

# **Altair Lander Life Support: Design Analysis Cycles 1, 2, and 3**

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## **ABSTRACT**

NASA is working to develop a new lunar lander to support lunar exploration. The development process that the Altair project is using for this vehicle is unlike most others. In “Lander Design Analysis Cycle 1” (LDAC-1), a single-string, minimum functionality design concept was developed, including life support systems for different vehicle configuration concepts, first for a combination of an ascent vehicle and a habitat with integral airlocks, and then for a combined ascent vehicle-habitat with a detachable airlock. In LDAC-2, the Altair team took the ascent vehicle-habitat with detachable airlock and analyzed the design for the components that were the largest contributors to the risk of loss of crew (LOC). For life support, the largest drivers were related to oxygen supply and carbon dioxide control. Integrated abort options were developed at the vehicle level. Many life support failures were not considered to result in LOC because they had a long enough time to effect that abort was considered a feasible option to safely end the mission before the situation became life threatening. These failures were then classified as loss of mission (LOM) failures. Many options to reduce LOC risk were considered, and mass efficient solutions to the LOC problems were added to the vehicle design at the end of LDAC-2. In LDAC-3, the new design was analyzed for large contributors to the risk of LOM. To avoid ending the mission early or being unable to accomplish goals like performing all planned extravehicular activities (EVAs), various options were assessed for their combination of risk reduction and mass cost. This paper outlines the major assumptions, design features, and decisions related to the development of the life support system for the Altair project through LDAC-3.

## **Introduction: The Altair Project**

The Constellation Program is an ambitious effort that has been said by some to include the efforts of Apollo with the Orion Crew Exploration Vehicle (CEV) and Altair Lander Lunar missions, the Space Shuttle with Orion CEV missions to the International Space Station (ISS), and the ISS with the establishment of continuous human presence on the moon. Whether one agrees with that statement or not, there is no doubt that it is a significant effort with significant funding challenges in NASA’s current environment.

In 2006, a study was conducted by a NASA internal team from multiple centers to identify the costs of a Lunar Lander development effort based on traditional standards for agency large scale projects. Funding for an effort that large would not have fit into the agency’s budget until 2011 or 2012, leaving very little time before the intended human return to the moon in 2020.

Instead of waiting, a small NASA internal team was formed in 2007 to begin exploring design and requirements issues for the Lunar Lander. The initial team included approximately

50 people focusing on a basic design concept to establish feasibility for a Lander concept. This design was the “Minimum Functionality” Lander.

Eventually, this team officially became NASA’s Altair Project within the Constellation Program. The team has grown in size as the design has grown more robust, more complex, and more detailed. Overtime NASA’s interaction with the contractor community on Altair has grown as well.

#### Altair Life Support System Functions

It is important to define what functions are included in the life support system. Previous vehicles have had a range of functions included as part of life support. Sometimes thermal control and life support are grouped together as “Environmental Control and Life Support System” (ECLSS). The interface line between life support and EVA systems can vary as well. Airlock components, consumable conditioning, and other functions might be included in either system. Sometimes crew accommodations life food, clothing, hygiene facilities, and medical equipment and sensors are included in life support, and sometimes as a separate system.

For Altair, the Life Support system controls the environment of the crewmembers within certain standards to protect their health. Controlling the environment includes the temperature, total pressure, oxygen, nitrogen, humidity, carbon dioxide, trace gas levels and odors, and particulates in the air or breathing gas of the habitable volumes such as the cabin and airlock. The Altair project started with a very small team, so many functions that historically are separated into unique subsystems were grouped together initially. Also dividing lines were drawn to split functions that might have been together in other vehicles.

The life support system also provides gas and liquid consumables (air and water, but not food) for the crewmembers. For now, the life support system is responsible for conditioning those supplies, such as heating or cooling water, or maintaining the water within required quality standards. In the future a separate crew equipment group or subsystem may be created to best integrate with the hygiene, housekeeping, or other systems that need the resource. The life support system is also responsible for providing the consumables and working fluids to space suits, such as breathable gas or cooling fluid for support via umbilicals while in or near the vehicle, or providing water and oxygen for use in the suits and their portable life support systems (PLSSs) for activities away from the vehicle. The life support also provides consumables such as oxygen or water to medical equipment or systems, but not the treatment devices themselves.

The life support system also manages metabolic wastes from the crewmembers (carbon dioxide, respiration and perspiration, urine and feces) to contain and control (including odor control), or dispose of them in a safe manner. It collects thermal loads from the cabin air, or other breathing gas heat exchangers, and transfers that heat to the thermal system, but the thermal system is ultimately responsible for rejection of that heat from the vehicle. The life support system also monitors the environment for off-nominal conditions such as smoke and fire detection and other trace gas or particulate release or accumulation events. Also included in life support are the systems that provide a survivable environment for the crew in these emergency situations, including fire suppression and emergency breathing gases or masks for the duration of the event.

Some of these functions (such as emergency systems) are not a part of a minimum functionality vehicle, and are not included in early versions of the design. As performance enhancements and additional functions are evaluated, more of these functions, and more elaborate versions of these functions, may be included.

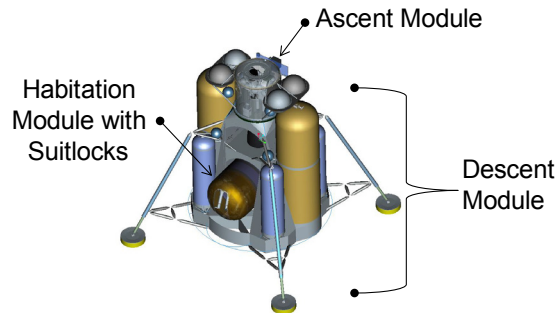
## LDAC-1 Overview

The requirements for the design of the minimum functionality vehicle were reduced to only what would be required to perform a basic mission. The basic mission for the lunar lander can be roughly defined as transporting 4 crewmembers to the south pole of the moon, enabling them to survive for 7 days, and allowing them to perform EVA activities to explore the surface of the moon while they are there. The design does not take into account contingencies or off-nominal situations. It does not include redundancy for system failures. It also neglects many requirements that are not critical to completion of the basic mission, but might be considered to enhance performance. For example, some level of communication is required to successfully navigate to the moon and dock with the Orion CEV. But high definition television feed, while highly desirable for many reasons, is not required to get to the moon. Providing sustenance for the crew is required to enable them to perform EVAs, but providing a pleasant (or even more than minimally tolerable) diet is not. It is important to note that no one in NASA, especially on the Altair team, ever intends for the minimum functionality design vehicle to be manufactured and flown. It is a design experiment that establishes a reasonable minimum mass to see if the project can be considered feasible from a mass perspective. Going through this process is also intended to make the members of the Altair team “Smart Buyers”, who will understand the reason that each requirement and resulting system is in place. From the minimum functionality vehicle, the design can be built by considering each safety and performance enhancing improvement piece by piece.

## LDAC-1 Overall Lander Concept

The initial lander concept in LDAC-1 included a descent module, an ascent module, and a habitation module, as shown in Figure 1. The descent module was the location of the descent stage engines that provided propulsion to perform the Lunar Orbit Insertion (LOI) maneuver and land safely on the surface of the moon. The habitat, or habitation module, was included to support the crew during their 7-day sortie missions with suitlocks on either end to perform EVAs. The habitat was carried by the descent module. It was considered a separate module because it would not be included in unmanned cargo missions. The lander also included an ascent stage, with a pressurized cabin just big enough for four suited crewmembers. The crewmembers would also be in this vessel during descent to the lunar surface in case of descent aborts, and then perform an EVA to move into the habitat for the duration of the surface mission. At the end of the mission, the ascent vehicle and its engines would lift the crew back to lunar orbit to rendezvous with the Orion Crew Exploration Vehicle (CEV).

The two pressure vessels in this concept had distinctly different duration and functional requirements. The ascent vehicle was only used to support the crew for a matter of hours, and they would wear spacesuits nearly all of that time. The habitat was needed to support shirtsleeve habitation for seven days, support EVAs, and provide food, hygiene, and waste facilities.



