Prototype Development of an Integrated Mars Atmosphere & Soil Processing System

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Introduction

In the past NASA In-Situ Resource Utilization (ISRU) field demos consisted of large components independantly developed powered by A/C generator power manually controlled by colocated operators, but with the Analog demo MARCO POLO (**M**ars **A**tmospheric and **R**egolith **CO**llector/**P**r**O**cessing for **L**ander **O**perations), NASA is striving for a demonstration lander to be a largely integrated system operating on DC distributed power and remotely controlled by operators at a control center away from the field. This will be the first time for a field demo that the ISRU Project attempts to produce methane, oxygen and hydrogen for use as rocket propellant and fuel cell consumables from Martian resources.

The field demo was envisioned to take place on the slopes of Mauna Kea in Hawaii with an initial checkout integrated test at the JSC Planetary Analog Test Site. The control center for the Hawaii test would be located at the Hale Pohaku facility ~1km away as well as utilizing the Mission Control assets in Houston.

Objectives for MARCO POLO

The analog field demo objectives can be split into Programmatic and Technical purposes for what NASA is trying to achieve with this Mars ISRU demonstration. On the programmatic side the expansion of NASA working with the international community is key and CSA and others will provide the excavators that will bring the Mars soil to MARCO POLO. Also ISRU needs to continue to refine and expand the technology, science and mission scenarios as well as improve remote operations so that future missions will consider ISRU as critical components for mission success. These demonstrations also provide the benefit of building on previous analog demos and continuing evolving the goals and technology towards future mission scenarios. Technically the goals for MARCO POLO align with the “game changing” technology mantra from NASA HQ in that space mining and resource utilization technology will help open the solar system to a broad spectrum of missions and capabilities once mission planners realize they can “live off the land” instead of bringing everything (power, water, propellant, breathable air) with them. By going with an integrated lander design MARCO POLO hopes to push beyond the large independent hardware of past demos to a more plug and play modular design with standard interfaces.

For MARCO POLO the design is to provide a demonstration of all aspects of Martian soil and atmospheric processing at a relevant scale while remotely operating the lander systems. To this end the lander will capture Carbon Dioxide (CO2) from representative Martian atmosphere to produce methane and extract water from representative Martian soil that will be electrolyzed into hydrogen and oxygen. The lander will operate on a 14 hour day/10 hr night cycle with the control centers monitoring the autonous onboard software and operations. The propellant produced by MARCO POLO will be offloaded to a cryocart for long term storage as wel as for use in LOx/Methane thruster firing to demonstrate the complete “dust to thrust” mission cycle.

Major Components/Modules

As stated previously MARCO POLO is designed in a modular fashion with self contained modules providing certain functions with their associated power and data connections. The 9’ by 9’ octagon lander (Figure 1) is laid out with the water cleanup module centrally located as it provides the necessary equipment to extract, clean and store the water vapor from both the Sabatier Reactor products of the Atmospheric module and the Soil Dryer before transferring to the water processing for electrolyzing. The modules are designed to be plug and play so that during build up they can be tested independently of the other systems and prior to integration into the distributed power system. The Command & Data Handling/Power Distribution Unit (C&DH/PDU) module provided the executive software functions as well as the power input from the various fuel cells to provide switching of the loads for all the component operations.

Atmospheric Processing Module

The core technologies in the Atmospheric module (Figure 2) is a CO2 freezer for capture from represtative Martian atmosphere, and a Sabatier reactor for methane production. An essential step in the production of rocket propellant is the capture and pressurization of carbon dioxide gas, which makes up 95% of the Martian atmosphere. Several methods have been investigated to perform this task, but freezing of the CO2 appears to be the most effective, both from an energy standpoint and the purity of the CO2 obtained. At the pressures on Mars, the freezing point of CO2 is 150 Kelvin, so a cryocooler is required to provide a condensation mechanism. The Martian atmosphere contains 2.7% nitrogen, 1.6% argon, and trace amounts of oxygen, carbon monoxide, water vapor, and several other gases. At 150 K and 8 mbar, nitrogen and oxygen will remain in the gaseous phase along with the other gases, except for water vapor because it’s vapor pressure is extremely low (~10^{-8} mbar). Nevertheless, the concentration of water vapor is so low that about 1 g would be captured for every 700 g of CO2 and it will not interfere with the Sabatier process at such low concentrations.

The design of the CO2 freezer for MARCO POLO uses copper fins to give a cold head for the 1.24 kg of dry ice to be collected during the 14 hr of daytime operations when sufficient power is available. This amount of CO2 will provide the 88 g/hr needed by the Sabatier reactor system. Warming sublimates the collected dry ice and provides high pressures sufficient to give the 50 psi needed by the Sabatier reactor. A complicating factor is the need to collect CO2 at the same time that the Sabatier reactor is operating. Several concepts were evaluated to do this, with two cryocoolers freezing and supplying CO2 on alternating days being selected. An efficient scroll pump (Varian IDP-3) provides vacuum to both simulate Mars pressure and to remove the nitrogen and argon from the system to prevent their buildup and inhibition of CO2 freezing by a diffusion barrier layer. Premixed Mars gas simulates the components of the atmosphere and provides feed to the CO2 Freezer through a regulator set at 8-10 mbar.

