

Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure

Zachary W. Greenwood¹, Morgan B. Abney², and Terry Wall³
NASA, George C. Marshall Space Flight Center, Huntsville, Alabama, 35812, USA

Lee A. Miller⁴
Jacobs Engineering, Huntsville, Alabama, USA

Richard R. Wheeler, Jr.⁵
Umpqua Research Company, Myrtle Creek, OR 97457

State-of-the-art life support oxygen recovery technology on the International Space Station is based on the Sabatier reaction where only about half of the oxygen required for the crew is recovered from metabolic carbon dioxide (CO₂). The Sabatier reaction produces water as the primary product and methane as a byproduct. Oxygen recovery is constrained by both the limited availability of reactant hydrogen from water electrolysis and Sabatier methane (CH₄) being vented as a waste product resulting in a continuous loss of reactant hydrogen. Post-processing methane with the Plasma Pyrolysis Assembly (PPA) to recover this hydrogen has the potential to substantially increase oxygen recovery and thus dramatically reduce the logistical challenges associated with oxygen resupply. The PPA decomposes methane into predominantly hydrogen and acetylene. A separation system is necessary to purify hydrogen before it is recycled back to the Sabatier reactor. Testing and evaluation of acetylene removal systems and PPA system architectures are presented and discussed.

Nomenclature

<i>AR</i>	= Atmosphere Revitalization	<i>MRSHP</i>	= Microwave Regenerative Sorbent-based Hydrogen Purifier
<i>C₂H₂</i>	= Acetylene	<i>OGA</i>	= Oxygen Generation Assembly
<i>C₂H₄</i>	= Ethylene	<i>PPA</i>	= Plasma Pyrolysis Assembly
<i>C₂H₆</i>	= Ethane	<i>PSI</i>	= Pounds per Square Inch
<i>C</i>	= Carbon	<i>PSIG</i>	= Pounds per Square Inch Gauge
<i>CM</i>	= Crew Member	<i>RGA</i>	= Residual Gas Analyzer
<i>CDRA</i>	= Carbon Dioxide Removal Assembly	<i>SBIR</i>	= Small Business Innovation Research
<i>CRA</i>	= Carbon Dioxide Reduction Assembly	<i>SDU</i>	= Sabatier Development Unit
<i>CH₄</i>	= Methane	<i>SI</i>	= Sustainable Innovations, Inc.
<i>CRA</i>	= Carbon Dioxide Reduction Assembly	<i>SmLPM</i>	= Standard milliLiters Per Minute
<i>H</i>	= Enthalpy	<i>UTAS</i>	= UTC Aerospace Corporation
<i>H₂</i>	= Hydrogen	<i>W</i>	= Watts
<i>H₂O</i>	= Water		
<i>ISS</i>	= International Space Station		
<i>MSFC</i>	= Marshall Space Flight Center		

¹ Aerospace Engineer, Space Systems Dept., NASA-MSFC/ES62.

² Assistant Branch Chief, Space Systems Dept., NASA-MSFC/ES62.

³ Aerospace Engineer, Space Systems Dept., NASA-MSFC/ES62.

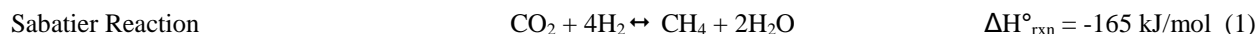
⁴ ECLSS Engineer, Jacobs Engineer ESSSA Group, NASA-MSFC/ES62.

⁵ Senior Research Engineer, R&D Division, 125 Volunteer Way /P.O. Box 609.

I. Introduction

LIFE support is a critical function of any crewed space vehicle or habitat. Human life support systems on the International Space Station (ISS) include a number of atmosphere revitalization (AR) technologies to provide breathable air and a comfortable living environment to the crew. The Trace Contaminant Control System removes harmful volatile organic compounds and other trace contaminants from the circulating air. The Carbon Dioxide Removal Assembly (CDRA) removes metabolic carbon dioxide (CO₂) and returns air to the cabin. Humidity is kept at comfortable levels by a number of condensing heat exchangers. The Oxygen Generation Assembly (OGA) electrolyzes water to produce oxygen for the crew and hydrogen (H₂) as a byproduct. A Sabatier reaction-based CO₂ Reduction Assembly (CRA) was launched to the ISS in 2009 and became fully operational in June 2011.

