A Discussion of Integrated Life Support and *In Situ* Resource Utilization Architectures for Mars Surface Missions

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Life support aboard the International Space Station is made possible by a combination of technologies to ensure the availability of clean water and air for the crew. Resources, including water and oxygen, are partially recovered and recycled; the balance is lost as waste either to space or incinerated during reentry into Earth's atmosphere. Frequent resupply cargo is provided to the ISS to replace these lost resources. For missions beyond Low Earth Orbit, resupply becomes increasingly challenging both economically and logistically. To limit the need for these resupply missions, three options are available: increase the recovery and recycling of necessary materials, leverage *in situ* resources available for a given mission, or a combination of both. Here we discuss several basic life support and *in situ* resource utilization (ISRU) architectures, identify common technologies, propose possible integrated architectures, identify benefits of and challenges to varying levels of life support and ISRU integration, and discuss several considerations for technology commonality, dissimilar redundancy, and developmental overlap.

Nomenclature

ARS	=	Atmosphere Revitalization System
BPA	=	Brine Processing Assembly
CM	=	Crew Member
DRA	=	Design Reference Architecture
DRM	=	Design Reference Mission
EM	=	Environmental Monitoring
EMC	=	Evolvable Mars Campaign
EVA	=	Extravehicular Activity
FC	=	Fuel Cell
IL	=	Ionic Liquid
ISRU	=	*In Situ* Resource Utilization
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LSS	=	Life Support Systems
JSC	=	Johnson Space Center
MISWE	=	Mars *In Situ* Water Extraction
MOXIE	=	Mars Oxygen ISRU Experiment
MSFC	=	Marshall Space Flight Center
OGA	=	Oxygen Generator Assembly

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NORS	=	Nitrogen Oxygen Recharge System
PEM	=	Proton Exchange Membrane
PPA	=	Plasma Pyrolysis Assembly
PVex	=	Planetary Water Extractor
RWGS	=	Reverse Water-Gas Shift
SAM	=	Sample Analysis on Mars
SBIR	=	Small Business Innovative Research
SOA	=	State-of-the-Art
SOCE	=	Solid Oxide CO_2 Electrolysis
TRL	=	Technology Readiness Level
UPA	=	Urine Processing Assembly
WE	=	Water Electrolysis
WPA	=	Water Purification Assembly
WRS	=	Water Recovery System

I. Introduction

THE International Space Station (ISS) has been continuously inhabited since November 2000, providing the longest sustained human presence beyond Earth's environment in history. This has been made possible by the life support systems (LSS) designed and developed by NASA and its industry and international partners to efficiently utilize the capability to resupply critical consumables and maintenance items from Earth. Similar accommodations will be required for all future long-duration crewed missions beyond low Earth orbit (LEO) such as to the surface of the Moon, during long duration Lunar orbit, transit to Mars, and during Mars surface missions. A key difference will be the reduced availability of resupply from Earth. As missions lead us further from Earth, resupply becomes logistically and economically more challenging. As NASA looks to pursue a sustained human presence beyond LEO, the life support community has focused on improving the reliability and robustness of existing systems while increasing the level of loop closure achieved for water (H_2O) and oxygen (O_2). For missions where *in situ* resources are available, such as the surfaces of the Moon and Mars, *in situ* resource utilization (ISRU) has been proposed. Here we discuss several basic life support and ISRU architectures, identify common technologies, propose possible integrated architectures, identify benefits of and challenges to varying levels of life support and ISRU integration, and discuss several considerations for technology commonality, dissimilar redundancy, and developmental overlap.

II. Background

Provisioning for and managing resources during crewed space exploration missions, particularly water and oxygen, are strongly dependent upon the mission's duration and proximity to Earth. As crewed exploration mission duration and complexity have increased from minutes to hours for a single astronaut during Project Mercury through days and months during the Apollo, Skylab, and Shuttle programs to ultimately support a permanent crewed presence in low-Earth orbit for over a decade during the ISS program, the means to support the crew has been adapted to the mission and vehicle design.[1] As humanity prepares to leave the safety of LEO, the experience in LSS design and flight operations gained over the past fifty-five years is an invaluable resource to inform, guide, and improve future LSS design and operations.

A. Life Support Systems

1. Pre-ISS Life Support System Architecture

Water and O_2 are principal resources that must be provided and managed by a spacecraft's LSS. Early space exploration objectives were short in duration and the crew size ranged between one and three astronauts. For U.S. space exploration programs before ISS, O_2 was supplied from either pressurized gas tanks or supercritical cryogenic storage. Chlorinated or iodinated water was supplied in tanks and wastewater was vented as a waste product.[2,3] Project Mercury and Skylab stored O_2 in tanks pressurized to 51.7 MPa and 20.7 MPa, respectively. Supercritical cryogenic O_2 storage was used during the Gemini and Apollo programs. The Shuttle program employed both pressurized storage at 20.7 MPa as well as supercritical cryogenic storage. The ISS program supplies O_2 via H_2O electrolysis with pressurized storage at 16.5 MPa as a functional backup.[4] Functional redundancy is provided by a Russian H_2O electrolysis unit and chemical O_2 storage in the form of lithium perchlorate canisters.[5] Electrolyzing H_2O was made possible by the station's proximity to Earth and the availability of a ground-based logistics resupply capability.

2. International Space Station Life Support Architecture

As exploration missions that extend humanity's reach into the solar system become better defined, the leading guidance is for a crew of four, with a capability to grow to six, to conduct mission durations of at least 500 days and up to 1000 days.[6, 7] Achieving the exploration mission goals requires either a regenerative, closed-loop LSS consisting of process technologies with a heritage of in-flight operations, or highly reliable and robust resource supply from *in situ* resources. As a baseline approach, NASA considers process technologies used aboard the ISS and seeks to improve them to realize the reliability, logistics reduction, and resource recovery targets necessary for future missions. The challenges associated with exploration missions far from Earth make it necessary to maximize efficiency of the water recovery systems (WRS) and reduce the atmosphere revitalization (AR) subsystem's H_2O demand when *in situ* resources are unavailable. As shown by Figure 1, the LSS aboard ISS is a highly interdependent architecture targeting maximum resource recovery with the available technologies. The AR subsystem, as shown in Figure 2, receives H_2O from the potable supply to produce O_2. By employing a resource recovery technology, H_2O can be returned to the vehicle to minimize the net mission H_2O demand. Wastewater is produced through the distillation of urine and collection of humidity condensate from a condensing heat exchanger, as shown in Figure 3. The wastewater is processed in the Water Purification Assembly (WPA) to produce and store potable water. In this embodiment, the life support system has demonstrated ~93% overall water recovery from the WRS and ~50% oxygen recovery from the AR subsystem.[8]