The Sabatier Reactor combines hydrogen(H2) with carbon dioxide in a exothermic reaction involving a ruthenium catalyst ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) to produce methane(CH4) and water vapor. The Sabatier Reactor was built in-house at JSC ~10 years ago, but never used before now. The Sabatier preheats the hydrogen by channeling it around the reactor chamber to reduce the overall length of the reactor. The reaction runs hydrogen rich and the resulant mixed gas is sent to water clean up module for condensing the water vapor and then returned to the module so that the hydrogen can be recycled back to the reactor and the methane can be dried of any remaining water vapor prior to storage. A regenerative dryer is used to dry the methane gas before it is sent to liquefaction. The regenerative dryer allows the dessicant to be heated up, the absorbed water removed and the reused.

Soil Processing Module

The Soil processing module(Figure 3) is basically a dryer that uses heat and a sweep gas to extract water from the regolith whether it be ice, absorbed or adsorbed water. The boom assembly allows the soil from the excavators to be raised from the ground up to the inlet of the vertical agitator and includes a grizzly screen for rejecting large objects and the horizontal auger sorting for medium sized objects that could clog the agitator. The hopper can accomadate several batches so that the lander is not waiting on excavators for just in time processing.

The Martian Simulant Dryer utilizes an internal auger to mix feedstock inside of a conically shaped vessel. Simulant enters and exits the chamber through two separate abrasive resistant valves located at the top of the vessel and at the bottom of the conical section respectively. The total chamber volume is approximately 0.016 m^3 (970 in^3), consisting of 0.012 m^3 (715 in^3) internal volume for the conical section and an additional 0.004 m^3 (255 in^3) for the cone to transition into the egress valve and cylindrical head space. The fill volume is approximately 50-60% to allow for the simulant to expand as the auger and gas flow lift and overturn it. The dryer was designed for a 10 kg (~22 lb) Martian regolith batch size with bulk density ranging between 1200-1600 kg/m^3 (0.043-0.057 lb/in^3). Assuming the lower density value of 1200 kg/m^3, a 10 kg batch size translates into a 53% fill volume. For terrestrial testing of JSC-Mars-1a, with a 870-1070 kg/m^3 (0.029-0.040 lb/in^3) bulk density range, the batch size is 7.2 kg (15.9 lb) assuming the same fill volume and lower density value.

The dryer is capable of heating simulant to 500^{o}C using either external heaters, internal heaters or a combination of both. Each heater group can provide up to 4 kW of power. A pyrometer will measure the temperature of the soil right above the auger blade and multiple thermocouples will measure the temperature of the exterior of the vessel. A series of load cells will measure the mass of the simulant before, after and during the drying process.

Depending upon the test series, nitrogen or carbon dioxide gas will be swept through the vessel to facilitate moisture removal. Temperature and pressure transducers will be located directly at the gas inlet and outlet of the dryer. A gas-gas heat exchanger will preheat the incoming gas stream using the heat from the outlet stream. Humidity sensors, pressure transducers, and thermocouples will be situated before and after the water condenser. The total water inventory will be calculated post test using mass flow, humidity, pressure and temperature measurements.

Water Cleanup Module

The centrally located Water Clean up Module (Figure 4) accepts mixed gas/water vapor from both the Atmospheric and Soil processing modules passes through the water clean up condensor for water recovery and cleanup. While the Sabatier reactor output is relatively clean water the soil reactor sweep gas contains various percholates liberated from the soil that must be removed before the water can be electrolyzed. The Water cleanup processes water in batches by circulating the water through a nafion membrane filter before storing it in the large clean water storage tank. The night time fuel cell water output is also stored in the clean water tank for processing the next day.

The Contaminant Removal from Oxygen Production Systems (**CROPS**) has been established to provide support to various oxygen production systems being developed under the In-Situ Resource Utilization (ISRU) project. During resources processing, especially soil processing systems, side reactions occur during the high temperature processing yielding significant amounts of contaminants. These contaminants are required to be removed from the product stream in order to protect the system and to provide pure products.

Terrestrial testing of regolith processing via hydrogen reduction, such as does developed by Lockheed Martin (Keller, 2009), resulted in significant production of hydrofluoric acid (HF), hydrochloric acid (HCl), and hydrogen sulfide (H_2S). Analysis of water collected from this systems processing JSC-1A lunar regolith simulant resulted in aqueous solutions containing 2% HF, 5-10% HCl, and 0.01% H_2S. Detailed elemental analysis on the simulant yielded concentrations of fluoride, chloride, and sulfur at 310ppm, 590ppm, and 100ppm, respectively. These values correlate well to the concentration of these elements in lunar soil (Heiken, 1991), requiring the implementation of a contaminant removal system for future ISRU systems.

