Testing and Results of Vacuum Swing Adsorption Units for Spacesuit Carbon Dioxide and Humidity Control

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A principal concern for extravehicular activity (EVA) spacesuits is the capability to control carbon dioxide (CO_2) and humidity (H_2O) for the crewmember. The release of CO_2 in a confined or unventilated area is dangerous for human health and leads to asphyxiation; therefore, CO_2 and H_2O control become leading factors in the design and development of the spacesuit. An amine-based CO_2 and H_2O vapor sorbent for use in pressure-swing re-generable beds has been developed by Hamilton Sundstrand. The application of solid-amine materials with vacuum swing adsorption technology has shown the capacity to concurrently manage CO_2 and H_2O levels through a fully regenerative cycle eliminating mission constraints imposed with non-regenerative technologies.

Two prototype solid amine-based systems, known as rapid cycle amine (RCA), were designed to continuously remove CO_2 and H_2O vapor from a flowing ventilation stream through the use of a two-bed amine based, vacuum-swing adsorption system. The Engineering and Science Contract Group (ESCG) RCA implements radial flow paths, whereas the Hamilton Sundstrand RCA was designed with linear flow paths. Testing was performed in a sea-level pressure environment and a reduced-pressure environment with simulated human metabolic loads in a closed-loop configuration.

This paper presents the experimental results of laboratory testing for a full-size and a sub-scale test article. The testing described here characterized and evaluated the performance of each RCA unit at the required Portable Life Support Subsystem (PLSS) operating conditions. The test points simulated a range of crewmember metabolic rates. The experimental results demonstrated the ability of each RCA unit to sufficiently remove CO_2 and H_2O from a closed loop ambient or sub-ambient atmosphere.

Nomenclature

acfm	=	actual cubic feet per minute
Btu/hr	=	British thermal units per hour
^oC	=	degrees Celsius
cfm	=	cubic feet per minute
CO_2	=	carbon dioxide
CRDS	=	Cavity Ring Down Spectrometer
DEV	=	dual end vacuum
ESCG	=	Engineering and Science Contract Group
EVA	=	extravehicular activity

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°F	=	degree Fahrenheit
GN_2	=	gaseous nitrogen
gm/min	=	grams per minute
HS	=	Hamilton Sundstrand
H_2O	=	water vapor
in Hg	=	inches of Mercury
ISS	=	International Space Station
JSC	=	Johnson Space Center
kg	=	kilogram
kmole	=	kilo mole
lpm	=	standard liters per minute
LiOH	=	Lithium Hydroxide
m	=	meter
mm	=	millimeter
MET	=	metabolic
MetOx	=	Metal Oxide
mm Hg	=	millimeters of Mercury
NASA	=	National Aeronautics and Space Administration
O_2	=	oxygen
PLSS	=	Portable Life Support Subsystem
psia	=	pounds per square inch absolute
RCA	=	rapid cycle amine
RH	=	relative humidity
scfm	=	standard cubic feet per minute
SEV	=	single end vacuum
SEV-I	=	single end vacuum Inlet
SEV-O	=	single end vacuum Outlet
SLM	=	standard liters per minute
TA2	=	test article 2

I. Introduction

One of the objectives of the National Aeronautics and Space Administration (NASA) for the next generation spacesuit is to develop a Portable Life Support Subsystem (PLSS) that is human-rated for use in a vacuum environment and a range of temperatures, such as on a meteor or a lunar surface. This advanced spacesuit will be capable of regenerating the environment in terms of carbon dioxide (CO_2) and humidity (H_2O) and will exceed the life expectancy of the current spacesuit. A principal concern for extravehicular activity (EVA) spacesuits is the ability of the PLSS to control CO_2 and humidity H_2O for the crewmember.

Basal metabolic rate is the rate at which heat is given off by an organism at complete rest, or the amount of energy expended while at rest in a neutrally temperate environment. The release of energy in this state is sufficient only for the functioning of the vital organs. As the body becomes more active as required during an EVA mission, the organs begin to function at a more rapid rate, thus increasing the metabolic rate. In conjunction with the metabolic rate increasing, CO_2 and H_2O levels increase within the spacesuit. Since the human body is a very dynamic system (i.e., each individual person exhibits different levels of CO_2 and H_2O at differing rates) the environment in which the subject is exposed to must be controlled. Therefore, CO_2 and H_2O removal become leading constraints in the design and development of the spacesuit. The release of CO_2 in a confined or unventilated area can lower the concentration of oxygen to a level that is immediately dangerous to life, or fatal, for human health.

In the past, spacesuits have used Metal Oxide (MetOx) and Lithium Hydroxide (LiOH) canisters to control CO_2 levels. LiOH is a non-regenerative source, meaning each LiOH canister has a limited onetime, 8- hour use, while the MetOX canisters are regenerated on the International Space Station (ISS). The ISS will not be a regenerative option for future exploration spacesuits. Traditionally, spacesuits have used separate systems to control CO_2 and H_2O levels within the spacesuit. H_2O has typically been collected by a condensing heat exchanger. With advancements in technology, a major goal for the advanced spacesuit is to reduce the overall mass of the PLSS and to increase durability and reusability. Previous spacesuits have experienced approximately

25 EVA hours, but the advanced spacesuit will have the capability of 100 EVA hours with a regenerative system.

Hamilton Sundstrand (HS) has spent many years developing amine-based vacuum-regenerated adsorption systems as alternative CO_2 sorption systems. The current iteration uses a pair of interleaved-layer beds filled with a sorbent material known as SA9T. The SA9T material is a sorbent comprised of plastic beads coated with an amine substrate. An amine substrate is an organic derivative of ammonia formed by the replacement of hydrogen with one or more alkyl groups. SA9T also has an affinity for water vapor and releases adsorbed water vapor. The interleaved bed system also minimizes total suit heat loads due to the adsorption and desorption processes. SA9T technology has proven to be very stable over long periods and is best suited for longer-term missions. This technology has been selected as the baseline primary CO_2 and H_2O removal device for the new spacesuit.

The CO_2 and H_2O control system for an advanced spacesuit PLSS will have to meet very specific and rigorous requirements. These requirements have been created to keep the breathing environment safe for an astronaut during an EVA. Two Rapid Cycling Amine (RCA) prototypes, one designed by Engineering and Science Contract Group (ESCG) and one designed by Hamilton Sundstrand (HS), are currently being investigated as viable systems for controlling CO_2 and H_2O within the spacesuit.

The solid amine-based prototype systems were designed to continuously remove CO_2 and H_2O from a flowing ventilation stream through the use of a two-bed amine based, vacuum-swing adsorption system. The CO_2 and H_2O removal performance criteria are based on scrubbing the expected CO_2 and water vapor generation rates over the range of anticipated metabolic rates for EVA operations. Additionally, the system outlet CO_2 partial pressure is to be maintained at or below the allowable helmet inlet (inhaled) limits established by the current requirement of 6 millimeters of Mercury (mm Hg)[6].

II. System Description

A. Test Article

For the continuous regeneration of a constantly flowing stream, the test article implemented alternating amine beds to adsorb and desorb CO_2 and H_2O. Each RCA unit uses a pair of interleaved-layer beds filled with SA9T within aluminum foam. Since the adsorption of the amine is an exothermic reaction, each layer is fabricated with integral, thermally conductive metallic foam elements to enhance the heat transfer between adjacent layers.

