's day night poses one of the abiding environmental threats to human missions. Christie, Plachta, and Hasan (2008, p.2) explain the heating of the lunar surface:

> The heat load on the surface is the product of the solar insolation of 1414 W/m^2, the cosine of the Sun's angle of incidence, and the surface's solar absoptivity of 0.87. A fraction of solar insolation, varying from 0.07 to 0.15 depending on terrain, is reflected from the surface. A "moonshine" value of 0.13 is used herein. The Moon has a black body temperature of 274 K, which is 20 K warmer than the Earth and emits heat with an infrared emissivity of 0.97.

The LMs were designed to operate only within a very narrow climatic band during the first three days after lunar dawn, so that they were exposed to limited thermal extremes. Altair's mission durations will be longer: 7 days for sorties, 14 to 30 days for Outpost construction, and 180 to 210 days for Outpost missions. Christie, Plachta, and Hasan (2008, p.1) summarize the Apollo surface findings:

> The Apollo missions measured surface temperatures at 20° and 26° N latitude that ranged from 102 to 384 K with an average of 254 K. The monthly range was ±140 K. There are no accurate temperature measurements of the polar regions but Clementine data just suggests that it is less than 200 K. Analytical models of Vasavada, et al have predicted day time surface temperatures at 85° N latitude of 225 K, while the nighttime predictions were 70 K.

These longer durations for Altair mean that any sortie to the equatorial or temperate zones will be there at least until the height of the lunar noon when local "hotspot" temperatures can reach ~140° C. These high temperatures will impose demands on many Altair systems including environmental control and life support systems (ECLSS), especially the thermal control subsystems and lubrication.

The Altair thermal insulation, conditioning, heating, cooling, and heat rejection systems will need greater dynamic ranges than the LM to survive under these thermal regimes.

At the opposite extreme, staying through the lunar night means exposure to ~-175° C. Landing in a permanently shadowed crater at the pole could mean sitting in ~70° K (~-200° C). Sending crew and machines into the permanently shadowed regions to seek or extract water ice will pose similar difficulties. These lunar night missions and missions into the cold zones will require heating sources and impose heating demands on the entire ECLSS to prevent freezing in the fluid loops and all the equipment that supplies them.

Lunar Light and Shadow

A concomitant of the extreme lunar cycling are the extremes of blinding light and deep darkness. H. G. Wells, after observing the crispness of the lunar day/night terminator as the lunar dawn moved across the moon’s surface, bringing the topography into sharp relief in the absence of an atmosphere, first predicted this phenomenon in his 1901 novel *The First Men in the Moon*, Chapter 7:

> The eastward cliff was at first merely a starless selvedge to the starry dome. No rosy flush, no creeping pallor, announced the commencing day. . . .
>
> So it was at first, and then, sudden, swift, and amazing, came the lunar day.
>
> The sunlight had crept down the cliff, it touched the drifted masses at its base and incontinently came striding with seven-leagued boots towards us. . . .
>
> Swiftly, steadily, the day approached us. Gray summit after gray summit was overtaken by the blaze and turned to a smoking white intensity. . . .
>
> And then - the sun!
>
> Steadily, inevitably came a brilliant line, came a thin edge of intolerable effulgence that took a circular shape, became a bow, became a blazing sceptre, and hurled a shaft of heat at us as though it was a spear.
>
> It seemed verily to stab my eyes! I cried aloud and turned about blinded, groping for my blanket beneath the bale.

Wells’ melodramatic descriptions were not far from the reality of the brilliant sunlight, untempered by the earth’s protective atmosphere. The Apollo and Soviet Lunokhod missions confirmed this phenomenon. Apparently never having read Wells, the Lunokhod-2 scientists expressed surprise in reporting one of the first direct measurements of the brightness of the lunar sky during the lunar day (landed 15 January 1973 in LeMonnier Crater):

> An astrophotometer was used for measurements of lunar sky brightness in visible and ultraviolet range during day and night. The data obtained showed unexpectedly high values of brightness during the lunar day in the visible region (Severny, Terez, Zvereva, 1975, p. 123).

The Apollo astronauts encountered the extremely bright light too. FIGURE 3 shows the contrast of light and dark on the Apollo 14 LM *Antares*, with the glare of the blinding sun reflected from its surface.