Current research and development efforts for CROPS have focused on the purification of water produced as an intermediate product in the oxygen production systems. CROPS is developing water selective membranes that would allow water to transport across, while sweeping the permeated water vapor using a dry gas circulation loop. Perfluorosulfonic acid membranes have been demonstrated to have good water transport properties, to be water selective, and to be resistant to a variety of chemicals. Membrane tests have been accomplished to determine the effect of temperature and membrane thickness on water transport as well as contaminant rejection. Figure 5 shows the water flux for two different membrane thickness, 51μm and 254μm, and two different temperatures, 20^oC and 80^oC as a function of dry nitrogen flow rate on the permeated side. As Figure 5 depicts, at low temperature the membrane thickness doesn't have an effect on water flux, but at higher temperature the water flux rate increases with decreasing membrane thickness. The water flux rate increases by a factor of 5 between the 51µm and the 254µm membranes at these temperatures.

Figure 6 shows the ion (contaminant) rejection performance of the un-modified membrane as a function of dry gas flow rate and membrane thickness. Chlorine is rejected (i.e. ion remained in the retentate) constantly at almost 100%, whereas fluorine rejection is affected by the gas flow rate from 90% to as low as 65% rejection for gas flow rates of 1 sLpm to 5 sLpm, respectively.

Current and future work will continue the research and development of modified membranes to decrease the permeation rate of fluorine across the membrane, while maintaining the water transport capability.

Water Processing Module

The water produced during several ISRU processes requires separation into Oxygen (O_2)and H_2 by water electrolysis that occurs in the Water Processing Module (Figure 7). Various types of electrolyzer stacks exist and each type of stack has its own advantages and disadvantages and come in different pressure ratings and feed configurations. Anode fed stacks have higher resistance to some contaminants at the ppm scale, higher efficiency in terms of W/g H_2O and W/cm^2 and are overall more reliable than cathode fed electrolyzers. Lower pressure systems are also less hazardous and have more component and material selection capabilities compared to higher pressure systems. For those reasons the MARCO POLO lander electrolysis module will incorporate two lower pressure Proton Exchange Membrane (PEM) 12-cell liquid-anode feed electrolysis stacks for water electrolysis.

The two Giner electrolyzer stacks can process 522 g/hr of deionized water at 3KW. The stacks can operate up to 695 g/hr but the power consumption was too much for the demo to accomadate. The water processing module transfers clean water from the water clean up module to circulate through the internal deionizing bed, electrolyzer stacks and seperation tanks before the resultant hydrogen and oxygen gas is dried via dessicant dryers.

Propellant and breathing specifications require gases with very low moisture content and to satisfy this requirement gases produced during water electrolysis must be dried. Desiccant materials remove water via absorption and adsorption and are good candidates for water vapor removal from gas. Previous ISRU systems have incorporated this concept with consumable desiccant beds to remove water content. Non-consumable means of drying the gas is preferred and testing was completed to characterize successful regenerable desiccant drying methods. Regeneration of desiccants is possible via the application of heat to break the bonds of hydration and a method is then need to remove the water from the system. For the oxygen the module uses a regenerative dryer which allows the dessicant to be heated up, the absorbed water removed and the reused. This design was not chosen for the hydrogen gas because the power and dessicant needs to meet the hydrogen dryness for metal hydride was unrealistic. Since no flight mission would use the hydride storage for hydrogen it was decided to not let that artifical dryness spec drive design and a replaceable dessicant dryer will be used for hydrogen and sized to minimize the number of changeouts during the demo.

Power Production Module

The Power production duties for the demo is split between a 13KW off lander fuel cell for daytime operations (to simulate power from a solar array) and the 1KW fuel cell located on the lander for night time operations. The consumables for the 1KW fuel cell are provided by the water that is electrolyzed each day and stored in metal hydride canisters for the hydrogen and gaseous oxygen tanks located under the lander deck (Figure 8). While no actual flight mission would use heavy metal hydride as the storage vessel for hydrogen it was used for the demo as the canisters were already available and footprint on the lander was the constraint more than mass as well as the power and budgetary considerations. The 13KW(117 cells Teledyne PEM fuel cell) off lander fuel cell will have it's consumables supplied by a tube trailer given the amount of hydrogen and oxygen needed can not be produced by the water processing module. While this is not a closed loop system for power the fact that the on lander 1KW fuel cell is recharged every day from the electrolyzer does close the power production loop. The 1KW Fuel Cell is an advanced design using a no flow through system that reduces complexity in the balance of plant by utilizing water wicking (Figure 9). This advanced design is being developed by the Glenn Research Center in conjunction with the Department of the Navy and as a back up the fuel cell team at JSC will provide proton exchange membrane 32 cell teledyne flow through stack.

Software

The software and avionics for MARCO POLO is based around a distributed, embedded command, control, and communications architecture. As shown in Figure 12 each module is outfitted with control node that is responsible for performing local command and control for each module as well as providing data and receiving high-level operator commands via a standard Ethernet connection. During the design and development of each module, the control nodes operate in a standalone fashion, thus enabling standalone laboratory testing of the various MARCO POLO modules. However, implementing a standard Ethernet connection to the control nodes provides a straightforward path for integration into the final system. Additionally, the standard Ethernet connections provide a communications architecture suitable for the laboratory environment or for connecting at large distances (such as would be required for connection to Mission Control in Houston).

