Carbon Dioxide Removal by Ionic Liquid System – Integrated (CDRILS-I) for a Mars Exploration Application

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Carbon dioxide (CO_2) and humidity control are essential features of the Extravehicular Mobility Unit (EMU) Portable Life Support System (PLSS). The PLSS for past EMUs such as those for the Shuttle and International Space Station (ISS) as well as the Exploration EMU (xEMU) have used solid adsorbents for CO_2 and humidity control. The Carbon Dioxide Removal by Ionic Liquid System (CDRILS) technology utilizes a continuously recirculated ionic liquid sorbent and hollow fiber membrane contactors for CO_2 removal. The CDRILS technology was initiated for a vehicle Environmental Control and Life Support System (ECLSS) application as a planned development for a flight demonstration on the ISS. The National Aeronautics and Space Administration Johnson Space Center Life Support Systems and the Space Suit and Crew Survival Systems Branches are collaborating with Honeywell Aerospace to explore a CDRILS – Integrated (CDRILS-I) for a Mars exploration application. CDRILS-I includes a space suit life support system for CO_2 and humidity removal referred to as CDRILS for Mobility (CDRILS-M) along with a CDRILS Regenerator (CDRILS-R) for a Mars Exploration EMU (mxEMU) concept. The CDRILS-R would be a habitat ECLSS unit to pair with CDRILS-M assuming an operating scenario of a 2-person crew living in a small surface habitat with both crew members performing extravehicular activity in space suits equipped with CDRILS-M. This paper discusses the CDRILS-I approach and development for the Mars exploration application.

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Acronyms and Nomenclature

AEMU	=	Advanced Extravehicular Mobility Unit
BER	=	Basic Express Rack
CDR	=	Critical Design Review
CDRILS	=	Carbon Dioxide Removal by Ionic Liquid System
CDRILS-I	=	Carbon Dioxide Removal by Ionic Liquid System – Integrated
CDRILS-M	=	Carbon Dioxide Removal by Ionic Liquid System for Mobility applications
CDRILS-R	=	Carbon Dioxide Removal by Ionic Liquid System Regenerator
CH_4	=	Methane
CO_2	=	Carbon Dioxide
ECLSS	=	Environmental Control Life Support System
EMIM Ac	=	1-Ethyl-3-methylimidizolium Acetate
EMU	=	Extravehicular Mobility Unit
EIS	=	End-Item-Specification
EVA	=	Extravehicular Activity
FDU	=	Flight Demonstration Unit
GFE	=	Government Furnished Equipment
H_2	=	Hydrogen
HRS	=	Hydrogen Recovery System
IL	=	Ionic Liquid
ISS	=	International Space Station
IVA	=	Intra Vehicular Activity
LEO	=	Low Earth Orbit
LSS	=	Life Support System
mxEMU	=	Mars Exploration Extravehicular Mobility Unit
NASA	=	National Aeronautics and Space Administration
PDR	=	Preliminary Design Review
PGA	=	Pressure Garment Assembly
PGS	=	Pressure Garment System
PLSS	=	Portable Life Support System
RCA	=	Rapid Cycle Amine
SWAP	=	Size, Weight, and Power
SWME	=	Spacesuit Water Membrane Evaporator
THL	=	Toxicity Hazard Level
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

THE Carbon Dioxide Removal by Ionic Liquid System (CDRILS) is a life support technology designed to remove carbon dioxide (CO_2), humidity, and trace contaminants from an enclosed environment. Since 2018 [1], Honeywell has been developing CDRILS with the National Aeronautics and Space Administration (NASA) to be a next-generation Life Support System (LSS) for Exploration vehicles and habitats. In 2022, NASA funded the development of a CDRILS Flight Demonstration Unit (FDU) concept. The CDRILS FDU concept includes a Sabatier reactor that avoids the need to vent the CO_2 removed from the cabin to space vacuum and provides semi-closed loop oxygen recovery by reacting CO_2 with hydrogen (H_2) to form methane (CH_4) and water. The recovered water provides 50% oxygen recovery, or when paired with a separate Methane Pyrolysis unit that could recover the hydrogen from CH_4 [2], would provide nearly 100% oxygen recovery in a closed loop Environmental Control Life Support System (ECLSS). The CDRILS FDU with Sabatier was designed to integrate into a Basic Express Rack (BER) on the International Space Station (ISS). The goal of the FDU was to demonstrate CO_2 removal and reduction at a 4-crew scale while maintaining a cabin atmosphere of 2 mmHg CO_2 [3], [4]. CDRILS is designed to intake an air stream directly from a cabin environment. The air stream is then contacted with an ionic liquid (IL) based sorbent in a hollow fiber membrane scrubber. The IL sorbent selectively absorbs the CO_2 and is continuously transported to the hollow fiber membrane stripper where heat and vacuum are applied to desorb the CO_2 and regenerate IL. CDRILS is unique in its use of a liquid sorbent which enables a continuous system as opposed to the solid adsorbents of legacy CO_2 removal technologies which use batch or alternating batch systems.