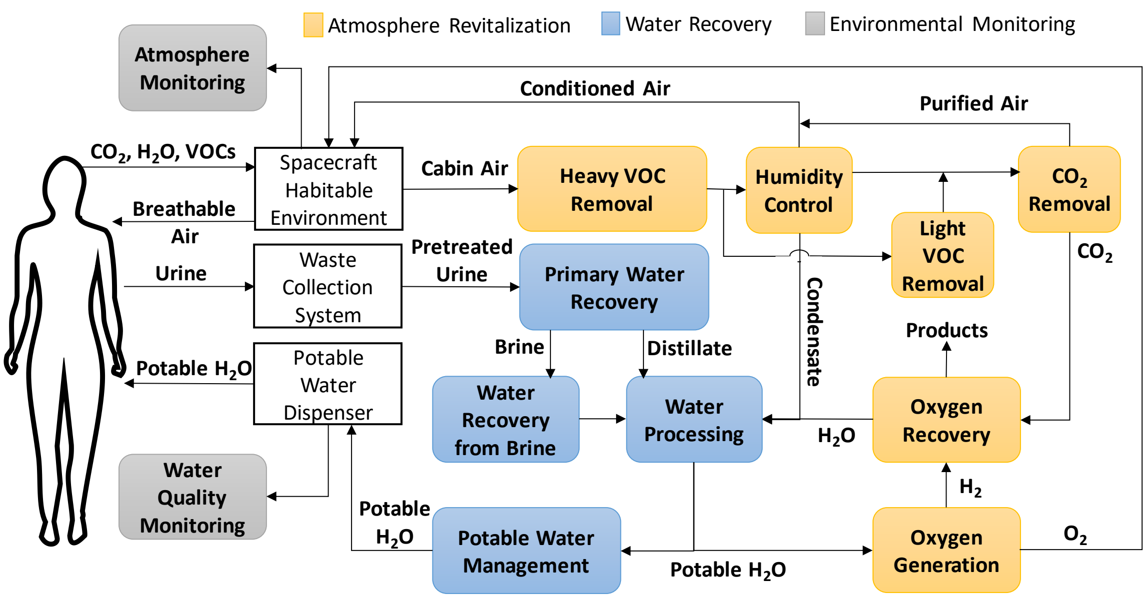

Figure 1. Life Support System functional architecture for exploration missions.[9, 11]

3. Lunar and Martian Surface Life Support System Architectures excluding ISRU

With nearly two decades of demonstrated performance, the technologies used for LSS aboard the ISS form the baseline of AR (Figure 2) and WRS (Figure 3) for lunar and Martian surface architectures.[10,11] Studies have suggested that for long duration missions, there is a potential benefit to having O_2 recovery and/or brine processing technologies despite the additional mass of hardware and consumables. The Brine Processing Assembly (BPA), in development by Paragon, Inc., provides a means to recover water from the brine produced in the Urine Processing Assembly (UPA). Recently, the UPA has consistently recovered ~85% of the water from crew urine.[8] Initial estimates predict water recovery from brine of about 80%, resulting in an overall water recovery of about 98.6% (combined UPA, BPA, and WPA recovery).[9] Several technologies are in development for recovering oxygen from metabolically produced carbon dioxide. These have been described in detail elsewhere, but generally take one of three approaches: electrolysis of carbon dioxide (CO_2) and H_2O to produce gaseous O_2 and some other product,[12,13] conversion of CO_2 to produce H_2O for electrolysis and methane (CH_4) with subsequent decomposition of CH_4 to recycle hydrogen (H_2) and produce either a gaseous hydrocarbon or solid carbon,[14] or conversion of CO_2 to H_2O and carbon monoxide (CO) with subsequent conversion of CO to solid carbon.[15,16,17] With varying levels of success, these technologies can, at best, recycle only 92% of the O_2 required for crew metabolism based on the assumed metabolic quotient.[18] Water resupply is assumed to make up this difference.

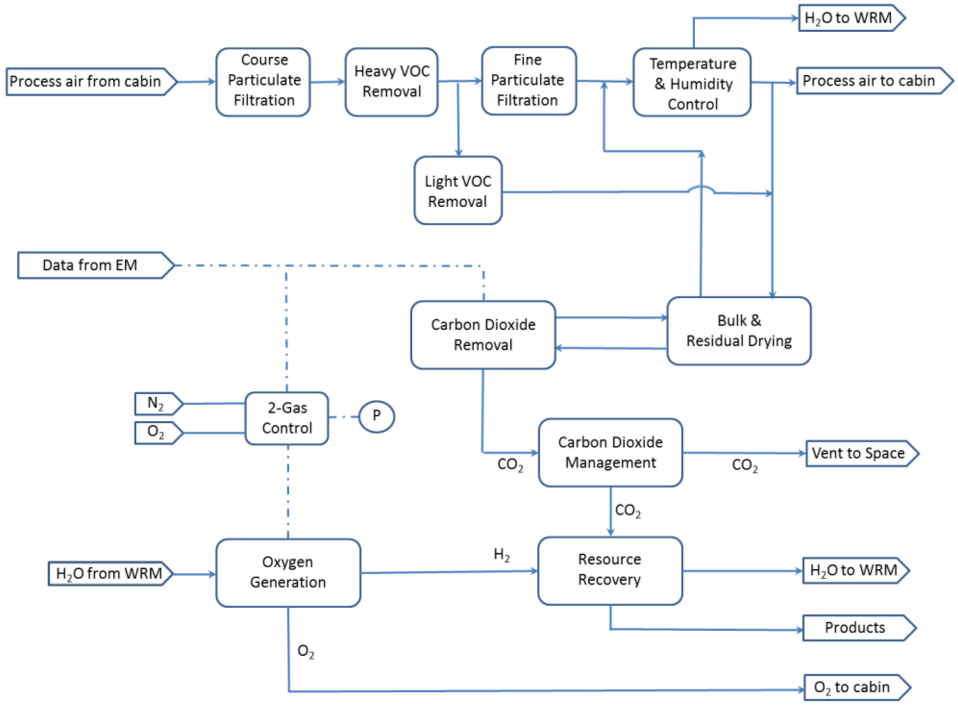

Figure 2. Exploration-forward atmosphere revitalization architecture concept. [10,11]

Additional O_2 and H_2O demands from Extravehicular Activities (EVAs) must also be taken into account given the open loop design of EVA LSSs. For lunar and Martian surface missions, EVAs may increase the O_2 demand of a crew member by as much as 40% and because the CO_2 produced during EVAs is either lost to Lithium Hydroxide (LiOH) beds or to vent, only 44% of the total crew O_2 is recoverable. The H_2O used by a crew member increases during EVAs due to both metabolism and suit cooling. The loss of H_2O is highly dependent on the cooling approach, but if H_2O sublimation is selected for lunar and Martian surface missions, H_2O would have to be resupplied at a rate of between 0.338 kg/CM-hr and 0.625 kg/CM-hr depending on the mission location. The combined additional requirement for EVA cooling H_2O and feed for electrolysis results in a net increase in H_2O loss/resupply beyond ISS of 5.37kg/CM-day for days with 8-hr EVA.

