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Development of Life Support System Technologies for Human Lunar Missions

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ABSTRACT

With the Preliminary Design Review (PDR) for the Orion Crew Exploration Vehicle planned to be completed in 2009, Exploration Life Support (ELS), a technology development project under the National Aeronautics and Space Administration's (NASA) Exploration Technology Development Program, is focusing its efforts on needs for human lunar missions. The ELS Project's goal is to develop and mature a suite of Environmental Control and Life Support System (ECLSS) technologies for potential use on human spacecraft under development in support of U.S. Space Exploration Policy. ELS technology development is directed at three major vehicle projects within NASA's Constellation Program (CxP): the Orion Crew Exploration Vehicle (CEV), the Altair Lunar Lander and Lunar Surface Systems, including habitats and pressurized rovers. The ELS Project includes four technical elements: Atmosphere Revitalization Systems, Water Recovery Systems, Waste Management Systems and Habitation Engineering, and two cross cutting elements, Systems Integration, Modeling and Analysis, and Validation and Testing. This paper will provide an overview of the ELS Project, connectivity with its customers and an update to content within its technology development portfolio with focus on human lunar missions.

INTRODUCTION

The Exploration Life Support (ELS) Project is one of over twenty technology development projects managed by NASA's Exploration Technology Development Program (ETDP), under the guidance of the Advanced Capabilities Division of the NASA's Exploration Systems Mission Directorate (ESMD). ELS was originally

chartered to perform research and technology development (R&TD) toward meeting specific critical architectural functional needs identified by the Exploration Systems Architecture Study (ESAS) in the categories Environmental Control and Life Support (ECLS) and Crew Support and Accommodations, with specific focus on atmospheric management – CO₂/contaminants and moisture removal systems, advanced air and water recovery systems, and habitability systems including waste management and hygiene [1, 2]. Other technical areas often associated with ECLS, including thermal control, environmental monitoring, and fire protection, were chartered as separate technology development projects.

The ELS Project's chief objective is to develop and mature relevant technologies that meet mission requirements and fill capability gaps or significantly improve the efficiency, safety, and reliability over the state of the art, providing risk reduction and developmental economy to flight projects [3]. CxP's policy is to ensure that technologies needed for Constellation projects are matured to technology readiness level (TRL) 6 in time to support system-level (Level III) PDRs [4]. With the PDR for the Orion Crew Exploration Vehicle planned to be completed in 2009 and the ELS Project's technology development tasks for CEV largely completed, the focus of the ELS Project's portfolio has shifted to emphasize technology needs for human lunar missions.

TECHNOLOGY NEEDS FOR HUMAN LUNAR MISSIONS

Each technology project manager is directed by ETDP to participate with technology development customers to

understand infusion opportunities, to establish customer advocacy, and to drive the technology development towards meeting customer capability needs [5]. CxP is operating primarily under a “technology pull” strategy, which is outlined in the Constellation Program Technology Insertion Strategy Document [4]. A requirements-driven approach is used to determine CxP technology needs. This strategy was put in place to ensure that ESMD’s technology investments are traceable to baseline requirements, validate the mapping of technology investments to mission needs and reduce

technical and programmatic risks.

Technology needs are reviewed and prioritized by CxP’s Technology Prioritization Panel (TPP) on a yearly basis. The third TPP was conducted in fiscal year (FY) 2009. The TPP has membership that includes representatives from various requirement owner organizations, including System Integration Groups, Constellation Project Offices, and Architecture Teams [6]. Needs are categorized as based on criticality or priority and are associated with a specific mission, including Initial Operational Capability (CEV to the International Space

Table 1. Lunar Transport and Lunar Surface technology needs applicable to ECLSS, ordered by mission, category, then ID.