In 2025, the NASA Space Suit & Crew Survival Systems Branch funded Honeywell to conduct a feasibility study to adapt the CDRILS technology for the Portable Life Support System (PLSS) of the NASA Mars Exploration Extravehicular Mobility Unit (mxEMU). This concept uses a liquid sorbent and scrubber contactor to accumulate the CO_2 and humidity generated by the astronauts in their spacesuit and is referred to as CDRILS for Mobility (CDRILS-M). When the astronaut completes an Extravehicular Activity (EVA), the liquid sorbent inside the PLSS will be CO_2 and humidity rich. The version of CDRILS that was developed for vehicles and habitats was designed to operate in steady state, in which CO_2 is continuously scrubbed from the cabin and then stripped from the sorbent to form a CO_2 product stream. The habitat version of CDRILS can also be used to regenerate the CO_2 and humidity rich sorbent from CDRILS-M post-EVA. This dual-use version of CDRILS is referred to as the CDRILS-Regenerator (CDRILS-R). The combination of the two CDRILS adaptations is referred to as CDRILS-Integrated or CDRILS-I and is illustrated in Figure 1.

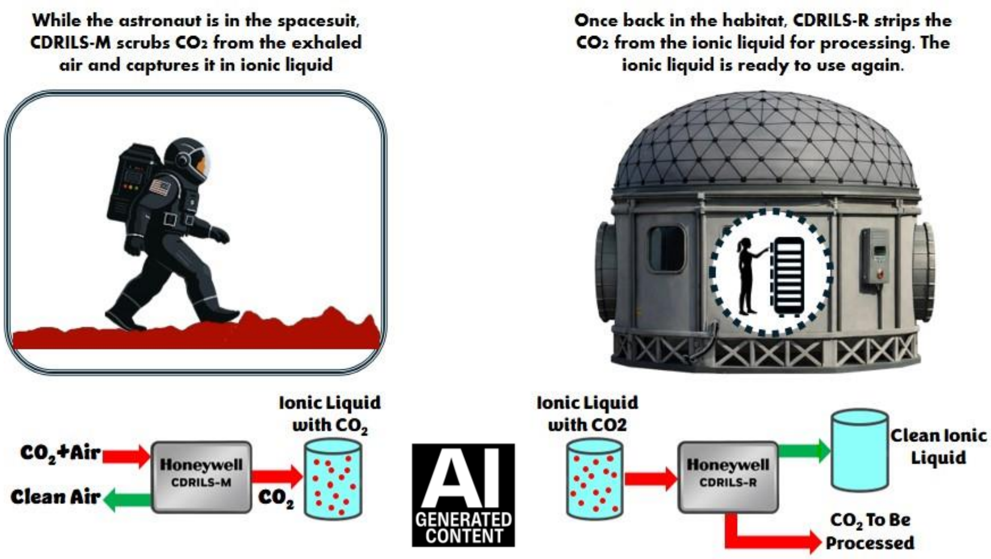

Figure 1. CDRILS for mobility applications (CDRILS-M) integrated with habitats (CDRILS-R) to illustrate the CDRILS-I concept

The NASA Life Support Systems Branch and the Space Suit and Crew Survival Systems Branch are collaborating to mature a CDRILS-I approach to realize the following technical benefits:

- A non-venting EVA capability in which H_2O and CO_2 captured in the sorbent are not vented into the environment during EVA and such an external vacuum environment is not required for operation
- Inclusion of trace contaminant removal in the sorbent without need for a separate consumable component to perform that function in the PLSS
- Improved EVA duration due to the ease of swapping out liquid mid-EVA if and when necessary
- Commonality between the space suit and an ECLSS processing loop such that sparing and maintenance could be reduced
- A Regenerator capable of recovering the CO_2 and water captured during an EVA
- The option to reduce the captured CO_2 via a Sabatier included in CDRILS-R

The work completed to date to explore the CDRILS-M feasibility, the path to achieving CDRILS-R by leveraging 10 years of CDRILS technology development, and the combination of these two efforts to achieve CDRILS-I will be discussed.