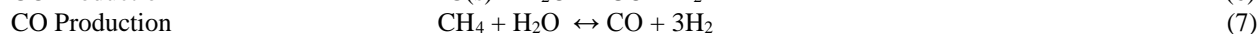
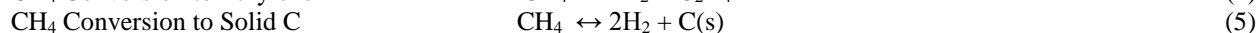
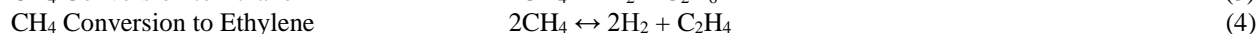
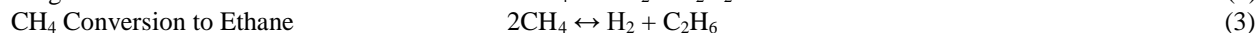
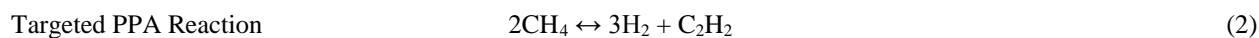
The CRA interfaces with both the OGA and CDRA. Carbon dioxide from the CDRA is compressed and stored in tanks until hydrogen is available from OGA water electrolysis. When the OGA is operational and there is CO₂ available, the CRA is activated and produces methane and water via the Sabatier reaction shown in Equation 1.



The water product is condensed out of the product stream, separated, and purified in the Water Processing Assembly before being recycled back to the OGA to be used to produce O₂ for the crew. Methane, saturated with water vapor at a dewpoint similar to the temperature of the ISS moderate temperature cooling loop that is used to cool the condensing heat exchanger, is vented to space as a waste product. The loss of H₂ in the form of vented CH₄ and uncondensed water vapor in the CH₄ stream limits the oxygen recovery to approximately 50% from metabolic CO₂.

Without the CRA, each Crew Member (CM) requires ~0.891 kg H₂O/day to be supplied from Earth to produce breathable oxygen via water electrolysis. The CRA can theoretically reduce this figure to ~0.459 kg/CM-day but that still equates to a total water resupply requirement of ~670 kg H₂O/year for a crew of four, just for breathable oxygen. To make long duration missions beyond Low Earth Orbit logistically feasible, greater oxygen recovery from metabolic CO₂ is needed. NASA is currently targeting technologies that achieve 75-90% O₂ recovery from metabolic CO₂¹.

One approach to achieve these higher recovery rates builds upon the ISS AR architecture and includes adding a methane post-processor to recover H₂ from CRA methane. NASA has been developing the Plasma Pyrolysis Assembly (PPA) to fill the role of a methane post-processor.^{2,3,4,5,6,7,8} The PPA uses a magnetron to generate an H₂/CH₄ plasma targeting Sabatier CH₄ conversion to hydrogen and acetylene (C₂H₂) as shown in Eq. 2. Secondary reactions with CH₄, as shown in Equations 3-5, and reactions with residual water vapor as shown in Eqs 6-7, also occur in the PPA resulting in an effluent mixture containing H₂, unreacted CH₄, product C₂H₂, and trace quantities of H₂O, carbon monoxide (CO), ethylene (C₂H₄), ethane (C₂H₆), and solid carbon (C).



When H₂ recovered by the PPA is recycled back to the CRA, and the CRA is operated at a H₂:CO₂ ratio of 4.25, a theoretical O₂ recovery of >86% may be realized (assuming a respiratory quotient of 0.92) from metabolic CO₂. This further reduces the water resupply requirement to ~0.18 kg/CM-day. However, before H₂ can be recycled to the CRA, C₂H₂ and other hydrocarbons must be removed from the gas stream to prevent fouling of the CRA catalyst. In 2015, four sub-scale hydrogen separation systems were delivered to NASA for evaluation. These included two electrolytic single-cell hydrogen purification cell stacks developed by Sustainable Innovations, LLC (SI), a sorbent-based hydrogen purification unit using microwave power for sorbent regeneration developed by Umpqua Research Company (Umpqua), and a LaNi_{4.6}Sn_{0.4} metal hydride produced by Hydrogen Consultants, Inc. Evaluation of the SI cell stacks was reported in Ref. 2.

Evaluations have been conducted on the Umpqua and metal hydride hydrogen separators. The results of these evaluations, discussion of potential architecture options, and proposed future work are presented here.

II. Hardware and Test Configuration

A. Hardware

1. Hydrogen Components, Inc. Metal Hydride

A $\text{LaNi}_{4.6}\text{Sn}_{0.4}$ metal hydride canister, shown in Figure 1, was purchased from Hydrogen Components, Inc. (Bailey, CO) with a maximum design pressure of 550 psig (28,440 torr). The canister housing, made of stainless steel, was provided with a 500 psi (25,860 torr) relief valve to protect from over-pressurization. These canisters are typically utilized for hydrogen storage but by adding an additional inlet/outlet port (they usually only have one) this technology could be evaluated for hydrogen separation.



Figure 1. Hydrogen Components, Inc. Metal Hydride Canister.