**Figure 1: Major Modules of the LDAC-1 Lander**

### Life Support for the LDAC-1 Ascent Stage

The mission duration and suited crewmember operations concept were the primary drivers of the life support system design. For duration, it was only required to provide life support for the crew for 12 hours. This meant that it could rely on consumable technologies without the mass growing too large. For the operations concept, it was assumed that the Orion CEV would provide life support to the crew working in the ascent stage when the two vehicles were docked. The ascent stage had no airlock, so depressurized operations were required, and it supported crewmembers wearing space suits. This meant that a suit loop architecture (where the vehicle provides life support to suited crewmembers via umbilicals) was appropriate. It was noted that spacesuits have a similar requirement set since they support crewmembers for short durations (8-hour EVAs). Using the Portable Life Support Systems (PLSSs) that the crewmembers would have used during lunar surface exploration was considered as an option. But the PLSSs don't provide all required functions (such as cabin pressurization and ventilation to dock to Orion). They also provide functions that are not useful in a powered, pressurized spacecraft, such as communication systems, power storage in batteries, and heat rejection by water evaporation. Bringing PLSSs rather than using a vehicle life support system was rejected because it was a more massive solution.

The ascent stage life support was very simple with only pressure control, air revitalization, and a small water subsystem.

The ascent stage only carried oxygen as stored gas. Repressurization of the mixed-gas cabin before launch from the lunar surface would be provided by nitrogen tanks stored on the descent stage. The oxygen tank was also used to provide pressure on the gas side of the bellows on the water storage tank shared between life support and thermal. The ascent stage was assumed to operate at 70 kPa (10.2 psia) because it had to dock with the Orion CEV at that pressure. A positive pressure relief valve would vent gas during the ascent from the Earth's surface so that the structure did not have to maintain a 101 kPa (14.7 psi) differential pressure. Valves on the hatches to equalize with the CEV or vent to the lunar environment were also included.

The air revitalization system, referred to as the "suit loop", maintained the air quality either of open cabin air or of gas flowing to suited crewmembers. The cabin air could be conditioned during the periods before the crew fully donned and leak checked their EVA suits for descent and when they opened their helmets after ascent when docked to CEV. In suited mode, the air revitalization system treated the oxygen flowing to and from the fully suited crewmembers via umbilicals. These umbilicals would also be used on the Orion CEV, so they were removable. The suit loop included a HEPA filter, Lithium Hydroxide (LiOH) canisters with a small amount of charcoal sorbents, and a condensing heat exchanger.

A water loop with a filter, gas liquid separator, pump, and heat exchanger provided cooling to suited crewmembers via their liquid cooling garment (LCG). Water stored for use in the vehicle's sublimator during ascent was also used as the accumulator and to provide pressurization to the water loop. Drinking water and waste facilities were not included because the crewmembers were assumed to be wearing spacesuits during the few hours in which the ascent vehicle was used.

#### Life Support for the LDAC-1 Habitat

The LDAC-1 lander habitat provided many more functions than the ascent stage, and had a more complex life support system.

The habitat was required to provide split-operations, meaning that some (normally two) crewmembers could be out performing surface exploration activities, while the remaining crewmembers were inside the habitat in a shirt sleeve environment. The habitat featured two-person suitlocks on either side of the habitat's horizontal cylinder shape. The crewmembers who were preparing for EVA needed to breathe pure oxygen, while the others continued to breathe an oxygen-nitrogen mixture. One air revitalization system cannot simultaneously condition pure oxygen and a mixed gas atmosphere.

Rather than create two air revitalization systems, the airlocks were to be equipped with vacuum ports that would enable the Portable Life Support Systems (PLSSs) on the spacesuits to begin to operate before the airlocks had been depressurized. The PLSS oxygen tanks needed to be refilled before each EVA. LDAC-1, oxygen for the habitation module was stored in a high pressure tank. But since the pressure in this tank would decrease over the 7-day mission, O<sub>2</sub> was taken from the primary storage tank and slowly pressurized to 25000 kPa (3600 psi), so that it could be used to refill PLSS tanks to 21000 kPa (3000 psi). The compression system was assumed to be a multi-stage system with both mechanical and sorption (solid-state) compressors. Since it was a multi-stage system, the early stages could be bypassed when the pressure in the source tank was still high. Water from a storage tank was circulated through a cooling system (much like in the ascent stage) and fed to the airlock. The PLSSs would accept this water to refill tanks and to recirculate it through the LCGs of crewmembers preparing for EVA.

Inside the habitat, the design included an oxygen-nitrogen mixture at 57 kPa (8.3 psia) controlled to just under 34% O<sub>2</sub>. Oxygen and nitrogen were stored in high pressure tanks. The nitrogen feed was also available as fire suppression by routing the flow to areas with large collections of electronics. The cabin air was drawn from vents throughout the volume and the waste and hygiene area. The air was filtered, and then slip streams were passed through trace contaminant control and CO<sub>2</sub> and H<sub>2</sub>O removal systems. Trace contaminant control was primarily assumed to be carbon sorbents, with some ambient temperature oxidation catalysis, and sorbents treated for ammonia removal. Control of carbon dioxide and humidity removal was performed with two amine swing beds common to the Orion CEV design. The dried air was drawn through the cabin fan. Finally, the air flowed through a non-condensing heat exchanger with a bypass for temperature control.

Food preparation, hygiene, and waste collection were also provided in the habitat module. The power system designed for DAC-1 featured fuel cells that produced water as a byproduct of reacting O<sub>2</sub> and H<sub>2</sub> to generate electrical power. The water produced by these fuel cells was stored by the life support system. A small tank of concentrated silver ion solution was included to be added as a residual biocide. This treated water would have been provided to the EVA suits and PLSSs. The water provided to the ascent stage sublimator was not treated with

the biocide because of concerns that it would be sensitive to accumulation of silver in the porous metal foam. It was provided to the crew via lines and manual valves at a galley station, and in the waste and hygiene area. In the waste area, urine would be vented directly overboard with a small amount of cabin air. Solid waste would be collected in a canister. For relatively little mass, a single-use bag based on the Shuttle Extended Duration Orbiter (EDO) Waste Collection System (WCS) and an odor-removing lid for the canister between uses was included. Since gravity is available on the lunar surface, including a fan in the waste collection system is not required to draw urine or fecal waste away from the human body, and, therefore, was not included.

#### Life Support for the LDAC-1 Descent Stage

The source and location of life support consumables did impact the descent stage of the LDAC-1D descent stage. In LDAC-1, it made sense to locate consumables for the surface stay with the habitat module. Since the habitable volume in LDAC-1D was the ascent module, keeping the consumables and tanks required for the mission on that module was not desirable. Mass on the ascent stage has the highest “gear ratio” of propulsion mass required of any location on the lander. Also during LDAC-1D, the quality of oxygen required for propulsion, fuel cells, and life support was compared. The standards for the three purposes are definitely different, but did not appear to be so different that a common definition could not be created that met all requirements. At the end of LDAC-1D, the life support system maintained a nitrogen tank on the ascent stage, assuming that it would eventually be needed for contingency repressurization after ascent. Oxygen tanks on the ascent stage were only designed for the same minimal duration of the LDAC-1 minimum ascent stage. During the surface operations for a Sortie mission, life support would utilize boiloff from the descent stage’s cryogenic oxygen tanks to provide for metabolic oxygen, airlock repressurization, and EVA needs.

#### Life Support on the LDAC-1 Descent Stage

In LDAC-1, the life support design did not include any mass as part of the descent module. Mass that did not have to return with the ascent stage was all labeled as part of the habitation module so that it could easily be removed for cargo mission mass estimates.

#### LDAC-1 Conclusion

Overall, the separation of functions between a habitat module and ascent module was efficient for the design of the life support system. The subsystem in LDAC-1 was estimated to have a mass of only 58 kgs in the ascent module and 240 kgs for the habitat module. However, the overall design was not as optimal for other vehicle systems. The lander was constrained to a diameter to fit inside shroud of the Ares-V rocket that would launch it from Earth. The habitat module needed to be placed on the center line of the vehicle to maximize their length, and potentially enable them to be used on the lunar surface as part of a permanent Outpost. To be useful, the habitat also needed to be close to the surface. Providing a structure that can survive the loads induced by the lander’s powerful descent stage engines and the Earth Departure Stage (EDS) while holding an open space in the center for the habitat ultimately was not an efficient structural solution and the overall lander mass was too high. Before the end of the analysis cycle, a “delta” design was developed. The biggest changes were in the structural system, but the other systems had to respond to the reconfiguration as well. This redesign period was called “Lander Design Analysis Cycle 1 – Delta” (LDAC-1D).