II. Background

Honeywell began developing CDRILS on internal funding in 2016. At that time, NASA had been exploring ionic liquid technology applications and recognized the potential benefit of the use of ionic liquids for CO_2 removal. In 2018, NASA and Honeywell decided to collaborate under contract with the goal to reduce risk in key aspects of developing this technology and create opportunities to provide a better CDRILS. As the technology matured, NASA recognized the potential of the technology for use in spacesuits and issued a contract for a feasibility study for use of CDRILS in a PLSS. The following provides brief overview of each program.

A. CDRILS for Vehicles Development on 80MSFC18C0045

On contract 80MSFC18C0045 the CDRILS technology matured from test beds to a 4-crew scale prototype. This CDRILS 1 contract had a period of performance of September 19, 2018, through March 18, 2024. The program focused on technology durability and the preliminary design of a Flight Demonstration Unit. Throughout the program, CDRILS gained 2.5 years of run time with demonstrations and a total of 4.5 years of run time including aging studies. Table 1 provides a summary of the work accomplished on this program.

Table 1. Summary of CDRILS 1 program

	Work Description	Hardware	Run time	Technical Results
System durability	Durability test [5]	Breadboard	6 months	Ionic liquid, membranes perform without CO_2 removal rate degradation over 6 months.
	6-month test with promoter [4]	Breadboard	6 months	Promoter more than doubles CO_2 removal rate vs without promoter Quantified performance degradation rate in presence of promoter
	Contamination test [6], [7]	Breadboard	>8 months over 5 tests	Trace contaminants in air will not impair the performance of CDRILS for CO_2 removal. Many trace contaminants are removed from the air stream by CDRILS.
IL, membrane durability	Ionic liquid aging [6]	Test stand	1 year	Promoter degradation rate is temperature dependent.
	Promoter modification [4]	Breadboard	1 month	Methods for stabilizing the promoter and slowing performance degradation rate
	Membrane aging [4]	Test stand, Brassboard	1 year	Preliminary membrane coating effort slows stripper leak rate and performance degradation rate, but still below requirement for 3-year maintenance interval
	Coating methods [4]	Breadboard	0.5 months	Refined coating methods slow membrane aging rate that when combined with promoter stabilization innovations is expected to provide a 3-year maintenance interval
Other ILs	Characterization of alternative ILs	Breadboard	various	Alternatives ILs to current EMIM Ac were investigated for inclusion in CDRILS to reduce size, weight, and power; EMIM Ac has the highest performance and reliability.
Preliminary flight demo design	Ground prototype [4], [7]	Prototype	7 months running	Completed exploration of variables to understand the design space for flight over 128 experiments; durability test demonstrated necessity of promoter and membrane stabilization
	Design concepts and requirements for a flight demo [3], [8]	N/A	N/A	Preliminary flight requirements and design developed. Vacuum pump upgrade design concepts for microgravity. Add CO_2 reduction function.
	Flight-scale contactors [4]	Brassboard	1 month	Flight-scale contactor tests validate and refine performance estimates.
	Dehumidifier trial	Prototype	N/A	Procure dehumidifier candidates for potential integration and testing (now in CDRILS-I scope).
	Total run time		**>2.5 Years**	**Total accumulated CDRILS run time across all systems > 4.5 yrs including aging studies.**

B. CDRILS for Mobility on 80NSSC25PA663

The original development of the Extravehicular Mobility Unit (xEMU) began during the Constellation Program, leading to the creation of the Advanced Extravehicular Mobility Unit (AEMU) [9], [10]. This design utilized lessons learned from the ISS extravehicular mobility unit (EMU) and incorporated new technologies, such as the Rapid Cycle Amine (RCA) swing-bed [11], the Spacesuit Water Membrane Evaporator (SWME), and the Primary Oxygen Regulator (POR) [12].

As the AEMU transitioned to serve as government-furnished equipment (GFE) for a demonstration on ISS, it was renamed the xEMU. The xEMU design aimed to create a versatile suit capable of operating for long durations on the ISS, in Low Earth Orbit (LEO), and serving as the EVA suit for early Artemis missions. A modular approach intended to make the design adaptable for Mars exploration. While achieving requirements like redundancy, extended mission durations, cross-compatibility with the ISS EMU, and connectivity across three different pressure garment assembly (PGA) architectures, this approach resulted in a design that was too heavy for Mars' gravity field. The design also relied on technologies that caused environmental losses, such as:

1. Thermal control via an evaporator, which rejects water vapor to the environment for heat dissipation.
2. CO2 and humidity removal using an amine swing-bed that desorbs collected CO2 and humidity into the vacuum environment.

