A Two-Stage Regenerable Filter for Collection and Disposal of Carbon Fines

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NASA is investigating the use of the Plasma Pyrolysis Assembly (PPA), which is a methane post-processing technology with the goal to recover hydrogen from the Carbon dioxide Reduction Assembly (CRA) currently onboard the International Space Station (ISS). The PPA can theoretically recover 75% of hydrogen from methane produced by the CRA. During methane processing the PPA creates roughly 40 mg/hr of carbon dust when operating at 4 crew member levels. The unwanted fines need to be removed from the stream to prevent any clogging of downstream components. The Regenerable Carbon Filter (RCF) was designed by Umpqua Research Company to address the carbon particulate created in the PPA. The RCF includes two stages. The first is an electrostatic precipitator designed to collect ultrafine particles. The second is a low pressure drop physical filter. Both filters are made of heat tolerant materials to allow regeneration of the filtration capacity by O_2 oxidation of captured carbon. This paper will discuss the RCF hardware and test plans.

Nomenclature

CM	=	crew member
CRA	=	Carbon Dioxide Reduction Assembly
ESP	=	electrostatic precipitator
GC-MS	=	gas chromatograph – mass spectrometer
HEPA	=	high efficiency particulate air filter
ISS	=	International Space Station
MSFC	=	Marshall Space Flight Center

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PPA = Plasma Pyrolysis Assembly
RCF = Regenerable Carbon Filter
SBIR = Small Business Innovation Research
SLPM = standard liters per minute
URC = Umpqua Research Company

I. Introduction

ENVIRONMENTAL control and life support technologies for future long term space missions will require a higher level of efficiency, reliability and robustness than current state-of-the-art technologies utilized for Low Earth Orbit missions that benefit from periodic resupply. Currently, on the International Space Station, the Carbon Dioxide Reduction Assembly (CRA) utilizes a Sabatier reactor to recover 50% of oxygen as water from metabolic carbon dioxide.[1]

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$$

NASA is targeting technologies that can increase the oxygen recovered to a minimum of 75% with a target goal of 90%. One way to achieve additional oxygen recovery is to utilize a methane post-processor to liberate and recycle the hydrogen in the methane being vented overboard by the CRA. For this purpose, NASA has been exploring the use of a Plasma Pyrolysis Assembly (PPA). The PPA was designed by Umpqua Research Company (URC) and has been undergoing ground testing. In a hydrogen rich flow (approximately 8 SLPM at 110 torr), the plasma converts methane to acetylene, theoretically recovering 75% of the hydrogen that would be lost with venting of the methane.[2]

$$2CH_4 \rightarrow C_2H_2 + 3H_2$$

In the course of the dehydrogenation of methane, a small amount of residual solid carbon is formed that coats the plasma-locating stubs and inner walls of the PPA. Operating the plasma system under a carbon dioxide-atmosphere is used to remove the surface coatings. During nominal 4-crew members (4-CM) flow rate operation, approximately 0.04g/hr of carbon particulate is generated. These carbon fines escape the reactor and pass downstream. The solid carbon that escapes downstream typically accounts for less than 0.2% of reacted carbon from the PPA. These ultrafine carbon particles (100-200 nm) must be captured to avoid clogs, shorting or other carbon-based fouling in the downstream systems.[3]

Multiple efforts have been made to capture this nuisance carbon to maintain the system in running condition with only short periods of regular maintenance. These systems were conceived to use carbon dioxide to oxidize the trapped carbon fines to return their filtration capacity.

$$CO_2 + C \rightarrow 2CO$$

In the past the goal was to match the carbon dioxide oxidation cycle of PPA plasma-locating stubs. The PPA typically will operate for 6-8 hours before needing to be cleaned, which takes about 30 minutes to complete. Porous ceramic and porous metal filters have been used as the filter material elements to allow for multiple regular heating cycles in the range of 600-750^{o}C.[4,5,6] Carbon dioxide is a byproduct and an available oxidizer that does not require processing to recover or additional effort to separate. However, oxygen will make for faster filter regeneration and return to operation.

In this paper, URC developed the Regenerable Carbon Filter (RCF) under an SBIR Phase II contract to capture carbon fines from the PPA.

II. Hardware Description

The RCF has been designed without use of traditional filter media. The first unit is an electrostatic precipitator (ESP) and a second unit is loosely packed with layers of high temperature resistant material to catch most of the carbon that passes through the ESP. Both units were designed to keep pressure drop low and to survive oxidation regeneration temperatures.

The RCF ESP, illustrated in figure 1, centers around a corona wire consisting of a central 2-strand twisted Nichrome electrode that under high voltage generates ions from the surrounding gas. This electrode is modified with 0.63 cm

long platinum wires mounted perpendicularly through the top 3.3 cm of the central twisted wire. The 2-strand spine lends added strength to the design while the "bottle brush" platinum wires lower the supply voltage required to initiate the corona. An electric potential of approximately -2000 V is used to generate the corona ions.