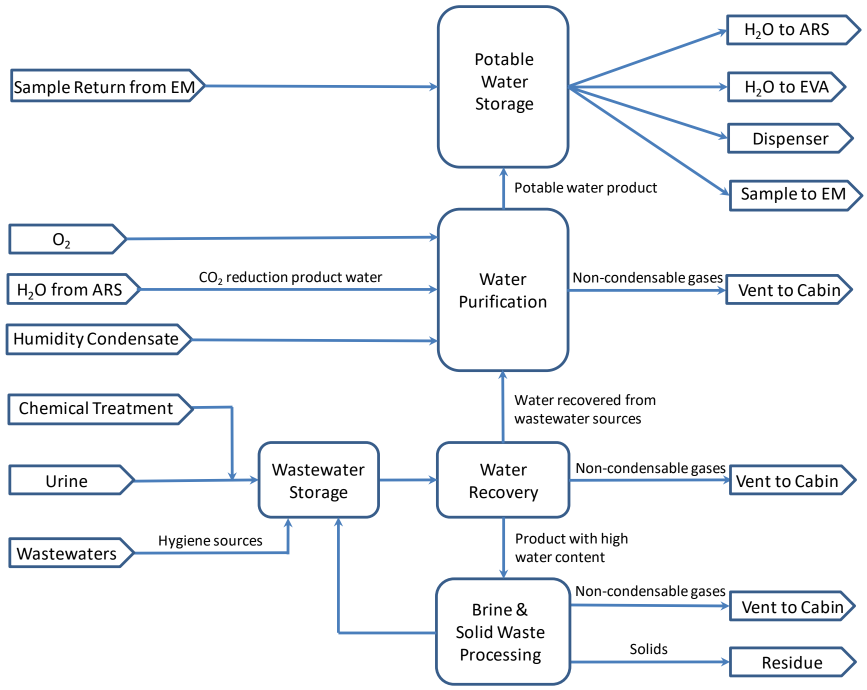

Figure 3. Exploration-forward Water Recovery architecture concept. [10,11]

Another required resupply gas is nitrogen (N_2). Reported assumption for N_2 resupply on ISS is 796 kg/yr. As a baseline assumption, N_2 would continue to be treated as a consumable to be resupplied from Earth.

Because of the considerable logistical and economical challenges associated with this level of resupply, *in situ* resources may provide an enabling capability for surface missions where H_2O and O_2 may be available.

B. ISRU

In Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes local or *in situ* resources to create products and services for robotic and human exploration. *In situ* resources can encompass natural resources such as the Mars atmosphere, water found in soils or subsurface ices, and oxygen and metals bound in minerals, as well as man-made resources such as crew waste and trash, discarded landers and tanks, and anything brought from Earth that has completed its nominal mission use. ISRU concepts and applications for human exploration and space commercialization are divided into six general capability areas:

1) Resource Assessment (i.e. Prospecting) includes the assessment and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and environment.
2) Resource Acquisition includes hardware and operations associated with acquiring and separating the resource of interest.
3) Resource Processing/Consumable Production includes the extraction and processing of resources into products with immediate use or as feedstock for construction and manufacturing.
4) *In Situ* Manufacturing involves the production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources.
5) *In Situ* Construction involves the manipulation of surface material (i.e. civil engineering) as well as the large scale fabrication of infrastructure from primarily locally derived material/feedstock, such as roads, landing pads, shielding, and habitats.

6) *In Situ* Energy includes the generation and storage of electrical, thermal, and chemical energy using in situ derived resources and materials. Potential products may include solar arrays, thermal and energy storage, and chemical batteries.

An important goal for NASA and the International Space Exploration Coordination Working Group is to expand human presence into the solar system enabled by sustained living and working on the Moon and Mars.[20] To progress from our current "Earth-Reliant" approach to exploration and eventually become "Earth independent," future missions will need to first identify and characterize resources in space and then learn to use and harvest them. There are three driving factors in why ISRU should be incorporated into future human exploration architectures: 1) to increase exploration sustainability and decrease life cycle costs, 2) increase mission performance and capabilities, and 3) to reduce mission and crew risk.

For increasing exploration sustainability and decreasing life cycle costs, ISRU can provide a source of life support consumables in addition to fundamental O_2 and H_2O required for crew survival. For increasing mission performance and capabilities, the production of mission consumables for propulsion, power, and life support can enable longer missions and expand areas of exploration beyond what is possible with only Earth delivered consumables. For reducing mission and crew risks, the ability to be self-supportive for life support consumables and spare parts eliminates mission risks from lack of spares or failures in critical mission support systems.

1. Mars ISRU Overview

There are three primary natural resources of interest on Mars for ISRU applications; gases in the Mars atmosphere, H_2O bound in the Mars soil and in subsurface ice deposits, and oxygen and metals bound in minerals. Since the initial study titled, "Feasibility of Rocket Propellant Production on Mars" by Ash, Dowler, and Varsi discussed how ascent propellants could be manufactured on the Mars surface, numerous studies have been performed for both robotic and human exploration missions that have examined use of either/both Mars atmosphere and water resources for the production of O_2, H_2O, N_2, and fuel (either H_2 or CH_4). For human exploration architecture studies, the primary emphasis has been production of propellants for crewed ascent, but backup and expansion of life support consumables has also been considered. In these studies, both the amount needed and the time allowed for production have varied. Table 1 and Table 2 depict the type and amount of consumables produced by Mars ISRU systems and the amount of time allowed for production for specific Design Reference Missions (DRM). The information in these tables is to provide

Table 1. ISRU Consumable Production Quantities.

	NASA Reference Architectures				Mars ISRU Studies & Calculations			
	DRM 1.0[21]	DRM 3.0[22]	DRA 5.0[23]	EMC ISRU	FC Powered Rover Study (14 day ops)[25]	Hab. FC Power Backup (14.8 KW -120 days)[25]	Hercules Reusable Lander[26]	Mars Water Rich Study[27]
O_2 for Ascent Prop (kg)	83,500	30,333	22,985	22,728[24]			59,004	29,758
O_2 for Life Support (kg)		4500	1906					
O_2 for Fuel Cell Power (kg)					1000	21,000		30,276
CH_4 for Ascent Prop. (kg)	23,200	8667	6250	6978[23]			17,102	8,748
CH_4 for Fuel Cell Power (kg)					350	9,000		9,936
N_2 for Life Support (kg)		3900	133	136[25]				
H_2O for Life Support/EVA (kg)		23,200	3192	3072 (EVA)[25]				24,379
H_2 Brought from Earth (kg)	5800	5420	399 (O_2 only)					

context for the relative amount of products needed for possible different applications verses as hard requirements for future design and mission needs.

Table 2. ISRU Consumable Production Durations.

NASA Reference Architectures					Mars ISRU Studies & Calculations	
	DRM 3.0[22]	DRA 5.0[23]	EMC ISRU	EMC ***	FC Powered Rover Study (14 day ops)[25]	Hercules Reusable Lander[26]
A. Time between ISRU Landing & Crew Leaving Earth (days)*	520	330				520
B. Contingency: Failures/dust storms (days)	40	30				40
Production duration (= A – B) (days)	480	300**	480	>14 mo. min (420 days) for SEP-Chem. >18 mo. min (540 days) for Hybrid	30 (1 trip per month)	480 (1/op) 365 (1/yr) 183 (2/yr)
ISRU Hardware Life: Days	▪ 480 min. ▪ Additional 240 days until crew arrives	▪ 480 min. ▪ 1200 desired for end of crew stay	▪ 480 min.			