This modular design approach prioritized LEO and lunar missions while anticipating future upgrades to integrate emerging technologies for extended missions. The Mars Exploration Extravehicular Mobility Unit (mxEMU) marks the start of this upgrade process by leveraging the xEMU design while incorporating a re-architected PLSS. The changes to the mxEMU aim to address the following improvements for supporting long-term missions, including later Artemis operations and Mars exploration:

1. Reduced mass to minimize effort required for movement in Mars' gravity field compared to LEO and lunar environments
2. Improved center of gravity for better crew stability and reduced effort
3. Enhanced integration with the rear entry hatch Pressure Garment System (PGS) architecture for increased packaging density and reduced front-to-back dimensions
4. Non-venting life support functions to conserve oxygen and water in nominal operations.
5. Enhanced in-mission maintainability with maximized compatibility with the vehicle's ECLSS.

In 2025, NASA funded a feasibility study under contract 80NSSC25PA663 to explore the adaptation of CDRILS technology for use in the mxEMU PLSS. At that time the spacesuit version of CDRILS was named CDRILS for Mobility or CDRILS-M [13]. During the feasibility study, Honeywell investigated various operating configurations, screened alternative sorbent formulations, conducted subscale simulated EVA experiments, and provided preliminary size, weight, and power (SWAP) estimates for CDRILS-M to NASA. The feasibility study defined a promising path forward for CDRILS-M development toward the xEMU application.

III. CDRILS-I Technology

CDRILS-I consists of the CDRILS-M xEMU CO_2 and humidity management system and the CDRILS-R Regenerator system.

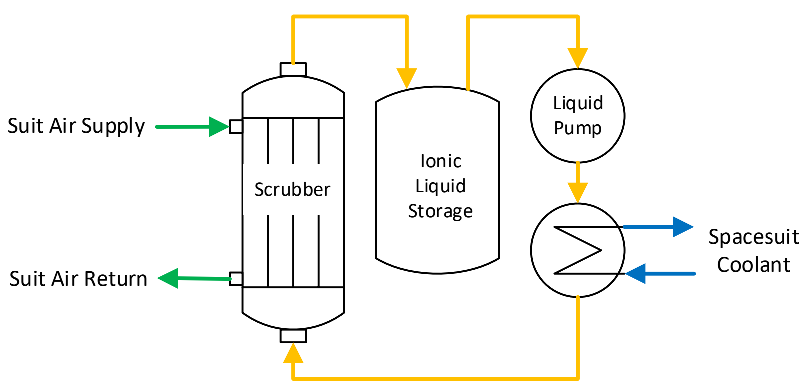

Figure 2. CDRILS-M notional high-level schematic.

As seen in Figure 2, CDRILS-M utilizes a liquid sorbent and hollow fiber membrane contactor in the spacesuit's PLSS to continuously absorb CO_2 and humidity during an astronaut's IVA (Intra Vehicular Activity) and EVA. A liquid pump controls liquid sorbent flow through the contactor and liquid loop. A heat exchanger interfaces with the spacesuit coolant loop to maintain the liquid at an ambient scrubbing temperature. The ionic liquid storage unit can be sized to meet EVA duration goals while balancing liquid sorbent mass and volume. The hollow fiber membrane contactor is sized to meet CO_2 removal rate requirements typically encountered during an EVA.

During the CDRILS-M feasibility study program, Honeywell evaluated baseline CDRILS liquid composed of a blend of 1-ethyl-3-methylimidazolium acetate (EMIM Ac), proprietary promoter, and water for use in the mobility unit system. Additionally, varying levels of promoter and alternative liquid sorbents were explored. A breadboard test simulating EVA conditions at subscale flow rates was utilized to evaluate different liquid systems. While the typical operating pressure in the PLSS is sub atmospheric, ambient pressures were used for these initial breadboard tests while matching the nominal CO_2 and water partial pressures encountered during an EVA. The schematic of a typical breadboard test is shown in Figure 3.

