Environmental Control and Life Support (ECLS) Systems

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Abstract

Environmental control and life support (ECLS) systems provide the conditions necessary to maintain astronaut's health during a mission. They have been a part of every human-rated vehicle from Mercury onward, from carbon dioxide scrubbers and drink bags, to sophisticated air and water recovery technologies. In order to enable human exploration beyond low Earth orbit for an extended time, such as a mission to Mars, closed-loop life support, the continuous use, reuse, and recycling of air, water, and waste will be necessary. This chapter provides a brief history of air revitalization, wastewater, and solid waste recovery systems from the early spaceflight era to the present,

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potential technologies in development to facilitate further loop closure, and considerations for future life support system development in support of exploration.

Keywords

Life support · Air revitalization · Water recovery · Solid waste · Loop closure · Spacecraft

Definition

A robust and reliable livable environment is necessary for humans to travel beyond low earth orbit. To be able to travel and live on another planetary body, the environment must be able to regenerate itself, similar to the biogeochemical cycles on earth. Environmental control and life support systems, also known as ECLS systems, provide that environment and the means to regenerate wastes to useful consumables.

Introduction

Astronauts living in space need many of the same things that people do when they're at home; they require clean air to breathe, clean water to drink, and someplace to put the trash at the end of the day.

There are many variables to consider when designing a life support system. Key drivers include mission architecture (i.e., mission duration, degree of EVA activity, availability of logistics), mass, power, volume, reliability, and redundancy. This chapter will provide an overview of air revitalization (ARS), water recovery (WRS), and waste management (WMS) systems, current and previous designs, as well as considerations for future system architectures where resupply will be limited.

Air Revitalization

Air revitalization is a series of processes and technologies that provide a breathable atmosphere for a crew. The primary job of this system is to remove carbon dioxide and trace contaminant

Table 1 CO_2 control options

Mission duration	Hours	<10 days	10–30 days	>6 months	>2 years
Critical attributes	Simple, reliable	Small, simple, and reliable	Very small or reusable, reliable	Recover CO_2 for loop closure, extremely reliable	Control CO_2 to low levels, reliable and repairable, recover CO_2 for loop closure
Method of operation	Irreversible, single use, chemical reaction	Irreversible, single use, chemical reaction	Reversibly adsorb at cabin pressure, vent to vacuum	Reversibly adsorb at ambient temperature, regenerate at 200 °C	TBD
Biggest problems	Single use, non-regenerable, caustic material that is prone to dusting	Requires crew change-out and substantial space in crew cabin area	Mechanically more complex, no CO_2 recycling with mixed CO_2 and H_2O venting	Requires power for thermal regeneration, prone to dusting	TBD
System name	LiOH	LiOH	Solid amine	Four-bed molecular sieve	TBD
Flight system	EMU portable life support system	Apollo and Shuttle	Shuttle and Orion	International Space Station	Exploration

species, provide oxygen, and, together with thermal control systems, control humidity and air temperature in the vehicle.

CO_2 Control

Carbon dioxide (CO_2) is the primary metabolic contaminant of a cabin atmosphere. Controlling CO_2 concentrations is rarely a problem on earth with large indoor volumes and with continuous gas exchange from the outside, but is more difficult in the closed and limited environment of a spacecraft and therefore is monitored very closely. Effects of excess CO_2 exposure include decreased blood pH, decreased cognitive ability, and disorientation and in extreme cases can lead to death (Davis et al. 2011). Table 1 provides a summary of CO_2 control options for various flight systems.

During the Gemini, Mercury, Apollo, and Space Shuttle programs, cabin CO_2 levels were controlled using lithium hydroxide (LiOH). As air circulated through the vehicle, it would be routed through a series of canisters containing LiOH. Carbon dioxide binds to the LiOH and is removed from the atmosphere via the following chemical reaction:

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O$$

While LiOH is very effective at removing CO_2 from the atmosphere, it has one significant limitation; it cannot be reused. Once LiOH reacts with CO_2, it is unable to react with another molecule of CO_2. Because the missions of these programs were of short duration (<2 weeks), a regenerative system was not needed to reduce CO_2 to reclaim the oxygen and carbon for other life support applications. However, as mission duration increased, the need to reduce consumables and recycle the end products for further use, aka “close the loop,” became necessary for longer duration missions as described below.