The adsorption reaction of the amine bed is exothermic. Implementing the solid amine technology requires some method for managing thermal loads because of the adsorption reaction. To maximize CO_2 removal, the sorbent must be maintained at a constant temperature; thus removing the heat of adsorption. Conversely, the desorption reaction is an endothermic reaction, thus the desorbing bed must be heated sufficiently to desorb the CO_2 from the amine. To keep a constant reaction temperature within the RCA, the test article is built with a series of adjacent sorbent sections that alternate between adsorption and desorption zones; as a result, the heat from the adsorption reaction is transferred to the desorption reaction.

Each RCA unit is comprised of an interleaved, two-bed, four-layer design; however, the HS RCA is a full-scale, linear flow rectangular unit, while the ESCG TA2 RCA is a sub-scale, radial flow unit as shown in Figure 1. The actual ESCG TA2 RCA full-scale design will consist of a two-bed with approximately 10 layers. Each prototype solid amine-based system was designed to continuously remove CO_2 and H_2O from a constantly flowing ventilation stream through the use of a two-bed amine based, vacuum-swing adsorption system. While one set of sorbent layers was exposed to the ventilation stream to remove both CO_2 and H_2O (adsorb), the other set of beds is regenerated by exposure to vacuum (desorb). Upon exhaustion of the capacity of the adsorbing bed, a valve mechanism is actuated to divert the ventilation flow stream to the desorbed bed while simultaneously exposing the exhausted sorbent bed to vacuum for regeneration. This alternating process continued for the duration over which the system was required to operate.

While the HS RCA was a full scale implementable prototype, the ESCG TA2 RCA was an experimental design test article to be used primarily to investigate the effects of a radial flow path in comparison to a linear flow path. Therefore, the ESCG TA2 RCA was not designed with a valve system to alternate the flow path between adsorbing beds nor with a vacuum source for the desorption configuration. Consequently, the ESCG RCA test team was tasked with designing and implementing a valve system that would alternate the flow between adsorbing beds while exposing the desorbing bed to an ultimate vacuum source. The ESCG RCA test team implemented a set of eight ASCO 8210 series valves to control adsorption and vacuum desorption configurations of the ESCG TA2 RCA. ASCO series 8210 valves are 2-way normally closed internal pilot solenoid valves designed for low pressure service.

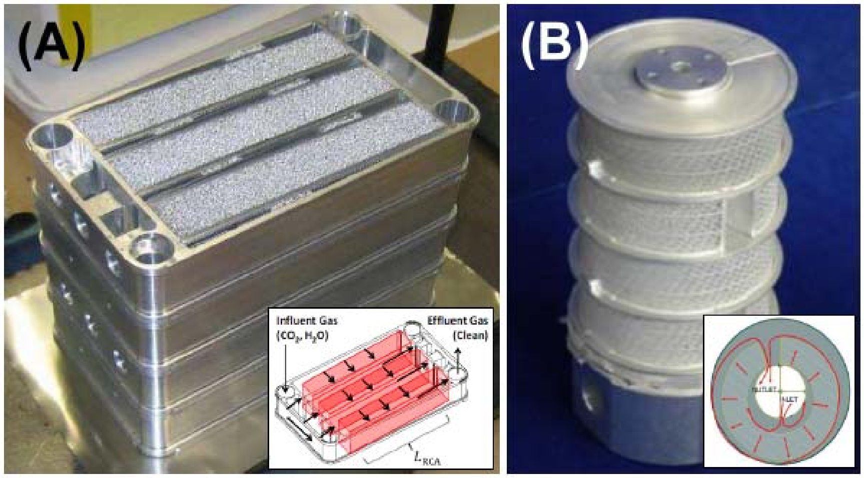


Figure 1. Hamilton Sundstrand Rectangular RCA Unit (A) and Engineering and Science Contract Group Cylindrical RCA Unit (B)

B. PLSS Ventilation Test Loop

Construction of the PLSS Ventilation Subsystem Test Loop, shown in Figure 2, was based on a re-circulating closed loop test system. The system was designed to integrate all required instrumentation to analyze the performance of each RCA test article while providing the proper system volumetric flow rate and metabolic CO_2 and H_2O injection rates. The system setup allowed for the collection of CO_2 concentration and relative humidity data immediately before and after the test article while collecting the system volumetric flow rate immediately prior to the test article. This allowed for analysis of removal rates of each of the constituents to be calculated based on the test article.

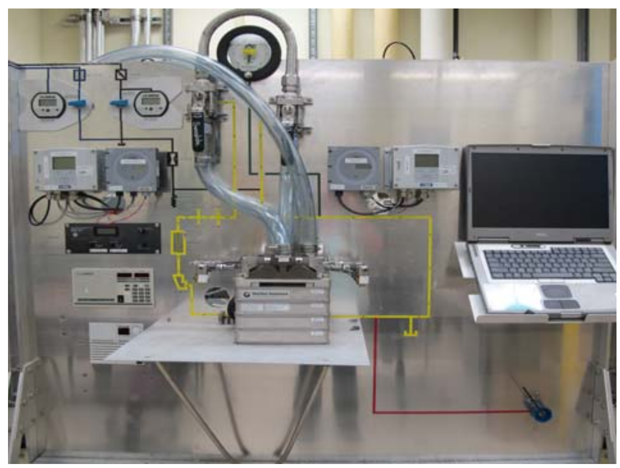


Figure 2. PLSS Ventilation Test Loop with the Hamilton Sundstrand RCA unit

The PLSS Vent Loop was constructed with 25.4 mm [1-inch (in.)] stainless-steel piping configured in a rounded rectangular loop with a total loop volume of approximately 2.4×10^{-3} m.^{3} (144 in.^{3}) The loop was configured with minimal fittings and connectors to reduce leak paths and to ensure maximum flow through the test article. The PLSS Vent Loop was connected to the Gas Console via ¼” Teflon coated flex hoses. The test article was interfaced with the PLSS vent loop via vacuum rated tubing.

There are two operational modes of the PLSS Vent Loop: test and bypass. The test mode was configured to provide the entire system flow rate through the test article and can be adjusted by two three way valves prior to the test article. By adjusting the three way valves in the bypass configuration, the PLSS Vent Loop can be operated bypassing the test article and allowing the entire system flow rate through the bypass loop. The bypass mode allowed for sensor evaluation while keeping the integrity of the test article.