As shown in figure 1 by the wavy black arrows, the hydrogen/acetylene effluent from the PPA carried the carbon fines through the top of the main RCF reactor into a plenum. The gas flow is distributed through multiple ports in the insulation around the ESP electrode (purple line). Carbon fines travel through the corona field where the ion charge is transferred to the particles. The gas flow moves out radially through the outer collection mesh and then through the quartz wool which is loosely packed above the gas exit ports.

During PPA operation, a hydrogen sweep gas flows up an alumina channel along the length of the corona wire to keep it free from interfering collected particles. The charged ions are accelerated axially through an accelerating mesh towards a second collecting mesh (straight purple arrows in figure 1 illustrate the path taken by the corona-formed charge). En route, the ions interact with and transfer charge onto nuisance carbon particles. The particles are then attracted to the oppositely charged outer collector mesh where the charge is dissipated and they are held by molecular forces until regeneration. Any remaining carbon fines must then pass through loosely distributed quartz wool where the high surface area provides an additional capture opportunity before exiting this filter. Initial tests showed that this filter alone captures approximately 80% by weight of the carbon created by nominal PPA operation over an 8 hour test.

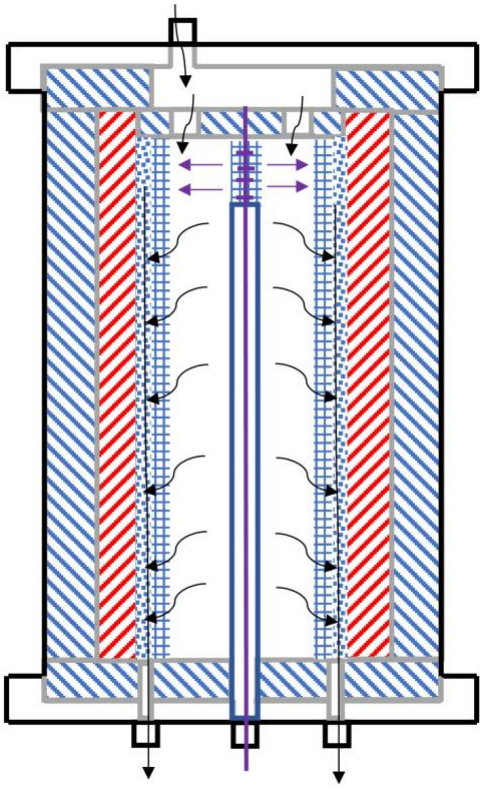

Figure 1. Diagram of main Regenerable Carbon Filter. Parts of the RCF starting at the left side and working to the middle: Stainless steel reactor wall (thick black line), Ceramic insulation (\ \-blue hatched boxes), Heating element (/ /-red hatched boxes), Quartz wool (fluffy gray area), Outer collector mesh (blue cross-hatched area), Alumina hydrogen channel (thick blue box), Accelerating mesh (blue cross-hatched area on top of the alumina hydrogen channel), Corona electrode (purple center line, with bottle brush at top). The thin black wavy flow arrows illustrate the passage of hydrogen/acetylene mix containing carbon particles during PPA operation/filter loading. The straight purple arrow illustrate the passage of ion charges moving from the corona electrode, through the accelerating mesh to the outer collector mesh.

To address this small amount of carbon fines that remain entrained in the air stream, a second After Burner reactor was added downstream of the main RCF reactor. This unit is based on layering progressively more compact refractory fibers over each other to allow most of the carbon material to collect by depth filtration on loose fibers that are

encountered first. This allowed for a small change in pressure drop, as the carbon particles deposit on loose wool before encountering the finer pores of the ceramic blanket and finally paper. This was achieved by layering quartz wool over 4 pound per cubic foot (64 g/L) Fiberfrax Durablanket-S over Fiberfrax 970J Ceramic Paper over a Nichrome mesh tube for support. Test loadings of the After Burner without the RCF in line, resulted in approximately 2% by weight of expected PPA-produced carbon being collected on a downstream HEPA filter, meaning that on its own for a short period, the After Burner captured about 98% by weight of the PPA-produced carbon fines.

Approximately 8 hours of PPA operation will occur before the PPA requires regenerations. The PPA will be regenerated with the carbon dioxide-rich mix, which also serves to flush the RCF volume of combustible gases. Regeneration of the RCF and After Burner under the same oxygen flow will follow. During the PPA regeneration, separate heaters in both RCF reactors will be heated to the desired temperature; 750ºC has been used to make both reactors visibly clean. Initial tests show that carbon oxidation in the main RCF reactor with two times the stoichiometric required oxygen at 110 torr (14.6 kPa) and 750ºC for 20 minutes removed all visible carbon from the inside of the reactor. This gas flow will be the initial condition tried for regeneration of both reactors simultaneously.