Skylab, the United States’ first orbiting space station, was the first space vehicle which contained a regenerative life support system. Instead of LiOH, Skylab utilized zeolites, aluminum silicate-based materials, to adsorb CO_2 from a cabin atmosphere (Isobe et al. 2016). A significant advantage zeolites have over LiOH is that they can be regenerated via a two-stage process, allowing the zeolites to be reused, rather than discarded. Elevating the temperature of zeolites releases CO_2 from the material, connecting the system to space vacuum facilitates the transfer of CO_2 out of the vehicle allowing the zeolite to be used again. During the Skylab program, the zeolite-based ARS was in operation for more than 4000 h, demonstrating its applicability for extended mission durations.

Carbon dioxide removal on the International Space Station (ISS) improved upon the design used on Skylab. The Carbon Dioxide Removal Assembly, or CDRA, was also a zeolite design with a key modification: the addition of a water vapor capture feature utilizing regenerable desiccant prior to CO_2 venting (Shayler 2001), which increased the number of beds from two to four. The addition of a separate desiccant bed reduced the humidity of the air and increased the efficiency of CO_2 removal.

While zeolite has been used as the primary material to remove CO_2 from ISS, other chemistries are also capable of removing CO_2. Amine-based CO_2 sorbents have been extensively tested as an alternative CO_2 removal technology since early in the Space Shuttle era. Amine chemistry simultaneously removes CO_2 and H_2O in a noncompetitive reaction. Amine chemistry also enables the desorption of water and CO2 under vacuum, without the need for supplemental heating.” (Button and Sweterlitch, 2014). The CO_2 And Moisture Removal Amine Swing-bed (CAMRAS) was developed as a technology demonstration unit for exploration applications in the early 2000s. It was tested on the International Space Station starting in 2013 and is currently used as a backup to the CDRA in the event of a system anomaly on orbit.

CO_2 Reduction

For extended missions that go beyond LEO, any ARS will need to increase its capability to remove contaminants from the air, as well as recycle atmospheric components for continual use. The carbon and oxygen from CO_2 will need to be reused to recycle the oxygen to supply breathable air to the crew and recycle the carbon for other life support purposes. NASA has been developing several technologies to reclaim the carbon and oxygen from CO_2 downstream of a CO_2 removal system; four of these, Sabatier, Sabatier with additional methane processing, Bosch, and co-electrolysis, reduce CO_2 on varying degrees of loop closure and have advantages and disadvantages (Smylie and Reumont 1964).

The Sabatier process, which is currently used to reduce CO_2 on ISS, was developed by the French chemist Paul Sabatier early in the twentieth century. Carbon dioxide is passed over a heated catalyst in the presence of hydrogen. Carbon dioxide is converted to methane (CH_4), and water is generated as a result of the process:

$$CO_2 + 2H_2 \rightarrow CH_4 + 2H_2O$$

The Sabatier process is relatively simple because all of the products and reactants are in the gas phase; however the current system on ISS recovers only half the oxygen from CO_2, and therefore the closure is partial.

The Sabatier process can be augmented by various methods of breaking down CH_4 into hydrogen and either carbon or another product with a higher C:H ratio than CH_4, such as acetylene (C_2H_2). The recovered hydrogen can be recycled back to the Sabatier reactor to convert additional CO_2 to H_2O.

The Bosch process uses hydrogen in the presence of high temperatures and a catalyst to fully reduce CO_2:

$$CO_2 + 2H_2 \rightarrow C + 2H_2O$$

The process can lead to the complete recovery of oxygen from CO_2 through water electrolysis; however flow control processing is difficult because the carbon reaction product is a solid and handling carbon waste is difficult in microgravity.