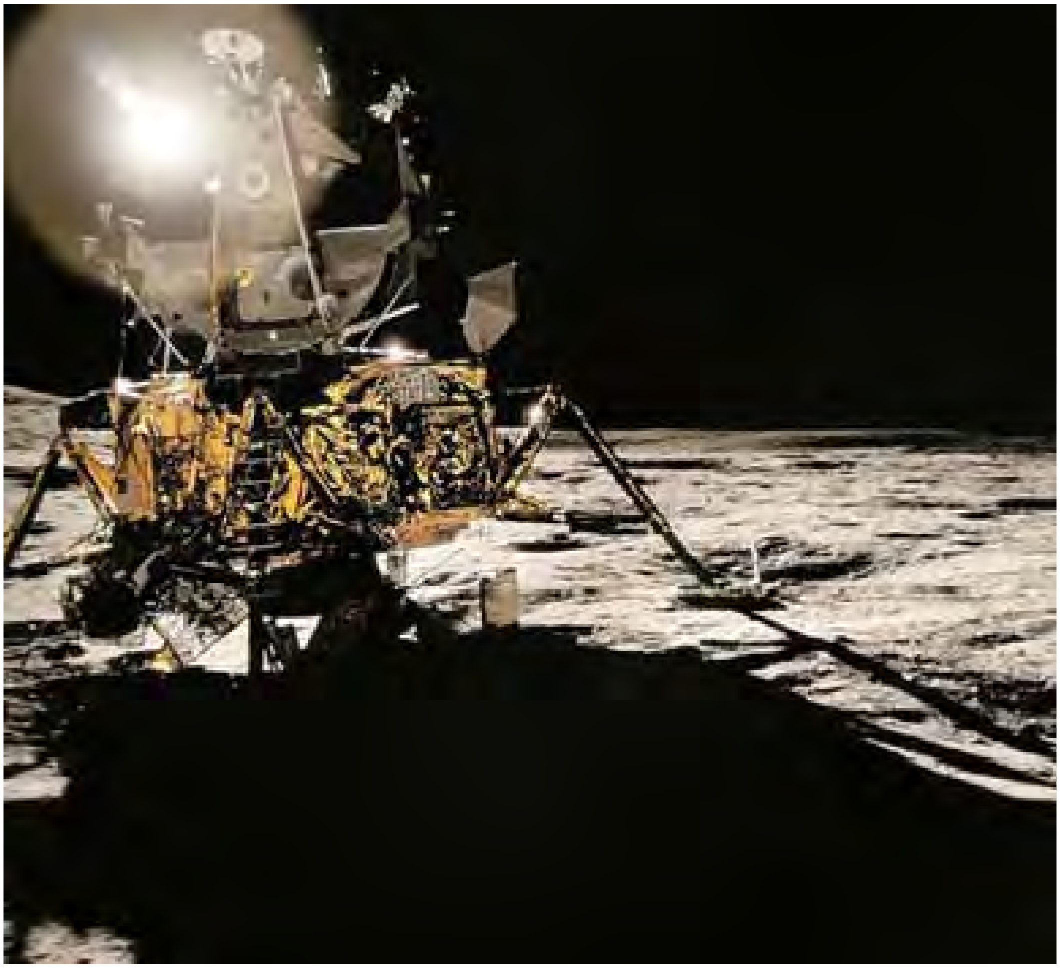

FIGURE 5. Apollo 14 LM *Antares*, showing extreme contrast of light and darkness, with reflected glare of the sun from the LM window. NASA Photo.

The contrast of dark shadow against this brilliant illumination can also pose challenges. This problem of the shadows arose for Pete Conrad and Alan Bean during the Apollo 12 mission:

> Apollo 12 astronauts Pete Conrad and Al Bean landed in the Ocean of Storms only about 600 yards from Surveyor 3, a robotic spacecraft sent by NASA to the moon three years earlier. A key goal of the Apollo 12 mission was to visit Surveyor 3, to retrieve its TV camera, and to see how well the craft had endured the harsh lunar environment. Surveyor 3 sat in a shallow crater where Conrad and Bean could easily get at it--or so mission planners thought.
>
> The astronauts could see Surveyor 3 from their lunar module Intrepid. "I remember the first time I looked at it," recalls Bean. "I thought it was on a slope of 40 degrees. How are we going to get down there? I remember us talking about it in the cabin, about having to use ropes."
>
> But "it turned out [the ground] was real flat," rejoined Conrad.
>
> What happened? When Conrad and Bean landed, the sun was low in the sky. The top of Surveyor 3 was sunlit, while the bottom was in deep darkness. "I was fooled," says Bean, "because, on Earth, if something is sunny on one side and very dark on the other, it has to be on a tremendous slope." In the end, they walked down a gentle 10 degree incline to Surveyor 3--no ropes required (NASA, 30 JAN 2006).

The shaded and tinted helmet visors can help EVA astronauts handle the glare of direct or reflected sunlight. Deep, dark shadows may require the astronauts to carry spotlights, even in the lunar day so that they can see their path. The Altair may need external landing lights for some daytime landings.

IV. Operations

The Altair Operations entail two principle domains: flight operations and surface operations. The ConOps varies with the mission and the Altair configuration.

Concept of Operations (ConOps)

The major challenge of the Altair mission to the lunar surface is the fact that there are three major variants: Sortie, Outpost, and Cargo. The first two, Sortie and Outpost will have crew performing piloting functions both for descent and ascent, and both will be "return anytime-capable." The Cargo lander must fly and land autonomously. In addition, their surface missions are very different.

The *Sortie lander* performs the "go anywhere" global-access mission to sites of scientific, engineering, and in situ resource utilization (ISRU) interest, with the crew living in its own habitation cabin and staging EVAs from its own airlock. The Sortie Lander's mission duration is up to seven days in LLO and seven days on the surface, plus up to 12 hours ascent to rendezvous with the Orion.

The *Outpost lander* flies exclusively to the Lunar Outpost site at Shackleton Crater on the Lunar South Pole. It does not carry a habitat cabin or airlock. The crew uses the Ascent Module as their airlock, depressurizing it to go EVA to traverse to the Outpost. The Outpost Lander's surface stay time is in the range of 180 days for the mission plus 30 days contingency. The LLO loiter time before descent is about 24 hours and the ascent to rendezvous time can be up to 12 hours, although probably only two to 3 hours will be normally necessary.

Finally, the *Cargo Lander* will fly completely automated, without an Ascent Module, habitat, or airlock. It will be capable of hazard avoidance to precision-land at the polar Outpost site where radio beacons will be pre-emplaced and at the sortie sites without pre-planted assets.

The Crew ConOps

The challenge consists of composing a Concept of Operations (ConOps) that takes into account the differences in these vehicles and their intended landing sites, and the degree of judgment the crew must exercise to ensure safe and successful landings. The crew must fly the vehicle under a variety of conditions and time constraints in concert with the mission timeline. Given that the Altair has a complete autonomous landing and hazard avoidance technology (ALHAT) that gives it the ability to fulfill all its functions without the crew, the human factors design for the pilot-in-the-loop becomes a new challenge. Despite the advances in autonomy and vehicle engineering, ***the crew is an essential and inseparable part of the Altair ConOps for Sortie and Outpost missions.*** FIGURE 6 shows the Apollo 12 crew in the LM Simulator in a "fish-eye" photograph that is one of the best portrayals of the crew in the LM, giving it a sense of scale.

Presumably, the Outpost landing zone will be well known and well documented, with radio beacons to guide the Outpost and Cargo landers down to a nearly precision landing. In contrast, the Sortie missions, whether piloted or cargo will need to approach and land over much less well-known terrain, with a much higher probability of unknown obstacles and hazards to landing. These approach trajectories may vary considerably in terms of orbital inclination, descent slope, and trajectory for terminal descent and landing (TDL). On these sortie missions, the crew will prove their unique capabilities of perception and judgment over uncertain terrain.

Flight Parameters

Table 3 presents the flight parameters for the Apollo LM and the Altair. This comparison highlights the distinctions between the two generations of lander. In fact, the similarities are much greater than the differences, but because the Constellation missions are different and more complex than the Apollo missions were, it is valuable to focus on the distinctions.

FIGURE 6. Apollo 12 Crew Members Charles “Pete” Conrad, Jr. & Alan L. Bean in the Apollo LM Flight Simulator, 22 OCT 1969. NASA Photo S69-56699.

Lunar Mission Launch Vehicle(s)

The immediate difference between the Apollo and Constellation lunar missions is that where the Apollo missions used one launch vehicle -- the Saturn V, the Constellation Systems require two launches per mission. The Altair launches first on an Ares V to a parking orbit in LEO to await the crew who launch in the Orion on the Ares I. The nominal wait time for the Altair in LEO is in the range of 4 to 14 days, but the vehicle should be robust enough to last longer.