ID	Title	Category*	Mission
105	Lunar Dust Filtration	Critical	Lunar Transport
594	Advanced Airlock/Suitlock with Dust Filtration	Critical	Lunar Transport
607	CO ₂ & Moisture Removal System	Critical	Lunar Transport
610	High Pressure Oxygen	Critical	Lunar Transport
103	Targeted Trace Contaminant Control	Highly Desirable	Lunar Transport
107	Deployable Post-Fire Cleanup Device	Highly Desirable	Lunar Transport
475	Biocide Development	Highly Desirable	Lunar Transport
476	Urine Pretreatment	Highly Desirable	Lunar Transport
477	Urine Receptacle Assembly	Highly Desirable	Lunar Transport
501	High Pressure Oxygen for Lander	Highly Desirable	Lunar Transport
627	Lander Dust Mitigation	Highly Desirable	Lunar Transport
678	Improved Trace Contaminant Control Catalysts and Sorbents	Highly Desirable	Lunar Transport
408	Quiet Fans	Desirable	Lunar Transport
617	Quiet Fans/Compressors and Small Mufflers	Desirable	Lunar Transport
618	Tox/Dust/Emergency Breathing Mask	Desirable	Lunar Transport
112	Improved CO ₂ Removal for Loop Closure	Critical	Lunar Surface
113	Carbon Dioxide Reduction	Critical	Lunar Surface
119	Water Recovery from Brine	Critical	Lunar Surface
469	Lunar Dust Filtration	Critical	Lunar Surface
517	Life Support Water Recovery	1	Lunar Surface
522	Life Support Air Revitalization	1	Lunar Surface
623	Dust/Regolith Mitigation Techniques within Habitable Cabin	Critical	Lunar Surface
625	Dust Control/Removal Airborne Dust	Critical	Lunar Surface
634	Brine Water Recovery	Critical	Lunar Surface
638	Carbon Dioxide Reduction	Critical	Lunar Surface
639	Water Recovery with Limited Resupply	Critical	Lunar Surface
644	Carbon Dioxide Reduction	Critical	Lunar Surface
645	High Pressure Oxygen Supply	Critical	Lunar Surface
115	Improved/Targeted Trace Contaminant Control	Highly Desirable	Lunar Surface
480	Urine Pretreatment	Highly Desirable	Lunar Surface
649	Simplified Robust Partial-Gravity Water Processing & Phase Separation	Highly Desirable	Lunar Surface
667	Waste Stabilization and Dewatering	Highly Desirable	Lunar Surface
675	Improved Urine Pretreatment Methods	Highly Desirable	Lunar Surface
681	Sustainable Food Production, Processing and Preparation	Highly Desirable	Lunar Surface
685	Deployable Post-Fire Cleanup	Highly Desirable	Lunar Surface
687	Advanced Clothing/Fabric Cleaning Systems	Highly Desirable	Lunar Surface
699	In-situ methane production	Highly Desirable	Lunar Surface
985	Waste Stabilization and Volume Reduction	2	Lunar Surface
712	Quiet Fans and Ventilation Acoustic Emission Attenuation Techniques	Desirable	Lunar Surface
715	LED Lighting	Desirable	Lunar Surface

*Category designations are as follows: C = “Critical”, HD = “Highly Desirable”, D = “Desirable”. Data from references 6 & 7. Three new needs identified during the third annual TPP in FY09 have been added and carry the following category designations: 1=“Must Fund For FY11”, 2=“Need to Fund As Funding Becomes Available”.

Station), Lunar Transit (CEV to lunar orbit and Lunar Lander) and Lunar Surface (including lunar habitats and pressurized rovers). Technology needs applicable to ELS for lunar missions are listed in Table 1. In some cases multiple needs address the same technical area. This may be due to similar submissions from different CxP customers or to reflect unique needs for specific vehicles or applications. More specific information on needs, requirements, architectures, design baselines and operational scenarios applicable to ECLSS is available [7, 8, 9, 10].

EXPLORATION LIFE SUPPORT (ELS) PROJECT ORGANIZATION

The ELS Project is managed from Johnson Space Center and includes Marshall Spaceflight Center, Kennedy Space Center, Ames Research Center and Glenn Research Center as participating Centers [3]. The Project is organized into seven elements including a project management office. The project office is responsible for project implementation, following mandatory technology development project requirements [11] and is responsible to the sponsoring program, ETDP [5]. There are four technology development elements within ELS: Atmosphere Revitalization Systems (ARS); Water Recovery Systems (WRS); Waste Management Systems (WMS); and Habitation Engineering. Two elements are cross-cutting, providing support to the four technology elements: Systems Integration, Modeling, and Analysis (SIMA), and Validation and Testing (V&T). The Work Breakdown Structure (WBS) for ELS is consistent with NPR 7120.8 and is tailored toward the unique needs for spacecraft ECLSS and habitation systems (Table 2).

