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Optimization of the Carbon Dioxide Removal Assembly (CDRA-4EU) in Support of the International Space System and Advanced Exploration Systems

James C. Knox[1]
NASA Marshall Space Flight Center, Huntsville, Alabama, 35812, USA

Christine M. Stanley[2]
Jacobs ESSSA Group, Qualis Corporation, Huntsville, Alabama, 35812, USA

The Life Support Systems Project (LSSP) under the Advanced Exploration Systems (AES) program builds upon the work performed under the AES Atmosphere Resource Recovery and Environmental Monitoring (ARREM) project focusing on the numerous technology development areas. The Carbon Dioxide (CO_2) removal and associated air drying development efforts are focused on improving the current state-of-the-art system on the International Space Station (ISS) utilizing fixed beds of sorbent pellets by seeking more robust pelletized sorbents, evaluating structured sorbents, and examining alternate bed configurations to improve system efficiency and reliability. A component of the CO_2 removal effort utilizes a virtual Carbon Dioxide Removal Assembly, revision 4 (CDRA-4) test bed to test a large number of potential operational configurations with independent variations in flow rate, cycle time, heater ramp rate, and set point. Initial ground testing will provide pre-requesite source data and provide baseline data in support of the virtual CDRA. Once the configurations with the highest performance and lowest power requirements are determined by the virtual CDRA, the results will be confirmed by testing these configurations with the CDRA-4EU ground test hardware. This paper describes the initial ground testing of select configurations. The development of the virtual CDRA under the AES-LSS Project will be discussed in a companion paper.

I. Nomenclature

AES = *Advanced Exploration Systems*
ARREM = *Atmosphere Resource, Recovery and Environmental Monitoring*
4BMS = *Four Bed Molecular Sieve*
CDRA-4 = *Carbon Dioxide Removal Assembly, Revision 4*
CDRA-4EU = *Carbon Dioxide Removal Assembly, Revision 4 Engineering Unit*
CO_2 = *Carbon Dioxide*
ISS = *International Space Station*
LSSP = *Life Support Systems Project*
$ppCO_2$ = *Partial Pressure Carbon Dioxide*

II. Introduction

The Atmosphere Revitalization Recovery and Environmental Monitoring (ARREM) project was initiated in September of 2011 as part of the Advanced Exploration Systems (AES) program. The stated purpose of the AES program is “pioneering new approaches for rapidly developing prototype systems, demonstrating key capabilities, and validating operational concepts for future human missions beyond Earth orbit.”[1] These forays beyond the confines of earth’s gravity will place unprecedented demands on launch systems. They must not only blast out of

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[1] Aerospace Engineer, Environmental Control and Life Support Development Branch/ES62.
[2] Chemical Engineer, Environmental Control and Life Support Development Branch/ES62,

Earth's gravity capably as during the Apollo moon missions, but also launch the supplies needed to sustain a crew over longer periods for exploration missions beyond earth's moon. Thus all spacecraft systems, including those for the removal of metabolic carbon dioxide from a crewed vehicle, must be minimized with respect to mass, volume, and power. Emphasis is also placed on system robustness both to minimize replacement parts and ensure crew safety when a quick return to earth is not possible.[1] Power is at a premium for ISS and exploration missions. While the ISS makes use of the sun to generate power, exploration missions will not have that luxury. Alternate power sources must be developed for longer term missions and the size and mass of these technologies are limited due to launch considerations. New life support technologies must be developed to minimize power requirements to insure mission success.

Under the ARREM Program, a 4-Bed Molecular Sieve (4BMS) system, the CDRA Dash 4 Engineeirng Unit (CDRA-4EU) was developed to more closely mimic the current CDRA configuration on the International Space Station (ISS), CDRA-4, and thus provide a better understanding of the state-of-the-art system performance and limitations. The CDRA-4 configuration is the result of an on-orbit anomaly investigation and includes redesigned heaters, the ability to service the screens on-orbit, and new sorbent materials.