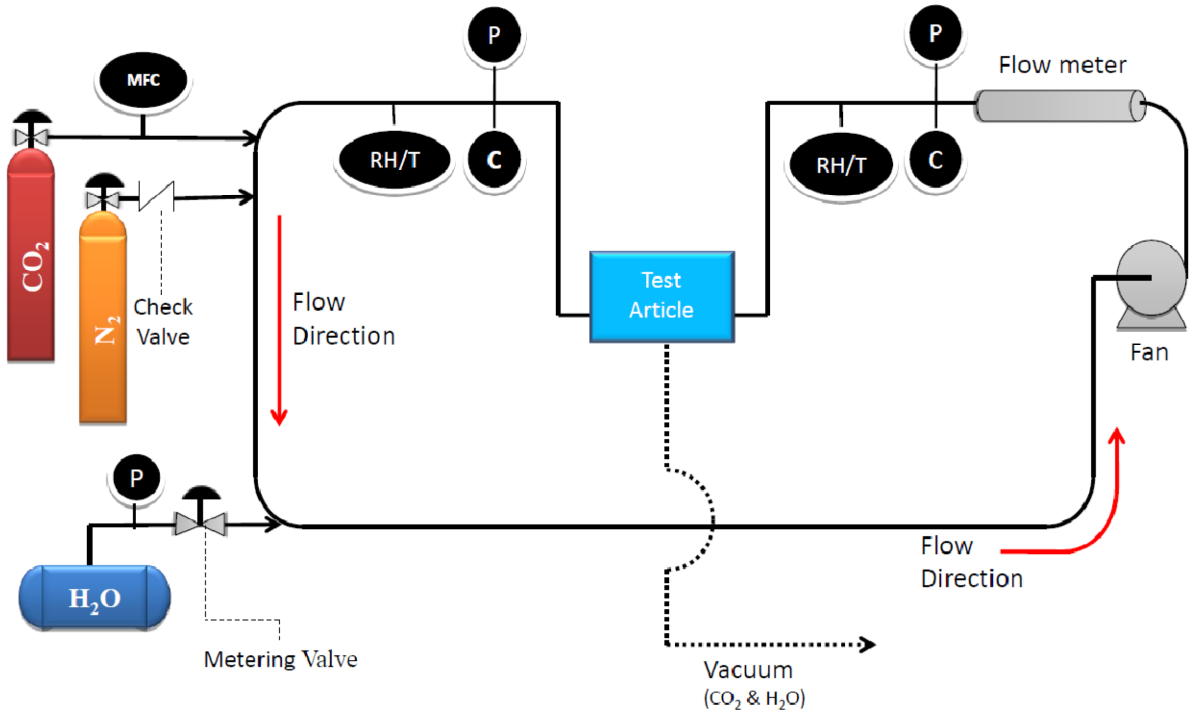


Figure 3. Schematic of PLSS Ventilation Test Loop

C. Test Loop Interfaces and Controls

The PLSS Ventilation Test Loop interfaced with facility gaseous nitrogen supply (GN_2) and a gaseous CO_2 supply via the Gas Console shown in Figure 4. The test loop was also integrated with a subsystem vacuum pump to provide the suitable reduced pressure test conditions for each test case. The facility GN_2 supplied the test loop with dry GN_2. Upon the cycling of the test article; the facility GN_2 supplied ullage lost due to the desorption process. For sub-atmospheric cases, the connection to facility GN_2 was regulated through a sub-atmospheric regulator. The subsystem vacuum pump drew the system pressure down to the desired operating pressure. CO_2 was injected into the test loop and controlled using a mass flow controller via LabVIEW.

Figure 4. Utility Vacuum Chamber (Left) and Gas Console (Right)

To simulate ultimate space vacuum, the Utility Vacuum Chamber (UVC) was designed. The UVC, shown in Figure 4, maintained a 100 milli-torr pressure (10^{-3} psig) for the desorption process. This allowed for the test article to be interfaced with a simulated ultimate space vacuum environment thus allowing for the desorption process to take place. The volume of the chamber was large enough to negate the effects of interfacing test articles at ambient pressure and maintain a relative constant pressure within the UVC. The interface between the UVC and the test article was supplied via vacuum rated flexible tubing.

D. Instrumentation

The system instrumentation was composed of multiple sensors to measure the CO_2 concentration, relative humidity, pressure and temperature at the inlet and outlet of the test article while measuring system flow rate at the inlet of the test article. All of these conditions were constantly monitored and recorded to ensure that the test conditions required were successfully implemented. Relative humidity and temperature were measured with a Vaisala HMT221 probe to maintain humidity injection rates and to monitor the outlet dewpoint of water. Flow rate was measured using a Teledyne Hastings HFM-200 with a laminar flow element upstream of the test article. Pressure was measured upstream and downstream of the RCA using Omega 0-1292 mmHg (0-25 psia) pressure transducers. The data acquired through the various sensors were recorded and displayed in a LabVIEW program. Data was taken at a 1 Hz frequency and recorded in a text file. Live data was monitored on a computer screen via display boxes or graphs to view trends within the test series.

CO_2 analysis was provided both upstream and downstream of the RCA by Vaisala GMT-221 in parallel with a Picarro Cavity Ring Down Spectrometer (CRDS) Real Time Gas Analyzer. These two instruments in parallel were able to measure partial pressures of CO_2 at reduced pressure while providing the opportunity to investigate the effects of a reduced pressure environment on the Vaisala CO_2 sensors. The Picarro CRDS sample lines were connected upstream and downstream of the RCA to allow for inlet and outlet concentrations to be monitored during test while maintaining the integrity of the test environment.

E. Metabolic Simulation

During an EVA mission, the crew member works at varying metabolic rates, thus producing constantly changing levels of CO_2 and H_2O. For each metabolic load, the corresponding CO_2 and H_2O injection rates were calculated and can be found in Table 1 below. A Reimers Electra Steam Boiler was used to simulate the human production of exhaled water vapor and sweat. The boiler turned liquid water into steam to allow for injection vapor phase water into the flowing gas stream. The boiler was operated at the maximum allowable working pressure of the boiler, 4897 mmHg (80 psig), to ensure the highest quality steam was produced. To ensure the steam remained in the vapor phase when transitioning from the boiler pressure to the test system pressure, a high temperature vaporizing regulator was implemented downstream of the boiler prior to the metering valve. The resulting steam was controlled at a metered rate to achieve the desired humidity injection rate, and the steam was injected directly into the re-circulating test loop. The H_2O was injected at an in-line location to reduce the condensate produced within the loop. Carbon dioxide injection was controlled via a Teledyne Hastings mass flow controller to allow for accurate injection rates from a pressurized gas console.

The testing encompassed the majority of operational EVA suit conditions during space flight missions. All single metabolic rate test cases were performed until cyclic steady state conditions were achieved, as indicated by a stable and accurate CO_2 and H_2O removal profile was achieved and approximately constant time between cycles.

Table 1. Simulated Metabolic Test Conditions

Test Case	Simulated Metabolic Rate	CO_2 Injection Rate (HS)	CO_2 Injection Rate (TA2)	H_2O Injection Rate (HS)	H_2O Injection Rate (TA2)
	BTU/hr	slm	slm	g/min	g/min
1	350	0.271	0.1084	0.60	0.24
2	520	0.402	0.1608	1.02	0.41
3	850	0.658	0.2632	1.13	0.45
4	1000	0.774	0.3096	1.44	0.57
5	1250	0.967	0.3868	1.59	0.64
6	1600	1.238	0.4952	1.36	0.54
7	2000	1.548	0.6192	1.29	0.51

F. Test Article Flow Rate

The flow rate through the RCA test article was controllable within a range of volumetric flow rates, depending on the simulated metabolic rate desired. The system fan was sized to overcome the pressure drop introduced by the mechanical design, instrumentation and test article interface. The instruments to measure the CO_2 concentration, system temperature and relative humidity were insertion probes; thus requiring the probes to be inserted directly into the flow stream while the system flow rate was measured using a laminar flow element. The remaining instrumentation was interfaced with the test loop via mechanical crosses and taps.