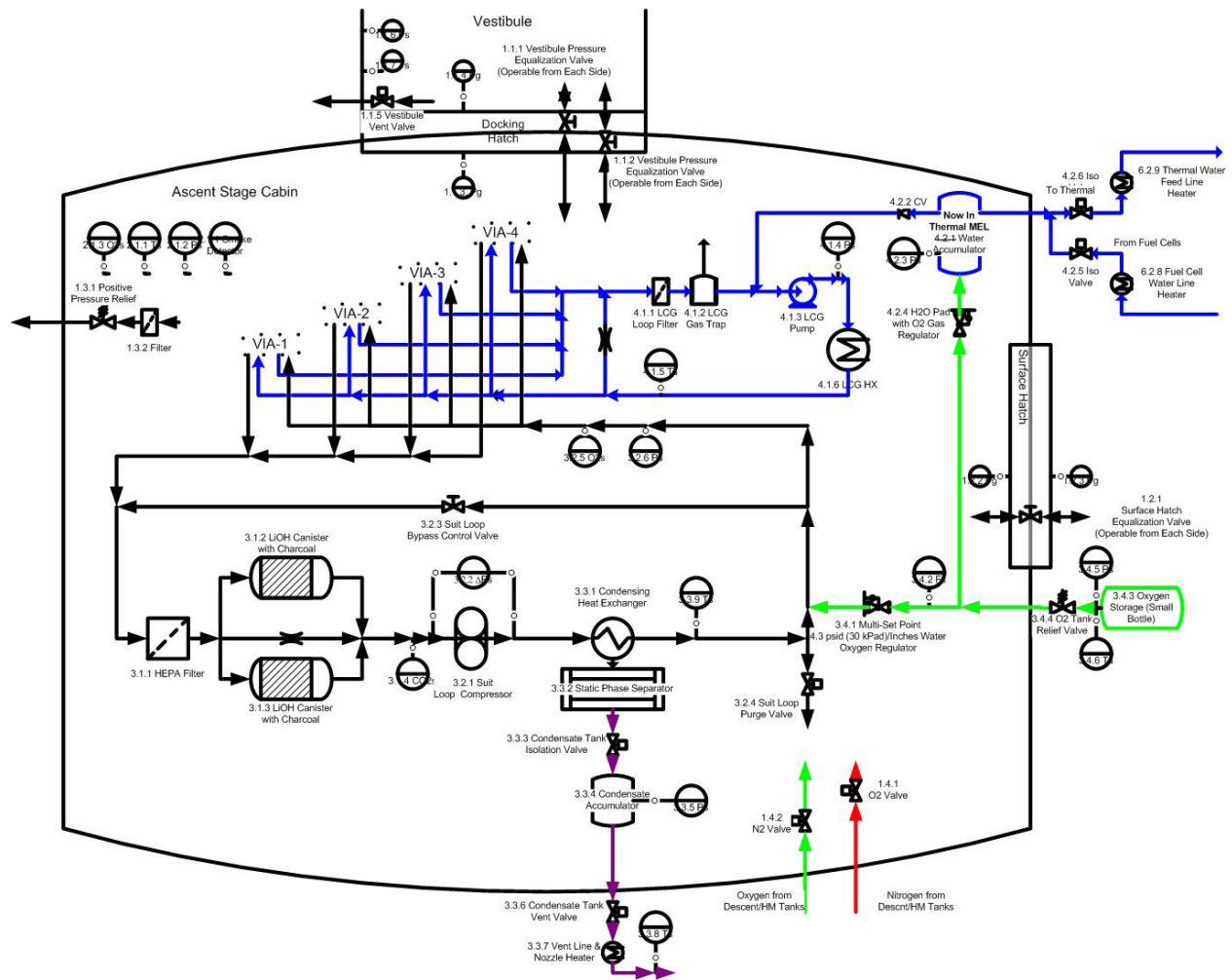
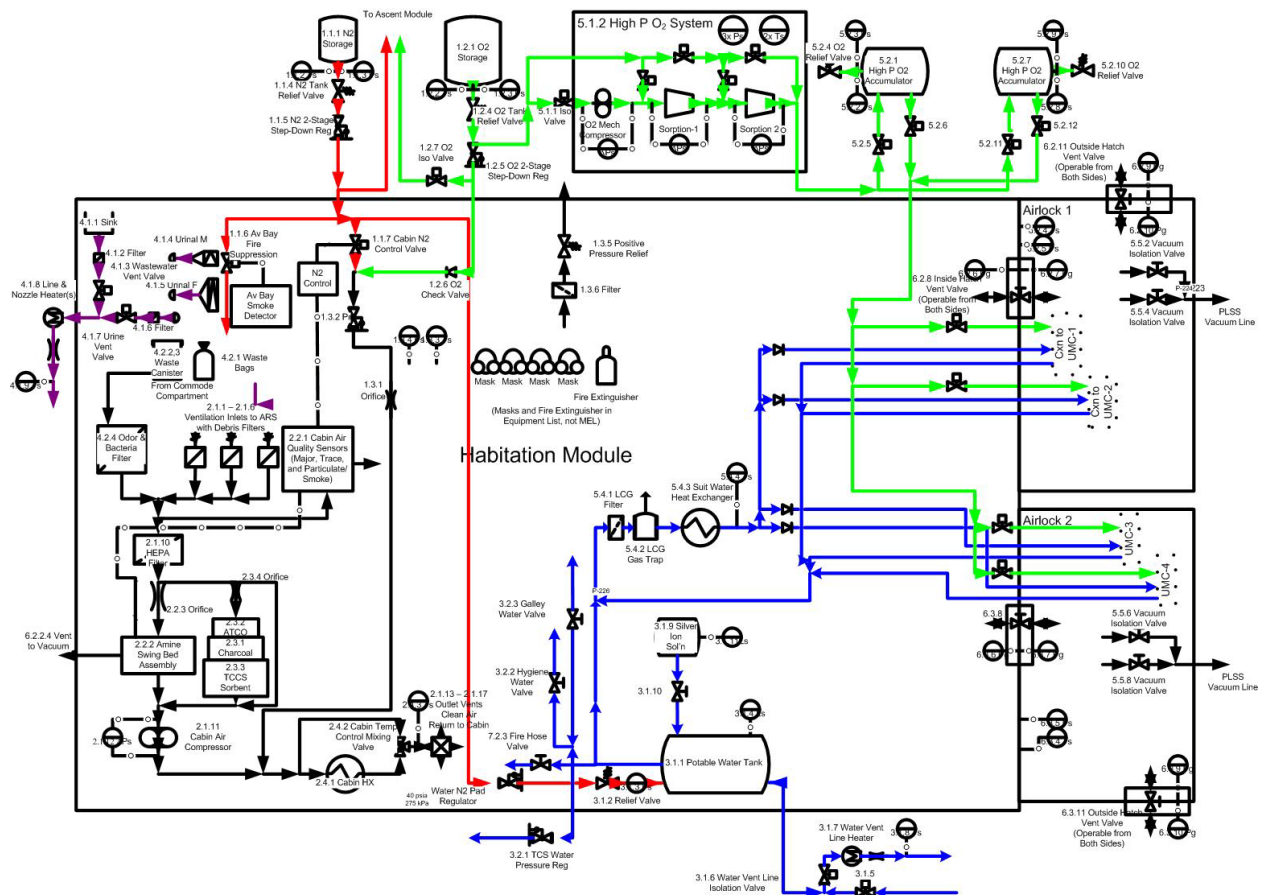