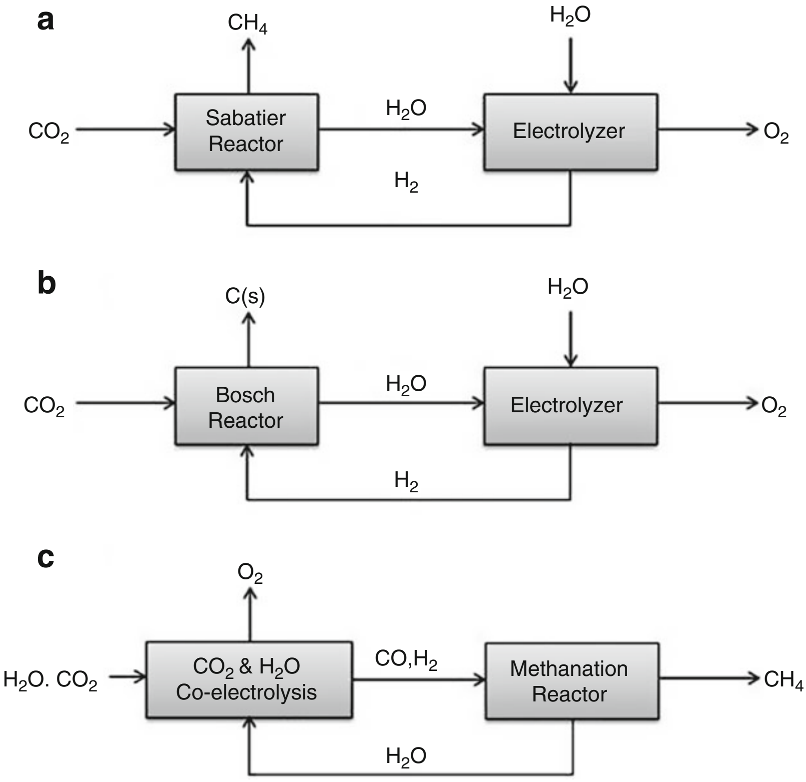

Fig. 1 CO_2 reduction technologies in order of higher loop closure: Sabatier (**a**), Bosch (**b**), and co-electrolysis (**c**)

Table 2 O_2 delivery options

Mission duration	Hours	<10 days	10–30 days	>6 months	>2 years
Critical attributes	Small, simple, and reliable	Small, simple, and reliable	Larger capacity for longer missions	Must store oxygen in a safe, compact, and stable form for extended periods	Must provide and store oxygen for an extended period of time, provide high-pressure, high-purity oxygen for EVA operations
Method of operation	High-pressure O_2 gas	High-pressure O_2 gas	Oxygen tanks are filled prior to launch, and then boil-off is used for gaseous oxygen	Oxygen is stored as water and then electrolyzed as oxygen is needed	TBD
Biggest problems	Limited capacity	Oxygen safety issues Large system size	Use life limited by boil-off limitations	Significant power required	TBD
System name	Primary O_2	O_2 tanks	Cryogenic O_2	Water electrolysis	TBD
Flight system	EMU	Mercury-Skylab	Shuttle (RCRS) and Orion	ISS	Exploration

Co-electrolysis is electrolysis of CO_2 in the presence of steam. It provides increased loop closure as compared to Sabatier, which recovers a larger percentage of the oxygen in CO_2, but the flow control processing is more difficult, because it is a two-phase (gas and liquid) reaction. It is also a relatively new technology, as compared to Sabatier and Bosch (McKellar et al. 2010) (Fig. 1). In addition to the three technologies discussed above, there are also emerging candidates that have promise in recapturing oxygen during spaceflight. These are described in Greenwood et al. (2018).

Oxygen

Just as important as it is to remove carbon dioxide from a cabin atmosphere, oxygen is needed to sustain a crew. The development of an oxygen delivery and generation system as an ECLS component has evolved as mission, and vehicle architecture has evolved. Table 2 provides a summary of characteristics for oxygen delivery systems for past, current, and potential future flight life support systems.