III. Performance Testing and Analysis

Each RCA test series included a sequence of representative EVA operational scenarios. Baseline cases for various metabolic loads were run at ambient pressure and 6 ACFM system flow rate to provide a standard for comparison with the analysis performed at HS and to be continued throughout all the remaining test articles[1]. Recommended operating parameters for each metabolic load were developed from the results of previous JSC test series and spanned all expected activity levels during an EVA[7]. These were selected to maintain the dew point and CO_2 levels in comfortable and acceptable ranges and to reduce ullage atmosphere loss from the standard air flow rate and pressure. Many of the recommended parameters had been interpolated from actual test results, so in the RCA testing they were validated through testing. Furthermore, all RCA data collected were utilized in the correlation and verification of a NASA developed computer model to be used in the prediction of future operational use[2].

The effects of varying operational flow rates were a major segment of the RCA testing. A phase of testing included the evaluation of various flow rates that could be experienced in the suit; thus facilitating the PLSS flow rate setting optimization. At the current time, the final flow rate for the PLSS is unknown, and this testing will provide data on the performance of the RCA at numerous flow rates which varies the residence time of the gas stream to the media within the RCA unit thus allowing for differing adsorption and desorption rates. Residence time is the average time a particle spends in the system. The HS RCA is a full scale test article thus allowing for actual flow rates of 4.0, 4.5, 5.0, and 6.0 ACFM to be achieved. The ESCG TA2 RCA is $4/10^{th}$ of a full-scale unit; therefore, the flow rates were scaled to allow for identical residence times to be experienced within the testing. The ESCG RCA TA2 was tested at flow rates of 1.6, 1.8, 2.0 and 2.4 ACFM.

The RCA testing characterized the effects of the reconfiguration of desorption flow paths. The HS RCA was evaluated in the DEV configuration only, due to the difficulty of reconfiguring the valve. The ESCG TA2 RCA testing evaluated three vacuum desorption configurations: Single End Vacuum – Inlet (SEV-I), Single End Vacuum – Outlet (SEV-O), and Dual End Vacuum (DEV). Each configuration controlled the desorption flow path of the test article and allowed for comparison of desorption rates of CO_2 and H_2O in the three different configurations.

Finally, several RCA test series were conducted to investigate the effects of reduced pressure on each RCA unit. This investigation consisted of testing each simulated metabolic rate at each flow rate and valve configuration at a reduced pressure of 248 mmHg (4.8 psia). These test conditions more accurately predict the operational suit conditions during an EVA.

A. Baseline Performance Testing

The first phase of testing for each test article was the baseline performance evaluation and characterization of CO_2 and H_2O removal at each simulated metabolic rate case listed in Table 1 above. This phase of testing was repeated for each test article at a residence time of less than one second. The residence time equated to a 170 lpm (6 ACFM) flow rate for the HS RCA and a 68 lpm (2.4 ACFM) flow rate for the ESCG RCA TA2[3-5]. The test conditions simulated an expected environment of the system and was evaluated at ambient pressure, 760 mmHg (14.7 psia), for baseline performance.

B. Data Analysis Overview

To evaluate the various flow rates, the volumetric flow rate of the subsystem was adjusted to represent a potential flow rate of the spacesuit PLSS. The data shows the flow rate effects on the removal of CO_2 and H_2O from the spacesuit system hence allowing for an accurate flow rate to be chosen based on the removal rates of CO_2 and H_2O. The ability to remove CO_2 and H_2O from the process stream while minimizing the ullage loss due to bed cycling defines the effectiveness of the RCA. To analyze the removal of CO_2, there were numerous factors to take into account. For each metabolic rate, there was a different CO_2 injection rate, and for each system flow rate, there was a different residence time within the test article. The inlet and outlet concentrations of CO_2 were analyzed to show the ability of the RCA to remove CO_2 from the process stream. Using the inlet and outlet CO_2 concentration, the amount of CO_2 the RCA removed per cycle was calculated. The inlet and outlet dewpoints were analyzed to show the ability of the RCA to remove H_2O from the process stream. The change in dewpoint temperature from the inlet and outlet of the RCA correlated to the amount of water removed from the process stream.

The half cycle time defines the amount of time it takes for the RCA CO_2 outlet concentration to reach a partial pressure of 6 mmHg. The effect of the CO_2 injection rate is the major contributing factor into the analysis of half cycle times as is the desorption rate of the bed exposed to vacuum. If the RCA is operating identically between each test scenario, then the amount of CO_2 required to make the RCA cycle would be identical; however, this was not observed.

C. HS RCA Data Analysis

a) Dual End Vacuum Configuration

In the DEV configuration under ambient test conditions, the HS RCA maintained an outlet dewpoint below -17.8 ^{o}C (0^{o}F) while the inlet dewpoint was maintained around a mean value of 12.7 ^{o}C (55^{o}F) as a function of the metabolic rate and increased system flow rate (Figure 5). The data suggests that the RCA was able to sustain the outlet dewpoint while cycling on a 6 mmHg CO_2 criteria at all metabolic rates and system flow rates. Concurrently, the data shows the ability of the RCA to remove CO_2 from the flow stream over the varying metabolic rates and system flow rates. The RCA maintained an outlet mean partial pressure of CO_2 less than 5 mmHg at the high metabolic rates while maintaining a mean partial pressure of 3 mmHg at the low metabolic rates as shown in Figure 6.

At cyclic-steady state, the half-cycle time is the time taken to reach an outlet CO_2 partial pressure of 6 mmHg. The half cycle times of the RCA significantly varied between metabolic rates, shown in Figure 7. At a 350 Btu/hr metabolic rate, the RCA half-cycle time was 25 minutes. While at a 2000 Btu/hr metabolic rate, the RCA half-cycle time was 1.12 minutes. Figure 7 shows the half-cycle times were unaffected by the system flow rates, thus showing CO_2 and water removal is independent of flow rate. At 1000 Btu/hr metabolic rate, the half-cycle time was a minimum of 4.04 minutes at 5 ACFM flow rate and a maximum of 4.21 minutes at 4 ACFM flow rate.

Overall, the change in system flow rates and the range of metabolic rates had little effect on the ability of the HS RCA to maintain a 6 mmHg outlet partial pressure of CO_2 throughout the test scenarios. The full-scale HS RCA maintained a lower outlet dewpoint and an increase in cycle times, thus showing the ability to remove more CO_2 from the process stream.