The Altair will be substantially larger than the LM. The shroud exterior diameter on the Saturn 5 was a maximum of 6.60 m at the base, tapering to 3.9 m at the top, whereas the Altair’s shroud at 10 m at top and bottom is much larger in maximum diameter. The cross-sectional area of the Ares V shroud at 78.50 m^2 is more than twice as large as the area of the Saturn V shroud was at 30.66 m^2.

Rendezvous, Docking, and Crew Transfer

The rendezvous, docking, and crew transfer strategy leads with the important distinction that where Apollo used lunar orbit rendezvous (LOR) for when the LM Ascent Stage returned from the surface to LLO to meet the Apollo CSM, the Constellation mission uses both Earth Orbit Rendezvous (EOR) and LOR. That said, the Constellation rendezvous strategy is similar to Apollo: the piloted vehicle is the active vehicle performing the chase and rendezvous maneuvers. This approach was simple enough in Apollo with the Command Module Pilot remaining on board the capsule while the LM descended to the surface and returned. In EOR, the crew is flying the Orion to rendezvous and dock with Altair. At LOR, there is a significant departure from Apollo, where both the LM and the CSM were piloted. While the LM was the primary active vehicle, the CSM could also maneuver in LLO, which was part of the LM rescue plan. For the Constellation Systems, only the Altair is piloted and active, therefore the Altair AM performs the chase, rendezvous and docking. FIGURE 7 shows the first Apollo test of crew transfer, rendezvous, and docking of during the Apollo 9 mission. The principles are the same for Altair and Orion.

TABLE 3. Apollo Program and Constellation Systems Flight Parameters

Flight Parameters	Apollo 17 Lunar Module	Altair Lunar Lander NG IR&D
Lunar Mission Launch Vehicle		
Crew Launch Vehicle	Apollo CSM and LM launched on Saturn V	Orion CEV launch on Ares I
Lander Launch Vehicle		Altair launch on Ares V
Lander Launch Shroud Diameter	6.6 m exterior / 6.2 m interior	10.0 m exterior / 8.4 m Interior
Shroud Area	30.66 m^2	78.50 m^2
Rendezvous, Docking, Crew Transfer		
Rendezvous Mode	Lunar Orbit Rendezvous	Earth Orbit Rendezvous & Lunar Orbit Rendezvous
LEO Chase & Rendezvous	None	Orion active; Altair & EDS passive
LLO Chase & Rendezvous	CSM active, LM nominally passive	Altair active; Orion passive
Crew Transfer from Earth Return Capsule to Lander	Docking Hatch & Tunnel	LIDS Hatch & Tunnel
Crew Transfer from Lander to Earth Return Capsule		LIDS Hatch & Tunnel; Contingency EVA return
Mass at Trans-Lunar Injection[5],[6] including payload		
Command / Crew Module	5,935 kg	8,900 kg
Service Module	24,772 kg	12,300 kg
Descent Stage/Module	11,641 kg	33,800 kg
Ascent Stage/Module	4,796 kg	6,800 kg
Airlock	N/A	1,300 kg
TOTAL VEHICLE AT TLI	47,144 kg	63,100 kg
Payloads to and from the Surface		
Down payload mass	309 kg scientific & comm equipment	500 kg Unspecified
Up payload mass (after weighing the crew and their flight suits)	110 kg samples + 110 kg PLSSs = 220 kg	250 kg, of which 100 kg is for ESMD Scientific Samples, Engineering & ISRU return.
Number of Crew		
On the Mission	3	4
Remain in Low Lunar Orbit	1	0
Propulsive Maneuvers		
Lunar Orbit Insertion Burn	Apollo Service Module	Altair Descent Module
Descent and Landing Propulsion	LM Descent Stage	Altair Descent Module

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[5] Mass properties provided by Oliver Philippi, Northrop Grumman.
[6] NASA (1969, August 20). CSM/LM Spacecraft Operational Data Book, Vol. III Mass Properties, Rev. 2. p. 3.1-2.

FIGURE 7. Apollo 9 Flight Test in LEO, with the LM “Spider” 7 March 1969.
NASA Photo AS09-21-3199.

For Constellation, there will not be an Orion pilot waiting for a week in LLO; all four crew descend to the surface in Altair. Therefore, when the crew returns from the surface, they will both fly the Altair and command the Orion remotely through the rendezvous and docking process. The baseline crew transfer in Constellation will occur essentially the same way as in Apollo, through a pressurized hatch (Low Impact Docking System or LIDS) at the frusto-conical flat end of the Orion to a corresponding LIDS port on the Altair. Altair adds the contingency option that if for some reason the LIDS mechanism fails or its hatches will not open, the crew can go EVA from the Altair to the Orion on umbilicals via the corresponding EVA hatches. FIGURE 8 shows the final CSM and LM rendezvous when the Apollo 17 LM Ascent Stage returned to the CSM.

Mass at Trans-Lunar Injection

The vehicle mass at TLI tells a great deal about its capability and the robustness of the program that delivered it to that point of departure. TABLE 3 shows that the Apollo stack of CSM and LM mass equaled 47,144 kg compared to the Altair and Orion 63,100 kg, approximate gross mass (fully fueled but not including cargo) at trans-lunar injection. The major difference in mass allocation reflects the shift of the LOI burn from the Apollo Service Module to the Altair Descent Module. Another potential difference derives from the opportunity to change from hypergolic fuels on the LM to liquid oxygen/liquid hydrogen (LOX/LH2) on Altair—at least for the DM—allowing a lower propellant mass fraction.

Minimum Payload Mass

The CARD requires a minimum down payload to the lunar surface on Altair of 500 kg and a minimum up payload from the surface of 100 kg. These payload masses compare as “in the ballpark” with the Apollo 17 payloads of 309 kg down mass and 110 kg up mass of scientific sample return. However, the Altair 100 kg up mass dedicated to ESMD payloads will be apportioned among several constituencies besides science. Altair up mass, particularly from the Lunar Outpost will include

ISRU samples, engineering tests such as long duration exposure experiments. Engineering payloads include hardware experiments and failed or broken equipment needing analysis to understand the failure and improve reliability.