During the Mercury, Gemini, and Apollo programs, oxygen was supplied via high-pressure tanks, which provided a pure oxygen cabin atmosphere at a reduced pressure, which is simpler to control than an oxygen-nitrogen system. The most significant drawback to a pure oxygen atmosphere is safety, as tragically demonstrated by the Apollo 1 fire in 1967. The Apollo 1 tragedy led to one significant change; nitrogen was added to the command module atmosphere on the launch pad while the pressure was at ambient; once reaching orbit, the system transitioned to a pure oxygen atmosphere but at reduced total pressure. This change reduced the initial concentration of oxygen in the command module from 100% to 60% prior to launch (Johnson and Hull 1975).

The Skylab program continued the transition away from a pure oxygen atmosphere to a nitrogen/oxygen mixed atmosphere for both safety and crew health purposes; high-pressure tanks were still used to supply oxygen to the crew, but the concentration of oxygen was lowered from 100% to 74% by volume (Shayler 2001).

The Space Shuttle program made a significant change in the design of the oxygen delivery system, transitioning from high-pressure oxygen tanks to cryogenic oxygen. Oxygen was stored as a liquid and would boil off during a mission, providing sufficient O_2 to the crew. The Space Shuttle had large cryogenic oxygen tanks for the change to electrical power generation, and the plentiful supply also enabled open-loop emergency breathing. But the drawback for long duration missions is that cryogenic oxygen delivery systems have a limited life; it entirely depends on the volume of liquid O_2 that is brought along.

The first venture in reclaiming oxygen from other ECLS systems and closing the life support loop for NASA missions is the Oxygen Generation Assembly (OGA) on the ISS. The OGA uses water electrolysis to provide oxygen to a crew. The OGA receives its water from the Water Processing Assembly (described below). The water is then electrolyzed, leaving oxygen for breathing and hydrogen to be used in the Sabatier process for water recovery (Bagdigian and Cloud 2005).

Oxygen systems for exploration are under development. For a mission to Mars, which can last as long as 3 years, an oxygen generation system will need to build upon the lessons learned from the development of the OGA. It will need to be highly reliable, producing pure oxygen which can be used for day-to-day consumption and which can be stored at high pressures for future use. A small experimental demonstration of the Mars Oxygen In Situ Resource Utilization Experiment (MOXIE) was included in the MARS 2020 Mission to operate on the surface of Mars. It would convert the CO_2 in the atmosphere to oxygen, for breathing air and for fuel production (NASA 2020).

Trace Contaminant and Particulate Control

Trace contaminant gases are those gases that are produced in low quantities (as compared to CO_2), but are nonetheless toxic to the crew or can lead to premature failure of life support hardware. These contaminants are often regulated by OSHA and related to other environmental standards, such as benzene and formaldehyde (National Research Council 2000). With the exception of unforeseen in-mission emergencies, systems are carefully developed and tested prior to installation to minimize generation of these contaminants as much as possible, although some inevitably are produced due to human metabolic activity (Perry and Kayatin 2015). Activated carbon has been the material of choice to remove trace contaminants from the cabin atmosphere throughout NASA's history, usually used with acid-treated carbon for ammonia removal and a low-temperature catalytic oxidizer for conversion of carbon monoxide (CO) to CO_2. For longer-duration missions, high-temperature catalytic oxidation can destroy contaminants that would not accumulate enough to pose a hazard in short-duration missions and would be costly to remove with single-use activated carbon systems.

In a closed environment, there are many types of particles that are present in the spacecraft habitat. These include skin cells, food, clothing fibers, and airborne microbes. For exploration missions, lunar dust and Martian regolith will pose unique hazards. Because of the lack of gravity, these particles do not settle to the ground, but remain suspended in the spacecraft environment. As the air circulates throughout, these particles are typically collected via small particle filters located throughout the station.