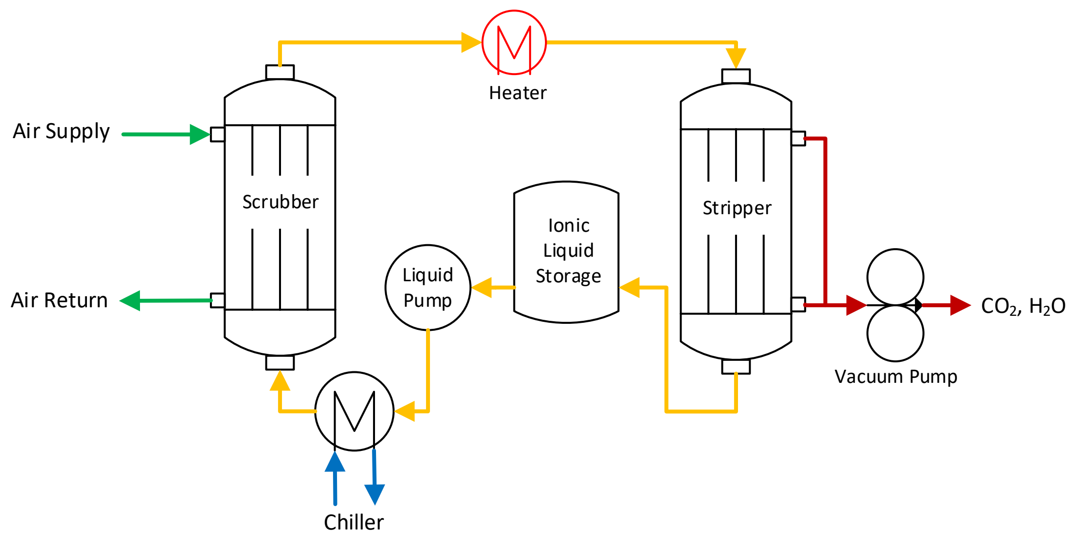

Figure 3. Simplified CDRILS breadboard schematic.

The liquid sorbent was first prepared by operating the breadboard [5] in a stripping only configuration in which liquid was heated to a nominal stripping temperature and recirculated to the stripper contactor under vacuum. Since no air was supplied to the scrubber contactor during this step, any residual CO_2 and humidity was removed from the liquid sorbent to a baseline level. The breadboard was then operated in a scrubbing only configuration to simulate an EVA with nominal metabolic rate of 1200 BTU/hr. During scrubbing only operation, simulated EVA air feed containing 6.5 torr partial pressure of CO_2 and 30% relative humidity was supplied to the scrubber gas inlet, while liquid sorbent was recirculated through the liquid loop and maintained at an ambient scrubber temperature. The CO_2 and water concentrations were monitored at the scrubber air inlet and outlet, and the removal rates were quantified using the total gas flow rate and difference between inlet and outlet concentrations. The test continued until CO_2 was no longer removed from the feed gas and the liquid was saturated. Since the breadboard test is subscale and not optimized for liquid sorbent and contactor volume, the scrubbing duration does not directly correspond to an EVA duration but rather provides sorbent capacity and kinetic data for designing a full-scale system. Liquid sorbent was then regenerated by repeating the stripping only operation. The scrubbing only and stripping cycles were repeated to evaluate cyclic performance of the liquid sorbent system. The results of the breadboard experiments are shown in Figure 4.

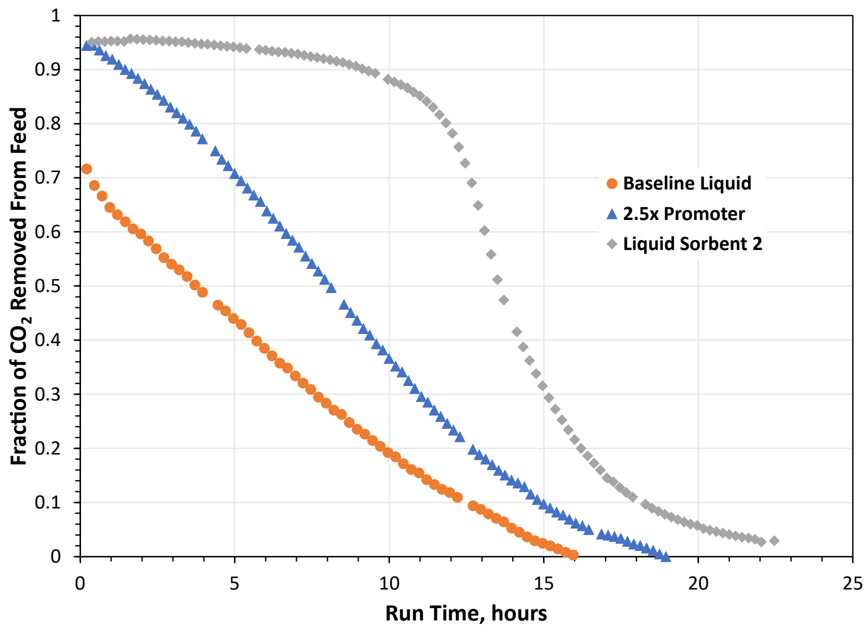

Figure 4. CDRILS-M: Simulated EVA breadboard experiments.