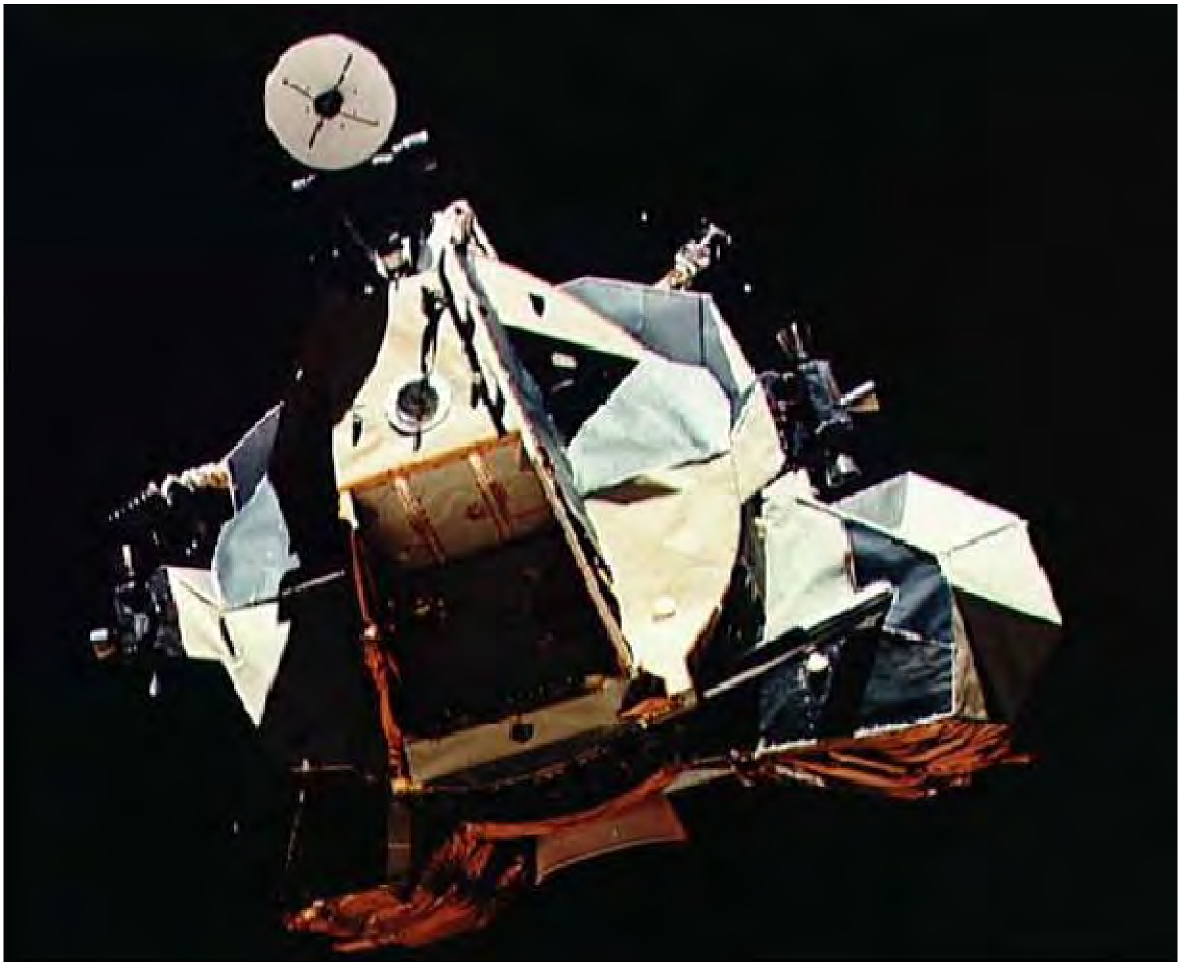

FIGURE 8. Apollo 17 LM Ascent Stage Challenger in return to the CSM America before rendezvous & docking. NASA Photo14 December 1972.

The CARD does not address whether the down payload is pressurized or unpressurized; presumably, it could be either or some of each. However, the up payload must all be pressurized because the Altair Ascent Module crew cabin appears to be the only place to put it for return to LLO. According to the Constellation Systems ground rule, EVA should not be part of the baseline for routine in-space flight operations. If it were possible to attach an up payload externally to the Ascent Module, it would necessitate a “routine” EVA operation to move it to the Orion, violating the contingency-only rule for in-flight EVAs.

Crew in the Lander

Constellation doubles the number of crew descending to the surface from two in the LM to four in Altair. On Apollo, both those crewmembers were experienced pilots; both were capable of flying and landing the LM. On Altair, there will be two pilots and two mission specialists whose real jobs do not begin until they land safely on the lunar surface. Because of the Go-Anywhere and Return Anytime requirements, the crew time in the Altair for some missions may prove much longer than the Apollo missions. TABLE 4 shows the range of mission phase durations and total potential crew mission time.

TABLE 4. Apollo LM and Altair Sortie Crew Mission Phase Times. Thanks to Warren James, Northrop Grumman Aerospace Systems for providing this data.

Mission Phase	Apollo-15, -16, -17 LM	Altair
Uncrewed Low Earth Orbit Loiter	N/A	Uncrewed 64 to 224 Orbits (4 to 14 days)
Crewed Low Earth Orbit Loiter	Crew in CSM: 3 Orbits Nominal, 4 Orbits provided (4.5 to 6 hours)	Crew in Orion: 2 days (assumes Orion arrives 2 days before TLI).
Trans-Lunar Injection Time	3 to 3.25 days	3 to 6 days
Time in Low Lunar Orbit before Descent	1 day	1 to 7 days
Time on the Lunar Surface	3.125 days (Apollo-17)	7 days
Time in LLO after Ascent and Before Trans- Earth Injection	1 day	1 to 6 days
Trans-Earth Injection Time	3 days	3 to 6 days
TOTAL Crew Time in Vehicle(s)	~11 to 12.5 days	~17 to 34 days

Propulsive Maneuvers in Lunar Orbit

Finally, there is an important difference between Apollo and Constellation in terms of the propulsive maneuvers. On Apollo, the Service Module engine performed the Lunar Orbit Insertion (LOI) burn and then the LM Descent Stage Engine performed the descent and landing burns. However, Constellation puts this critical 1,000 m/sec LOI burn on the Altair Descent Module (DM) engine, which next also performs the 1,800 m/sec descent burn. Because of the rocket equation, the LOI burn consumes half the DM propellant. This difference means that the Altair carries a substantially larger propellant capacity in its Descent Module than the Apollo LM did in its Descent Stage.