Table 3 Water system architectures

Flight system	Types of wastewaters	Water recovery architectures
Apollo	Urine	N/A-used stored water
Shuttle	Urine	N/A-used stored water
Skylab	Urine	N/A-used stored water
Shuttle	Urine	N/A-used stored water
ISS	Urine, humidity condensate	
Initial base	Urine, humidity condensate, hygiene	
Mature base	Urine, humidity condensate, hygiene	

Water

Water is the second most critical ECLS system component behind a breathable atmosphere. Potable water is necessary for consumption, food rehydration, and basic hygiene activities (e.g., hand wash, oral care, and shaving) by a crew and is also used as a coolant fluid for spacecraft thermal systems. Depending on the mission architecture, water can also be used for medical applications (e.g., IV fluid preparation), advanced hygiene activities (e.g., shower), laundry, and crop hydration. A table outlining the types of wastewaters for a given mission architecture is given in Table 3.

Stored Water System Design

Prior to the water recovery system on the ISS, stored water was used for crew consumption, either by itself or for food rehydration and rudimentary hygiene activities, and was discarded after use. The critical attribute of a stored water system design is the need to maintain potability for the entire mission. There are strict microbial limits on potable water for a space vehicle; currently the limit for bacteria (heterotrophic plate count or HPC) on ISS is 50 colony forming units (CFU) per ml; by comparison, most municipalities try to maintain the concentration of HPC in household drinking water, where there is no EPA standard, to approximately 500 CFU/ml. The low concentration of bacteria is maintained through the addition of a biocide to the water. The current potable water biocide that has been in use since Apollo is iodine; however due to concerns that excessive iodine may affect tissues having thyroid function, and because it is a consumable, NASA is evaluating alternative technologies and chemistries to maintain low bacterial counts in drinking water.

Water Recovery from Wastewater

Any mission lasting beyond 30 days requires some sort of water recycling capability, and for any mission continuing more than a few months, water recovery from wastewater is likely to be more cost-effective than supplying water (Swickrath et al. 2011). There are two general classes of water recovery system architectures; one is a physiochemical-based system, which is currently utilized on ISS. The second type of system, a biologically based water recovery system, uses living systems to recover water from wastewater. No matter the type of architecture, a water recovery system will need to remove contaminants wastewater at a high (>98%) recovery rate with a minimal amount of consumables for any long-duration mission beyond LEO (Chandler 2015) to enable self-sufficiency from earth.

International Space Station

The International Space Station utilizes an exclusively physiochemical system to reclaim water from wastewater. A schematic is given in Fig. 2.

The WRS on ISS is made up of two systems, a Urine Processor Assembly (UPA) and Water Processing Assembly (WPA). The UPA reclaims water from a process known as vapor compression distillation (VCD). Urine travels from the Waste Collection System (WCS or toilet) to a waste holding tank. A volume of chemical pretreatment is added at the collection point for two purposes: (1) to prevent urea hydrolysis and the subsequent generation of ammonia as the product of degradation and (2) to prevent precipitation of urine salts. From the holding tank, the stabilized urine enters the distillation assembly (DA). The DA uses a process known as vapor compression distillation to reclaim the water from the urine; the temperature within the distiller is elevated and under vacuum while rotating so that the water evaporates and can be collected downstream. The product from the DA is combined from the water collected