III. Hardware Integration

The RCF was delivered to NASA Marshall Space Flight Center for integration with the ground-based engineering PPA 4-CM unit. The technology is housed Environmental Control and Life Support (ECLS) Test Facility. More specifically, the PPA and RCF have been integrated into the Exploration Chamber for test. It is in the process of being integrated into the automated operational interface. Safety checks and reviews focus on the new hardware but also the changeover to oxygen as the regenerative oxidizer from carbon dioxide. Initial leak checks and powering up have been done to confirm that the equipment survived transport and was reassembled properly.

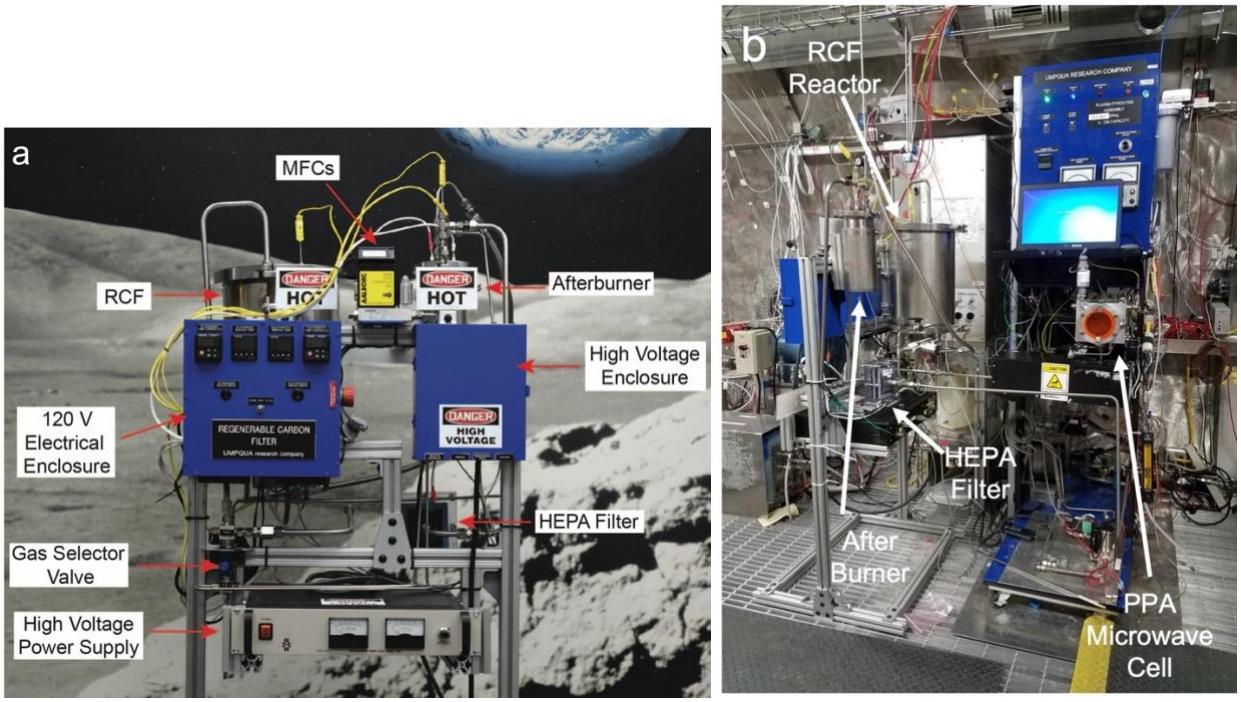

Figure 2. Images of the RCF installed at MSFC next to the PPA. a) Control panel for reactor heaters and power system. b) The back of the RCF attached to the PPA. Both RCF reactors are shown.

IV. Future Work

Once the RCF is fully integrated with the PPA, tests will begin. The PPA/RCF system will be operated at full 4-CM flow rates. The PPA baseline operation is already well characterized. The system will be run on bottled gas inputs until the PPA power rise indicates a need for regeneration or the pressure drop across the RCF filter rises too high. Loading of the RCF will be monitored for change in pressure drop. During regeneration, active oxidation will be monitored by GC-MS sampling of effluent gas – carbon dioxide production will show successful oxidation of

carbon and when the process has been completed. Over multiple cycles, performance will be compared – both pressure drop and regeneration gas – to determine how the system works under prolonged operation and different conditions. A HEPA filter placed at the downstream end of the RCF will be opened and weighed to measure how much carbon breakthrough has occurred to allow evaluation of continued operation of the RCF. Conditions necessary to regeneration will be varied – including oxidation flow, pressure, temperature and duration.

Acknowledgments

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