SYSTEMS ANALYSIS - The ELS project uses systems analysis to guide investments in technology development and evolution of life support system architectures. The Systems Integration, Modeling and Analysis (SIMA) Element of ELS fulfills this responsibility and has developed various analytical tools and resources. SIMA helps determine the equivalent system mass (ESM) of competing technologies for Constellation missions as well as doing more detailed performance analysis. ESM is an analysis method developed by SIMA, which combines the launch mass of hardware and consumables with mass penalties for volume, power and crew time requirements into a single 'equivalent system mass [12].

Although lunar exploration missions are becoming better defined, many assumptions must still be made in order to carry out meaningful analyses. Therefore, SIMA has developed and maintains various products to document mission details, analysis methods and necessary assumptions. The primary documents are listed and briefly described in Table 3. Within this framework, more meaningful engineering trade-off studies, architecture assessments and parametric analyses can be conducted. In 2008, the Exploration Life Support

Baseline Values and Assumptions Document, the Exploration Life Support Reference Missions Document and the Exploration Life Support Requirements Document were all updated to reflect the most recent information available from the Constellation program [13, 14, 15].

Examples of recent ELS studies completed by SIMA include "Exploration Life Support R&TD Metric of the Lunar Outpost" [16], "Bosch Carbon Dioxide Reduction System Model" [17], "Laundry Study for Constellation" [18] and "SPR ECLSS Sizing Analysis: Carbon Dioxide and Humidity Control" [19].

Systems analyses such as these lead to findings concerning optimization of life support systems for exploration missions. For example:

- Atmosphere, water and food systems understandably require significant launch mass from Earth to support humans at a lunar outpost, but this amount can be cut in half by using advanced technologies under development by ELS compared to state-of-the-art [16].
- Water based laundry systems trade well for a lunar outpost when a brine processor is used [18].
- The use of 2 spacesuit-sized CO₂ removal units in the lunar rover will meet requirements for non-exercise nominal and contingency cases, but may not meet requirements for exercise cases [19].

In addition to creating original models and studies, SIMA analyzes test data produced by other elements of ELS, such as "Post-test Modeling and Analysis of Phase I CAMRAS/Constellation Suit Integrated Test" [20]. SIMA has been heavily involved with subsequent tests of the CAMRAS technology as well as water distillation technology testing [21].

VALIDATION AND TESTING - Through the process of technology development and maturation, component or breadboard validation is performed in laboratory environments and then moves to testing in relevant environments. This second cross cutting element (supports all other ELS technical elements) provides this later function and is composed of two sub-elements, Flight Experiments and Integrated Testing.

Flight Experiments – The Flight Experiments technical element manages testing of technologies under hypogravity and microgravity conditions in order to complement the activities conducted in ground laboratories and ground test bed facilities. Process technologies under development by ELS for lunar missions will be assessed for gravity sensitivity and tested in the appropriate relevant environment to assure that the hardware performs as designed.

The Flight Experiment element technical approach is to schedule up to two flight campaigns for each fiscal year using commercial or government-owned reduced gravity

Table 2. ELS Project work breakdown structure with relevant lunar mission needs and technology development tasks.