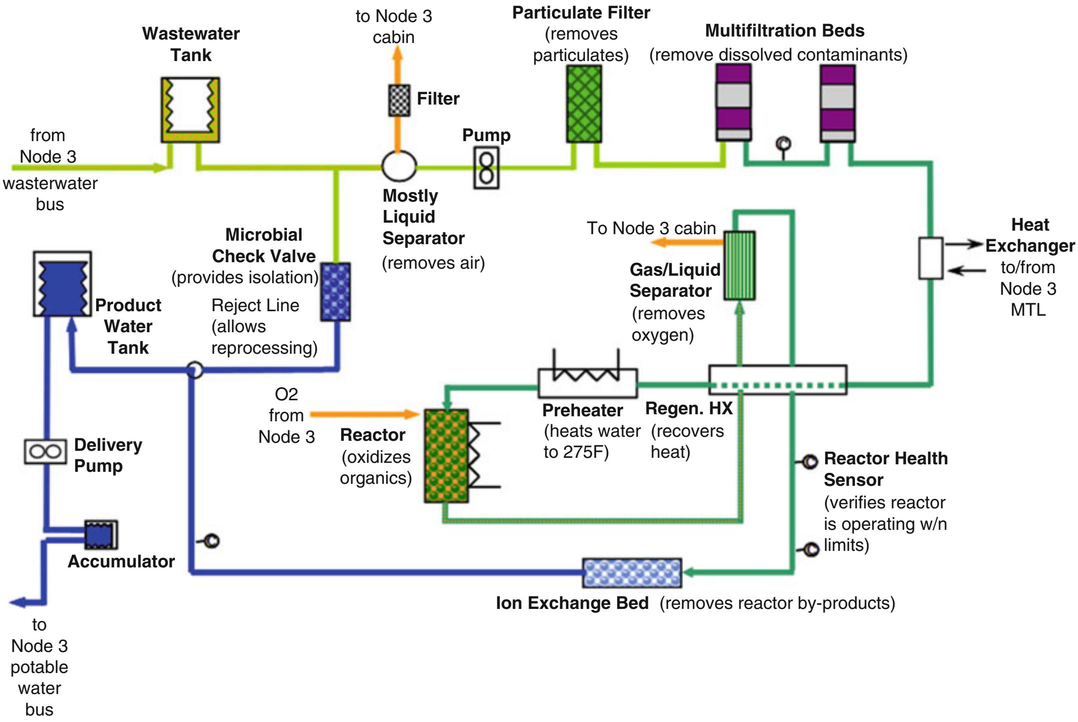

Fig. 2 Schematic of ISS WRS. Courtesy of L. Carter

from heat exchangers that collect the humidity from the cabin and process it through the WPA. The WPA organic carbon and ion exchange resin beds, as well as catalytic oxidation, remove the remainder of organic carbon and ions from the water. Once the trace contaminants are removed from the water, iodine is added to prevent microbial growth.

There are a number of advantages to a strictly physiochemical system; it has a documented operational history in spaceflight which has produced thousands of liters of water during its operational lifetime, and it has a known maintenance program (Carter et al. 2015). Its main drawback is that chemical pretreatment is required to stabilize the urine prior to processing. The current chemical stabilization formulation is a toxic, corrosive consumable, and therefore alternative formulations and processes need to be identified for exploration applications. A second drawback is that there is a limit to the amount of water that can be recycled. A secondary product from distillation is a brine, a concentrate containing magnesium, calcium, and potassium salts which are sequestered and difficult to reclaim for any other life support activities.

Alternative Water Recovery Architecture: Biological Water Recovery

An alternate water recovery architecture utilizes microorganisms to break down the waste stream, as is used in wastewater treatment plants to break down household generated wastes. There have been a number of NASA-funded projects evaluating the use of bioreactors as primary water processors (Jackson et al. 2011; Pickering et al. 2001; Verostko et al. 1992). Most of these concepts utilize two microbial processes: carbon oxidation and nitrification. Autotrophic nitrification converts ammonium from urea hydrolysis into nitrite and nitrate, which is then used by another group of bacteria which use the two nitrogen species as terminal electron acceptors for carbon oxidation. The end products are CO_2, which can be recycled by the air revitalization system, and nitrogen gas (N_2) which can be used to provide the cabin atmosphere with a ready supply of nitrogen (Tchobanoglous et al. 2003).