Figure 2: Altair LDAC-1 Life Support for the Minimum Ascent Stage

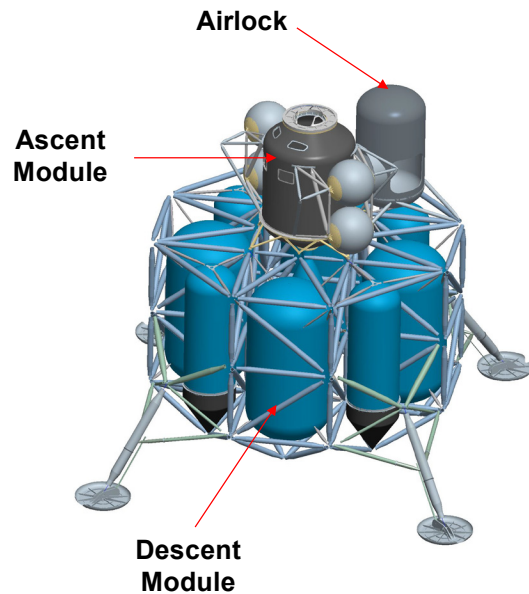


**Figure 3: Altair LDAC-1 Life Support for the Habitation Module for the Sortie Missions**

### LDAC-1D Overview

In the beginning of the LDAC-1D process, the team broke the pressurized volumes of the lander into three functions: an ascent vehicle, a 7-day habitat, and an airlock. Many configurations were considered grouping these into 1 to 3 volumes. For completeness, all were considered at least briefly. Some of these did not make much sense for the life support system. For example, one of the permutations that was projected to save mass had an ascent vehicle with air revitalization equipped to support the non-EVA crewmembers, but any habitation functions that were not required for ascent would be moved to a detachable airlock. But this would have left waste collection and drinking water unavailable to the non-EVA crewmembers while the others were away, so that the airlock could be available for quick return. Even though this combination saved mass, it was not very effective at performing the required functions for habitation. Ultimately the configuration selected was an ascent-stage/habitat, with a detachable airlock that could be left on the lunar surface, as show in Figure 2. This two-volume configuration has continued to be the basis of design work since then.





**Figure 4: Major Modules of the LDAC-1D Lander**

#### LDAC-1D Life Support

With the new allocation of functions to volumes, most of the life support functionality was contained in the ascent stage. The air revitalization system was split into two separate flow paths: the suit loop system, and the cabin fan system. With the longer duration, the regenerable amine swing beds used in the habitat in LDAC-1 were used for CO<sub>2</sub> and H<sub>2</sub>O control in the ascent stage now. Only the amount of air required for CO<sub>2</sub> and H<sub>2</sub>O control would flow through the suit loop air revitalization system. The connectors for the umbilicals that to connect the life support system to the crew in the suits add pressure drop, and therefore power cost, even when the life support system is conditioning the cabin directly. More flow is required to control air temperatures in the cabin. A separate cabin fan and heat exchanger was used to remove any remaining heat not controlled by the suit loop air revitalization so that this larger flowrate went through a lower total pressure drop system. Pressure control in the ascent stage became a multi-setpoint system to enable surface operations and docked operations with the Orion CEV, but the other aspects of the design remained the same. Waste systems and potable water systems were moved to the ascent module but were largely unchanged from DAC-1. EVA water systems provided the liquid cooling garment support to suited crewmembers in the ascent stage, and included a path to deliver water to the PLSSs where it could be recirculated for cooling or used to fill tanks for use during the EVA. The oxygen compression system was included with the detachable airlock, which still had vacuum vents to enable the PLSS to function while the airlock is pressurized. The total life support system mass was estimated at 211kg. This is a net reduction in life support system mass, since only one air revitalization system is included. But much more life support mass is placed on the ascent module, so it bears a higher penalty for propulsion to land it safely on the surface and return it to lunar orbit with the crew.

#### Life Support on the LDAC-1D Descent Stage

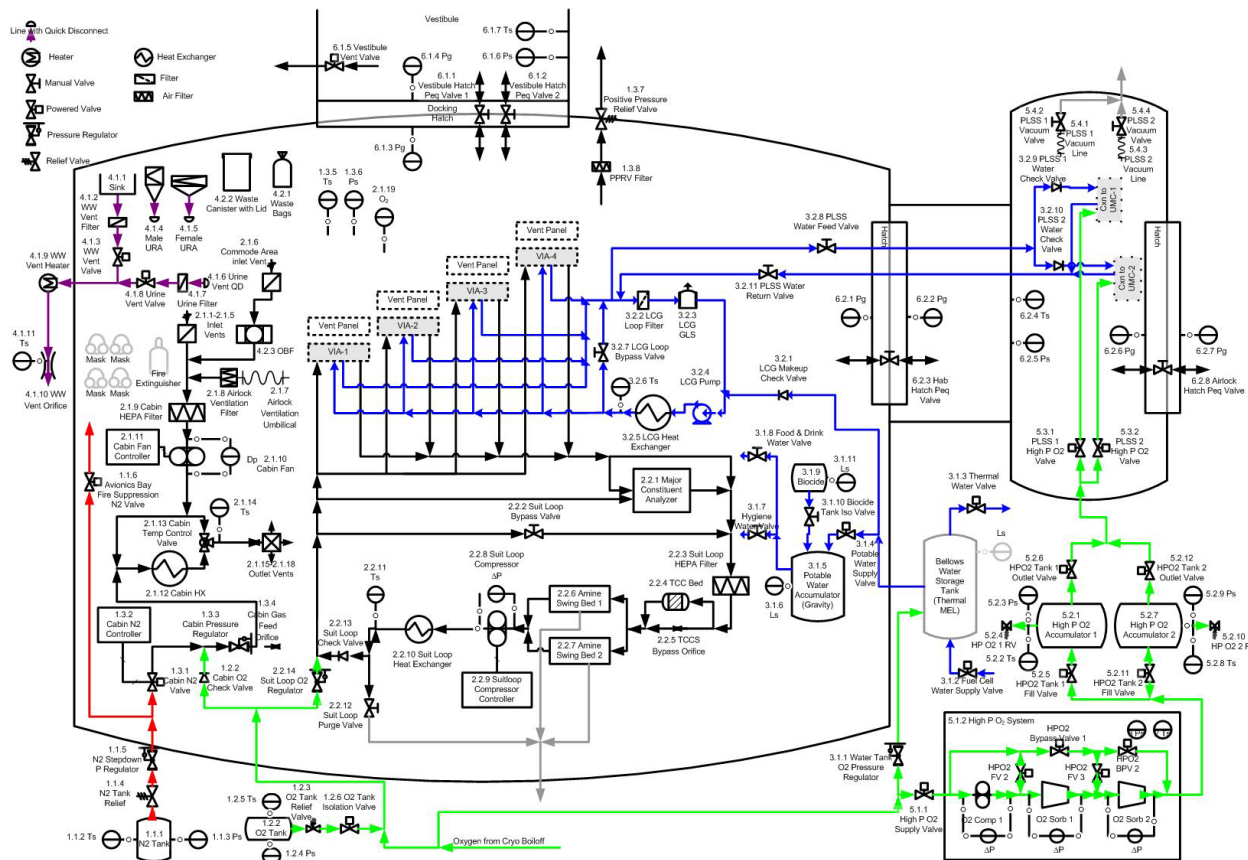
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#### LDAC-1D Conclusion

The final LDAC-1D Lander concept, while not without errors, was considered a sufficiently “closed” concept for a minimally functional (not flyable) vehicle for a minimal mass solution. The mass of the vehicle was beneath the target established for Altair by the lift or Delta-V capability requirements of the Ares V launch vehicle and Earth Departure Stage. Parametric studies at the vehicle level were conducted to estimate the mass of a flyable vehicle so that the team could move forward with sufficient confidence that a flyable design within limits could be achieved.

The LDAC-1D lander was also used as the starting point for an Altair project “Broad Area Announcement” contract announced in December of 2007. In the first part of this contract, companies were asked to identify any improvements in a minimal-mass minimum functionality design. Those results were compared to the LDAC-1D design to see where there were areas for improvement. The life support design results were largely supported by the contractor efforts. In the second part of the contract, the contractor teams used their own analysis methods and techniques to independently determine what changes should be made to reduce the “Loss of Crew” risks in the LDAC-1D vehicle design. Those results were then compared with the NASA LDAC-2 designs. The contract also asked for industry input on effective teaming between government and industry during the development phase as the Altair design matures.