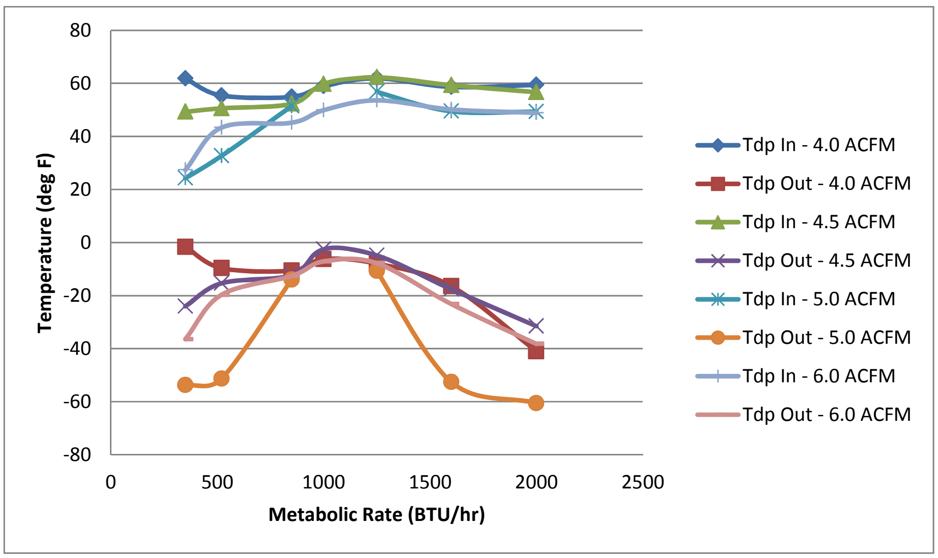


Figure 5. HS RCA DEV Ambient Inlet & Outlet Dewpoint Temperature

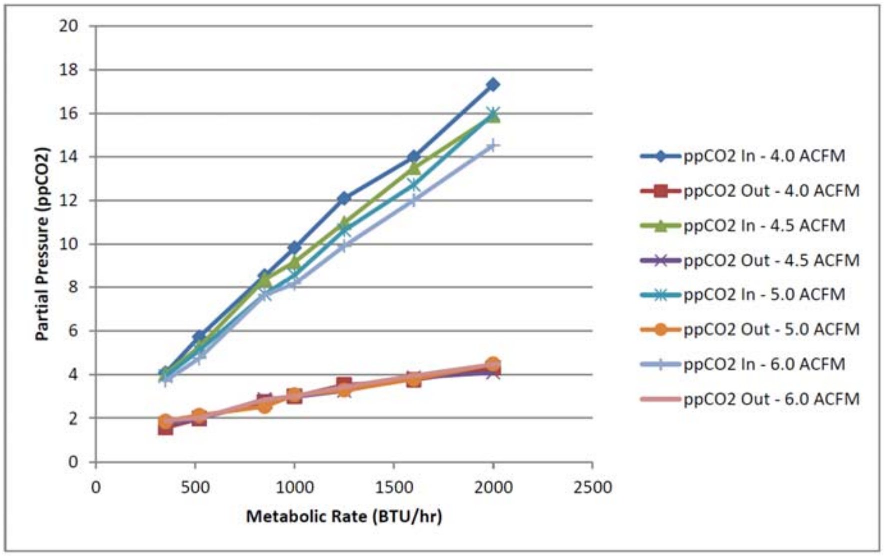


Figure 6. HS RCA DEV Ambient Inlet & Outlet Carbon Dioxide Partial Pressure

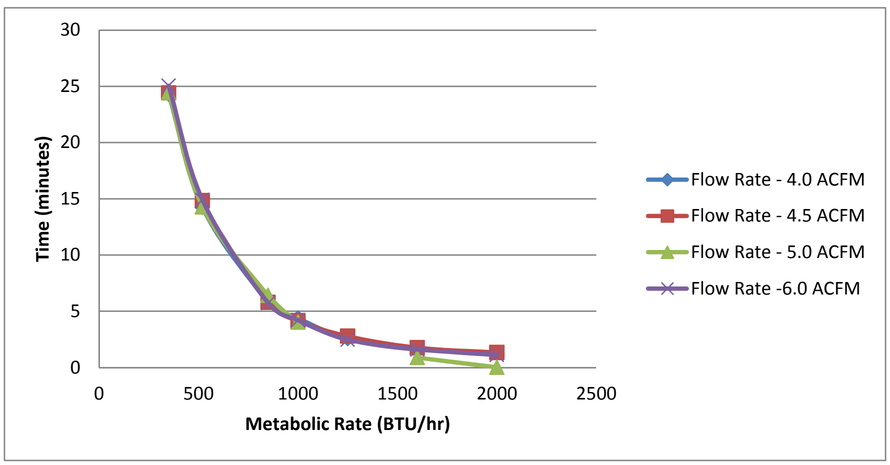


Figure 7. HS RCA DEV Ambient Half Cycle Time

D. ESCG RCA TA2 Data Analysis

a) Dual End Vacuum Configuration

In the DEV configuration under ambient or sub-ambient test conditions, the ESCG RCA TA2 consistently maintained an outlet dewpoint of -8°C ±3°C (17.6 °F ±5.4°F) while the inlet dewpoint increased as a function of the metabolic rate and increased system flow rate (Figure 8). The data suggests that the RCA was able to sustain the dewpoint while cycling on a 6 mmHg CO_2 criteria at all metabolic rates and system flow rates. Concurrently, the data shows the ability of the RCA to remove CO_2 from the flow stream over the varying metabolic rates and system flow rates. The RCA maintained a mean outlet partial pressure of CO_2 at 4 mmHg at high metabolic rates while maintaining a mean partial pressure of 2 mmHg at low metabolic rates, as shown in Figure 9.

The half cycle times of the ESCG RCA in the DEV configuration varied between metabolic rates, shown in Figure 10. At the 350 Btu/hr metabolic rate with a 2.4 ACFM system flow rate, the RCA half-cycle time was 11.0 minutes. While at a 2000 Btu/hr metabolic rate, the RCA half-cycle time was 1.08 minutes. The data suggests that the half-cycle times were unaffected by the system flow rates, thus indicating CO_2 and water removal is independent of flow rate. At a 1000 Btu/ hr metabolic rate, the half-cycle time was a minimum of 2.73 minutes at a 2.4 ACFM flow rate and a maximum of 2.85 minutes at a 1.6 ACFM flow rate.