For an Outpost mission, the Orion/Altair ensemble will inject into a polar orbit. For a “Go-Anywhere” Global Access mission, the mated vehicles may go into polar orbit or into an orbit of lesser inclination. Regardless of the orbital inclination, after arriving in LLO and circularizing the orbit, the next phase involves waiting for the moon to rotate below until it aligns the trajectory with the intended landing site. This waiting for the precession of the orbit can take up to six days (in addition to the standard one day of a nominal mission), depending upon where the moon is in its rotational cycle upon arrival of the Orion/Altair combination. Once the orbit aligns to the descent trajectory, the crew can fire the descent initiation burn, and they are on their way to landing. The complement of the “land anywhere” capability is the “return any time” requirement. Return Anytime means that if the crew needs to evacuate from the lunar surface before the planned completion of their mission, they can launch to LLO and rendezvous with the Orion. The mission design impact of Go Anywhere/Return Anytime will drive the sizing of the ascent and rendezvous Delta V, making it larger than on Apollo. The 12-hour battery capability on the Altair Ascent Module is central to providing this assurance, as it was on the Apollo LM.

Lunar Surface Operations

TABLE 5 presents the salient characteristics of the Apollo LM and the Constellation Altair for the lunar surface mission. Although Apollo and Constellation exhibit important differences in getting to the Moon, there has yet to be detailed work on how the Altair would enable a more capable sortie than the Apollo LM. Instead, most of the focus to date on the increased Altair capability concerns how the uncrewed Cargo Lander variant would support the construction of the Lunar Outpost. The most recent surface systems manifest shows a cargo flight delivering two pressurized rovers; the crew lives in these rovers for the next crewed mission. A subsequent cargo flight delivers a surface habitat that will become part of the Outpost.

TABLE 5. Comparison of Apollo 17 to Altair Crew Surface Operations Parameters.

Surface Operations Parameter	Apollo 17 Lunar Module (NASM, 2009)	Altair Lunar Lander (NGC LLDS, 2008)
Crew & Crew Time on the Surface		
Number of crew on the lunar surface	2	4
Mission duration on the lunar surface	3 days	7 days
Surface IVA Hours	53 hours	120 hours
Science on the Surface		
EVA Science	Collect samples for return to earth	Collect samples and perform in situ analysis with instruments
IVA Science	None	Test samples destructively in a “glovebox” in the crew cabin
Extravehicular Activity		
Number of buddy pair EVAs	3	6
Typical EVA time	7 hours	8 hours
Total buddy pair EVA time (x2 crew)	22 hours	48 hours
Rover	Unpressurized Lunar Roving Vehicle (LRV)	TBD
Pressurized Volume	**TOTAL = 6.65 m^3**	**Average = 27 m^3**
Piloting Function	6.65 m^3	8 to 10 m^3
Habitat Function		9 to 11 m^3
Airlock Function		8 m^3
Pressurized Volume / Crew Member	**Average = 3.325 m^3**	**Average = 4.75 m^3, exclusive of the Airlock**
Piloting Function	3.325 m^3	2 to 2.5 m^3
Habitat Function		2.25 to 2.75 m^3
Airlock Function		4 m^3 for 2 crew per EVA

Crew and Crew Time on the Lunar Surface

Altair doubles the number of crew on the lunar surface over Apollo, from two to four, and more than doubles their nominal surface mission time from the Apollo 17 maximum of 75 hours to 168 hours. Of this surface time, the crew spends 48 hours in six buddy-pair EVAs, compared to 22 hours on three EVAs on Apollo 17. Conversely, the Apollo 17 crew spent 53 hours of IVA time in the LM, including sleeping three “nights.” The Altair crew spends 120 hours of IVA time with all crew in the cabin, and another approximately 24 hours with two crew in the cabin while the others are out EVA. According to the timeline that Northrop Grumman used for the 2008 Lunar Lander Development Study, after landing, the crew would spend a 6-hour “daytime” (completing the day that began with preparation for the descent initiation burn in LLO) on the lunar surface, then sleep for the ”night” and commence EVA the next day.

Science on the Surface

Science on the surface is a “flagship” mission where the Altair’s capabilities have yet to come into alignment with the prospective mission objectives. During the six Apollo landings, the crew deployed various instruments and pursued geology by collecting samples of regolith, rocks, and dust. It was only on the last Apollo mission that a true geologist, Harrison Schmitt, brought an expert’s eye to the terrain. In all the Apollo missions, there was no capability to assess the lunar materials in real time on the surface beyond the simplest visual inspection and what Schmitt could do with a rock hammer. Apollo 17 returned 110 kg up mass payload of lunar samples.

The Altair will offer an up mass capability of 250 kg, of which 100 kg may be dedicated for science return; presumably, the scientists will be obliged to share it with other research missions such as ISRU and environmental exposure experiments. This reduction in up mass for scientific samples will place a much greater burden on the Altair's ability to support real time science on the surface. This real time science need will go far beyond better instruments for the crew to employ during EVAs. As on Apollo, the crew will need to climb the Altair ladder to bring sample containers into the cabin. FIGURE 9 shows Alan Bean descending the ladder from the EVA hatch on Apollo 12 LM Intrepid. The crew will need the ability to put samples into a "glovebox" accessible from the crew cabin where they can test samples destructively, using sensitive instruments. Then they will need to be able to remove selected samples into archival containers for further study and return to the earth.

FIGURE 9. Alan Bean descends the ladder from the Apollo 12 LM *Intrepid* on the Lunar Surface. NASA Photo.

Pressurized Volume

One area where the Altair far exceeds the Apollo LM is in providing pressurized volume to the crew for mission operations and their living and working environment. The Apollo LM provided 6.65 m^3 of pressurized volume for a volume per crewmember of 3.325 m^3. We have demonstrated previously that the engineering value for pressurized volume is more reliable and exact than vaguely defined and inconsistently measured "habitable" volume (Cohen, 2008, p. 2). The Apollo LM cabin served as pilot station, habitat, and EVA airlock, all in one. Based upon the 2008 LLDS, the Altair provides from 23 to 27 m^3 of pressurized volume, distributed over the Ascent Module, the Habitat function or module, and the EVA Airlock. Once the EVA Airlock goes into use, it will become contaminated with lunar dust, and so no longer be suitable for the habitable living environment. The subtraction of the 8 m^3 airlock from the livable pressurized volume reduces the amount per crewmember to the range of 3.75 to 4.75 m^3/crew member, which puts it in the ballpark of the Apollo LM, given the greater quantity of internal equipment in Altair. Since the goal for the Ascent Module is to minimize its mass and volume to minimize the mass driven by the propellant "gear ratio," the logical place to install a science lab is in the Altair habitat module. This module would remain with the Descent Module on the surface after the Ascent Module fires its engine to return to LLO.