WBS Title	Specific Needs Addressed*	Technologies**
.01 Project Management		
.02 Systems Integration, Modeling, and Analysis		
-01 Management and Systems Engineering Support	†	
-02 Systems Analysis & Simulations	†	
-03 Technology Analysis and Simulations	†	
-04 Reference Documents	†	
-05 Test Analysis and Support	†	
-06 Online Project Information System	†	
.04 Technology Development		
.04.01 Air Revitalization Systems (ARS)		
-01 Carbon Dioxide Partial Pressure Control	112, 522, 607	CAMRAS, SBAR, LPCOR, NGARS, ESS
-02 Control Trace VOC Concentrations	103, 107, 115, 522, 618, 678, 685	VOC Sorbents and catalysts, ESS, ATCC, Toxic Atmosphere Recovery
-03 Particulate Matter Removal	105, 469, 522, 594, 623, 625, 627	Atmospheric dust removal, vacuum cleaner
-04 Resource Recovery and Recycling	113, 522, 638, 644	Sabatier, Bosch, methane pyrolysis, SOE, TSAC
-05 Atmospheric Gas Storage and Supply	501, 610, 645	High pressure oxygen (swing bed & mechanical compression, electrolysis), Subcritical LOX Storage, ISRU integration
-06 Supporting Infrastructure	408, 522, 617, 712	Quiet fan development
.04.02 Water Recovery Systems (WRS)		
-01 Wastewater Pretreatment and Storage Systems	119, 517, 634	Alternative urine pretreatment, cleansers, detergents and personal care products
-02 Potable Water Disinfection and Storage Systems	475, 517	Alternative biocides, point of use filtration,
-03 Primary and Secondary Water Processing Systems	517, 639, 649	CDS, DOC, OD, EWRS, VPCAR, LWCWT, gravity dependent water processor, <i>bioreactors</i>
-04 Improved Post-processing Systems	517, 639, 649	Thermal, vapor phase and photo- catalysis
-05 Water Recovery from Brine Systems	119, 517, 634	Several candidate technologies are under evaluation
.04.03 Waste Management Systems (WMS)		
-01 Human Metabolic Waste Management	667	<i>Flexible Membrane Commode</i>
-02 Volume Reduction of Waste	985	Compaction, Heat Melt Compactor
-03 Resource Recovery and Drying	667, 699, 985	Waste drying, Heat Melt Compactor
-04 Waste Mineralization	699, 985	<i>Pyrolysis, Incineration</i>
-05 Waste Stabilization and Storage	667, 985	Waste drying, Heat Melt Compactor, VOC characterization
.04.04 Habitation Engineering		
-01 Hygiene and Housekeeping Technologies	477, 105, 469, 522, 594, 623, 625, 627	<i>Waste collection, vacuum cleaner</i>
-02 Interior Clothing Systems	687	Advanced clothing and laundry
-03 Crew Accommodation Technologies	681, 715	<i>Cabin Solid State Lighting</i>
.05 Validation & Testing		
-01 Flight Experiments	†	
-02 Integrated Testing	†	

* Need ID numbers shown. See Table 1 for titles of needs.

** See appendix for definitions of acronyms. Technologies in italics have historically had funding or may be subject to decision points.

† SIMA and Validation & Testing, by their cross-cutting nature, support all needs and technologies.

aircraft. The flights provide the opportunity for experimenters to perform tests at various levels of gravity allowing for evaluations of hardware components early in the technology development sequence. Flight experiments on the ISS and other orbital or sub-orbital platforms may be considered if necessary for research or technology validation and if sufficient resources are available.

Integrated Testing - Integrated testing, in which candidate technologies are evaluated at subsystem or systems levels while interfacing with other life support hardware and challenged by real metabolic loads, is a necessary component of any technology development activity to advance a technology's maturity level. Integrated testing allows for demonstration of technology-to-technology interface compatibility and end-to-end functionality, including operability of life support hardware and software. Integrated testing is also useful in identifying weaknesses in technologies, allowing for more efficient focusing of future technology development resources. In some cases comparison tests are conducted to obtain data to assist in the down selection of competing technologies, such that the hardware with the best characteristics are chosen for further technology advancement.

Technologies are first evaluated in a laboratory setting using component or breadboard level hardware to demonstrate basic functionality and performance. Technology maturation is achieved as higher fidelity hardware is evaluated in relevant environments until ultimately a higher fidelity system/component, such as a brassboard or prototype, that adequately addresses scaling issues, is operated in a relevant environment to demonstrate operations under critical environmental conditions. For lunar missions, candidate technologies will require some level of evaluation under reduced atmospheric pressures, elevated oxygen levels and exposure to potential lunar dust particulates as may be present in a lunar lander and outpost.