2. Mars ISRU Atmosphere Only Architecture Options

The Mars atmosphere is primarily made up of CO_2 (95.32 vol%), N_2 (2.7 vol%), and argon (Ar) (1.6 vol%), with minor amounts of O_2 (0.13 vol%) and CO (0.08 vol%), and trace amounts of H_2O (210 ppm), nitric oxide (NO) (180 ppm), and other elements.[28] The pressure and temperature of the atmosphere varies as a function of altitude, latitude, season, and time of day. The surface pressure can range from 4 to 9 mbar (0.06 to 0.13 psi), and the temperature can range from 5 to -112 °C (41 to -170 °F).

Oxygen from the Mars Atmosphere. For propulsion applications, the largest consumable needed is oxygen. This translates well for LSS, where O_2 is a fundamental resource for crew survival. For production of O_2 from the Mars atmosphere, the primary source of oxygen considered is CO_2. Several technologies exist to convert CO_2 into O_2. For ISRU applications, the two processes that have been most developed have been Solid Oxide CO_2 Electrolysis (SOCE) and Reverse Water Gas Shift (RWGS) with Water Electrolysis (WE). As can be seen in the functional block diagrams for the two processes depicted in Figure 4, the SOCE process can provide a much simpler approach to obtaining dry O_2 from Mars atmospheric CO_2. Since SOCE only converts approximately 50% of the CO_2 input into the device into O_2 and CO, and RWGS only converts 10% for conventional reactors and possibly up to 50% for microchannel reactors in a single pass, ISRU designers are considering the implications of including a CO/CO_2 separation and CO_2 recirculation loop into the system.

Currently, work on SOCE is progressing to flight as part of the Mars Oxygen ISRU Experiment (MOXIE) aboard the Mars 2020 rover mission. This device uses a scroll pump to increase the Mars atmosphere pressure up to ~1 bar (15 psi) to produce 0.01 kg/hr of O_2 (~1/200th scale for human ascent propellant production), and is designed to operate for about 1 hour and a minimum of 15 operating cycles during the Mars 2020 mission.[29,30,31] For RWGS, significant work has been performed by Pioneer Astronautics under NASA Small Business Innovation Research (SBIR) and lately by the spin-off company, Pioneer Energy. In a test in Nov. of 2017, Pioneer Energy reports running a prototype RWGS system at an average rate of 70 liters per minute CO_2 and hydrogen feed. It reportedly averaged about 99% efficiency in reducing CO_2 to CO. Conversions as high as 99.8% were achieved.[32] This RWGS system prototype operation is at a scale relative to Mars human mission O_2 production rate needs for the crewed ascent vehicle. While a conventional RWGS reactor is currently at NASA Technology Readiness Level (TRL)[33] 5 and water electrolysis capabilities are at TRL 5 to 9 (operation aboard ISS), further work may be warranted on microchannel RWGS reactors to increase single pass conversion efficiency based on work performed by the Pacific Northwest National Laboratory in the 1990s and early 2000s.[34]

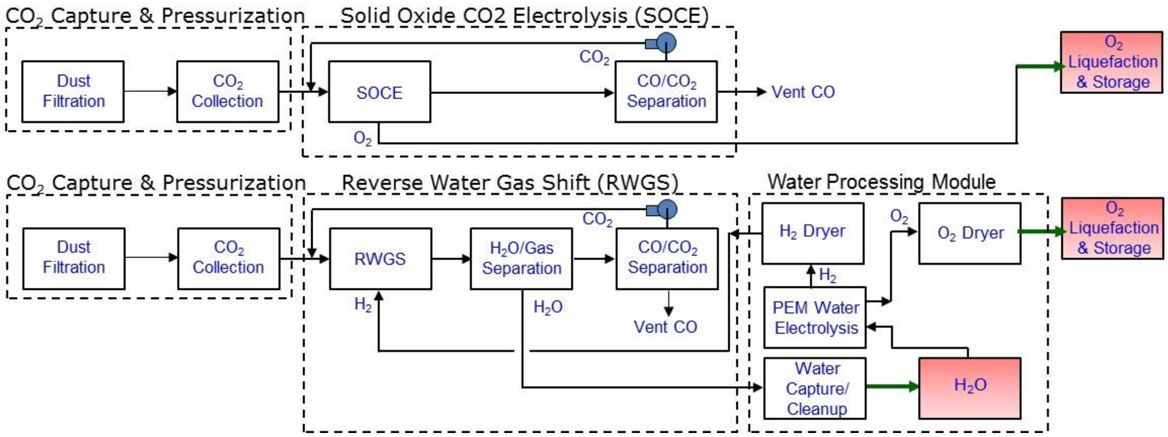

Figure 4. Function Block Diagrams for Oxygen Production from Mars Carbon Dioxide.

In the 1990s and early 2000s, two other approaches were considered for O_2 only production on Mars. One was methane pyrolysis to recover the hydrogen after performing a Sabatier reaction to make methane (CH_4) and water. The other was the Bosch reaction to convert CO_2 into carbon and O_2. Due to the amounts of oxygen needing to be produced, the complexity, and the low efficiencies of the processes at the time, pursuit of these technologies for ISRU applications was stopped.

Today, besides interest and development of SOCE and RWGS technologies and systems, two alternative CO_2-to-O_2 technologies are being examined by ISRU developers in on-going research activities. The NASA Marshall Space Flight Center (MSFC) has been performing research on the use of ionic liquids (ILs) for both CO_2 capture and electrolysis into oxygen.[35,36,37] The concepts show promise, but are near TRL 3 and further research is required on ILs that can both absorb a significant amount of CO_2 by mass and allow for electrochemical conversion of the CO_2 into O_2 in the presence of water. Also, companies such as Opus 12, are examining the use of proton exchange membrane (PEM) technologies to covert CO_2 with water into O_2 and carbon monoxide or a higher hydrocarbon such as ethylene. This work is currently progressing into Phase II under a SBIR contract.[38] This technology is of particular interest since PEM based processes are low temperature compared to SOCE and RWGS reactors, and are potentially easily scalable through the use adding PEM cells to a stack as is achieved with PEM water electrolysis devices.

<u>Nitrogen from the Mars Atmosphere</u>. To make approximately 23 metric tons of O_2 for crewed Mars ascent, requires about 69.5 metric tons of CO_2 to be collected and processed, assuming 95% conversion of CO_2 into CO. If N_2 is also separated from the atmosphere during or after separation and pressurization of CO_2, then approximately 1500 kg of N_2 can be acquired. The only currently identified customer for nitrogen product is life support systems, and only a small amount is expected to be needed to handle losses due to habitat/cabin leakage and airlock depressurization to perform EVA operations. The approach used to separate and collect N_2 from the Mars atmosphere will be based on the approach used to collect and pressurize CO_2. ISRU developers are currently considering three methods for CO_2 separation and pressurization: CO_2 freezing, rapid cycle CO_2 adsorption pumps, and mechanical compressors .[31] The first two options separate CO_2 from the Mars atmosphere at low pressure and the remaining Mars atmosphere gases are 'pushed' out of the devices using a low delta-pressure blower. If CO_2 freezing is used in the ISRU system, then further cooling of the gases could separate the N_2 as well, however the much lower freezing point compared to CO_2 (-210 vs -78.5 C) and the possible collection of other atmosphere constituents with similar or higher freezing points (-164 °C for NO and -205 °C for CO) make this approach most likely unattractive. If mechanical compression is utilized, raising the pressure above the triple point of CO_2 at Mars ambient pressures (~5.3 bar or 77 psi) may allow for both separation of CO_2 via liquefaction and storage of high pressure of the remaining N_2/Ar gas mixture. This gas will undoubtedly contain other trace gases, necessitating further separation and processing for use in crewed habitats.