2. Umpqua Microwave Regenerative Sorbent-based Hydrogen Purifier (MRSHP)

The Microwave Regenerative Sorbent-based Hydrogen Purifier (MRSHP), as in Figure 2, was the result of a Phase III Small Business Innovation Research (SBIR) development effort conducted by Umpqua Research Company of Myrtle Creek, Oregon. The result of the development effort was the delivery of a sub-scale hydrogen purifier that utilized molecular sieve 13X to carry out the separation between hydrogen and acetylene and employed the novel use of microwave power to heat the sorbent for regeneration. Extensive discussion of the development of the MRSHP may be found in Ref. 9.



Figure 2. Microwave Regenerative Sorbent-based Hydrogen Purifier (MRSHP).

B. Test Configurations

Both the metal hydride canister and the MRSHP were integrated with the 2nd Generation PPA. The PPA was operated at a 1-Crew Member (CM) rate of CH_4 production and an $\text{H}_2:\text{CH}_4$ ratio of 4:1. The reactor was maintained at ~ 52 torr with an applied microwave power of 550 W. This resulted in a PPA effluent containing H_2 , C_2H_2 , unreacted CH_4 , ethylene, and ethane. Operation in this manner was notably devoid of CO and water vapor. Since 13X will adsorb water vapor preferentially to acetylene, testing in this configuration gives a bounding best case performance. Adsorption cycles conducted with the MRSHP in this configuration are hereto described as “Dry” adsorption cycles. It should be noted that the metal hydride was tested only in the Dry configuration. The gas leaving the separator was analyzed using a Hiden Analytical residual gas analyzer (RGA) mass spectrometer.

The MRSHP was also operated with the PPA being fed CH_4 from a Sabatier Development Unit (SDU) designed by Precision Combustion, Inc. The SDU was operated such that 350 SmLPM CH_4 was produced with minimal unreacted CO_2 . Water vapor content was maintained at a dewpoint of ~ 31 °C. Additional hydrogen was fed to the PPA to maintain the overall 4:1 ratio of $\text{H}_2:\text{CH}_4$, and the PPA reactor was maintained at ~ 52 torr with an applied microwave power of 550 W. Because the PPA was fed CH_4 containing water vapor, the resulting effluent contained all previously indicated components including CO and H_2O . Adsorption cycles conducted in this configuration are hereto described as “Wet” adsorption cycles. Gas leaving the separator was analyzed using a Hiden Analytical RGA mass spectrometer. In all cases the gas was mixed with 50% argon diluent prior to analysis in the mass spectrometer.

C. Methods

1. Hydrogen Components, Inc. Metal Hydride

The use of metal hydrides for a hydrogen purification application targets the capture and storage of hydrogen on the metal hydride. Testing was conducted by flowing a slipstream of the PPA effluent through the metal hydride canister and analyzing the inlet and outlet constituents. Separation runs were carried out with the canister at temperatures including ambient, heated to 120 °C, and cooled to 2 °C. The flow through the canister was varied from zero to 300 SmLPM.

2. Umpqua Microwave Regenerative Sorbent-based Hydrogen Purifier (MRSHP)

In the MRSHP, targeted sorbates for the microwave waveguide-based 13X sorbent media are the acetylene and ethylene byproducts present in the predominately hydrogen product stream exiting the PPA. Testing of the MRSHP involved adsorption runs (either “Wet” or “Dry”) followed by a desorption run. Adsorption runs were performed with a constant feed from the PPA effluent equivalent to a 1-CM product rate while maintaining an MRSHP inlet bed pressure of ~720 torr. Each adsorption was allowed to continue until partial breakthrough of acetylene was observed.

Desorption of the 13X sorbent bed was accomplished using a microwave powered thermal desorption performed under vacuum. Desorption cycles were performed at a variety of microwave power levels and durations, as shown in Table 1. The goal for desorption following

Table 1. Desorption conditions following each adsorption cycle.

Microwave Desorption #	Microwave Power Level (Watts)	Duration (Hours:Minutes)
1-Post Dry Adsorption	110	24:42
2-Post Dry Adsorption	135	16:2
3-Post Dry Adsorption	Varied	Long
1-Post Wet Adsorption	130	15:45
2-Post Wet Adsorption	130	15:00
3-Post Wet Adsorption	130	06:28
4-Post Wet Adsorption	130	06:45
5-Post Wet Adsorption	130	06:45

the Dry runs and Wet runs 1 and 2, was to achieve complete desorption and subsequent recovery of the beds. The goal for desorption following Wet runs 3-5 was to examine the effect of cycle time on bed capacity for operation where the adsorption cycle was required to be equivalent in time to the desorption cycle.