Recently, integrated tests were conducted in support of validation of the CO₂ and Moisture Removal Amine Swing-Bed (CAMRAS). The technology is under development for Orion and other future vehicles including Altair and pressurized rovers. Two integrated tests were completed in FY08 and FY09. The test series was titled the CAMRAS Constellation Suit Integrated Test (CCSIT). This three phase test program was developed for integrated testing of different hardware components (CAMRAS, prototype suit umbilicals, and pressure suits) alone or in configurations prototypic of the proposed ECLSS system for Orion. Phase I, completed June 1, 2008, involved human tests with CAMRAS in a cabin atmosphere revitalization configuration at ambient atmospheric pressure [20]. Phase 2, completed April 3, 2009, investigated CAMRAS performance in a suit-loop configuration, with enriched oxygen levels at suit pressure and at evacuated cabin conditions. Phase 3, planned to be

Table 3. Exploration Life Support Reference Documents.

Document Name	Description
Exploration Life Support Baseline Values and Assumptions Document [13]	<i>Provides analysts, modelers, and researchers a common set of initial values and assumptions as a baseline. This baseline provides a common point of origin from which Systems Integration, Modeling, and Analysis (SIMA) Element studies can depart.</i>
Exploration Life Support Reference Missions Document [14]	<i>Provides the ELS Project with several specific reference missions that are likely scenarios for human space exploration, consistent with Constellation plans as they evolve.</i>
Exploration Life Support Requirements Document [15]	<i>Outlines ELS Project requirements for ELS technologies. Used as a tool for Element Leads and hardware developers. Based on Constellation Program requirements where available.</i>

completed before the Orion CDR, will involve human subjects with and without pressure suits, at variable chamber pressures and oxygen concentrations. These tests have direct relevancy to Altair, as CO₂ and moisture removal swing-bed technology is a strong candidate for use on a lunar lander.

TECHNOLOGY PORTFOLIO

The suite of specific technology development tasks within the ELS Project's portfolio is determined by CxP vehicle priorities, mission and technology trade studies, and available resources. The ELS portfolio is evaluated yearly and documented in the ELS Project Plan [3, 22]. The Work Breakdown Structure (WBS) for ELS is tailored toward the unique needs for spacecraft ECLSS and habitation systems. The WBS for ELS is given in Table 2, with corresponding needs and associated technology development tasks. A top level roadmap showing major technology tasks by year and mission is given in Figure 1. Key mission dates applicable to technology infusion are also shown. The figure illustrates that following the Orion PDR, emphasis will be on technology development supporting Altair and Lunar Surface Systems. Certain tasks, including waste management and trace gas contaminant control, were reduced in scope in FY09 due to conflicting priorities and