<u>Mars ISRU Water Architecture Options</u>. Water as an ISRU resource has been identified from several sources on Mars including from the soil, from hydrated materials (granular regolith and minerals), and subsurface ice.

Until science data from the Mars Odyssey orbiter and subsequent robotic missions revealed that H_2O may be widely accessible across the surface of Mars, prior Mars ISRU studies that considered production of hydrocarbon fuels were limited to either processing the Mars atmospheric for the small amount of H_2O vapor available or bringing H_2 from Earth. Water is useful on its own for drinking, washing, food production, and shielding, as well as a source of O_2 and H_2 for life support, regenerative fuel cell power systems, and potentially for propulsive applications. In December 2007, NASA completed the Mars Human Design Reference Architecture (DRA) 5.0 study which considered H_2O on Mars as a potential resource for the first time in a human mission architecture. For this study, NASA only considered H_2O in the top few centimeters of soil on the Mars surface due to limitations place on the study to elevate planetary protection concerns.[39] With increased knowledge of H_2O on Mars since Mars DRM 5.0 was performed, other potential H_2O resources can now be considered for ISRU applications

Neutron spectroscopy data from Mars Odyssey shows that H_2O content varies from a low of <1 wt% to >10 wt% in the mid latitude band of Mars (-30 to +30 latitude) in the upper 1 meter of Mars surface material.[40] Other orbital instruments have located deposits of phyllosilicates, carbonates, sulfates, and silica bearing deposits in the same region that should contain enhanced H_2O content from 6 to 10 wt%.[41] Even the loose granular soil found across Mars is expected to contain 1 to 3 wt% water based on Viking I and II and Sample Analysis on Mars (SAM) instrument data on the Curiosity rover.[42]

Because of the close proximity of the H_2O deposits to the surface and the potential commonality of excavation and soil processing technologies associated with lunar regolith excavation and hydrogen reduction of regolith, NASA has focused on and performed several studies examining the hardware needed and the mission impacts associated with hydrated material water resources on Mars.[43,44] While these studies have focused on extracting water for use in O_2/CH_4 production, the ability to extract H_2O can still provide significant mission benefits depending on the mission consumable requirements. For H_2O extraction from granular and hydrated minerals, several technology options have been studied, and have or are being evaluated including: 1) a fluidized bed, internal auger/heater based on lunar hydrogen reduction reactor experience, 2) a microwave heating device, 3) an auger screw soil dryer, and 4) an open reactor heating concept.[31,43] Each of these technologies show promise and further work and testing is required before down-selection of a baseline approach will be made.

From Mars orbital radar measurements (SHARAD and MARSIS), and from locating and imaging recently formed craters on the surface of Mars, more and more evidence suggests that vast subsurface ice deposits may exist near the Mars surface (top 10 m) in the mid to mid-upper latitudes (+/- 35 to 60 degrees).[42] Depending on how close to the surface the ice deposits are as well as the concentration of water/ice in the soil, different techniques for water extraction may be utilized.

For large scale water mining of subsurface ice sheets, removal of the overburden first to expose the ice layer may be preferred.[42] For permafrost or ice relatively close to the surface several approaches have been proposed including applying microwave energy down the hole to cause the H_2O to vaporize and be collected has been examined,[47] but concerns continue to exist that H_2O vapor released will re-condense elsewhere in the hole before being collected. To overcome the concern about H_2O vapor released re-condensing below the surface, Honeybee Robotics has developed and demonstrated two near surface H_2O extraction concepts; the Mars In Situ Water Extraction (MISWE) and Planetary Volatile Extractor (PVEx).[48] The MISWE concept utilizes an auger to bring subsurface material into a heating chamber for H_2O extraction. This approach can obtain material progressively deeper below the surface in batches. The PVEx concept utilizes a double walled corer with a perforated inner wall to allow material to be heated within the corer while below the subsurface. For cemented icy soils, both approaches require significantly less energy for material penetration and removal then other excavation approaches. However, both concepts rely on the icy resource to be near the surface.

For deeper subsurface ice layers, a terrestrial H_2O extraction approach developed for the artic regions of Earth called the Rodriquez Well (or Rodwell for short) is being examined.[27] The Rodwell concept first utilizes a drill to create a shaft from the surface into the subsurface ice sheet. Tubes with a H_2O pump and/or heater unit are lowered into the subsurface ice sheet. Heat is then applied (via hot H_2O or heater) to liquefy the ice into a pool of H_2O which can then be pumped to the surface. This concept requires a significant amount of thermal energy, but can allow for significant amounts of H_2O to be extracted in situ with minimal excavation and drilling compared to the open pit mining and MISWE/PVEx extraction concepts.

III. Potential Combined ECLSS/ISRU Architectures

Life support based on ISS architecture is highly dependent on resource recycling for long-duration operational feasibility in exploration missions. However, by leveraging resources available *in situ* on the surface of the Moon or Mars, new architectures emerge with dramatically decreased complexity, mass, volume, and consumable requirements. Four potential resources are considered below: H_2, O_2, N_2, and liquid H_2O.

A. Utilization of ISRU Products to Complete Closure of Current LSS Architecture

1. Hydrogen as an ISRU Product for LSS

In the baseline ISS architecture, H_2O is electrolyzed to provide O_2 for the crew at a nominal of rate of 0.818kg/CM-day. Hydrogen is consequently produced at a rate of 0.102 kg/CM-day. This H_2 is used as a reactant for the reduction of metabolic CO_2 via the Sabatier reaction, producing H_2O and CH_4. Given a nominal metabolic CO_2 production rate of 1.04 kg/CM-day, a total of 0.189kg/CM-day of H_2 would be required to recover and recycle all of the O_2. Due to the limited available H_2 and system inefficiencies, only about 50% of the O_2 is recycled from metabolic CO_2 on ISS. To increase this for exploration missions, numerous technology options are under development to increase the oxygen recovery and recycling.[17,49,50] The most advanced of these is the Plasma Pyrolysis Assembly (PPA) which recovers and recycles H_2 from CH_4, as shown in Figure 5.[50] Targeted O_2 recovery with the inclusion of a PPA in the LSS architecture is >80%. However, the PPA requires excess (albeit recycled) H_2 for optimum efficiency and will likely add an additional 3kW power load to the life support system as well as require occasional maintenance and possibly consumables throughout its lifetime.