III. Results and Discussion

The metal hydride hydrogen separator and MRSHP were tested at NASA MSFC in 2016 and early 2017. Both technologies were evaluated integrated with the PPA. In addition, the MRSHP was evaluated with the PPA supplied methane from the SDU. The results of this testing and a discussion of its relevance are provided below.

A. Metal Hydride Performance

The metal hydride showed no substantial capability to separate hydrogen from the PPA effluent at any of the test conditions. PPA effluent was supplied to the metal hydride at approximately ambient pressure. The composition of the flow stream leaving the metal hydride canister matched the inlet conditions to the limits of detection. To make a viable hydrogen separator the metal hydride would have had to capture all, or at least a substantial majority of the hydrogen out of the gas stream. Since the canister effectively captured none of the hydrogen it is not a viable candidate for the separation architecture.

For hydrogen storage applications these canisters are typically “charged” at 200 psig (10,340 torr). Operating at ambient pressure would likely significantly reduce the metal hydride capacity due to the relative reduction in driving force. In addition, the testing suggests that at ambient pressure the hydrogen capture occurs too slowly to be of value as a separator (slow kinetics). It is possible that there is a metal hydride other than $\text{LaNi}_{4.6}\text{Sn}_{0.4}$ that has a high affinity for hydrogen at the necessary conditions and is compatible with acetylene, but no further testing is planned at this time.

B. MRSHP Performance

The MRSHP was evaluated using Dry and Wet PPA effluent gas streams. The performance of the technology with these streams is reported below. Additionally, a discussion of the observed changes in acetylene capacity, characteristic adsorption curves, and overall performance is discussed.

1. MRSHP Dry Performance Results

A representative gas concentration curve for the first three Dry adsorption cycles is shown in Figure 3. Elapsed time in hours is shown on the x-axis. The y-axis provides the residual gas analyzer raw output on a log scale and can be interpreted as relative quantities of each gas component. Data from each run demonstrated relatively uniform and repeatable acetylene adsorptions up to four hours of adsorption. The third adsorption cycle had the distinction that it was continued for a total of just over 11 hours, vs. under six hours for the first two cycles, in order to capture complete break-through of the acetylene contaminant. Complete break-through of a particular contaminant is distinguished by a return to the influent gas concentration as measured in the sorbent bed effluent. Elevation above this level would represent a displacement of the contaminant from the bed that is generally induced by a more strongly adsorbed competitor. Partial break-through of C_2H_2 was observed at just under 3 hours of adsorption (hour 4 on the graph) and accelerated at just under 7 hours from baseline (hour 8 on the graph) before a full return to influent levels.

Desorption between each run was varied. However, gas analysis of desorption products, combined with very low outlet pressure at the end of each desorption suggested that complete desorption was achieved. The similar performance following each desorption also suggests that complete desorption was achieved.

2. MRSHP Wet Performance Results

The acetylene data for all six wet adsorption cycles are shown in Figure 4. The x-axis provides the elapsed time for the run while the y-axis shows the normalized RGA response for acetylene. This value was calculated by dividing the RGA response at a given time with the RGA response for that component prior to adsorption (100% of gas). The data from each run was shifted such that at 0.75 minutes into the run, the normalized RGA response for acetylene was 0.4. This was to provide a clearer visual comparison of the breakthrough curves. Note that due to the shift in data, the RGA response for Run 1, indicating complete adsorption of acetylene, was observed at 1 hour into the run. All other runs are compared based on this alignment of curves.

The first Wet adsorption cycle shows a rapid return to low baseline concentration for acetylene. This is potentially

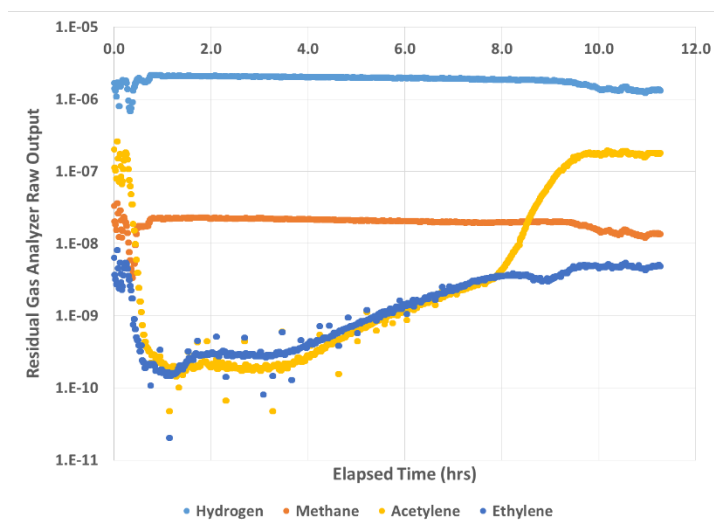


Figure 3. Third MRSHP Dry Adsorption run. Data shown is representative of all three dry runs up to 4 hours of adsorption. Run 3 is the only run to exceed 4 hours of adsorption.