V. DESIGN AND ENGINEERING

FIGURE 10a shows the Lunar Test Article 1 (LTA-1) Apollo LM Ascent Stage sitting atop the Descent Stage. Virtually every aspect of this vehicle was engineered and designed to withstand the dynamic flight environment, the vacuum of space, and the conditions on the lunar surface. FIGURE 10b shows a detailed view of the Ascent stage with the EVA hatch and the piloting window. The ribbed Iconel crew cabin marked a great milestone in the development of lightweight structures, with the skin of the pressure vessel only about 2.5 mm thick. The thermal insulation and micrometeoroid bumpers were installed over this structure.

FIGURE 10a. Apollo LTA-1 LM structural prototype at the Cradle of Aviation Museum, Long Island, NY. Photos by author.

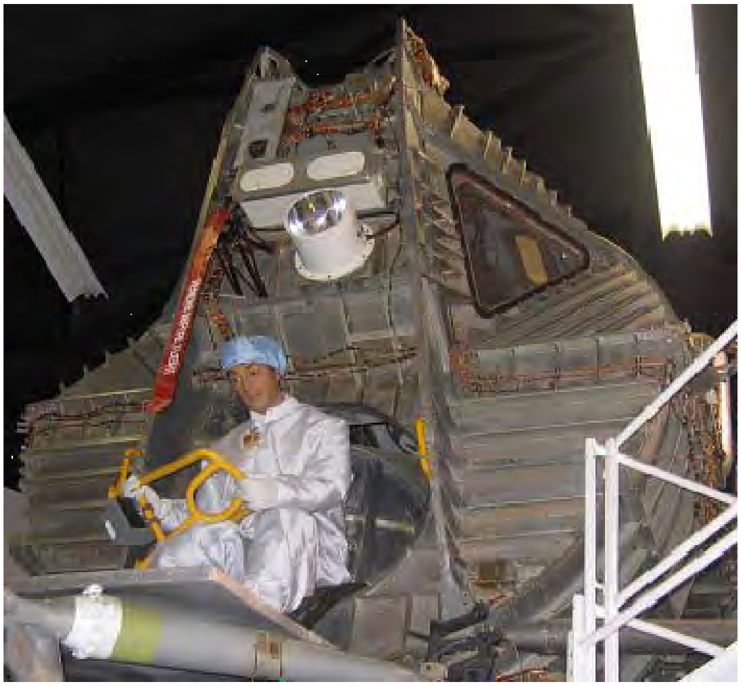

FIGURE 10b. Detail of Apollo LTA-1 LM pressure vessel structure showing rib-backed Iconel and pilot window. Cradle of Aviation Museum.

FIGURE 11 shows NASA's Lunar Development Analysis Cycle One (LDAC-1) Altair on the moon. It marks a dramatic change in size from the LM. The top deck of the LM Descent Stage was about 3 m above the surface; the top deck of the Altair Descent Module will be about six to seven meters above the surface. The reason for this greater height is the much greater volume of the tanks for the cryogenic propellants, which appear in this figure wrapped in silver MLI. In addition to the AM, the small cylindrical module on the top deck with the outboard thrusters on truss booms, the Altair carries the EVA airlock, which sits behind the AM.

FIGURE 12 illustrates the three Altair variants from LDAC-3. The LDAC-3 iteration shows the tanks on the DM enclosed in an orange-colored common micrometeoroid and thermal cover. FIGURE 12a shows the Sortie variant, with the EVA Airlock visible behind the AM. FIGURE 12b shows the Outpost variant, on which an equivalent mass of down cargo would replace the EVA Airlock. FIGURE 12c shows the Cargo variant, on which more cargo would replace the AM. In other respects, these Altair DMs would be identical to one another, maximizing the commonality among the variants.