While the baseline CDRILS liquid performs well for the vehicle steady state operation in which CO_2 and humidity are continuously scrubbed from a cabin and stripped from the liquid, this formulation does not appear feasible for the CDRILS-M application. Almost immediately, the CO_2 removal rate begins to decline as the baseline liquid accumulates CO_2, demonstrating a capacity of about 2.7% CO_2 by weight. The sorbent exhibited excellent humidity removal properties, removing 96% of the total humidity fed to the system throughout the duration of the experiment. Another benefit of the baseline liquid is its low toxicity. During the NASA CDRILS 1 contract, NASA conducted a preliminary hazard assessment on baseline CDRILS liquid [3]. Toxicity Hazard Level (THL) is evaluated on a scale from 0 (marginal severity) to 4 (catastrophic). The CDRILS baseline liquid was assigned a THL of 1 [14], which indicates slight to moderate irritation and minimal systemic effects [15]. As new liquid formulations are screened, Honeywell remains cognizant of the low toxicity requirement for ECLSS and PLSS applications.

A formulation including 2.5 times (2.5x) the nominal promoter concentration increased the CO_2 removal rates compared to baseline for the duration of the experiment and increased the capacity of the liquid to about 4.1% CO_2 by weight. The best CO_2 removal performance was observed by an alternative sorbent, labelled Liquid Sorbent 2. This liquid scrubbed CO_2 in the breadboard experiment for 12.5 hours before CO_2 breakthrough was observed. The capacity of Liquid Sorbent 2 was quantified at 7.3% CO_2 by weight. The improved CO_2 capacity of Liquid Sorbent 2 paves a promising path forward for the CDRILS-M liquid based sorbent approach.

CDRILS-R recovers the CO_2 and humidity captured during an EVA by the CDRILS-M unit, regenerates the liquid sorbent for CDRILS-M, and provides the CO_2 removal functionality for a 2-person crew habitat. During the NASA CDRILS 1 program, Honeywell developed a CDRILS FDU design concept, as seen in Figure 5, for a 4-person crew vehicle that is efficiently packaged to fit in half an ISS Basic Express Rack with a bump out. Honeywell will use the FDU design as a starting point for the CDRILS-R design.

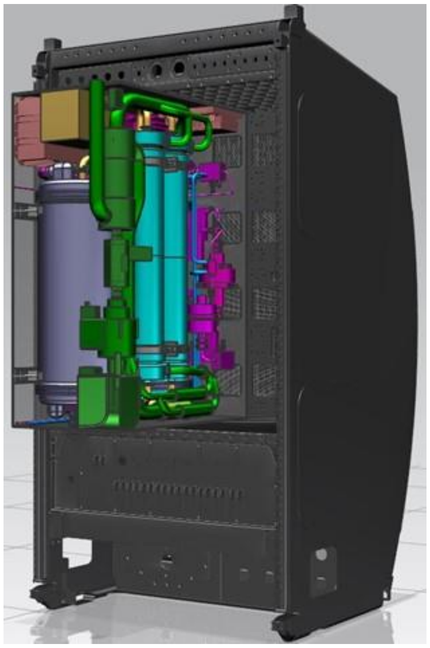

Figure 5. CDRILS FDU design in 1/2 a BER with bump out.