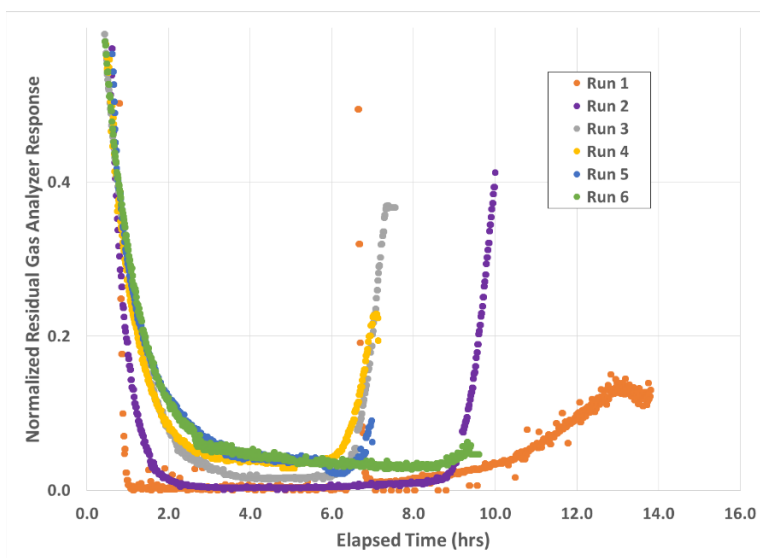


Figure 4. Combined acetylene adsorption breakthrough curves for Wet adsorption runs.

due to the long duration and higher power desorption performed prior to this adsorption cycle as indicated in Table 1, as well as there being no water on the bed initially. Adsorption occurred over a 7.5-hour period until the beginning of acetylene breakthrough with subsequent gradual rise to accelerated breakthrough beginning just after 9 hours of adsorption. This indicates relatively high acetylene capacity. The second Wet adsorption cycle showed a more gradual decrease to the baseline acetylene level, yet once to baseline, the time to initial breakthrough is around 5 hours, which is similar to that observed for the Dry adsorptions. However, continued breakthrough occurred much more rapidly than that observed in Run 1. This suggests a very sharp acetylene front within the bed. Subsequent runs showed a decreased capacity observed by initial breakthrough occurring approximately 5 hours after baseline (shown at hour 6 on the graph). However, a return to the longer breakthrough time was observed for the final run. The reason for the change in breakthrough time is not clear as conditions were not significantly different between runs. Relatively shorter desorption times explain the shorter breakthrough time for runs 3-5, but do not explain the higher capacity observed for run 6.

A second observation is the relative decrease in the time to reach baseline acetylene. Each subsequent run demonstrated a more gradual curve from the 0.75 hour mark. Although not confirmed, it is possible that the presence of CO₂ and water may be affecting this. All the Wet adsorption cycles show an elevated level of water vapor and CO in both the influent and effluent streams. This is to be expected due to the SDU product feed stream to the PPA containing residual CO₂ as well as H₂O at SDU effluent condenser saturation levels. Water vapor in particular is expected to have the greatest impact on 13X bed capacity due to its strongly held adsorptive properties on this molecular sieve, out-competing all other contaminants.

A third observation from the wet data was the change in adsorption performance of ethylene compared to that of acetylene. As seen in the Dry runs (Figure 3), ethylene and acetylene adsorption tracked with one another. However, in the Wet runs, there was a significant difference in adsorption and breakthrough between the two gases as seen in Figure 5. Acetylene clearly had a greater capacity than ethylene suggesting a higher affinity of 13X for the acetylene than the ethylene. For use in an oxygen recovery architecture, breakthrough of ethylene is just as important as acetylene since neither is desired to be recycled to the PPA.