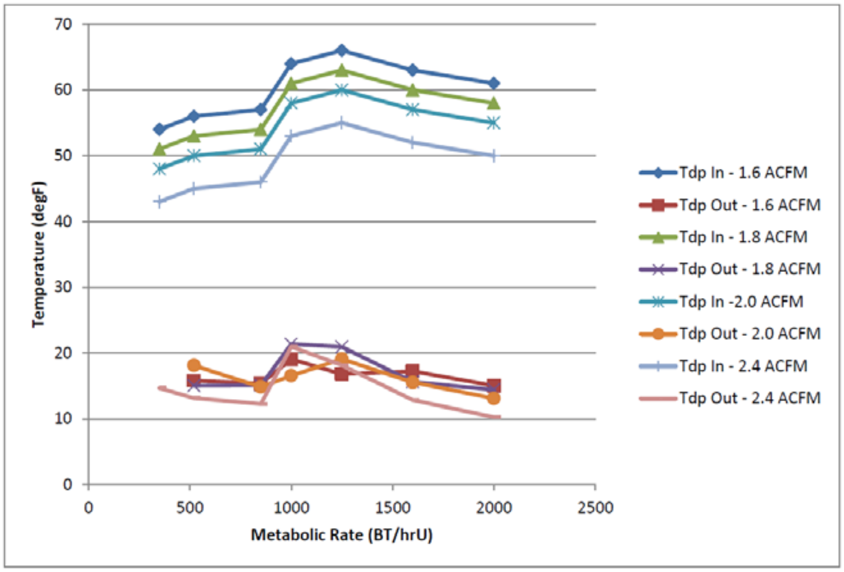


Figure 8. ESCG RCA TA2 DEV Ambient Inlet & Outlet Dewpoint Temperature

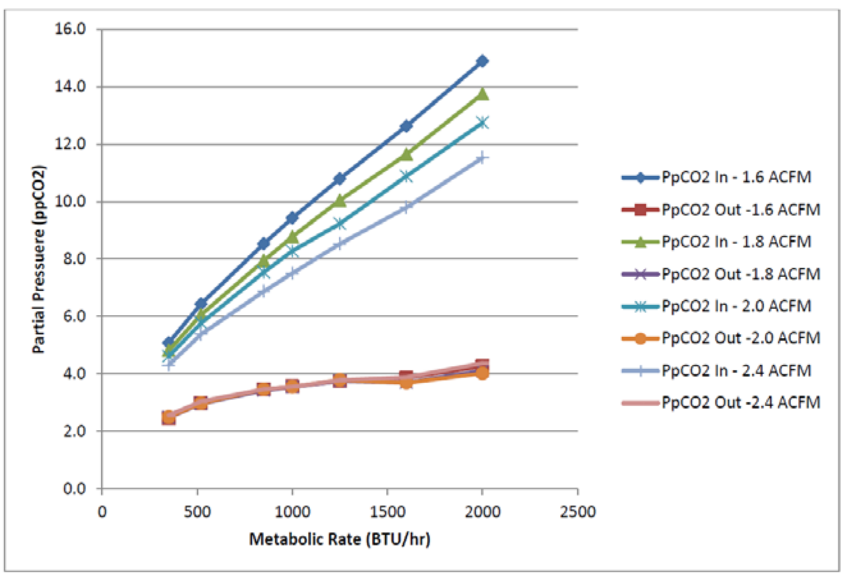


Figure 9. ESCG RCA TA2 DEV Ambient Inlet & Outlet Carbon Dioxide Partial Pressure

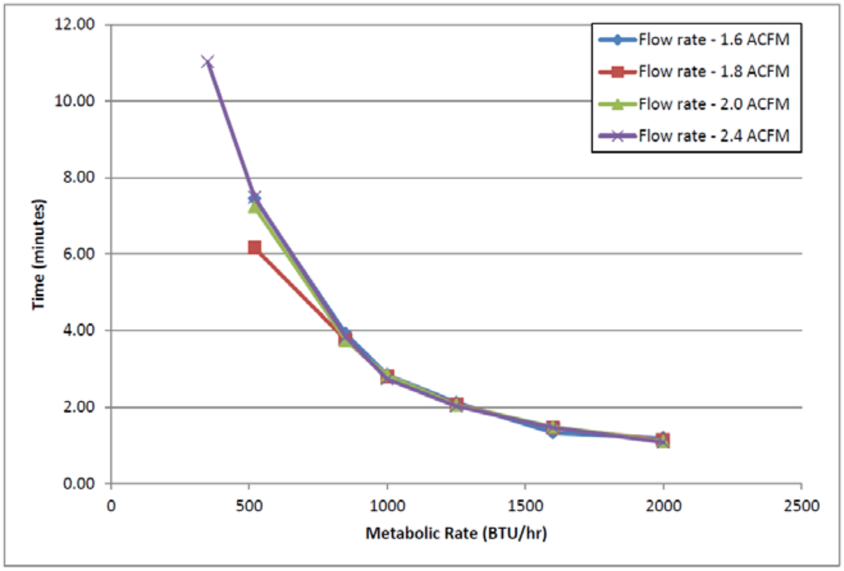


Figure 10. ESCG RCA TA2 DEV Ambient Half Cycle Time

Figure 11 depicts ambient outlet CO_2 concentration for the 1250 Btu/hr. metabolic rate at 2.0 ACFM flow rate, in DEV configuration. The smooth linear trend for CO_2 concentration indicates adsorption taking place, while the significant decrease indicates the switching of the beds. This data is a representation of the expected CO_2 removal performance for all test conditions. The graph shows equal performance between both beds of the RCA based on the similar performance of outlet CO_2 concentration per cycle.

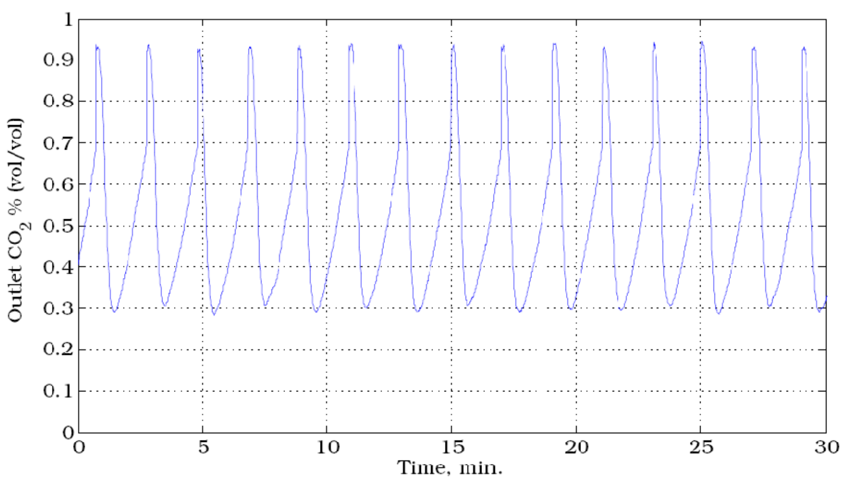
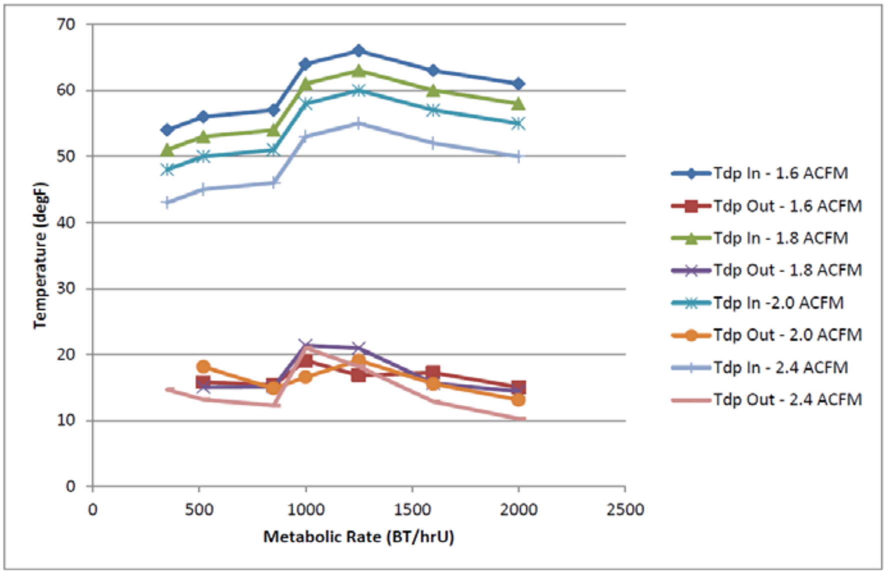
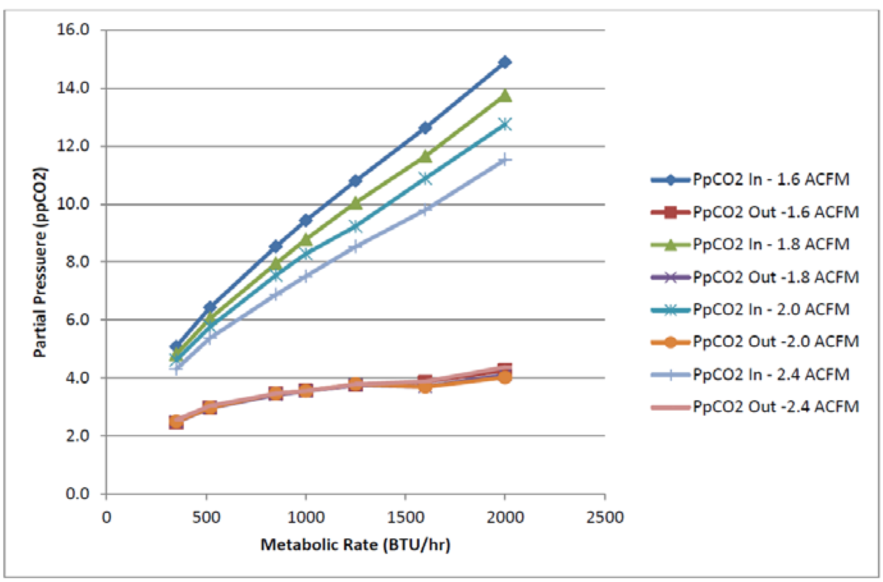