User interaction with MARCO POLO occurs at a remote command center where each module's operator can monitor data streamed over the network from the various control nodes. Also available at these stations is the ability for limited commanding for scenarios where user interaction is required. As noted before, these user interface stations could be physically located near to the MARCO POLO control nodes, or they could be located large distances away given that communication is accomplished over a standard Ethernet connection.

The Command and Data Handling (C&DH) / Power Distribution Unit (PDU) control node is unique among the control nodes in that it also serves as the main executive for the entire MARCO POLO system. The C&DH/PDU control node will manage module-to-module interfaces and constraints to ensure that the integrated MARCO POLO system functions within the constraints of each module while achieving the overall production goals of the system.

National Instruments (NI) products and software have been chosen to perform the various functions defined for each control node and user interface station. Specifically, each control node consists of a NI CompactRIO™ real-time controller (as shown in Figure 11) configured with the appropriate input and output modules necessary to fully instrument and control each MARCO POLO module. NI LabVIEW™ software is used to program both the CompactRIO™ controllers and the user interface stations. LabVIEW™ provides a unified environment for graphical system design of both real-time executables and standard Windows™ user interface executables. This integrated environment allows programming constructs utilized for traditional Windows™ executables to be transferred seamlessly to a real-time environment with maximum skill and code reuse.

Current Status/Forward Plan

The original concept for the field demo was to perform two weeks of continuous remote operations on the slopes of the Mauna Kea volcano in Hawaii, but due to changes in NASA Headquarter priorities and resources, MARCO POLO is now being prepared for a 2012 two week demonstration at the JSC Planetary Analog testsite (aka the Rockyard). The goal of remote autonomous operations is still in place for the Rockyard demo as the integrated system will operate 24 hours a day with the control team located in the Mission Control building across the campus. The concept for the demo is still to operate on a 14 hr day and 10 hr night cycle though the plan is to invite local schools and other organizations to provide the excavators to deliver to the soil dryer instead of the international participants that would have been at Mauna Kea.

The team was completing Critical Design Review, finalizing their procurements and working towards build up and testing. Due to the cut in resources the liquefaction of methane and oxygen on the lander have been abandoned in favor of gaseous storage and transfer to the cryocart. The demonstration will still achieve the goal of “Dust to Thrust” by having the cryocart peform the liquefaction and thruster firing (Figure 12).

The team is already looking beyond the 2012 small scale production demonstration to which systems need to be upgraded to simulate a large scale Mars sample return type production rate. The Atmospheric Processing module would need to be completely upgraded from CO2 acquisition to Sabatier Reactor and Methane separation to meet the production rate needs of a sample return sized mission. The large scale demonstration would also most likely abandon the fuel cells so that high power requirements of the Electrolyzers and other components can be accommadated as well as process 24 hours per day to produce the oxygen and methane for a possible Morpheus Lander refueling in approximately 90 days.

Long term the team is investigating a 2018 robotic mission to Mars using a SpaceX “Red Dragon” capsule as part of a science effort lead by the Ames Research Center(ARC). ARC and Honeybee Robotics are providing an icebreaker drill to sample permafrost and other Martian soil in hope the science instruments will detect life in the core samples. The MARCO POLO team has begun exploring which ISRU technologies fit within the scope of the Red Dragon mission and the forward plan to design and prototype an integrated system for a precursor field demonstration prior to a 2018 flight.

It is an exciting and dynamic time for In Situ Resource Utilization and NASA JSC and KSC are pushing the technology forward so that future mission planners like those working Mars Design Reference Architecture (DRA) 6.0 will be confident in the technology for inclusion in the critical path for mission success.

Refernces:

1. Keller, B., et.al. “Field Test Results of the PILOT Hydrogen Reduction Reactor.” AIAA-2009-6475, AIAA SPACE 2009 Conference and Exposition, Pasadena CA, Sept 14-17, 2009
2. Heiken, G. et.al. *Lunar Sourcebook* Cambridge, NY. 1991