**Figure 5: Altair LDAC-1D Life Support for the Sortie Vehicle**

## LDAC-2 overview

The Altair team began LDAC-2 with the goal of finding mass efficient solutions to reduce the LOC risk of the design. The vehicle configuration for LDAC-2 that drove life support design were very similar to LDAC-1D, though the vehicle had expanded it's width to a 10-m maximum diameter in the Ares V launch shroud.

The LDAC-2 work began by identifying life threatening hazards and the single point failures that could cause them. The vehicle hazards included "Failure to Ascend or Rendezvous with CEV", "Impact or Crash", "Explosion", "Fire", "Loss of Control", "Radiation", and "Loss of Breathable Atmosphere". Several different types of options were to be considered for those failures. One path was to determine whether dissimilar redundancy was present by using other vehicle capabilities, or if a dissimilar system solution was available to be implemented. A second option was to see if there was a more reliable single string solution available, or if testing or other development could make the system more reliable. For some systems (such as the structural pressure vessels, or engines) testing and development work to increase confidence in the single-string solution may be the most appropriate solution. Finally, adding a redundant string (or distributing the function into redundant strings each with reduced capability). Aborting the mission was not supposed to be considered by the subsystem teams as a valid solution for dealing with their failures. However, mission aborts were considered in DAC-2 at the vehicle level. The lander team also used DAC-2 to evaluate capabilities required for mission aborts. Subsystems were asked to examine a "lifeboat" mode for surviving extended durations, or with reduced power, for some of these cases.

## LDAC-2 life support system

Defining LOC failures in the life support system for LDAC-2 required a little bit of negotiation. Almost by definition, anything appearing in a minimum functionality and single string life support system is required to keep the crew alive! Even failed waste collection systems could eventually become life threatening if infectious microbial growth spread, or offgassed chemicals overwhelmed the design size of the trace contaminant control system allowing ammonia or other hazardous gases to exceed their Spacecraft Maximum Allowable Concentration (SMAC) limits. But it was unreasonable to imagine that a crew would stay on the surface until they became very ill, when ending the mission and returning to the CEV would quickly bring them to a fully functional life support system. However, calling this early return to the CEV an abort implied an increased risk because actions were not taken per the nominal plan. Eventually it was determined that the life support system would consider LOC failures that would prove life threatening within a few hours. Failures that became life threatening after days would allow enough time to have an early mission end that included the nominal ascent procedure. All of the single point life support failures that fit into this category reduced to the “Loss of Breathable Atmosphere” hazard.

## Loss of Atmosphere Failures

The first set of failures that were examined under “Loss of Breathable Atmosphere” were those that resulted in the complete loss of atmosphere. Many of the cabin penetrations that could leak to vent the atmosphere were assumed to be small enough that they could be sustained by the cabin pressure system until they could be capped. If the leak could not be identified, the crew could don their space suits and use the suit loop life support to return safely to the CEV. Examples of these leaks were the urine and wastewater vent line, a leaky hatch seal, or a leaky pressure equalization valve. Three possible leak paths were identified that did not have those solutions, and are discussed below.

The first potentially serious leak was the positive pressure relief valve (PPRV). Detailed orifice sizing had not yet been performed on this valve. But the design had established that it would be mechanical to automatically relieve pressure, and large enough to vent cabin pressure from Earth atmosphere to something slightly above the 70 kPa (10.2 psia ) atmosphere the Lander would use when docked with CEV. Since ascent on an Ares V is expected to be fast, the valve was expected to have a relatively large orifice. If it accidentally opened while the crew was sleeping, they might not have time to reach it and attempt to manually close it before pressure in the cabin dropped significantly. An electronic valve was added to the PPRV assembly that would be closed automatically by vehicle control if cabin pressure dropped rapidly. The valve would be “normally open” to reduce the risk of it accidentally failing closed and preventing the PPRV from performing the relief function during ascent from Earth.

The second leak path identified was the suit loop purge line. When the purge valve on this line was open, gas would be vented from the suit loop to space. The suit loop, umbilicals, and space suit free volume all need to be flushed with oxygen so that nitrogen from the cabin air is removed before low pressure suited operations. In a small volume, this could add oxygen to the cabin quickly and exceed the 34% O<sub>2</sub> concentration limit, so the purge gas was dumped overboard in the minimum functionality design. Even though this purge is a small flow rate, it does not fit into the first category of leaks that can be “fed” because neither the cabin nor the suit loop can be sustained as a pressurized environment with a reasonable quantity of consumables

long enough to survive ascent. As a solution, the line was routed to dump the oxygen to the cabin. This may require use of extra nitrogen to maintain O<sub>2</sub> concentrations, and possibly venting of cabin gas. That cost was considered acceptable compared to the potential loss of life from losing pressure in the suit loop.

The third leak path considered critical was in the amine swing bed units used to control carbon dioxide and humidity. Each unit is constructed like a heat exchanger with alternating layers of sorbent beds. The technology uses a pressure swing adsorption process. In each unit, one “bed” is exposed to cabin air, while the other “bed” is exposed to vacuum. If a leak path was present in the valve that controls air flow or in the heat exchanger style assembly itself, it could create a path from the suit loop to vacuum. This is unacceptable for the same type of reasons that it was in the suit loop purge valve case. The amine swing bed does require vacuum to operate, so it cannot simply be routed to the cabin. As a solution, the two amine swing bed units were given separate overboard vent lines, and a normally open valve was placed on the line to isolate a leaky amine swing bed unit from vacuum. These amine swing beds are still considered a technology development project for NASA’s Exploration vehicles. The Altair team recognizes that highly reliable construction and performance on the Orion CEV, redundant sealing surfaces in the valve, or valve designs that cannot physically create such a leak path may remove the need for these isolation valves.

### Loss of Oxygen Control Failures

The second category of failures considered that could cause “Loss of Breathable Atmosphere” were those that resulted in a loss of oxygen control. Lack of oxygen due to tank failures, control systems that added too little oxygen, or control systems that added too much oxygen creating a fire hazard were all examined.

The loss of oxygen stores were assumed to be related to the small oxygen tanks on the ascent module. If the supply of oxygen scavenged from the descent stage was interrupted, the ascent stage oxygen tanks could be used to supply breathable atmosphere to the crew, though the duration would likely increase. Failure of an oxygen storage tank, or the valve isolating the tank during the surface stay, was a critical failure. If the valve stayed open, the oxygen in the tank would be consumed during the surface stay and not be available for ascent. If the valve failed to open during ascent, the crew metabolism would reduce the oxygen in the suit loop and cabin atmosphere to unacceptable levels. The oxygen tanks also became an important part of the abort studies examined at the vehicle level. Several of the abort cases required extended loiter durations in lunar orbit before the Altair lander could rendezvous with the Orion CEV. As a solution, a second ascent stage oxygen tank and isolation valve was added to the vehicle. Each tank was sized to survive a nominal mission alone. The two tanks together could survive an extended duration abort.

Failure of the control system that would introduce oxygen was also a critical failure. A multi-component sensor measured the oxygen levels in the vehicle to control gas addition. It is referred to as the “Major Constituent Analyzer”, but not assumed to be identical to ISS hardware of the same name. If the sensor failed completely, the crew could don their suits and breathe pure oxygen in the suit loop where no composition control is required. Analysis or ground tests could determine the amount of time required to purge the loop even if the sensor was not operating to verify the purge was complete. But if the sensor was reading incorrectly, the crew could asphyxiate or be working in a highly flammable environment without notification. This is especially important if the failure occurred while the crew was sleeping and unable to notice

their own symptoms. Two additional oxygen sensors were added to the design to check the measurements of the MCA. The total of three O<sub>2</sub> measurements allowed voting logic so that if the sensors started to disagree, the one with the disagreeing reading would be assumed to be incorrect. Even if two sensors were wrong, and one was right, the disagreement would cause the crew and ground support to begin a diagnosis and troubleshooting process to find the issue.