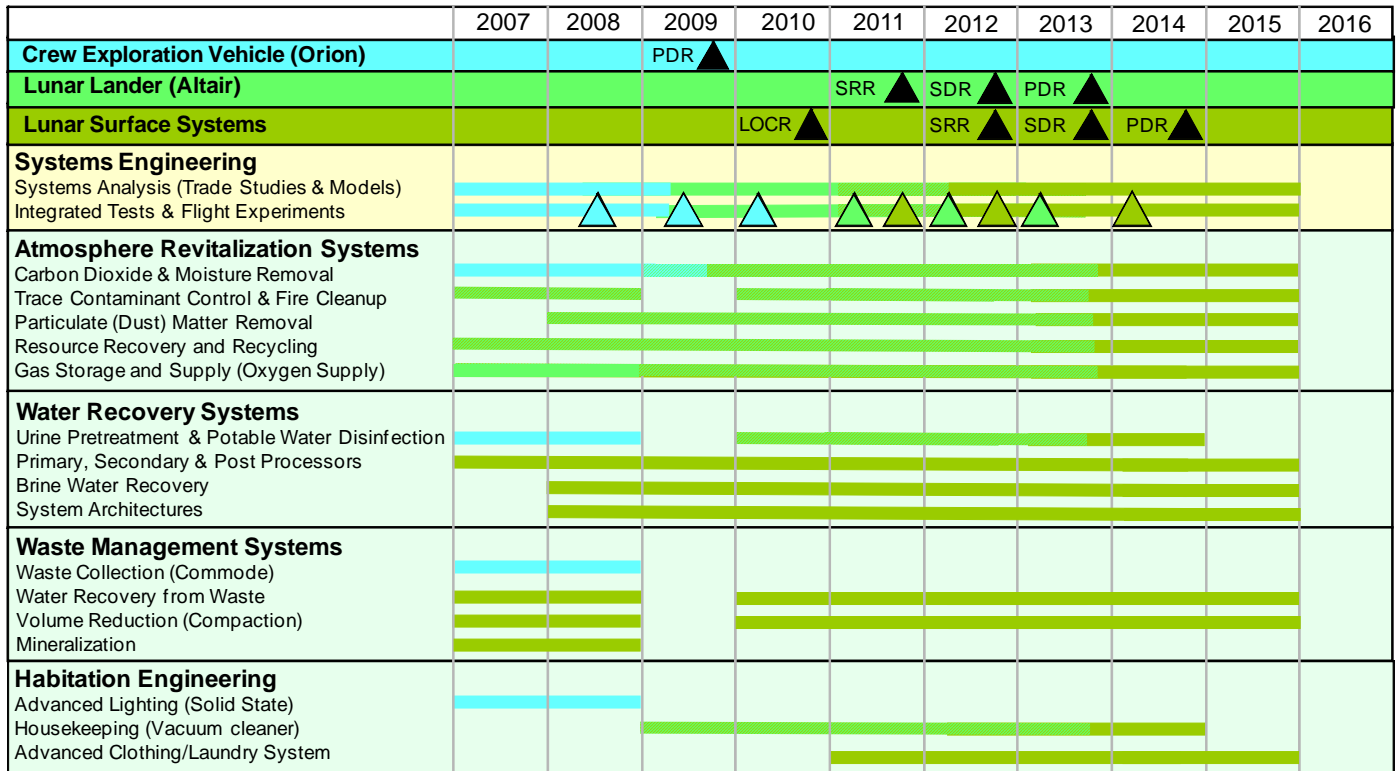


Figure 1. Summary Roadmap for Exploration Life Support.

funding limitations, but the work is planned to be resumed in later years.

ATMOSPHERE REVITALIZATION SYSTEM (ARS) - The Atmosphere Revitalization Systems (ARS) element objectives are to identify and to mature process technologies that directly address specific needs identified by CxP. Process technology maturation tasks are conducted for atmosphere revitalization functions that include CO₂ partial pressure control; moisture removal; trace chemical contaminant control; particulate matter removal and disposal; atmospheric gas supply, storage, conditioning, and distribution; resource recovery, storage, conditioning, and recycling; and supporting infrastructure for the most promising process technologies. Emphasis for lunar lander includes carbon dioxide and moisture removal, cabin atmosphere particulate management directed at lunar dust, and high pressure oxygen systems in support of EVA recharge. These technologies also have applicability to Lunar Surface Systems, including pressurized habitats and rovers. The focus for LSS is closure of the ARS loop, including advanced carbon dioxide removal, carbon dioxide reduction, oxygen generation and trace contaminant control. Technologies and interfaces in support of EVA recharge, pressurized rovers and In Situ Resource Utilization (ISRU) will be investigated.

WATER RECOVERY SYSTEMS (WRS) – For lunar missions, the WRS element is primarily focused on development of closed-loop water recovery systems for Lunar Surface Systems, where recovery and production

of potable water from wastewater with high levels of closure is necessary for mission success. Initial emphasis is on development and evaluation of physicochemical systems that can recover approximately 90% of wastewater to potable water quality. Technologies for further recovery of water from waste brines will be investigate to increase the level of closure. A set of competing technologies will be evaluated, with down selects/key decision points (KDP) to determine the systems for continued investment of technology funding.

WASTE MANAGEMENT SYSTEMS (WMS) - The WMS element is focused on the development of waste management technologies to recover resources, increase crew safety and performance, and protect planetary surfaces while decreasing mission cost. Technology gaps to be addressed for Lunar Surface Systems include water recovery from waste (supporting closure of the water loop), stabilization and odor control, waste/trash volume reduction, and disposal.