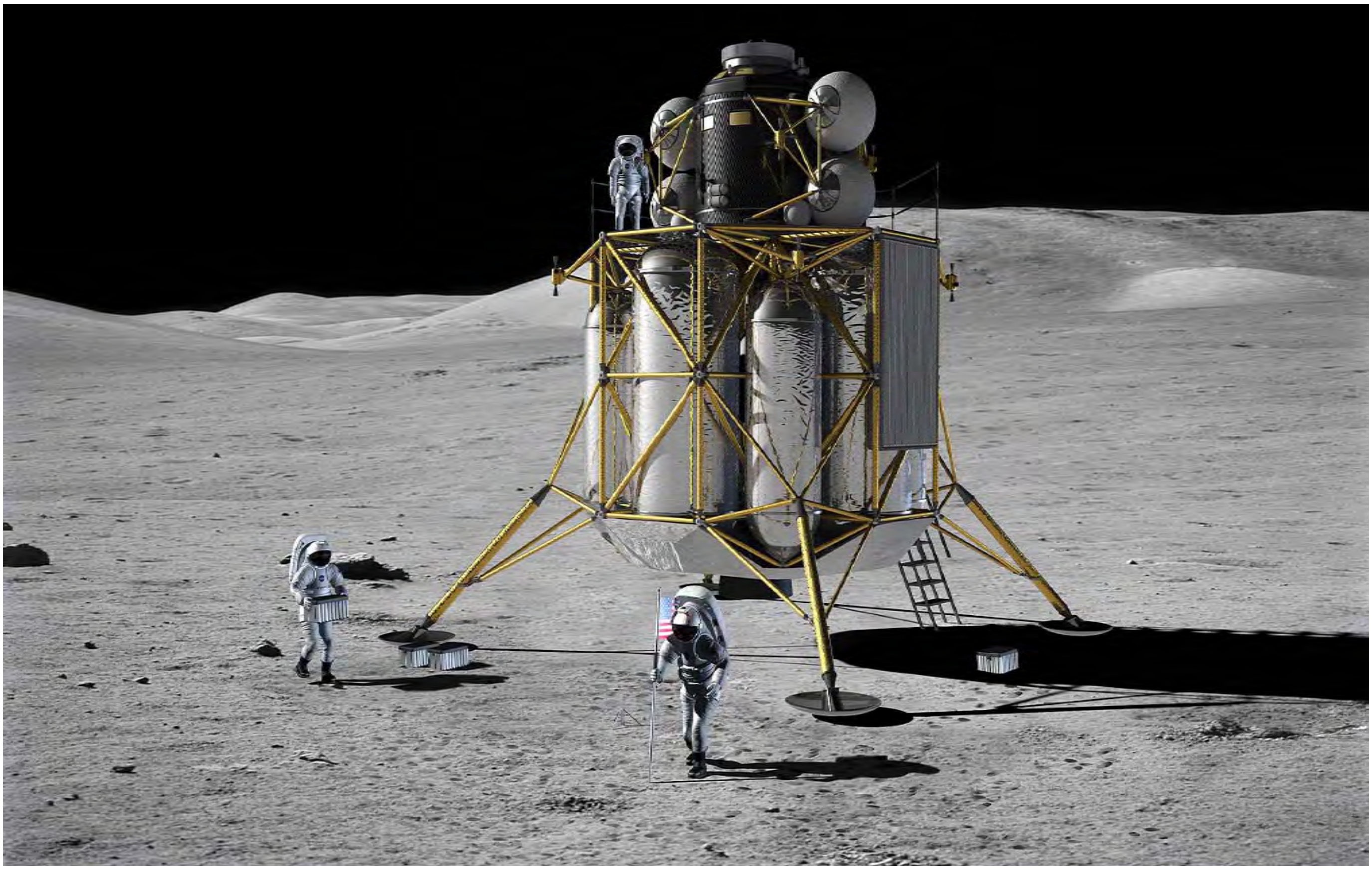

FIGURE 11. Altair LDAC-1 concept on the Lunar Surface. NASA image courtesy of Clint Dorris.

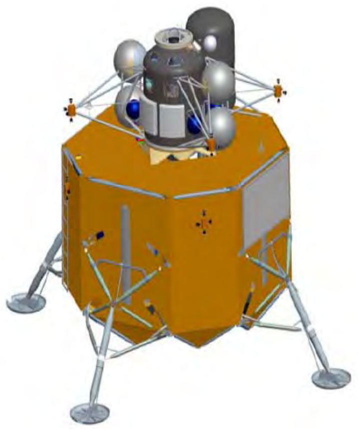

FIGURE 12a. Altair LDAC-3 Sortie Lander consisting of Ascent Module, EVA Airlock, and Descent Module.

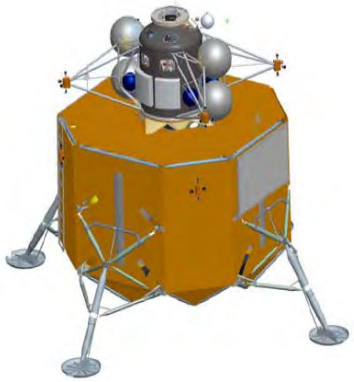

FIGURE 12b. Altair LDAC-3 Outpost Lander consisting of Ascent Module and Descent Module.
NASA images courtesy of Clint Dorris.

FIGURE 12c. Altair LDAC-3 Cargo Lander consisting of the Descent Module.
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Design and Engineering Standards

Design and engineering standards have advanced far beyond their status in the 1960s. There are many more documented standards of all kinds, and they nearly all tend to be more conservative than the standards, practices, and rules of thumb that prevailed during the Apollo program. The baseline today is that many of the risks that Apollo endured simply could not be accepted today by any engineering organization that exercised due diligence and the professional standard of care. NASA maintains extensive organizations dedicated to safety and mission assurance, and especially to protecting the health and safety of the crew. In nearly every hazard described above, these NASA organizations play a role and have important concerns to express.

A prime example of such a standard comes from NASA STD-3000, a compendium of nearly everything collected as "lessons learned," empirical, and experimental results that derive from humans in space vehicles. The key areas include ergonomics, human factors, life support, habitability, food systems, sleep, exercise, and internal architecture such as minimum circulation cross-sections. During Apollo, the knowledge to create this standard did not exist, although most of the formative observation and work occurred during the Apollo-Skylab Program in 1973-1974. Originally entitled the Man-Systems Integration Standard, NASA STD-3000 was first published in 1987, with the first major revision in 1995. In 1999, a Space Station-specific customized version came out under the title International Space Station Crew Integration Standard, (NASA STD-3000/T, also designated SSP 50005). In December, 2005, NASA released the Human-Systems Integration Requirements (HSIR), CXP-01000, a significant condensation and customization of the MSIS for the Crew Exploration Vehicle (CEV) Program. On 15 DEC, 2006, NASA reissued an extensively revised HSIR, with the new number CxP-70024. In 2006, NASA also announced a new effort to extensively rewrite and condense NASA STD-3000 as the *Human System Integration Standard*.

Life Support Example[7]

The CO_2 removal subsystem gives an example of a technological advance from Apollo to Constellation, exerting a transformational effect on the environmental control and life support system (ECLSS). Both the Apollo CSM and LM used lithium hydroxide (LiOH) canisters for CO_2 removal from the cabin atmosphere -- the square "filters" that had to be made to fit into a round hole made famous in Apollo 13: Lost Moon (Lovell, Kluger, 1995). Each of these canisters has a time limit before it becomes necessary to replace them; the spacecraft must carry sufficient supplies, which take up volume both before and after use. In principle, how many single-use LiOH canisters the spacecraft can carry would limit the Apollo mission duration.

Regenerable Air Revitalization

The Constellation Orion and Altair use a new and more reusable system for CO_2 removal, *amine swing beds*. The CO_2 removal subsystem consists of two swing beds, each of them regenerable and reusable throughout the mission. One bed adsorbs the CO_2 by causing the CO_2 to adhere to the surface of the amine and then it discharges its adsorbent material to vacuum while the second amine bed performs the adsorption. When the second bed is saturated, it begins discharging its CO_2 to vacuum while the first bed resumes the process. The amine beds offer a system that eliminates the needs for regular replacement of spares during the period of Orion and Altair missions, allowing the ECLSS to be more compact, lighter weight, and more reliable. Because the amine bed system is more self-sufficient and reliable than the Apollo era LiOH, it requires less crew time for operations and maintenance.

Atmosphere Selection

The Apollo LM used the same atmosphere selection in flight as the Command Module: 34.5 kPa (5.0 psia) of 100 percent pure oxygen. At the time, there were persuasive engineering arguments for this atmosphere design, despite the tragic and fatal Apollo 204 (Apollo 1) fire in February 1967; NASA took many other precautions to prevent a fire from reoccurring. In retrospect, the reasons for this cabin atmosphere design were that (Bonura, Nelson, 1967; Seamans, 1967, p. 4):

1. The reduced atmospheric pressure allowed less Delta P across the pressure vessel structure, so that it could be much lighter in weight,
2. The Apollo CSM operated at 34.5 kPa, so operating LM at the same pressure and gas mix meant there was no need to adjust or equalize pressure between the two vehicles.
3. The space suits operated at 34.5 kPa, so there was no need to loose time on adjusting pressures or on prebreathing to prevent aerospace bends from nitrogen in the cabin atmosphere, and
4. It was much easier and more reliable to monitor the oxygen pressure with pure oxygen than when there was a buffer gas.