Failure of the nitrogen system was not considered a LOC failure. Since nitrogen is not metabolically consumed, the levels in the cabin should remain relatively constant for awhile after the supply fails. The nitrogen control valve that determines whether O<sub>2</sub> or N<sub>2</sub> was added was assumed to be in the cabin volume where the crew could try to manually close it if it failed open. This would provide the crew with enough time to don their space suits and use the suit loop as the controlled, pressurized volume for a safe ascent.

### Accumulation of CO<sub>2</sub>

The only gas phase contaminant expected to accumulate to serious levels before the crew could return to the Orion CEV was carbon dioxide. CO<sub>2</sub> could accumulate if the amine swing beds failed to operate. It would also accumulate if the suit loop compressor or controller failed to operate and didn't force the CO<sub>2</sub> through the swing beds.

The LDAC-1D vehicle already included two swing bed units. One unit would be sufficient to provide CO<sub>2</sub> control for the vehicle, but two units were expected to be required for humidity control during high metabolic load periods. This sizing was based on commonality with the units developed for Orion, and not for deliberate redundancy. But it was the need to maintain this redundancy that drove the need for separate vent lines and isolation valves when solving the amine swing bed leak risk.

The suit loop compressor and the amine swing bed controller were considered potential critical failures. In LDAC-1D, the life support design included a suit loop compressor that would provide low flow through high pressure drop to suited crewmembers, or higher flowrates through a reduced pressure drop to the open cabin. The Altair team considered trying to break the compressor into more smaller compressors, similar to the strategy that works for the amine swing bed. But losses due to flow mixing mean that two compressors manifolded together may not necessarily produce double the flow of the original compressor. Multiple distributed compressors that could sustain performance after one failure were estimated to be more massive than simply two redundant compressors. A redundant controller was added to the system as well. The complexity of the controllers was increased so that it could direct the remaining compressors and amine swing beds to adapt to a failed state by increasing flow or changing cycle time.

The suit loop compressors were also considered important for the lifeboat cases examined at the vehicle level. The compressors are the largest power draw in the life support system, and would be a significant load if the vehicle was trying to survive on a trickle of power. Several chemical methods of CO<sub>2</sub> were considered as a low power backup. Many of the highly exothermic systems were rejected because the Altair lander is such a small vehicle. LiOH systems were selected as the most reasonable choice. A LiOH canister still requires a fan to draw cabin air through it. Instead, a LiOH mask was selected. The mask would be designed to allow the crewmembers to breathe cabin air, but exhale through a LiOH cartridge. With this design, CO<sub>2</sub> levels would not rise in the cabin like they would if the mask filtered LiOH as the crewmember inhaled, and the environment would be safe when the Lander docked with the CEV.

Humidity was considered as a potential LOC failure. While humidity should not be life threatening to the crew, condensation could potentially disrupt avionics systems. The Altair team assumed that all avionics and electrical wiring in the design that are inside the pressurized ascent module would be coated to protect them from humidity.

## LDAC-2 Conclusion

Changes to the life support system provided effective ways to reduce risk of loss of function in the most critical systems. In many cases, since an efficient single string design had been selected in the first place, adding a redundant component of the same design was still the most mass-effective choice. Life support systems were mostly added as “cold spares”, or components that only actuated after a failure. As a result, they created relatively little impact on the power and heat rejection capability for the vehicle. Each of the critical functions examined in LDAC-2 remained important in LDAC-3. Loss of one of the components performing these functions would leave the vehicle one failure away from LOC, and possibly require an early end to the mission. Functions that were not included

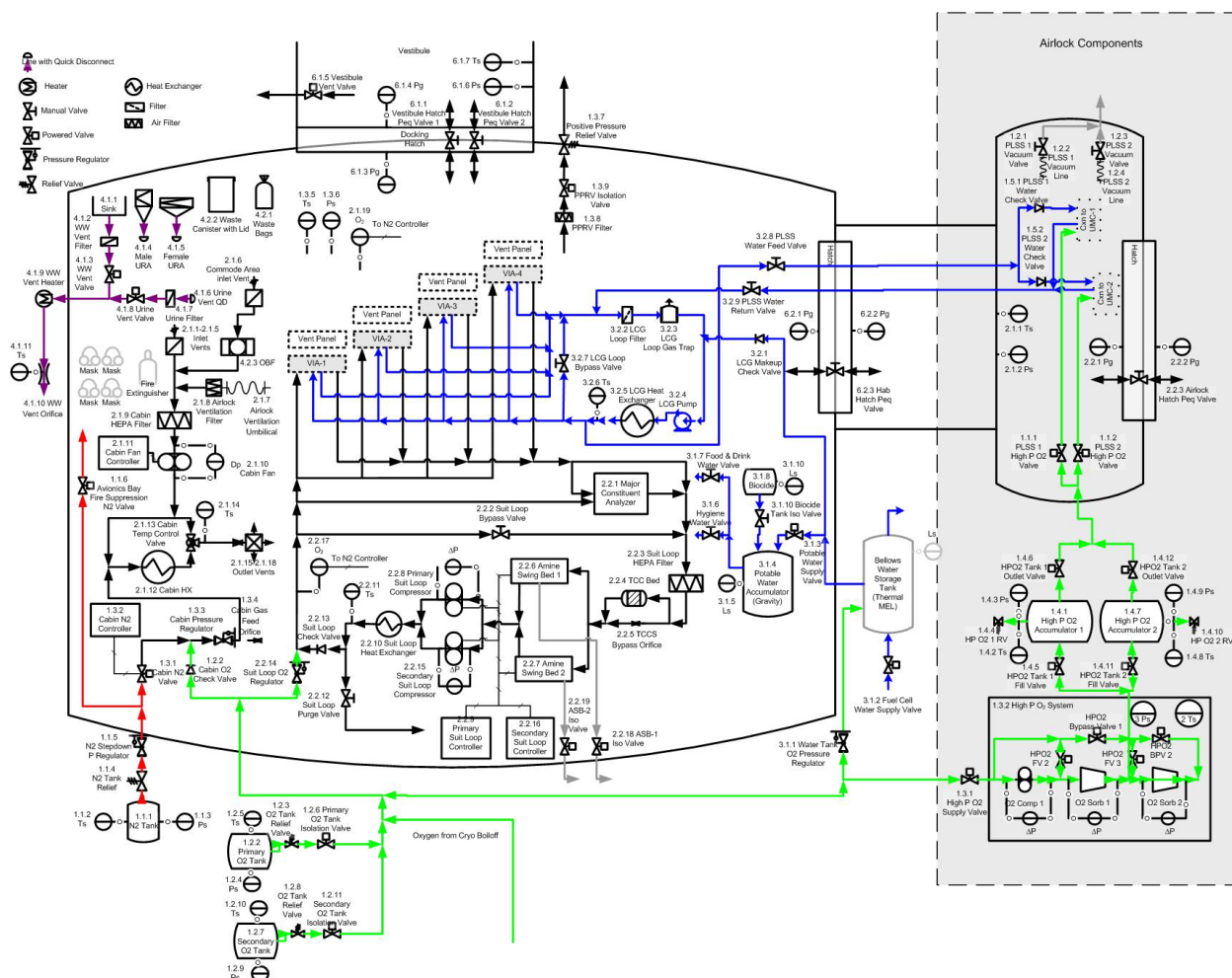


Figure 6: Altair LDAC-2 Life Support System for the Sortie Vehicle

## LDAC-3 Overview



The Altair team's efforts in LDAC-3 were organized around reducing the risk of Loss of Mission. The first challenge was for the technical management of the Altair team to define what would count as losing the mission. Several of the criteria for loss of mission were not usually relevant to life support:

- 1) Lander fails to reach the desired lunar landing area,
- 2) All cargo is not transferred to the surface,
- 3) Vehicle data and communication is maintained for health monitoring of critical systems and uplink of critical data, and
- 4) Crew and cargo returns to Orion through the Low Impact Docking System (LIDS) hatch.