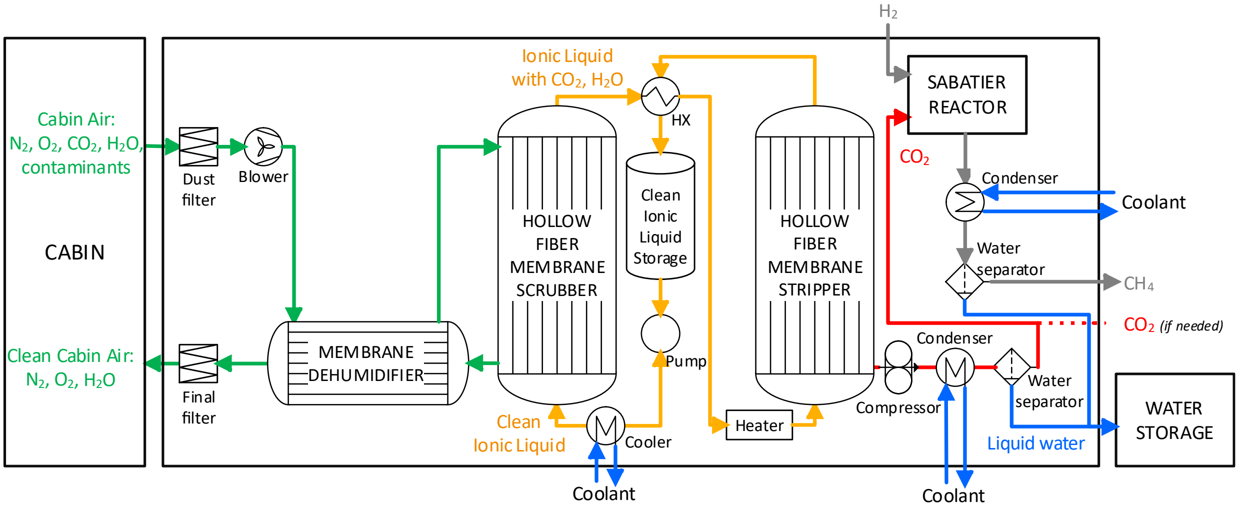

Figure 6. Simplified habitat CDRILS schematic.

As seen in Figure 6, cabin air is supplied to the habitat CDRILS unit via a blower and dried through a dehumidifier before flowing to the hollow fiber membrane scrubber contactor where CO_2 is removed. The CO_2 lean air is humidified and returned to the cabin. Liquid sorbent is recirculated through the scrubber contactor where it absorbs CO_2 and humidity. CO_2 rich liquid is then heated and delivered to the stripper contactor which allows for the desorption of CO_2 and humidity with the use of a vacuum pump. A condenser and water separator isolate the water and CO_2 into separate product streams. With an integrated Sabatier reactor, the CO_2 product stream can be converted to methane and water by reaction with hydrogen. A methane product stream can be further processed by a Hydrogen Recovery System (HRS) such as the methane pyrolysis assembly, currently under development at Honeywell Aerospace [2]. The CDRILS-R unit will use this base design while incorporating interfaces at the liquid heating loop and vacuum system to allow for the regeneration of CDRILS-M sorbent and the recovery of captured CO_2 and water during an EVA. Additionally, the CDRILS-R unit will need to have the capability of regenerating the CDRILS-M sorbent while simultaneously removing CO_2 from the cabin.

IV. Future Development of CDRILS-I

The goal of the current CDRILS-I program under contract 80JSC026C0004 is to develop of a 2-person CDRILS-R system to pair with CDRILS-M on the mxEMU suits. The design will assume an operating scenario with 2 crew living in a small surface habitat with both crew performing EVA in space suits equipped with CDRILS-M. In early 2027, Honeywell shall undergo a Systems Requirements Review that outlines a Concept of Operations, a Hazard Assessment, and an End-Item-Specification (EIS) with defined interfaces of CDRILS-I. Honeywell has years of experience working with this technology and access to in-house test stands built throughout the last 10 years.

The designs for a CDRILS FDU were based on extensive testing performed on the 6 CDRILS demonstrators during NASA programs, including a Honeywell breadboard, two NASA CDRILS breadboards, a Honeywell brassboard, prototype, and membrane aging test stand (Figure 7). During the CDRILS 1 program, Honeywell evaluated and optimized the stability of the core components of CDRILS, the IL mixture and the hollow fiber membrane contactors. Early versions of the liquid mixture and hollow fiber membrane contactors demonstrated aging, which has been quantified and mitigated for enhanced durability to meet the needs of a 4-crew flight demonstration [4]. Demonstrated stabilization methods identified for the promoter and membrane are intended for advancement during the NASA CDRILS-I program and further testing will be performed on the demonstrators that will provide pertinent data for both CDRILS-R and CDRILS-M designs.