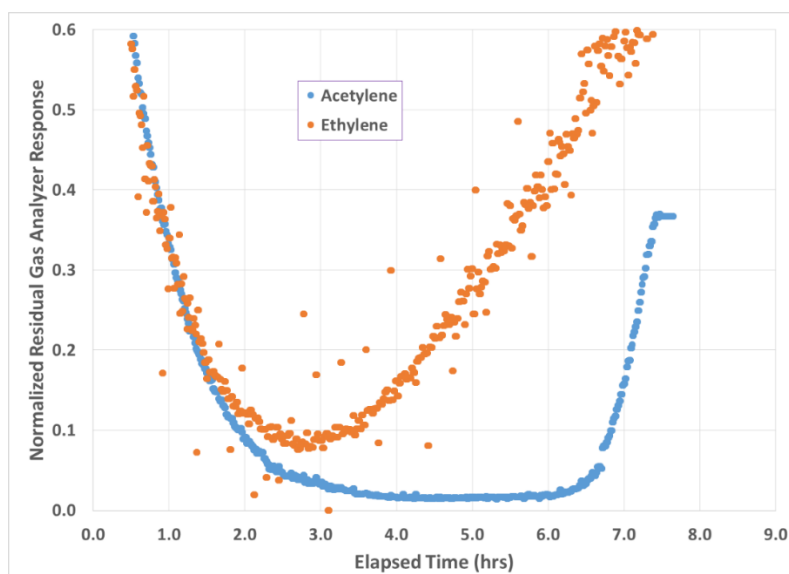


Figure 5. Wet adsorption run #4 contrasting ethylene and acetylene breakthrough curves.

3. MRSHP Bed Disassembly

Following the final Wet adsorption cycle a subsequent desorption was performed and the waveguide-based sorbent bed was removed from the MRSHP prototype and the bed disassembled. The sorbent bed exit end piece was taken off to expose the 13X media which was then gradually removed. Darkened media was observed predominantly down the center of the bed as seen in the disassembly photos shown in Figure 6 A-F. This has been hypothesized to be due to the presence of carbon that formed from thermally decomposed acetylene. It is unclear as to when this carbon formed. It may be that a significant amount of carbon formed during the “super” desorption cycles that were executed between the last Dry adsorption and the first Wet adsorption, however there is no sign of this in the first Wet adsorption cycle which, as noted earlier, shows a fast drop to a very low baseline and greatly extended adsorption capacity. A closer review of all the data for the various desorption cycles may reveal elevated temperatures corresponding to elevated microwave power levels or perhaps certain exceptionally lengthy adsorption cycles. It is also possible that the carbon simply formed gradually over the course of the 10 cycles or alternatively during some preliminary adsorption/desorption experiments. In any case operation at lower power levels for the initial part of the desorption cycle could well be all that is required to mitigate this decomposition. The presence of carbon coating the 13X sorbent