The other 5 criteria selected were relevant to life support system failures. These criteria were:

- 1) The entire crew is not able to exit the lander, access the lunar surface, and perform two-person per day EVAs,
- 2) The lander does not maintain an acceptable environment for the EVA crewmember outside the lander,
- 3) The pressurized ascent module is not maintained with an environment suitable for shirtsleeve (unsuited) operations
- 4) 7 day stay on the lunar surface is not achieved due to a loss of a function or capability
- 5) 7 day stay on the lunar surface is not achieved due to a loss of redundancy in a life critical function or capability

During LDAC-3, some of the lander subsystem teams, including life support, investigated what other sensors would be required to detect the failures identified in LDAC-2 and LDAC-3 so that contingency action could be taken.

#### LDAC-3 Changes in the Pressure Control System

The pressure control system includes critical, life sustaining functions and functions that are not critical for crew survival but enable EVA operations or interfaces with CEV.

The simplest PCS changes in LDAC-3 were in pressure equalization or venting valves. Redundant manual pressure equalization valves with caps were used on all the hatches. This gives redundancy to the pressure equalization or airlock depressurization capability so surface EVAs can be performed, and shirt sleeve transfer to and from the Orion CEV can be performed. The caps provide a second method of closing the valves in case they are leaky or stuck. The powered vestibule vent valve, which relieves the pressure trapped between the Orion CEV and Altair lander before separation or maneuvers, was given a redundant valve in series. The Orion CEV already has a vestibule vent valve, so redundancy to perform the function was not needed. But since the valve is not always accessible to the crew, using a cap is not a feasible method for stopping a leaky valve. A redundant positive pressure relief valve (PPRV) assembly with filter and isolation valve was also added. A PPRV that fails to open is not life threatening, because no crew is present during the launch of the Altair lander from Earth. But failure to open would rupture the pressure vessel, ending the mission before the vehicle even leaves Earth orbit and begins to travel to the moon.

The next set of failures addressed was in the cabin pressure control for shirtsleeve environments. The nitrogen tank itself was considered reliable enough that additional tanks were



not required. In future DAC cycles, the stored nitrogen may be split into ascent stage and descent stage stores to optimize the mass of the ascent stage. This strategy has not yet been implemented while there is still an undefined requirement for nitrogen required after ascent for vehicle repressurization or O<sub>2</sub> concentration control in contingency scenarios. From the single nitrogen tank, dual delivery paths were included with isolation valves for the tank, step-down pressure regulators, and nitrogen control valves inside the cabin. Inside the cabin, each delivery line leads to one of two redundant electronic cabin pressure regulators. The electronic regulators were selected to make the Altair design flexible, since multiple pressure set points are required throughout the mission.

Changes were also made in the oxygen supply systems in LDAC-3. Because ascent module oxygen tanks are so critical to the crew during ascent, a third oxygen tank was added. The capacity of the new tank will be just enough to perform a nominal ascent or descent abort. Each of the three oxygen tanks has an isolation valve, a step-down pressure regulator, and a check valve. Also, the interface for the delivery of scavenged oxygen from the propellant tanks was more clearly defined. At the separation interface between ascent module and descent module, two parallel paths for O<sub>2</sub> delivery are included. Each of these paths has a powered isolation valve with a backup a check valve to close the line after separation.

After oxygen from any of these sources flows to the cabin, there are many routes available to deliver it to the crew. Oxygen flowing to the cabin passes through two check valves in series so that the higher pressure nitrogen cannot flow back into the O<sub>2</sub> supply lines. A selector valve determines which of the two cabin pressure regulators are being supplied. A manual oxygen bleed valve was added to the cabin supply to provide metabolic oxygen to the crew long enough to don suits or establish workarounds if there are problems with the cabin pressure control system. In suited modes, a 3- way valve ( with A, B, and Off positions) determines which of two demand pressure regulators are supplying O<sub>2</sub> to the suit loop if that mode is being used at the time. Redundant check valves in series were used in the suit loop to ensure that oxygen is forced through the purge operations rather than short circuiting to the vent. A manual bypass valve around those check valves was added in case a check valve fails closed.

### LDAC-3 Changes in the Air Revitalization System

Very few significant schematic changes were added to the lander ARS in LDAC-3. Design maturation or refinement did change the mass estimates for several components. A more detailed sizing estimate was performed on the trace contaminant control system and HEPA filtration system to update the mass of those components. Also, Altair agreed to provide forced ventilation of filtered air to Orion after a nominal ascent from the moon. This ventilation would be provided by the cabin fan by pushing air through the umbilical hose normally used to draw air from the airlock when the hatch is open during surface operations. This design decision should reduce the amount of lunar regolith or dust that moves from the lander to the CEV after ascent.

Humidity control was considered as a possible loss of mission threat in LDAC-3. Detailed transient analysis of the system was performed to investigate whether the size assumed for the amine swing beds would provide sufficient humidity control after one failure. The analysis showed that one unit was more than sufficient to support nominal metabolic rates. The Orion units have to provide humidity control while one crewmember is exercising and three others are present. Altair has not yet added all of the Human Systems Integration Requirements (HSIR) document content to the vehicle design. For LDAC-3, the team assumed that crewmembers would only have to exercise on days when they did not perform EVAs. The

exercise mode would only be for one crewmember exercising, and one at nominal rates. Estimates showed that two crewmembers donning suits and two at nominal rates became the most challenging case, and the full Orion capability was not required to support this. A reduced mass estimate for the amine swing beds was implemented based on this analysis. After one failure, Altair would still be able to support nominal metabolic rates without condensation in the vehicle. Cleaning up condensation could be required for a system with one failed amine swing bed unit, but vehicle operators could decide whether they wanted to continue the mission with that capability, and immediate abort would not be required. It is very important to note that the Altair team's interpretation of the HSIR exercise requirement will almost certainly be challenged as part of its System Requirements Review, and the units may need to return to their original design size.

The cabin fan and cabin ventilation system was not identified as a critical function in LDAC-3. On the lunar surface, natural convection will provide some gas mixing in the cabin. Critical systems in the Altair vehicle will already have to be liquid cooled, rather than passively cooled, to survive during depressurized cabin contingencies, or portions of the Outpost mission when the crew enters or exits the vehicle.

### LDAC-3 Changes in the Water System

Changes to the water systems in LDAC-3 focused on maintaining water quality during the mission, and providing water to the sublimator. Microbial control strategies have to acknowledge that no biocidal agent is going to kill all microbial life (or at least no biocidal agent that is not life threatening to the crew). Filters were added to the water design at the hygiene valve and the food & drink water supply valve. A pore size of 0.2 micron was selected as a reasonable size to block most bacteria. Also, the team addressed microbial control in the LCG loop during the long dormant period during Outpost missions. Unlike EMU experience on the ISS, the new PLSS proposed for lunar Exploration does not use condensate from human respiration and perspiration as a source of water for heat rejection. As a result the LCG loop in the lander will be exposed to much less microbial contamination than previous systems. The team decided to try to keep the lander at a low temperature (but above freezing) during dormancy to slow microbial growth. But no additional measures were added.

LDAC-3 work also resulted in changes to the sublimator water storage tanks. Incomplete work from LDAC-2 had left the thermal system with a single microgravity compatible bellows tank. The potable water tank in the life support system was not required to be operable in microgravity, and was not a bellows tank. Failure of the sublimator tank was a LOC failure because the vehicle would not survive ascent without cooling. The team selected a design that made the potable water tank a fixed charge pressurized tank. Several changes in assumptions made this possible. The silver biocide in the potable water tank may not be acceptable for nominal use in the sublimator. It was assumed the the sublimator could survive at least ascent durations while being fed with water containing silver biocide. Also, the sublimator operates at very low pressure, and does not need the same level of water pressure required for potable water delivery to the cabin. If the pressurization system to the sublimator tank failed, water could be drawn from a potable water tank with a contained gas charge in microgravity. Loss of drinking water would be a LOM failure, but the team determined that a simple tank was reliable enough that it did not need to be made redundant.