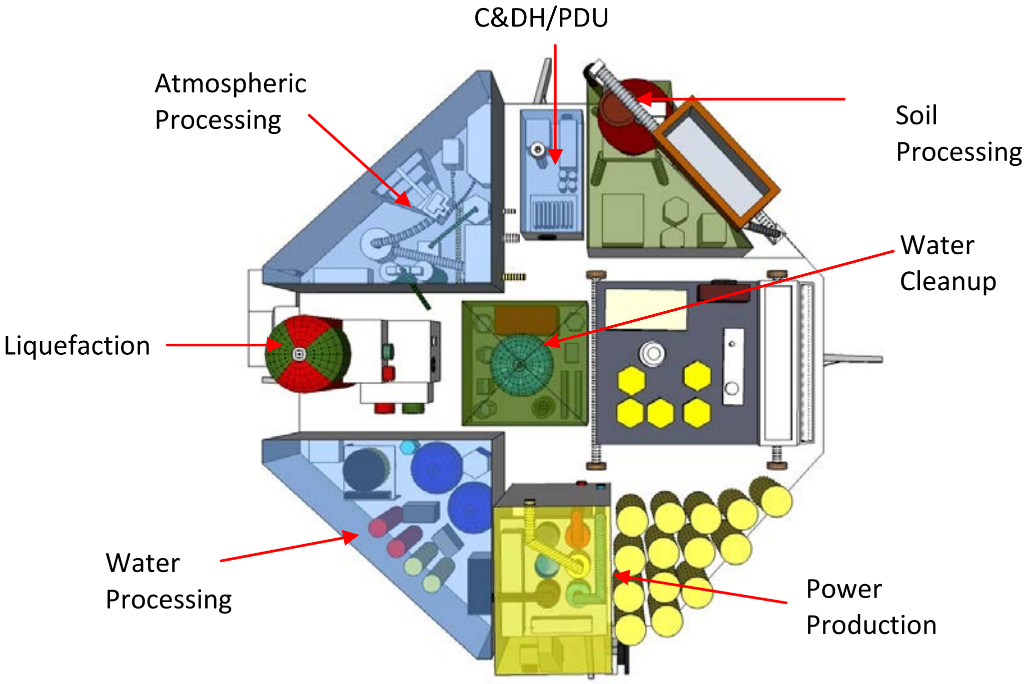

Figure 1 MARCO POLO System

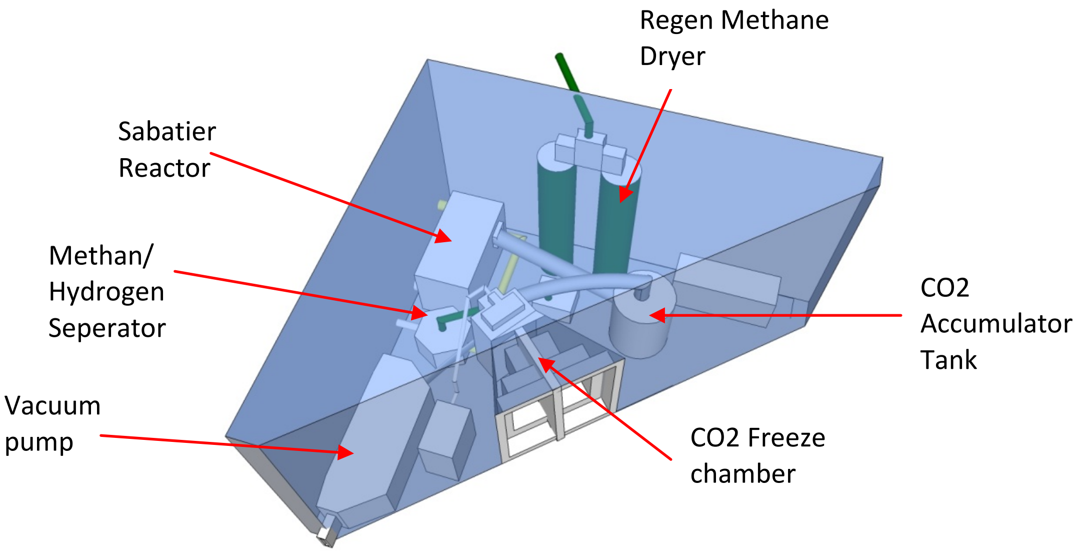

Figure 2 Atmospheric Processing Module

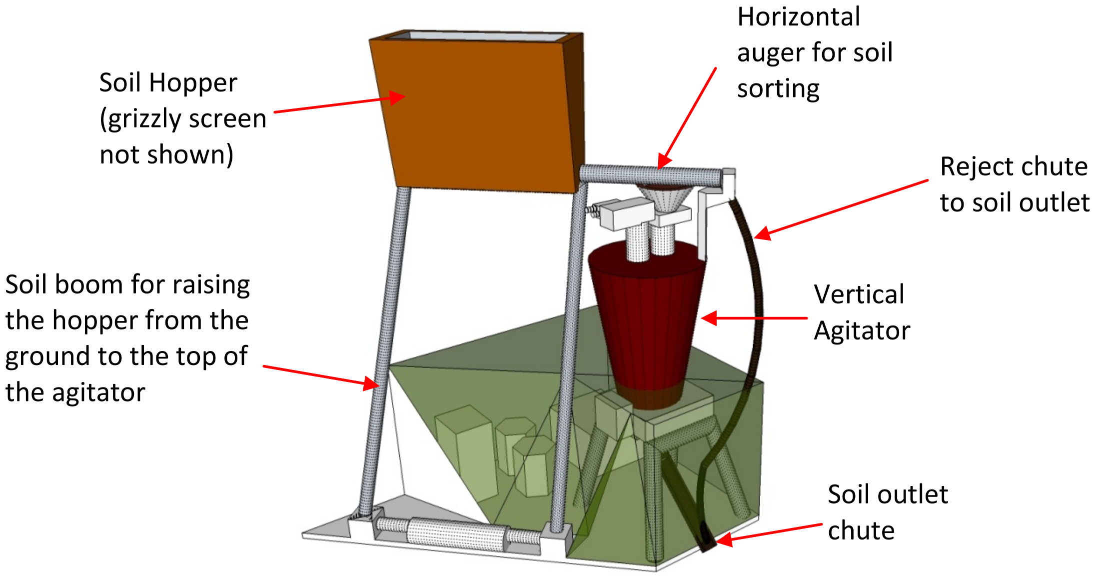

Figure 3 Soil Processing Module

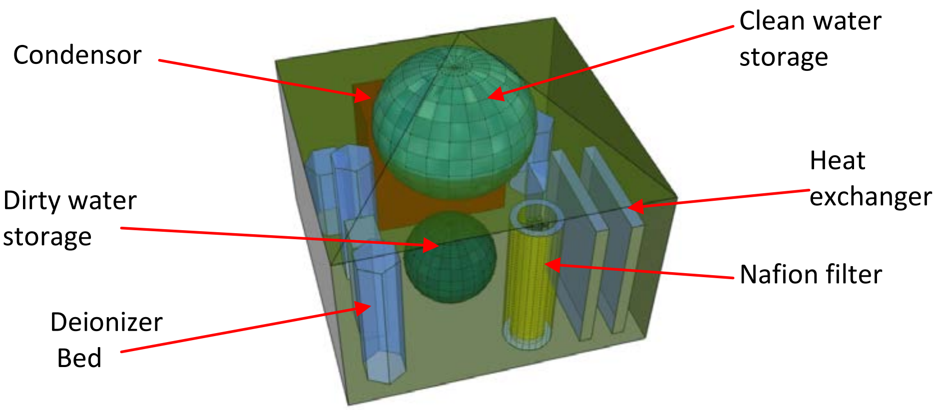

Figure 4 Water Cleanup Module