Figure 11. ESCG RCA TA2 2.0 SCFM–1250 Btu/hr Ambient Outlet CO_2 Concentration-DEV

b) Single End Vacuum Inlet Configuration

Similarly, the SEV-I configuration under ambient or sub-ambient test conditions was able to maintain an outlet dewpoint between -15 ^{o}C (5^{o}F) and -3.96 ^{o}C (25^{o}F) while the inlet dewpoint increased from a minimum of 7.2 ^{o}C (45^{o}F) to a maximum of 23.9 ^{o}C (75^{o}F) over the varying metabolic rates, as shown in Figure 12. This data also suggests that the RCA was able to sustain the outlet dewpoint while cycling at 6 mmHg CO_2 for all metabolic rates and system flow rates. Concurrently, the data shows the ability of the RCA to remove CO_2 from the flow stream over the varying metabolic rates and system flow rates. The RCA maintained an outlet partial pressure of CO_2 at 4 mmHg at the high metabolic rates while maintaining an outlet partial pressure of 2 mmHg at the low metabolic rates, as shown in Figure 13.





The half cycle times of the ESCG RCA in the SEV-I configuration varied between metabolic rates, shown in Figure 14. The RCA half-cycle time was 11.1 minutes at the 350 Btu/hr metabolic rate with a 2.4 ACFM system flow rate. While at a 2000 Btu/hr metabolic rate, the RCA half-cycle time was 0.96 minutes. SEV-I data has the same trend as the DEV configurations for half-cycle time. At a 1000 Btu/hr metabolic rate, the half-cycle time was a minimum of 1.77 minutes at a 2.0 ACFM flow rate and a maximum of 2.02 minutes at a 1.6 ACFM flow rate.

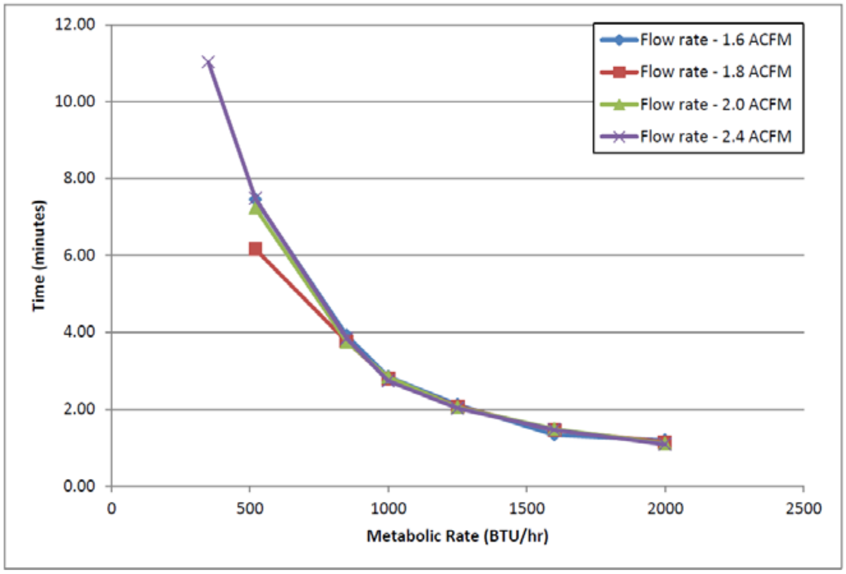
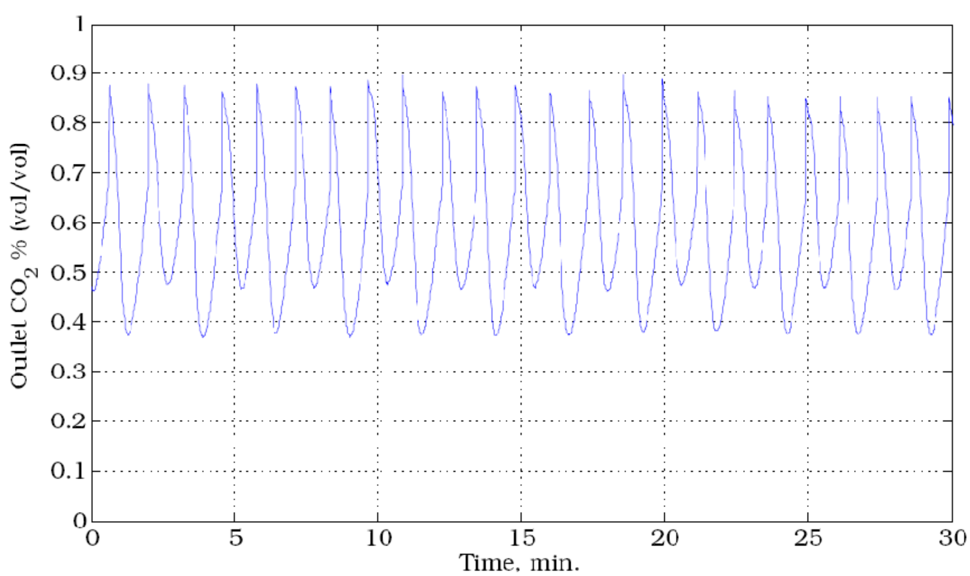