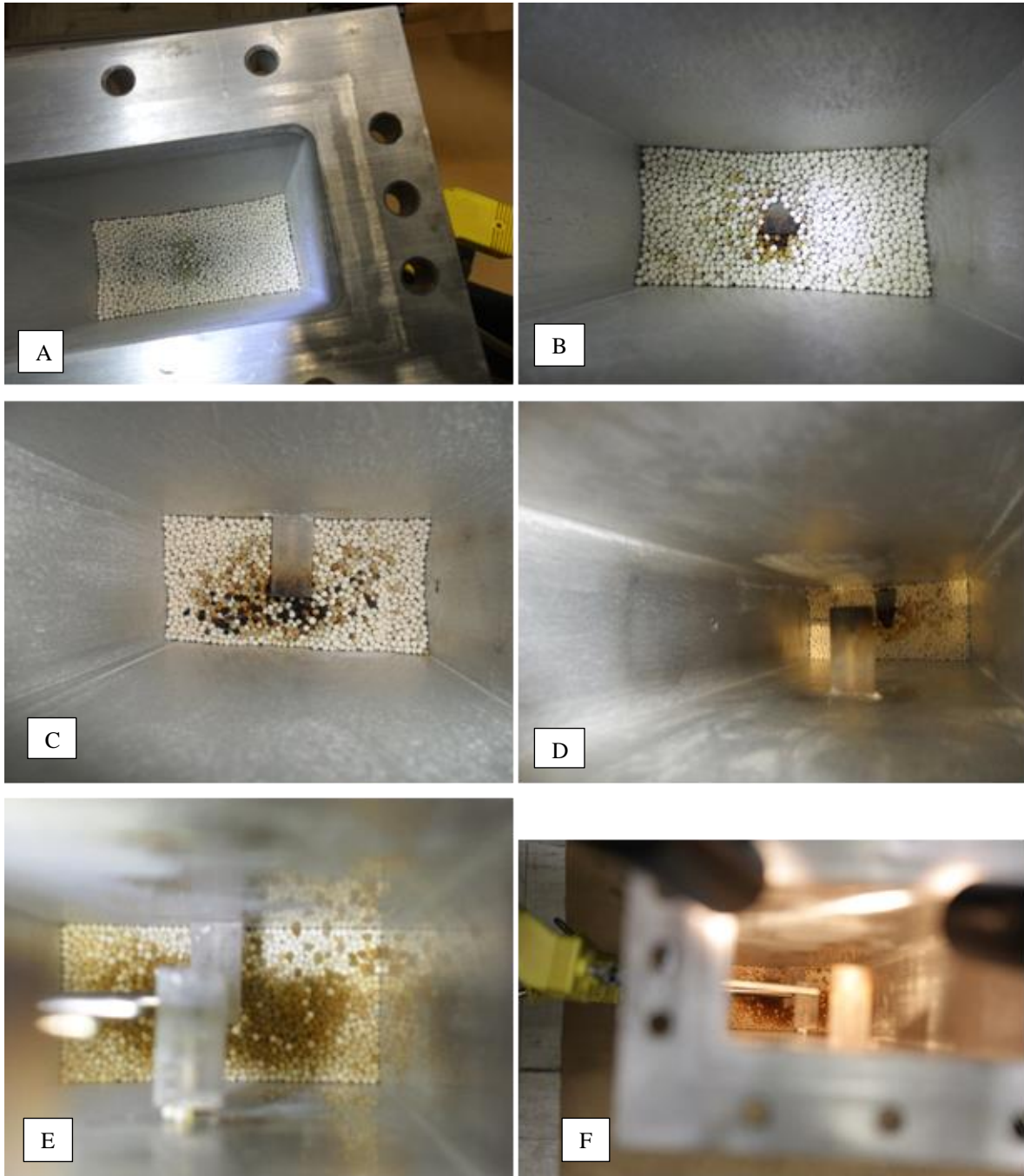


Figure 6. 13X sorbent media following testing. *The 13X media was gradually removed from waveguide bed starting at the adsorption exit flow end (A) and progressing downwards (A-F) to exposed 3rd antenna quartz sleeve (F).*

media, predominantly down the center of the bed, may potentially explain the elevated baseline, with yet unchanged adsorption duration observed in the final five Wet adsorption cycles. Figure 7 shows a micrograph of two bisected discolored beads of 13X sorbent. The discoloration is clearly distributed throughout the bead and is not just a surface phenomenon, which suggests a potential bulk change in sorbent characteristics. If the carbon on the 13X media serves to block a significant portion of the adsorption surface area, then a reduced capacity for adsorption will clearly result. This reduced capacity media surrounded by restored capacity media existing down the length of the bed will effectively act as a bypass flow for the contaminant loaded hydrogen stream. As such, as the bypass flow valve is first

turned to the sorbent bed a slow gradual drop to an elevated baseline would be expected since a portion of the influent stream survives to the end of the bed and mixes with the purified portion of the stream (assuming unmixed laminar flow conditions) and eventually results in an elevated baseline level. The time to breakthrough, however, can be expected to remain essentially unchanged since the fully restored perimeter media capacity remains unchanged and still sees the same influent contaminant level throughout adsorption and as such will require the same amount of time to reach capacity.

Despite a variety of anomalous operating fluctuations and the formation of carbon within the 13X media this set of sequential adsorption/desorption experiments has successfully demonstrated the feasibility of using microwave induced thermal-vacuum techniques to desorb contaminants from 13X sorbent media that had been earlier used to purify a hydrogen stream emanating from a PPA. The formation of carbon should be easily mitigated by operation at lower microwave power levels for the first part of the desorption cycle and then ramping to even higher power levels than those used in this testing for the latter part of the cycle. Alternatively, wider diameter quartz sleeves could be used to effectively lower (via $1/r^2$ distance drop off) the intense microwave power flux; here a 50% increase in diameter would result in an additional 56% drop in intensity at the quartz sleeve/13X media boundary. Yet another approach would be to further distribute microwave power within the media thereby achieving lower local power levels by use of additional antennae (say 6 or 8 total vs. the 4 currently employed). Combinations of each of these approaches and more would need to be explored in future advanced development work. It would be logical to not only refine the bed design and desorption cycle for optimal efficiency, but to also investigate scaling the 13X bed and more generally the MRSHP system design to accommodate a full 4-CM capacity PPA effluent.



Figure 7: Micrograph of bisected discolored 13X sorbent beads.

IV. Architectural Options

Various architectures for hydrogen separation technologies to be used in conjunction with the PPA were presented and discussed in Ref. 2. The primary PPA system architecture currently being considered by NASA for integration with the ISS life support system, and ultimately for exploration systems, is shown schematically in Figure 8.