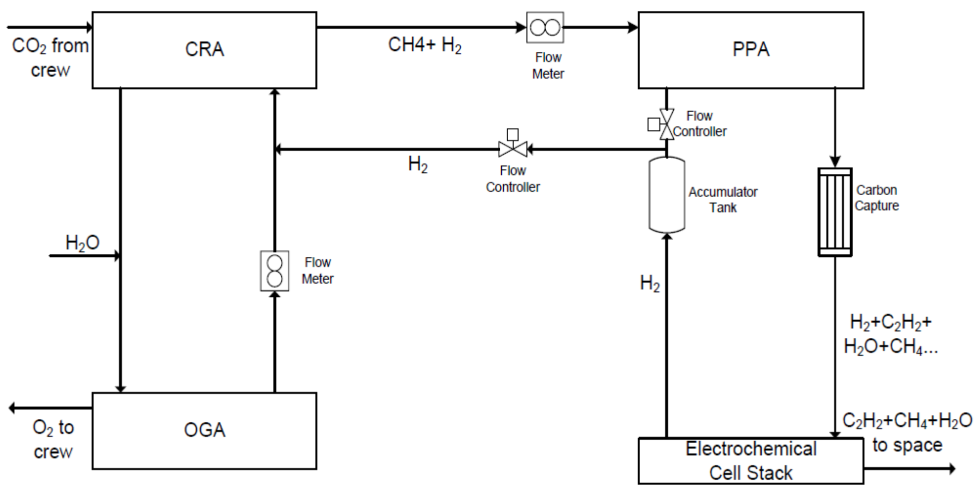

Figure 5. Notional Sabatier and PPA architecture.[50]

The availability of H_2 from ISRU would enable two potential architectural advantages for LSS. First, additional H_2 provided from an ISRU source would eliminate the need for H_2 recycling from CH_4, thus obviating the need for the PPA and peripherals (or alternative Sabatier-post-processors). Second, H_2 from an ISRU source would provide the quantity necessary to fully recover oxygen from metabolic CO_2 with only the Sabatier reactor. Thus, with additional H_2 available, existing, proven ISS architecture would be sufficient to recycle 100% of the oxygen with the state-of-the-art AR system. Third, the availability of excess H_2 has the potential to eliminate the need for CO_2 storage. The ISS architecture includes CO_2 compression and storage (CO_2 management) due to the transient availability of H_2 from the Oxygen Generator Assembly (OGA). With a consistent source of excess H_2, CO_2 could be fed directly from an upstream CO_2 removal system, eliminating the need for a CO_2 management sub-system, as shown in Figure 6.

Despite the obvious benefits of this approach, considerations must be made to the challenges. The primary concern from an LSS perspective is the purity of the H_2. Sabatier technology requires the use of a catalyst operated at high temperature conditions. Impurities in the H_2 could result in fouling of the reactor. Given the integrated nature of the LSS, if those impurities made their way into the Sabatier product H_2O, they would be exposed to the WPA with potential fouling risk to the catalytic oxidizer or simply additional load on the filtration and/or ion exchange beds.

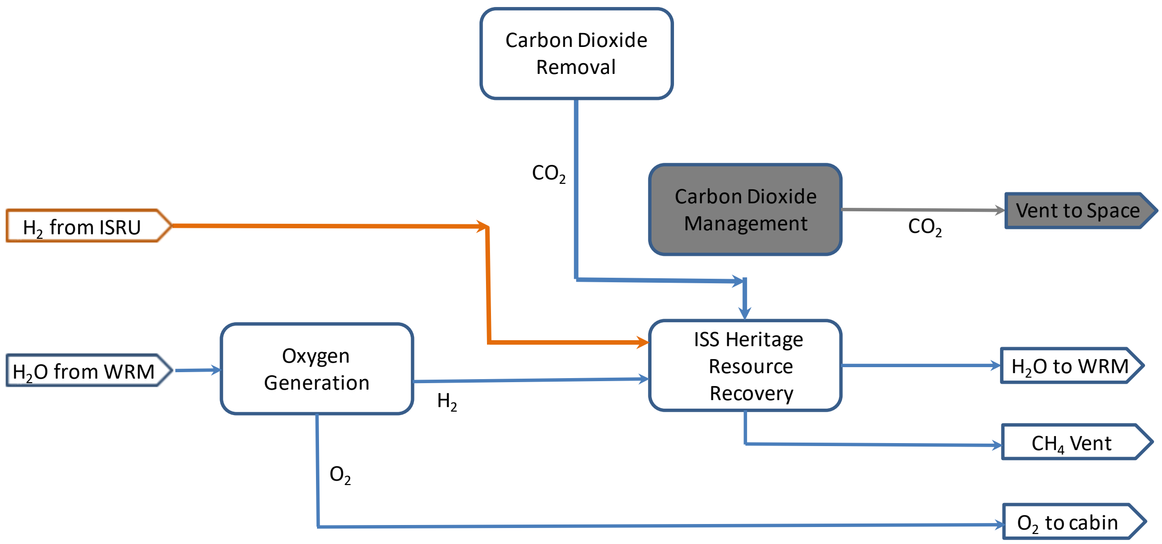

Figure 6. Changes to LSS AR architecture with ISRU-supplied H_2. *Carbon dioxide Management (grey boxes) eliminated from architecture due to availability of H_2 from ISRU (orange). ISS heritage Sabatier technology used for resource recovery.*

2. *Oxygen and Nitrogen as ISRU Products to LSS*

Life support on ISS relies on the generation of O_2 from the electrolysis of water in the OGA. This O_2 is necessary for crew respiration in the habitat or vehicle and is recycled, to the extent possible, using resource recovery technology. High pressure O_2 is required for EVAs and is currently supplied to ISS using Nitrogen Oxygen Recharge System (NORS) tanks. No O_2 recovery is currently available from EVAs. The O_2 lost through these activities must be resupplied. Nitrogen is used on ISS as a buffer gas to provide an Earth-like atmospheric balance of N_2/O_2 and is resupplied from NORS tanks as required based on leakage rates.

The availability of O_2 and N_2 from ISRU would have several benefits to the LSS architecture. First, N_2 could be replenished as-needed and *in situ*. This is of particular interest due to the anticipated high frequencies of EVA for surface missions and in the event of catastrophic atmospheric loss (complete loss of habitat pressure) where *in situ*-generated N_2 would be available to reestablish a stable environment.[19] Second, the availability of O_2 would have the single greatest effect on reducing the complexity of LSS architecture by eliminating the need for O_2 generation, Resource Recovery, and CO_2 Management sub-systems within the habitat, as shown in Figure 7. If supplied at high pressure, the availability of ISRU O_2 would also eliminate the need for LSS in the habitat to compress O_2 for EVA use, and possibly medical use, as well. While it is true that these functions would simply be transferred outside the habitat to the ISRU architecture, the fact that the ISRU systems would already be required for propulsion O_2/CH_4 generation, provides an overall simplification to the mission. Further, systems external to the habitat reduce the overall safety requirements as compared to systems operational within the habitat and increase the total available space within a habitat for non-life support systems.