The Skylab crews lived at the Apollo atmospheric pressure of 34.5 kPa but with a modified gas mix of 70 percent oxygen and 30 percent nitrogen (Skylab Program Office, May 1974, p. 2.2.3.1) from 28 days on Skylab 2 up to 84 days on Skylab 4.

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[7] Thanks to Don Sandersfeld for his insights and mentorship on life support.

According to Hanford, the crew “reported numerous discomforting effects” (p. 48 footnote). The Skylab crews also reported poor audible voice transmission in the 34.5 kPa atmosphere (Skylab Program Office, August 1974, p. 167).

Altair will operate at 70.3 kPa (10.2 psia), the same pressure as the Orion, at least when they are docked (Anderson, Curley, Stambaugh, Rotter; 2009, p. 9). The Altair may retain the LDAC-1 “minimum functionality’ capability of operating at 57 kPa (8.3 psia) (Anderson, Curley, Stambaugh, Rotter, 2009, p. 4), the threshold for not needing to prebreathe pure oxygen before going EVA. The fraction of oxygen will range from a low of 18 percent to a high of 23.1 percent (Hanford, 2006, p.48). Nitrogen will serve as the buffer gas. NASA selected the pressure of 70.3 kPa because it represents a balance between reducing the EVA prebreathe time to about one hour (compared to the three hours on the ISS with its 100 kPa atmosphere) and maintaining enough buffer gas to stay above the threshold of increased flammability in a hypobaric atmosphere. This cabin atmosphere is also better suited to maintain crew health and comfort over a longer duration than the Apollo missions.

Contaminant Detection

Another advance in the life support arena concerns detection of contaminants. Apollo used electrochemical sensors that were battery-like devices designed to conduct electricity when a specific contaminant came in contact with them. Each electrochemical sensor served to detect only one species of contaminant molecule. They drifted constantly from their baseline set point and had lifetimes of variable duration. The Orion and Altair life support systems use a modern mass constituent analyzer (MCA). The MCA incorporates a mass spectrometer that can detect and identify many different gas species. It has a long life and requires little or no maintenance during a mission.

VI. Conclusion

Given what NASA and the space community knows today, the Apollo program was amazingly successful to return all the flight crews safely to the Earth, and for all the missions except Apollo 13 to complete their planned itineraries. A large part of the success of Apollo was due to very rigorous reliability and contingency planning – and a lot more testing than typically gets performed today. However, the evolution of NASA’s requirements for the Altair in terms of mission, environments, and standards means that the Altair will be a very different vehicle than the LM. TABLE 6 shows a top-level comparison of the topics addressed in this essay. The path to success for Altair is to recognize the limits of comparability. Certainly, the common subsystems are candidates for replacement with modern methods, process, technologies, materials, and structures. However, equally important is to distinguish the new requirements that the march of progress described here levies upon the new vehicle, and to separate them from the comparison.

The things the LM and Altair have in common such as propulsion, tankage, structure, power, communications, avionics, GNC, etc, are amenable to comparison, but they are all conventional, well-known disciplines. Given that Altair optimizes the functions that correspond to the LM’s capabilities, the resulting margins in mass, power, propellant, communications bandwidth, and other reserves enable Altair to meet more demanding requirements, assert a larger performance envelope, and offer new and better capabilities.

This essay addresses the five domains of design, environments, infrastructure, missions, and operations as the indicia that show the evolution from LM to Altair. While each of these domains affords a major distinction between the two generations of vehicle, one of them exerts the most important influence: environments. The major differences between LM and Altair derive predominantly from the environmental threats that may make or break the Altair and Outpost missions: thermal, radiation, micrometeoroid, dust, and possibly other threats not yet recognized. All four of the other domains respond to the expanded understanding of the lunar environments through the enhanced analysis, engineering, and planning that characterize the Constellation Program.

Northrop Grumman is engaged in research and development to understand better these environmental threats. This research provides the basis for engineering analysis, operational protocols, mission planning, and design development to create new solutions that will enable Altair to fulfill the Vision for Space Exploration.

TABLE 6. Comparison of the Differing Requirements for the Apollo LM and the Altair.

Requirements	Apollo LM	Constellation Altair
MISSION		
Landing Sites	Equatorial and temperate zones on the nearside.	Go anywhere; set up Outpost at South Pole.
Crew	2	4
Sortie Mission Duration	2 to 3 days on the lunar surface. 10 to 12 day total mission.	17 to 46 days total mission with LEO loiter, 7 days on the lunar surface.
Mission Strategy	“Flag and Footsteps” sortie	Outpost-first, then go-anywhere.
ENVIRONMENTS		
Thermal	3 days at the lunar dawn ensured minimum of thermal extremes.	Hot lunar day ~140° C, 6 month Outpost: ~-100° C night. South Pole permanently shadowed crater: ~-~70° K.
Radiation Career Exposure Limits	4 Sv (400 REM) 1970.	0.9 Sv female, 1.4 Sv male, 1997; 0.6 Gy-Eq. female, 1.0 Gy-Eq. male, 2000
Micrometeoroid Flux	MLI bumpers	TBD
Lunar Dust	Determined only that LM & crew would not sink in dust. EVA: Depress Cabin.	Dust is recognized as a major threat to crew health, life support, EVA systems, & mechanisms. Airlock for dust exclusion.
DESIGN and	**ENGINEERING**	**STANDARDS**
Availability of Design Guidelines & Standards	Apollo Program mostly wrote them as they went.	Extensive NASA and Industry Standards impose constraints.
Human System Integration	First NASA standards came out of Apollo-Skylab.	3rd major revision of NASA STD-3000 HSIS in progress.
SYSTEM OVERHEAD	**And INFRASTRUCTURE**	
Safety	Apollo was fortunate with tight safety margins and accepted risks.	NASA is more conservative now about safety, mission assurance, and acceptable risk.
Multi-Use	LM was single-function for a single mission objective.	LL will be multi-function for multiple mission objectives.
Operability and Autonomy	Houston instructed astronauts step-by-step, switch-by-switch	LL will have much greater autonomy, rely more on crew decision-making.
Interfaces	Simple interfaces, few processors	Many complex interfaces & processors.
Telecommunications	Limited bandwidth, data rate, poor video images	High bandwidth, very high data rates, hi-resolution video.

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