### LDAC-3 and the Waste System

During LDAC-3, the technical management team did not accept failure of the waste system as a reason for loss of mission. For the minimum functionality vehicle, solid waste collection is little more than individual use bags under a minimal seat and a collection canister with a lid. Credible failure modes are hard to identify. The urine system vents directly overboard. On the moon having a gravity field means that collection of urine does not have the same phase separation challenges as in toilets designed for microgravity use. For the minimum functionality design the waste canisters, or absorbent material in zip-top bags was proposed as backups if the vent system failed. In the final design, using a set of lower powered heaters in parallel on the vent line to prevent freezing of fluids could help create a more robust system.

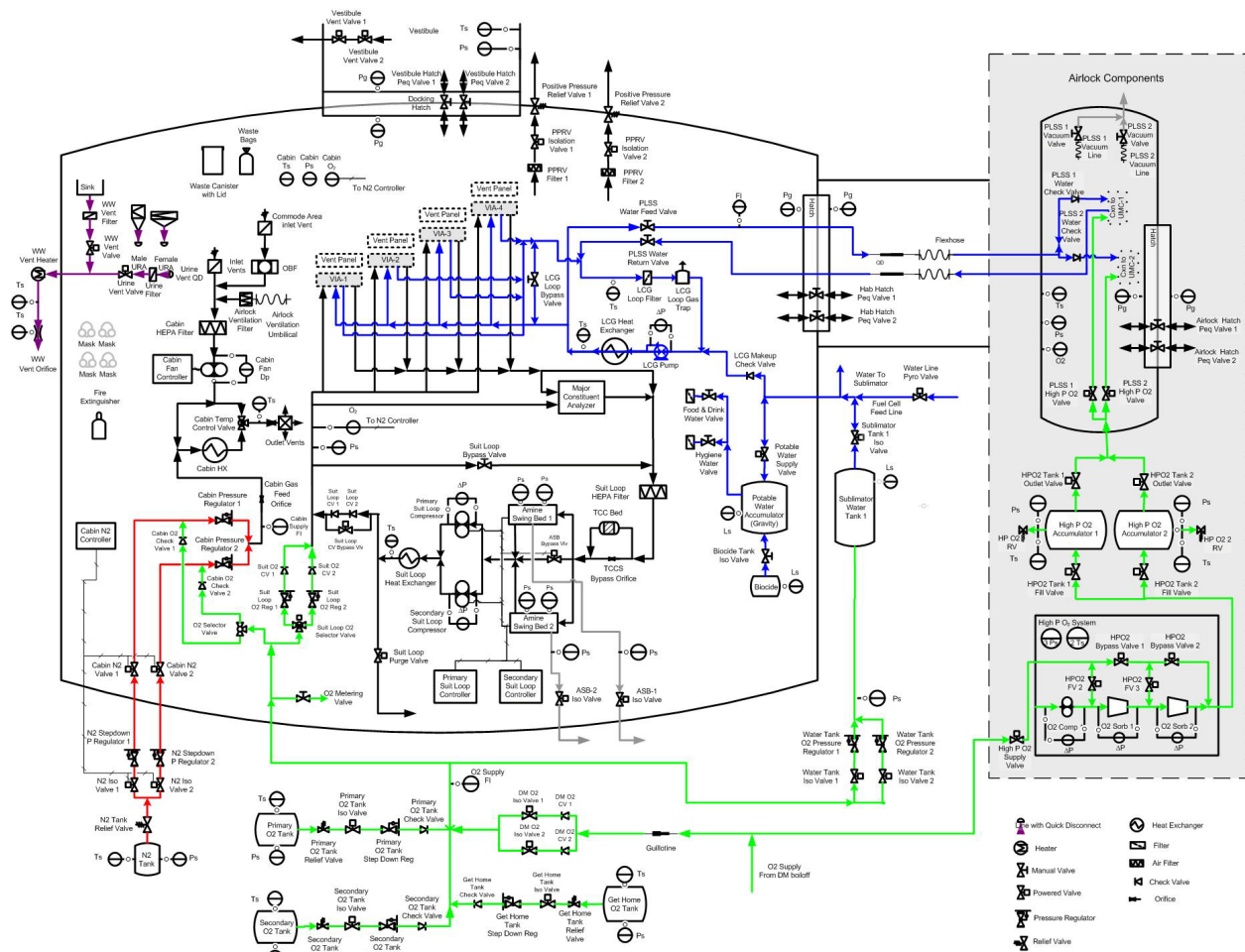
### Fire and Emergency Systems

The life support system typically has responsibility for fire detection and suppression on a NASA spacecraft. While a fire is certainly a failure that could lead to loss of crew, in LDAC-2 the analysis method did not identify life support functions that would directly lead to a fire. In LDAC-3, however, the team acknowledged the need to study fire suppression options as part of having a vehicle that was not one failure away from being unable to maintain the environment as materials burned. Several factors are important when considering the risk of fire on the Altair lander. The nominal vehicle atmosphere could be up to 34% O<sub>2</sub>, which increases flammability risk. The lower total pressure of the lander also will increase the flammability of materials in the vehicle. NASA is considering, and likely to accept, a change from a 28VDC electrical system to a 120VDC electrical system for the Orion CEV and then the Altair lander, which increases the risk of electrical discharge as an ignition source.

NASA would like to find a single fire suppression method that is applicable for all Exploration vehicles. Altair has selected a fine water mist fire extinguisher as the preferred solution for the lander. Many of the Altair avionics units are installed outside the pressurized vessel. Since Altair does not have the localized pressurized avionics bay Orion does, an automated diluent gas purge is not an effective solution in Altair. In the small volume of the ascent module, a diluent like nitrogen or halon could cause a hazardous environment for the crew trying to fight the fire. The diluents systems also had higher mass estimates. Water mist was preferable to water foam solutions or water spray solution because it was less damaging to equipment, and had a lightweight mass estimate.

### LDAC-3 Conclusion

The changes made to design LDAC-3 life support system resulted in a design with significantly lower LOM risk. Several significant risks still exist, and will be addressed in later work. Also, while the LDAC-3 is a safer design than the LDAC-1 minimum functionality design, it is not “fully functional”.



**Figure 7: Life Support Schematic for the Altair LDAC-3 Sortie Vehicle**

## Conclusions

The Altair life support team, with contributions from many people over the last few years, has made significant progress in finding a feasible design to meet a minimal requirements set for a lunar lander. The team has learned a great deal about the requirements considered so far, and the options and costs required to implement them. But the work is far from complete.

Several areas of immature requirements, or requirements not yet considered, could have major impacts on the life support system design. The Altair lander is expected to primarily interface with the Lunar Surface Exploration configuration of the new spacesuit, which is still highly undefined. This leaves uncertainty in the interfaces to the EVA suits and PLSSs, but also in defining the methods and quantities of lunar regolith or dust that will be brought into the Altair environment via EVA. The Altair life support system relies heavily on oxygen scavenged from propellant tanks. The time it will take to make that oxygen available to other vehicle systems, and the amount of helium initially present are still undetermined. Also, the Altair team did not include all of the NASA Constellation level requirements in the minimum functional design. Contingency cases defined in the Constellation Architecture Requirements Document (CARD) and many functions or constraints from the Human Systems Integration Requirements (HSIR) are not yet included. Each of these areas will require more work in the future, and could drive changes to the architecture.

Also, some systems have been neglected from study so far due to immaturity. NASA has organized technology development research under the Exploration Technology Development Program (ETDP). One area of research critical for Altair is systems to compress the scavenged oxygen high enough to resupply PLSS tanks. Altair is also depending on the development of air quality monitors that can measure oxygen with sufficient accuracy to narrowly control cabin pressure and atmosphere composition, while providing monitoring of CO<sub>2</sub>, humidity, and fire products in lightweight systems. Technologies to mitigate contamination with lunar regolith or dust are in development, and research to assess hazards associated with lunar regolith or dust is in progress. Lunar dust could also pose a challenge to fire detection systems that would use particulates as a sign of a smoke.

The Altair team will continue to develop the vehicle design as it progresses to a formal System Requirements Review. All of the functionality required by the Constellation documents must be assessed for inclusion in the vehicle, while still maintaining a safe, reliable, and mass or cost effective design. NASA will continue to work to develop a vehicle concept that safely, reliably, and efficiently to enable human exploration of the Moon, and prepare us for further journeys.