Introduction of N_2 and O_2 from ISRU sources would also introduce risks to an LSS architecture. First, a key risk is the potential for contamination from atmospheric CO_2 or O_2 generation byproducts, depending on the ISRU generation approach, such as carbon monoxide. The O_2 and N_2 would be required to meet LSS purity standards. Second, availability of O_2 is life- and time-critical. Therefore, reliability of the ISRU O_2 generation system would have to be sufficiently demonstrated before the approach could be baselined for manned missions. A mitigation to this would be to provide ISRU O_2 as back-up only to LSS systems. However, this serves only to reduce reliability/robustness risks for

LSS and does nothing to reduce complexity. Finally, O_2 would have to be generated at a rate sufficient to meet crew respiration rates and would require sufficient storage to meet requirements for catastrophic failure scenarios.

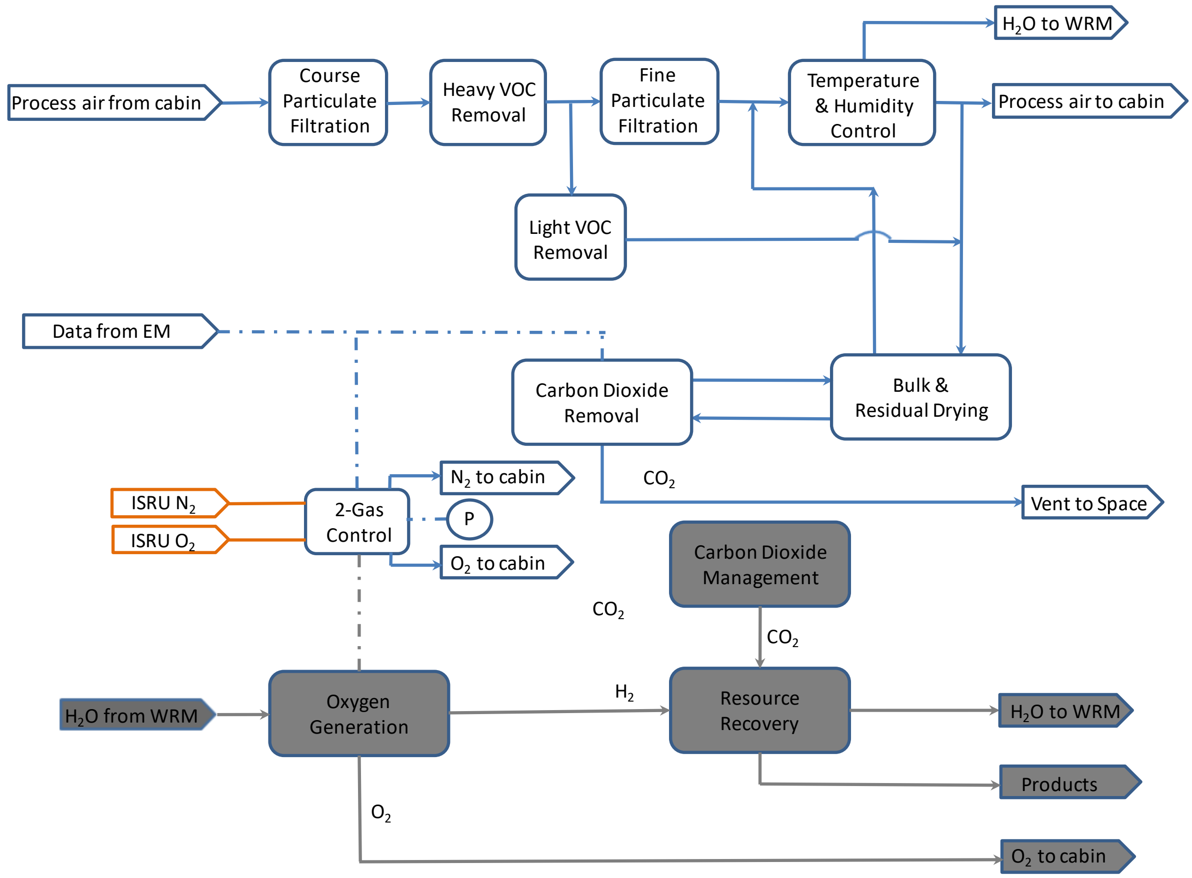

Figure 7. LSS AR Architecture with ISRU-provided O_2 and N_2. *Oxygen generation, CO_2 management, and resource recovery eliminated from the architecture (in dark grey) by the availability of ISRU N_2 and O_2 (orange).*

3. H_2O as an ISRU Product for LSS

Aboard ISS, H_2O is recycled from several sources. The Urine Processing Assembly (UPA) recovers H_2O from urine via distillation; the condensing heat exchanger recovers humidity from the cabin air; the Sabatier reactor recovers O_2 from metabolic CO_2 in the form of H_2O; and the WPA combines all these sources and produces potable H_2O. Make-up H_2O is resupplied from Earth when required for crew consumption, experiments, and for electrolytic O_2 production. ISRU-provided H_2O has the potential to enable numerous opportunities for crewed surface missions, dependent entirely on the quantity available.

The state-of-the-art (SOA) ISS H_2O processing systems recover ~93% of the water in the WRS loop. This results in a resupply requirement of~0.063kg/CM-day to provide sufficient drinking water and electrolyzed water for O_2. With the addition of EVAs, this can increase to as much as 3.074kg/CM-day. ISRU-provided H_2O will reduce or eliminate the need to resupply H_2O from Earth for this purpose. A second need for H_2O is electrolysis to produce O_2. The quantity of available H_2O will drive the level of O_2 recovery required in an LSS AR architecture. Further needs for water include experiments and plant growth. Any quantities of H_2O available beyond the LSS needs will result in additional science and the potential for vegetation. Figure 8 provides a graphical indication of the architectural implications of increasing quantities of available ISRU water on future surface missions. Water recovery at 98.6% assumes an architecture comprised of SOA ISS technology plus a Brine Processing Assembly recovering 80% of the water from UPA brine. ISS SOA technology is assumed for H_2O recovery of 93%. Water recovery at <60% assumes that SOA Urine Processing technology is eliminated from the architecture. No further reduction in water recovery capability is considered for two reasons. First, condensing heat exchanger technology provides thermal and humidity control to the habitat and would not be eliminated from the architecture regardless of ISRU-produced H_2O availability.

Second, the potential for contamination of ISRU-produced H_2O demands that the Water Purification technology is in use. Oxygen recovery at 80% assumes a Plasma Pyrolysis Assembly is included in the Exploration architecture. ISS SOA Sabatier CO_2 reduction technology is assumed for 50% O_2 recovery. Finally, O_2 recovery of 0% assumes that SOA Sabatier technology is eliminated from the architecture. Oxygen generation technology cannot be eliminated from the architecture given the need to produce O_2 for crew respiration from water. However, if ISRU systems were capable of providing both H_2O and O_2, it would be possible to eliminate the OGA within LSS architecture and the crewed habitat as discussed previously.