There are many advantages of a biologically based water recovery system. The first is that the contaminants are transformed, rather than filtered and concentrated; it is essentially a closed ecosystem in outer space. Because the chemical pretreatment is not needed, the brine from a biological system can be reused further (e.g., fertilizer for crop production). The main drawback of a biologically based water recovery system is that microorganisms, for research or environmental applications, either as individual species or as a mixed community, have not been extensively studied in LEO. In limited studies, bacterial species have exhibited changes in cellular mechanisms in spaceflight, but understanding how those differences may impact life support systems is unknown (McLean et al. 2001; Pyle et al. 2001). Biological systems are also more difficult to control, and it may be challenging to achieve rapid startup at the beginning of a mission or control the systems through wide variations, in both volume and wastewater composition.

Brine Water Recovery

Brine comprises 5–15% of wastewater leftover by a distillation-based primary water processor. The brine produced from the ISS WRS has a very unique physical consistency due to the addition of the stabilizing solution and its concentration during the distillation process. The brine is a very viscous solution, and the water remaining in the brine is very difficult to remove. Recent research efforts are underway to identify and develop technologies to reclaim the water in order to reach the goal of 95% water recovery from waste (Kelsey et al. 2017).

Solid Waste

Solid waste management is the ECLS subsystem responsible for controlling trash generation and disposal. This includes things such as metabolic, non-urine waste such as feces and vomit, trash and other refuse, and inedible biomass from plants.

Solid waste can be managed in three ways: remove, stabilize, and recover. For all of NASA's history, "space waste" has been collected, stored, and disposed of Fisher et al. (2008). As with air and water, the need to reuse solid waste in another form for other purposes becomes paramount as the length of a mission increases and minimal resupply is a mission parameter. Stabilizing these solid wastes in some way is likely to be required to protect crew health and maintain the environmental quality in the spacecraft if the solid waste will be stored for a long time before removal/disposal. For some missions, solid waste may be valuable for recycled resources that could be recovered, such as water, carbon, or minerals. The following section discusses potential technologies to recycle solid waste for potential exploration applications.

Drying and Water Recovery

Many of the solid wastes generated by a crew contain a significant amount of water which can be reclaimed and recycled via a water recovery system. Leachate, a slurry of wastes high in organic content and inorganics, can be processed by a water recovery system, either physiochemically or biologically based. Drying either at elevated temperatures or reduced temperatures under vacuum (lyophilization) can be used to reclaim the leachate from various wastes (Litwiller et al. 2005; Wignarajah et al. 2010).

Heat Melt Compaction, Incineration, and Pyrolysis

Once water has been removed from the solid waste, what is to be done with the remaining solids? Heat melt compaction has been studied for exploration applications for nearly two decades. The solid waste is heated to a temperate where the plastic is liquefied and sterilized, then cooled to solidify into smaller volume. Initially thought to be just for habitation use or radiation shielding, however given the advances in 3-D printing technologies, it is possible that the products from heat melt compaction could be reused for other purposes.

Incineration is a process that has been used for more than a century. After heating and combustion, the products are CO_2 and H_2O. Pyrolysis is similar to combustion as both use heat to drive decomposition; however pyrolysis uses higher temperatures in the presence of oxygen and a catalyst to drive the reaction to gas products. Those products would be sent to the ARS for further processing and reuse (Hintze et al. 2012).

Design Considerations for Future Missions

In closing, while much has been accomplished to enable humans to work and live in space, there are a number of technological challenges for humans to go beyond LEO to establish a permanent presence on another planetary body.

First is to continue to improve upon current ECLS technologies and to identify additional technologies which can provide the air, water, and materials needed to travel to another planet. Second, while systems must operate nominally within certain design parameters, they must have engineered flexibility to handle realistic emergencies for short periods and must be able to respond rapidly. System redundancies are a requirement to prevent loss of mission in the event of an emergency. This may mean that systems will require additional consumables in order to respond to an emergency and to provide sufficient time to repair and restore those systems. Finally, while this chapter has discussed the need for loop closure for exploration systems, a cost trade will need to be calculated for each type of exploration mission to identify the optimal ECLS system design, the level of system and subsystem loop closure, and the type of system redundancies needed.

These are not insurmountable challenges.

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