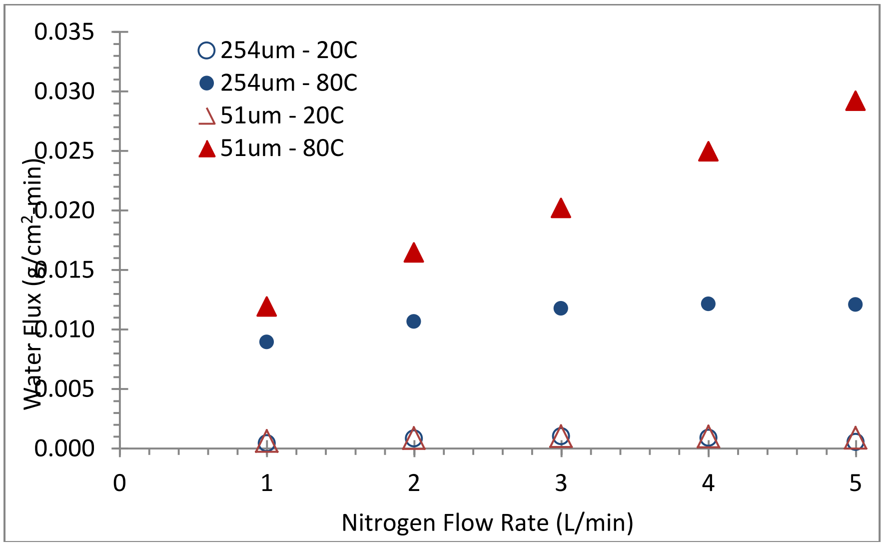

Figure 5 Temperature and membrane thickness effect on water flux versus dry nitrogen flow on the permeate side

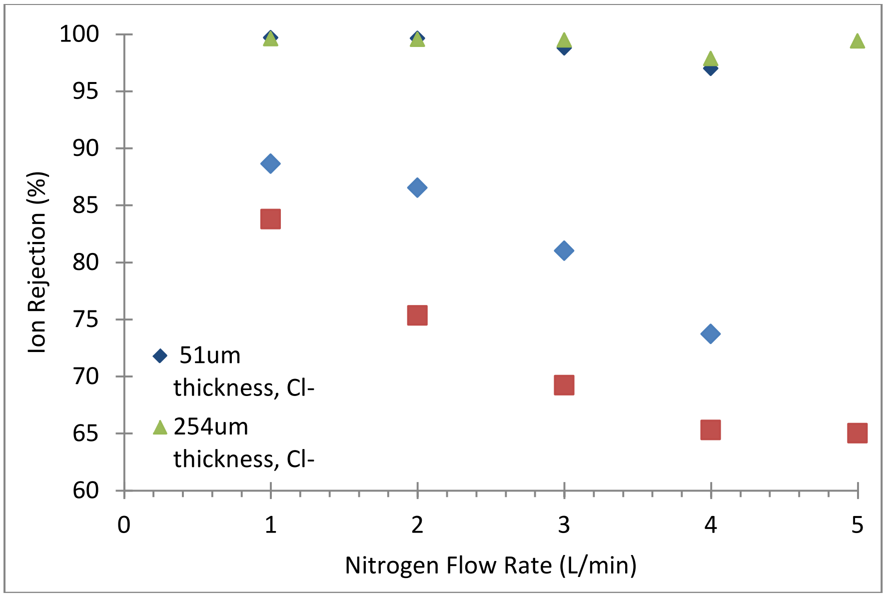

Figure 6 Ion Rejection (i.e. ion in retentate) as a function gas flow rate for two membrane thickness.