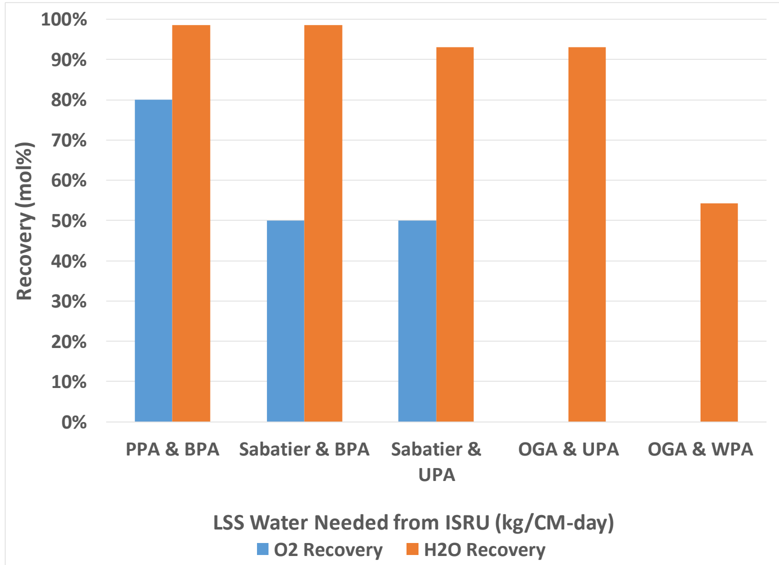

Figure 8. Effect of increased ISRU water on required LSS resource recovery. *Water recovery at 98.3% assumes BPA in addition to ISS SOA architecture, 93% assumes ISS SOA technology, <60% assumes elimination of Urine Processing from ISS SOA. Oxygen recovery at 80% assumes PPA in ISS SOA architecture, near 50% assumes ISS SOA technology, 0% assumes elimination of Sabatier technology.*

B. Optimum and Likely Scenarios

Given the technical options and integration potential mentioned, H_2O provided from ISRU to the LSS at a rate of ~3.4kg/CM-day would be sufficient to eliminate the need for four substantial technologies currently under development for LSS. The addition of N_2 would eliminate the need for resupply tanks from Earth. Further, delivery of O_2 from ISRU in addition to N_2 and water would effectively eliminate the need for all LSS, as shown in Figure 7 and Figure 9, with the exception of trace contaminant control, CO_2 removal, thermal/humidity control, and water purification. Key to this approach, however, would be the considerable data and demonstration necessary to prove ISRU technologies, their reliability, and the product stream purities for use in a habitat.

A more likely approach will be the use of SOA LSS systems with ISRU used as dissimilar redundancy or in emergency situations. Overall, this does nothing to reduce logistics, launch mass, or complexity, but it does serve to reduce the risk of loss of crew and loss of mission due to failure of either critical ISRU or LSS systems.

Several considerations to the future of ISRU and LSS interactions are necessary for ongoing and future discussions. First, considerable overlap in product streams, separation technologies, and purity requirements between LSS and ISRU have been identified. Limited resources for development in both areas require that cross-pollination of ideas, cooperative development, and thorough analysis to ensure efficient use of available funding and workforce be pursued.

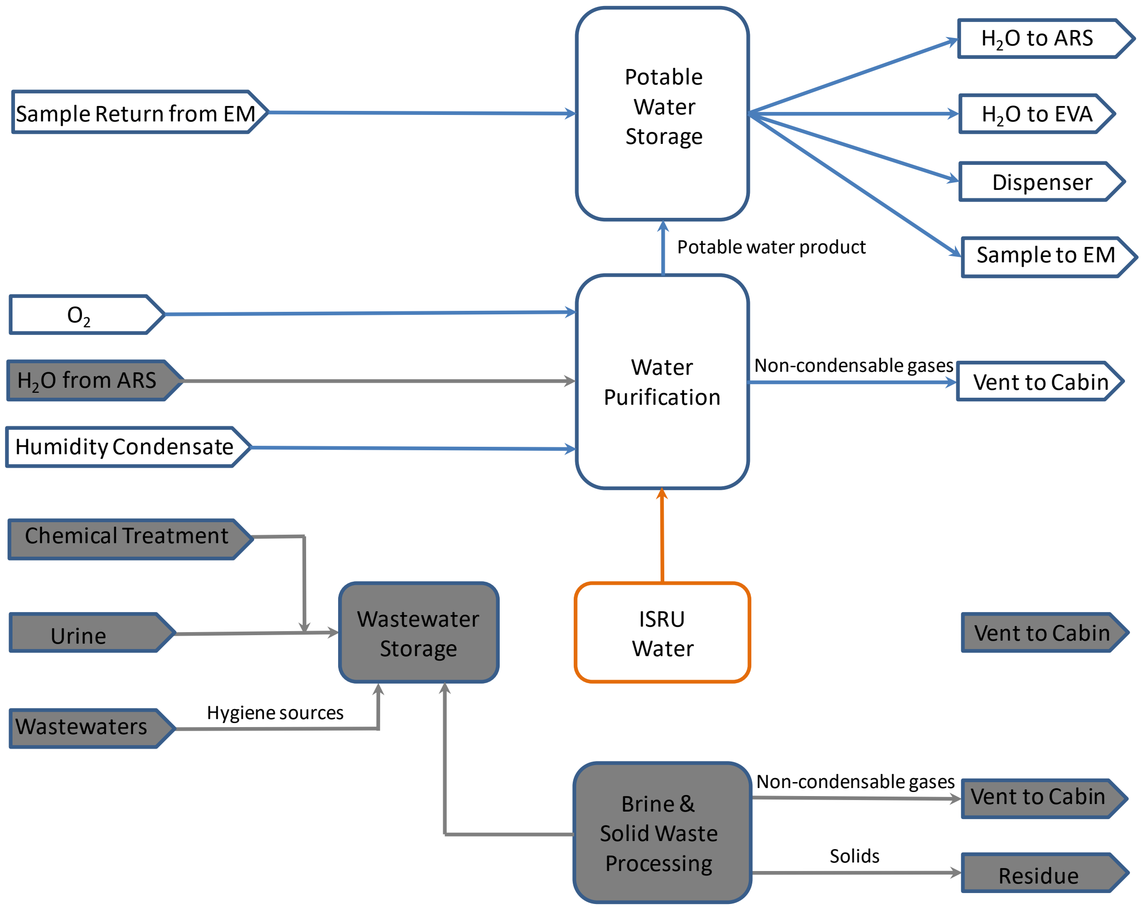

Figure 9. Water Recovery architecture with water provided by ISRU.

IV. Conclusions

ISRU has long been discussed as a potential resource for life support consumables on long-duration manned surface missions. Several architectures for integrated ISRU and LSS have been identified and the benefits, challenges, and limitations discussed. An optimum scenario for a Mars surface mission would include the use of O_2, H_2O, and N_2 as feed streams from ISRU to the LSS. While this approach does not eliminate the need for technology to produce these feed streams, the benefits of eliminating redundant systems and moving high temperature systems with explosive gases outside the habitat has clear advantages. Regardless, the most probable and least risky approach would be to baseline an architecture in which exploration LSS systems are designed to maximize resource recovery and recycling and gradually reduce reliance on Earth resupply as ISRU demonstrates long term and reliable performance.

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