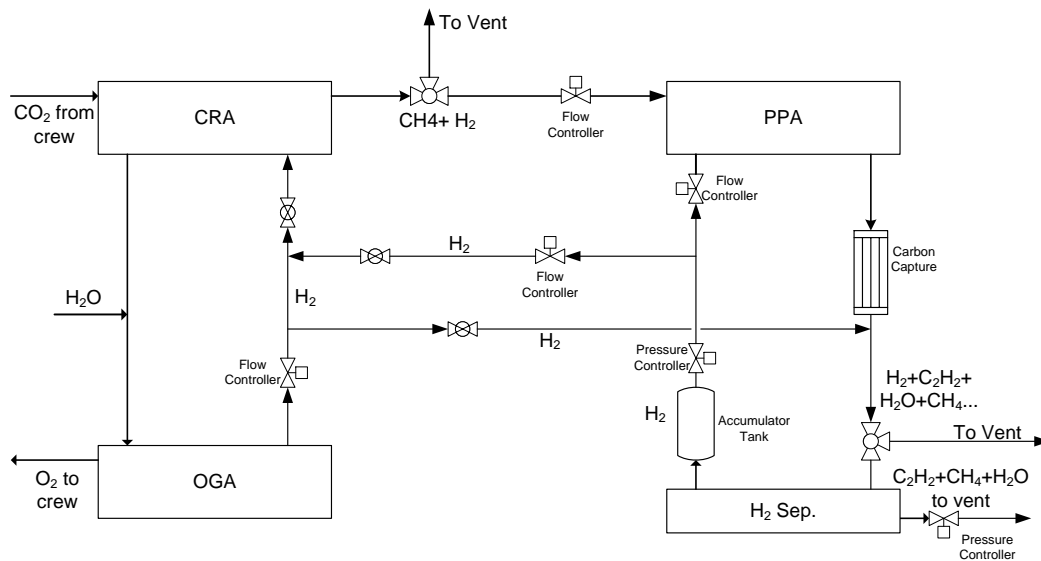


Figure 8: Proposed PPA system architecture.

This architecture reflects the use of an electrochemical cell stack to carry out the hydrogen separation step. While the MRSHP has demonstrated its potential as an effective hydrogen separator its use would add a number of complexities to the system architecture. The use of any zeolite sorbent-based system in an architecture similar to this would necessitate the use of an upstream desiccant to remove water vapor and a compressor, since the PPA reactor is expected to operate at 110 torr, to bring the feed stream up to a pressure where the sorbent can be effective and to charge an accumulator. The electrochemical cell stack has no issue with water vapor and could supply purified hydrogen at the necessary system pressure without the use of an additional compression step.

A flight experiment on the ISS is the next logical milestone for demonstrating the PPA methane post-processing architecture but an ISS flight experiment presents a number of challenges. Included among these challenges are the necessarily tight physical and operational coupling with critical ECLSS assemblies in the Oxygen Generation System rack, the additional volume of combustible hydrogen necessary for the accumulator, and the perceived risks of flying a high powered microwave induced plasma in a habitable volume.

The PPA could be flown and demonstrated by flying a supply of compressed methane and hydrogen; however, this would severely limit its operation time, raise questions about the behavior of the PPA system with the “real” methane mix coming from the Sabatier reactor, and pose its own challenges by necessitating the flight of large volumes of combustible gases.

The accumulator volume and required system operating pressures are currently under investigation at NASA MSFC. A test is planned to start later this year to demonstrate and evaluate this architecture. Of primary interest is minimizing the accumulator volume and pressure. Ideally, it will be possible to operate the system entirely at sub ambient (1 atm) pressure. This would mitigate any concerns of combustible gas leakage into the cabin environment since any leakage that occurred would push air into the system instead of pushing combustibles out.

There have been concerns expressed about crew exposure to microwave radiation. The PPA makes use of a substantial microwave power system to produce methane/hydrogen plasma. During normal processing at a 4-CM rate the PPA applies ~800 W of microwave power to the plasma. However, because of the use of effectively sealed microwave system components the emitted microwave radiation from the PPA is substantially less than a cell phone during a call.

While there are a number of challenges associated with flying a PPA on the ISS they are largely manageable and the rewards of developing and demonstrating advanced ECLSS far outweigh the challenges. In addition to providing a demonstrated solution for oxygen recovery requirements for an exploration system architecture there are other benefits to a PPA flight demonstration, most notably a net financial benefit. The cost of such a flight demonstration would not be insignificant but over a three year period of operation could save the ISS program over \$83M (assuming PPA operation at a 4-CM rate and the current resupply cost of \$68K/kg) in water resupply costs.

V. Conclusion

Over the past two years four different hydrogen separation technologies (two Sustainable Innovations (SI) electrochemical cell stacks, the metal hydride, and the MRSHP; see Ref. 2 for discussion of the SI cell stack testing) have been evaluated at MSFC. While both the MRSHP and the SI cell stacks show the potential to meet the requirements for a hydrogen separator in a PPA system architecture, NASA’s planned testing and development will focus on the use of electrochemical cells because of the simplified system architecture that they provide. A fully integrated test with the PPA, OGA, and CRA, including a hydrogen recycle loop, is planned for 2017. While there are substantial challenges associated with it, a flight demonstration on the ISS is the next logical step for the PPA architecture. Not only would a flight demonstration help to substantially improve the maturity of AR ECLSS it also has the potential to save the ISS program over \$83M in water resupply costs.

Acknowledgments

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