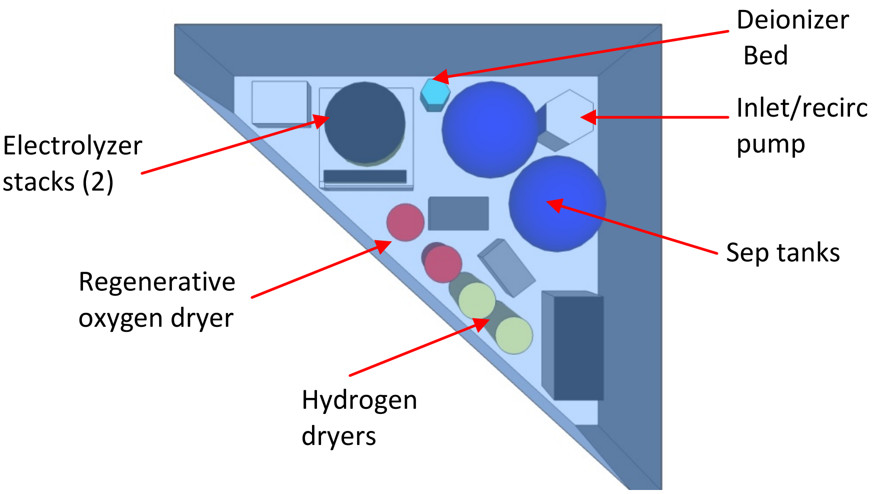

Figure 7 Water Processing Module

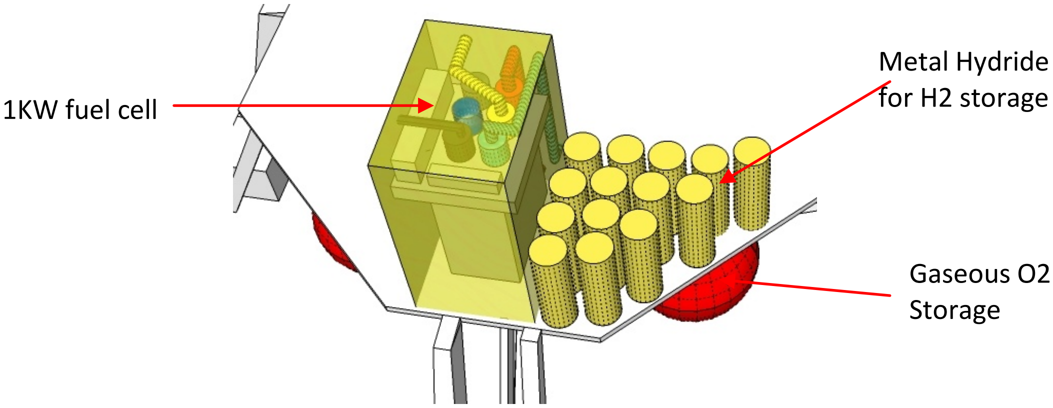

Figure 8 Power Production and Storage

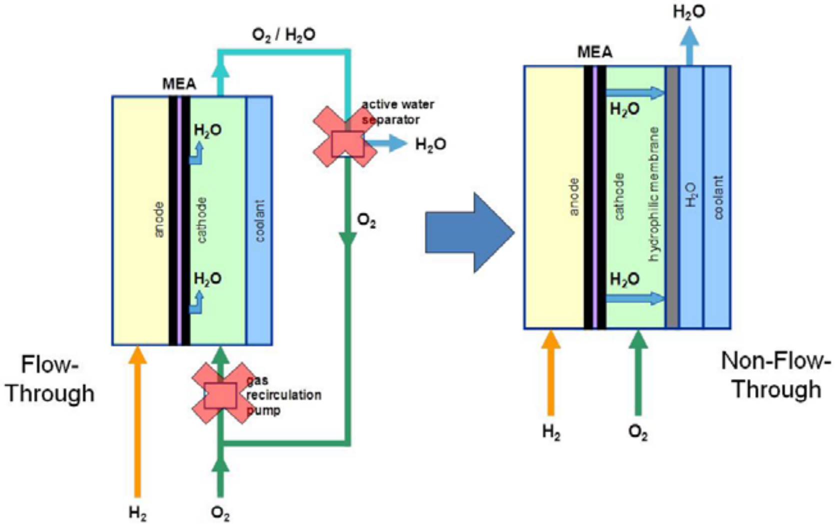

Figure 9 Differences between a Flow Through and Non Flow Through Fuel Cell System