Figure 14. ESCG RCA TA2 SEV-I Ambient Half Cycle Times

Figure 15 presents the unexpected behavior of the CO_2 removal performance. As previously stated, half-cycle times should be similar as long as the beds perform similarly. However, the unexpected behavior of the half-cycle times became more evident as the metabolic rates increased thus the unit had to cycle faster to achieve equivalent removal rates. The data suggests that in SEV-I configuration the beds did not adsorb an equivalent amount of CO_2 per cycle between configurations. One bed would desorb to a minimum CO_2 outlet concentration of approximately 0.4% while the other bed would desorb to a minimum CO_2 outlet concentration of approximately 0.5%. The difference in the initial CO_2 outlet concentration per cycle confirmed that the beds did not adsorb an equivalent amount of CO_2 per cycle.



c) Single End Vacuum Outlet Configuration

The SEV-O configuration performed very similarly to the DEV and SEV-I configurations under ambient and sub-ambient test conditions. SEV-O was able to maintain a consistent outlet dewpoint ranging from -10 to -3 ^oC (13 to 26 ^oF) while the inlet dewpoint ranged from 6 to 19 ^oC (43 to 66 ^oF) over the metabolic rates, as shown in Figure 16. Figure 17 shows the ability of the RCA to maintain a consistent outlet CO_2 partial pressure over the varying metabolic rates and system flow rates. The data shows a minimum CO_2 partial pressure of 2.4 and a maximum CO_2 partial pressure of 4.7.

The half cycle times of the ESCG RCA in the SEV-O configuration varied between metabolic rates, shown in Figure 18. At the 350 Btu/hr metabolic rate with a 2.4 ACFM system flow rate, the RCA half-cycle time was 12.5 minutes. While at a 2000 Btu/hr metabolic rate, the RCA half-cycle time was 1.03 minutes. SEV-O data has the same trend as the DEV and SEV-I configurations for half-cycle time. At a 1000 Btu/ hr metabolic rate, the half-cycle time was a minimum of 2.54 minutes at a 1.6 ACFM flow rate and a maximum of 2.95 minutes at a 1.8 ACFM flow rate.

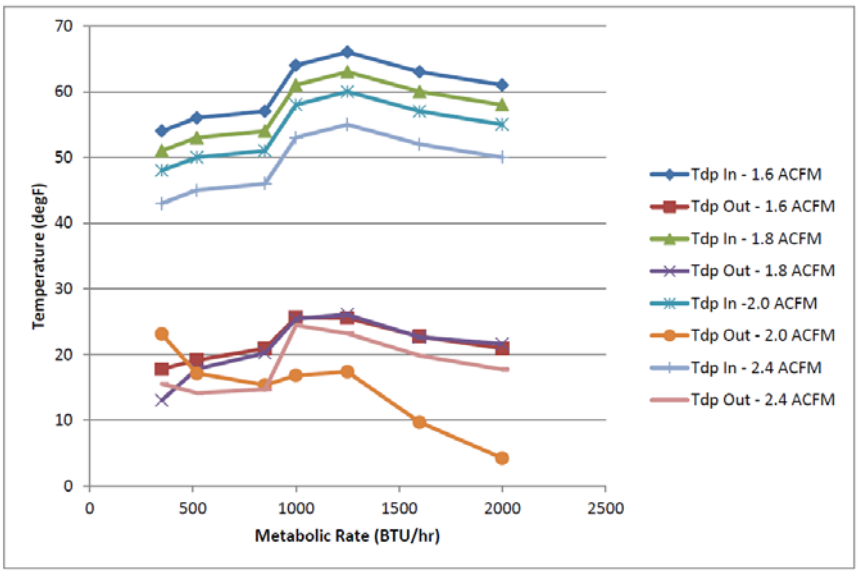


Figure 16. ESCG RCA TA2 SEV-O Ambient Inlet & Outlet Dewpoint Temperature

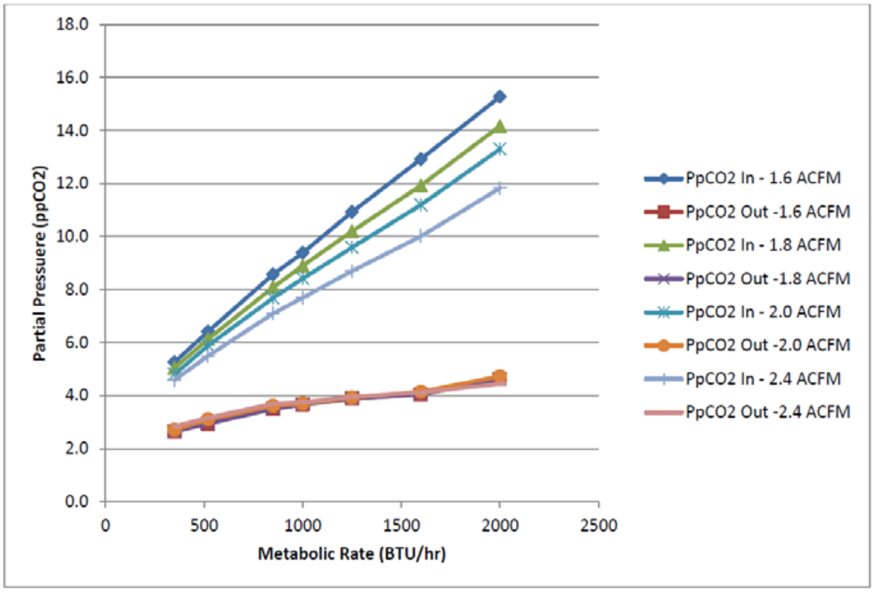


Figure 17. ESCG RCA TA2 SEV-O Ambient Inlet & Outlet Carbon Dioxide Partial Pressure

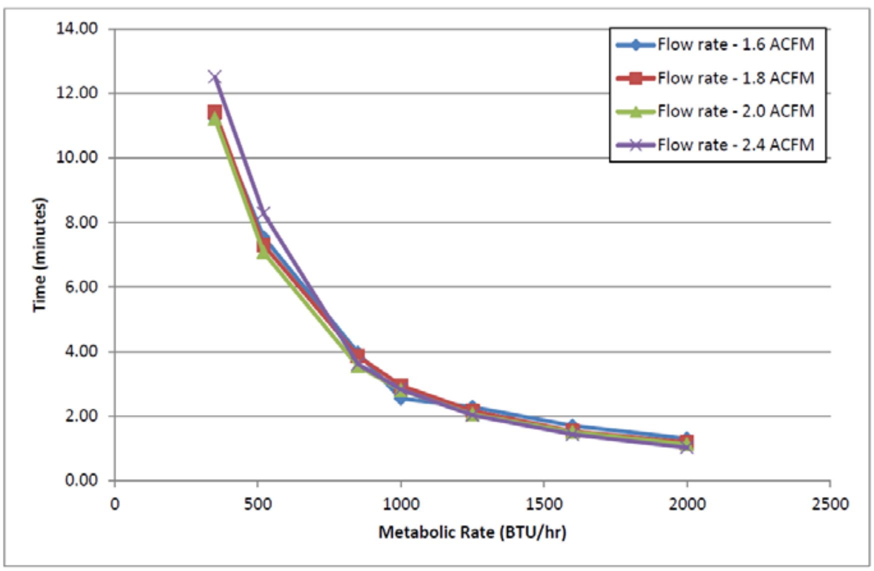


Figure 18. ESCG RCA TA2 SEV-O Ambient Half Cycle Time

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