In FY14, the CDRA-4EU was used in the ARREM Cycle 2 testing which is discussed in detail in Ref 5. In addition, CO_2 removal performance testing was also carried out. The objective was to evaluate the CDRA-4EU performance when flow rate was increase to approximately 42.5 m^3/hr (25 SCFM) from the the nominal flow of 34.7 m^3/hr (20.4 standard cubic feet per minute (SCFM)), while the cycle time was reduced from the nominal 144 minutes to 90 minutes, near the minimum that would allow time for the CO_2 sorbent beds to heat to the nominal set point of 204°C (400F). The objectives for these tests are listed below:

1. 4.1 crew equivalent removal at an inlet CO_2 partial pressure of 2.0 torr (test ran on 5/17/14)
2. 10.5 crew equivalent removal at an inlet CO_2 partial pressure of 5.0 torr (test ran on 5/27/14)

Performance results from these tests were favorable; the test results demonstrated that one key exploration objective was met, that is, reducing cabin CO_2 levels to 2 torr with 4 crew members. This is an important result as crew members have experienced headaches and other medical issues due to the current CO_2 concentration on ISS. For exploration missions, a performance goal is to maintain CO_2 levels at or below 2 torr for 4 crew members. Removal capacity for a high crew load was demonstrated in order to determine if the CDRA-4EU is capable of handling a much higher CO_2 load. However, the combination of higher flow rates and reduced cycle times resulted in considerably higher power requirements. Heater power alone increased by 200 Watts (average) compared to a nominal operational configuration; blower power (not measured) would also increase significantly.[4]

III. Objective

For FY15, the objective was to optimize the CDRA operational configurations such that exploration goals are met while increases in power requirements are minimized. The approach incorporates a virtual CDRA test bed via computer modeling and simulation. Computer modeling and simulation of the CDRA adsorption process requires the coupled solution of heat transfer, mass transfer, and low pressure fluid dynamics. As this advanced capability is unavailable commercially (or otherwise), development was initiated as part of the ARREM project and continues under the AES/LSSP. A detailed discussion of the modeling and simulation work is found in Ref. 6.

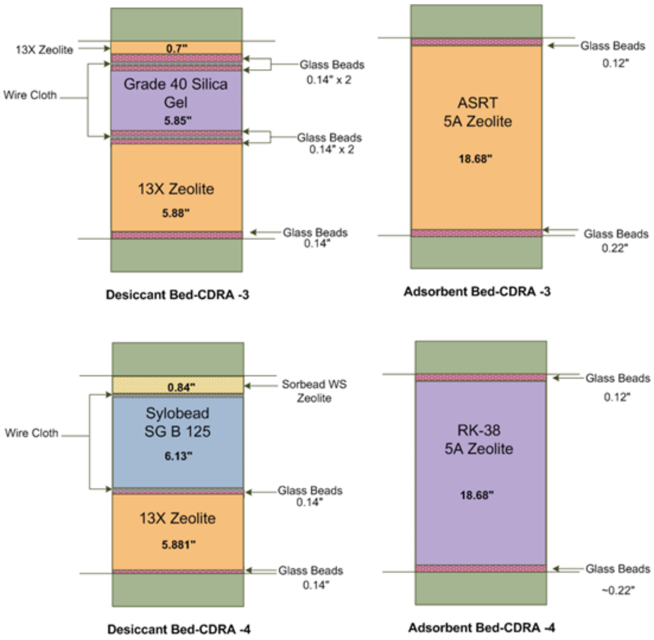
The virtual CDRA test bed will be used to test a large number of potential operational configurations with independent variations in flow rate, cycle time, heater ramp rate, and set point. Once the configurations with the highest performance and lowest power requirements are determined, the virtual CDRA results will be confirmed by testing these configurations with the CDRA-4EU ground test hardware. This approach is intended to reduce the number of tests and to the minimize costs associated with extended duration ground testing. The initial virtual CDRA test bed will integrate validated 1-D, single component (or single-gas equilibrium adsorption capacity correlations) models developed during the ARREM project, and be used for the initial optimization studies. A final CDRA simulation will be developed and applied to obtain the final optimized configurations.