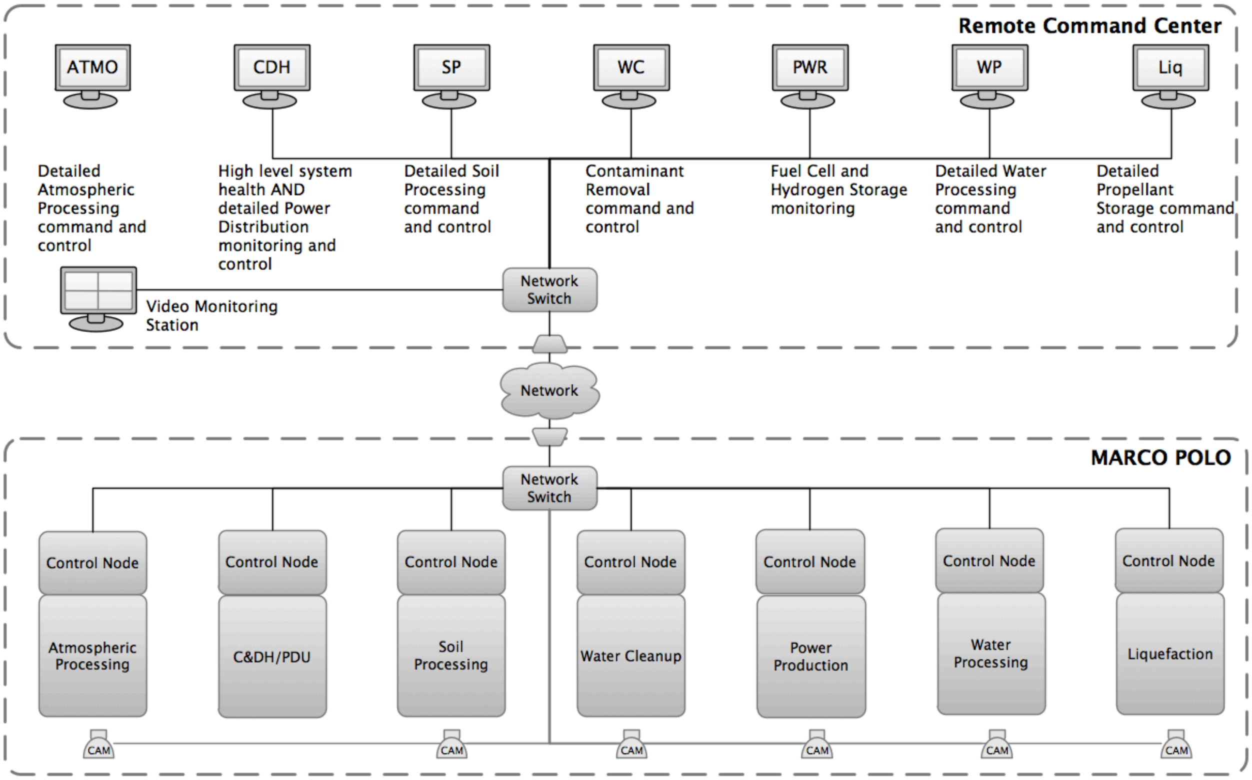

Figure 10 MARCO POLO command, control, and communications architecture showing local control nodes and remote user interface stations.

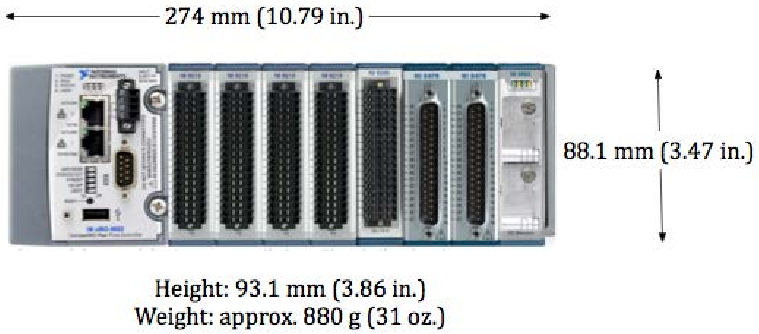

Figure 11 National Instruments CompactRIO™ real-time controller with representative input and output hardware

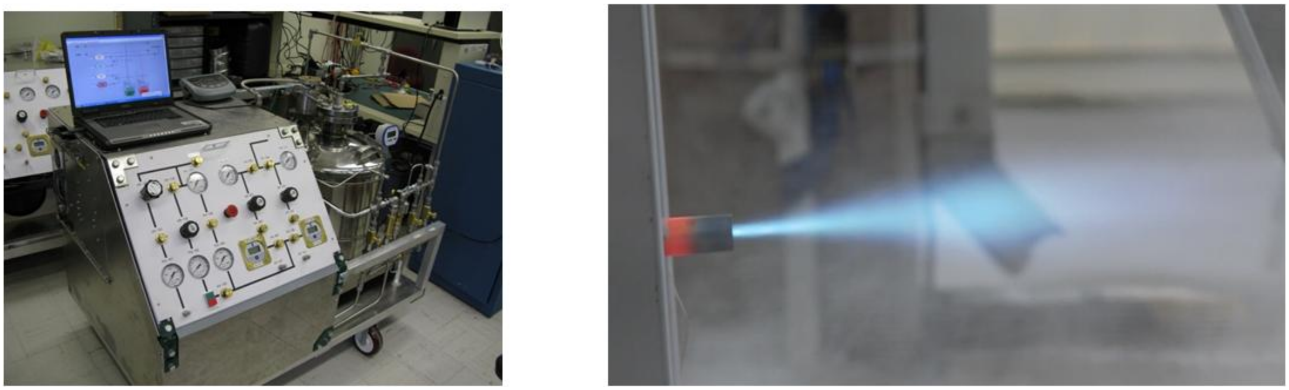

Figure 12 JSC Cryocart for long term Methane and Oxygen storage and thruster firing demonstation.