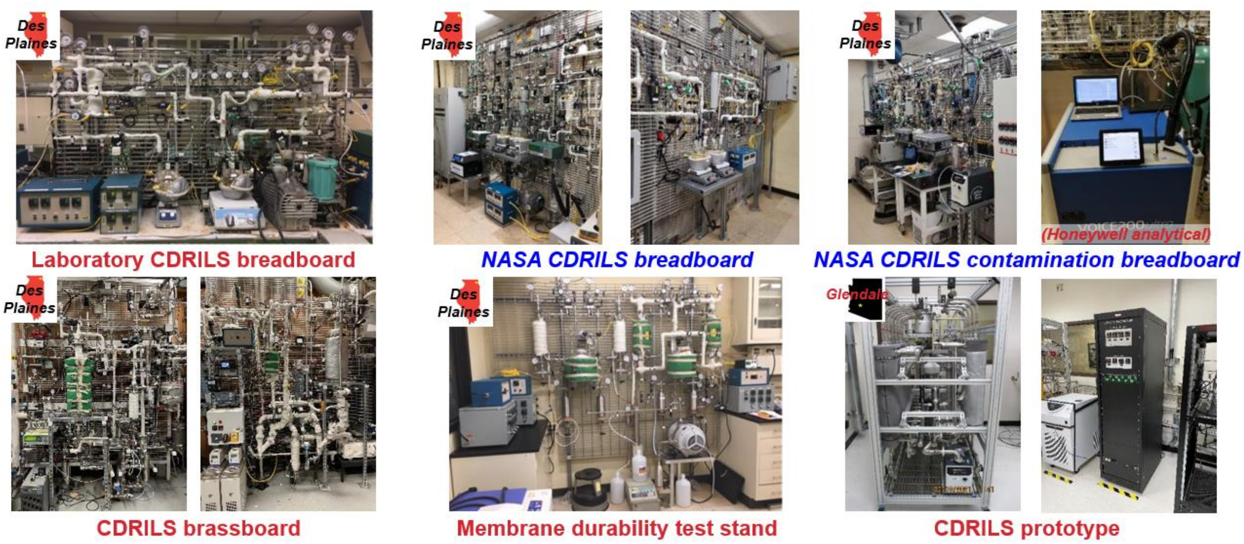

Figure 7. Existing CDRILS ground demonstrations. Demonstrators with names in blue, bold italic labels are owned by NASA, and those with names in red bold labels are owned by Honeywell.

A space suit test stand will be built on Honeywell funding to enable full scale PLSS air flow rates and operating pressure for CDRILS-M experiments while enabling the parallel development of both aspects of CDRILS-I. Honeywell will use this new test stand to select a CDRILS-M configuration that will provide the best capacity and removal rates when paired with a CDRILS-R. Additionally, Honeywell plans to evaluate NASA's SWME [16] contactor as a potential scrubber contactor for use in the CDRILS-M unit and the Calnetix Advance Magnetic-Bearing-Supported blower [17] as a candidate in the CDRILS-R unit. Honeywell and NASA will continue to mature CDRILS technology with dehumidifier screening and down select, contactor coating scale up and aging, and continued liquid promoter stability development._

The Systems Requirements Review will include options to achieve a Preliminary Design Review (PDR) and Critical Design Review (CDR) for CDRILS-I design detailed with CDRILS-M and a CDRILS-R. The goal is to work toward a flight demonstration of technology on a future platform in 2028 or 2029. The scalability of liquid-based technology, as demonstrated by the scale-up of CDRILS from breadboard scale to brassboard scale to 4-crew scale prototype, enables adaptations to other platforms such Commercial LEO Destinations and Lunar habitats or rovers. While this technology is targeting a Mars application, this demonstration approach is in alignment with NASA's Moon to Mars Architecture objective [18] to "*Develop and demonstrate an integrated system of systems to conduct a campaign of human exploration missions to the Moon and Mars, while living and working on the lunar and Martian surface, with safe return to Earth*" and recurring tenants to "*leverage infrastructure in low-Earth orbit to support*

Moon to Mars activities" and to "*design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence*."

V. Conclusion

Honeywell's CDRILS development has focused on scaling, durability component design, packaging, and preparing for flight, with these advancements now supporting maturation of the CDRILS-R architecture. In parallel, CDRILS-M research for the mxEMU advances the core technology by improving system configuration, size, weight, and power. Successful laboratory demonstrations of CDRILS-M reinforce the path toward integrating CDRILS-M and CDRILS-R through the CDRILS-I concept, enabling recovery of stored CO_2 and water from EVA operations and strengthening closed-loop life support. As NASA prioritizes enabling the United States to be the first nation to send humans to Mars, the need for regenerable, mission-ready life support systems has become increasingly urgent. CDRILS-I directly supports this objective by leveraging prior NASA investments to create a system that operates within the mxEMU and can be regenerated in a small surface habitat or vehicle. Together, Honeywell and NASA continue to advance CDRILS toward more sustainable, resource-efficient capabilities for long-duration human exploration.

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GPT-4.1 architecture was used to create the visualization shown in Figure 1. The content has been reviewed and edited by Mark Triezenberg.

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