HABITATION ENGINEERING - Habitation Engineering is a distinct technology area directly applicable to human mission success. It provides crew interfaces to life support equipment and improves crew function, comfort, and quality of life to enhance crew productivity. Capabilities have historically been designed for Low Earth Orbit (LEO) missions with frequent resupply, and thus may not be sufficiently optimized for reliability, mass, volume, or autonomy which are critical design drivers for exploration missions. Development of

systems for use in partial gravity, low atmospheric pressure and elevated oxygen concentrations will be a challenge. Habitation technologies focused at lunar missions include vehicle and habitat housekeeping/cleaning including dust mitigation, advanced clothing and laundry, and acoustic mitigation.

CONCLUSION

The Exploration Life Support technology development project is responsive to changes in architectures, requirements and organizational relationships as NASA's implementation of the U.S. Space Exploration Policy matures and as lunar architectures become more defined. With most tasks in support of the Orion Crew Exploration Vehicle nearing completion, the Exploration Life Support Project has shifted the emphasis of its research and technology development effort in support of critical needs for lunar transit and surface missions. Technology maturity dates of candidate technologies are aligned with key programmatic milestones for Altair and Lunar Surface Systems. The ELS project has a well established, active group of technologists throughout the agency dedicated to carrying out the U.S. Space Exploration Policy by reducing life support consumables and improving system performance and robustness.

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ACRONYMS

ARC: Ames Research Center
ARS: Atmosphere Revitalization Systems
ATTCS: Advanced Trace Contaminant Control System
BVAD: Baseline Values and Assumptions Document
CO₂: Carbon Dioxide
CAMRAS: Carbon-Dioxide and Moisture Removal Amine Swing-Bed
CCSIT: Carbon Dioxide and Moisture Removal Amine Swing bed (CAMRAS) / Constellation Suit Integrated Test
CDR: Critical Design Review
CDS: Cascade Distillation System
CEV: Crew Exploration Vehicle
CFR: Carbon Formation Reactor
COTS: Commercial Off The Shelf
CR: Contractor Report
CTSD: Crew and Thermal Systems Division
CxP: Constellation Program
DOC: Direct Osmotic Concentration
ECLS: Environmental Control and Life Support
ECLSS: Environmental Control and Life Support System
ELS: Exploration Life Support

ESAS: Exploration Systems Architecture Study
ESM: Equivalent System Mass
ESMD: Exploration Systems Mission Directorate
ESS: Engineered Structured Sorbents
ETDP: Exploration Technology Development Program
EVA: Extra-Vehicular Activity
EWRS: Exploration Water Recovery System
FY: Fiscal Year
GRC: Glenn Research Center
H₂: Hydrogen
HE: Habitation Engineering
HQ: Headquarters
IC: Initial Capability
ISRU: In Situ Resource Utilization
JSC: Johnson Space Center
KDP: Key Decision Point
KSC: Kennedy Space Center
LaRC: Langley Research Center
LED: Light Emitting Diode
LEO: Low Earth Orbit
LOCR: Lunar Operations Concept Review
LOX: Liquid Oxygen
LPCOR: Low Power CO₂ Removal
LSS: Lunar Surface Systems
LT: Lunar Transport
LWCWT: Light Weight Contingency Water Treatment
MSFC: Marshall Space Flight Center
NASA: National Aeronautics and Space Administration
NGARS: Next Generation ARS
NP: NASA Publication
NPR: NASA Procedural Requirements
OD: Osmotic Distillation
P/C: Physicochemical
PDR: Preliminary Design Review
R&TD: Research and Technology Development
SBAR: Sorbent-Based Atmosphere Revitalization
SDR: Systems Definition Review
SOE: Solid Oxide Electrolysis
SPR: Small Pressurized Rover
SRR: Systems Requirements Review
SIMA: Systems Integration, Modeling, and Analysis
TM: Technical Memorandum
TPP: Technology Prioritization Panel
TRL: Technology Readiness Levels
TSAC: Temperature Swing Adsorption Compressor
U.S.: United States
V&T: Validation and Testing
VOC: Volatile Organic Carbon
VPCAR: Vapor Phase Catalytic Ammonia Removal
WBS: Work Breakdown Structure
WMS: Waste Management System
WRS: Water Recovery System