In support of this effort, initial baseline testing with the CDRA-4EU was performed to provide pre-requisite source data for computer model refinement and to provide baseline data for comparison with future testing. The tests discussed here were very specifically controlled tests where the half-cycle times were set at either initial breakthrough or at 50% breakthrough.. The results of these supporting tests provide insight into optimization for a select range of parameters with the focus primarily on the power utilization and CO_2 removal aspects of the CDRA. True optimization of the CDRA will be accomplished virtually and then validated with final CDRA-4EU testing.

In addition to supporting the virtual CDRA test bed development, this test data provides immediate benefit to the ISS program. A single CDRA may be operated to meet reduced CO_2 concentrations as needed instead of both CDRA's by using the optimized operational parameters described herein.

IV. Preliminary Optimization Testing

The Carbon Dioxide Removal Assembly (CDRA), built by Honeywell (formerly AiResearch and Allied Signal) utilizes a fully regenerative thermal/pressure swing adsorption process to remove CO_2 from the ISS cabin air. The CDRA operates cyclically and employs two desiccant beds and two adsorbent beds. As one desiccant bed and one adsorbent bed operate in adsorption mode, the other two beds are desorbing (regenerating). Half-way through a cycle, the beds switch modes, providing continuous CO_2 removal capability. There are two versions of the CDRA on the ISS, one retains the CDRA-3 configuration and the other employs the CDRA-4 configuration. The differences between the adsorbent packing configurations are shown in Figure 1.



*Not to scale

Figure 1: Comparison of Bed Packing Between CDRA -3 and CDRA -4

The recently built CDRA-4EU, positioned in the Environmental Chamber (E-Chamber) located in Building 4755 at MSFC, was used for performance testing to provide additional validation that the new materials used in CDRA-4 would be adequate to meet the ISS requirements for CO_2 removal; the results of this testing are documented in Ref. 1.

The CDRA-4EU sorbent beds are were packed in the same configuration as the CDRA-4 for the ARREM Cycle 2 Test. There were no changes to either the hardware or the packing configurations prior to the preliminary optimization testing. The duration for each test run was between 16-24 hours, insuring that a minimum of four half-cycles at steady state were captured.

V. Experimental

1. Power Minimization Testing (PW)

Minimizing power requirements of life support processes is a high priority for space flight, especially for long duration missions due to limited availability. Therefore, a key objective for optimizing the CO_2 removal process is reducing the power requirements. In support of the virtual CDRA test bed development, a set of test parameters for the CDRA-4EU were developed to provide insight into CDRA power usage during various runtime configurations. The nominal CDRA flow rate is 34.7 m3/hr (20.4 SCFM). Flow rates in increments of 8.5 m^3/hr (5 SCFM) were chosen. Approximate cycle time for stoichiometric breakthrough was calculated for 2 to 4 torr inlet $ppCO_2$ at each selected flow rate for the CDRA-4EU. This is the cycle time when 50% breakthrough was predicted to occur. The test points are shown in Table 1.

Table 1. Power Minimization Test Parameter Matrix

Half-Cycle Time for Minimum Heater Power, minutes			
Flowrate, m^3/h (SCFM)	**CO2 Partial Pressure, torr**		
	2	**3**	**4**
34 (20)	215	177	154
42.5 (25)	172	142	123
51 (30)	144	118	103
59.5 (35)	123	101	88

2. *Performance Optimization Testing(PF)*

Performance optimization is another key objective for the development of the virtual CDRA. To gain insight into the performance aspect of CDRA operations, each PW test run had a companion Performance Optimization (PF) test run. The only difference between the two tests was the half-cycle time. The half-cycle time for the PF runs were established from the breakthrough data collected during the PW testing and were set at the time that breakthrough of CO_2 was just beginning, but far enough along the curve to confirm that breakthrough had indeed occurred. An additional 10 minutes was added to the observed time to insure that initial breakthrough would be achieved during the performance test. A breakthrough concentration of percent $CO_2 \geq 0.01$ was chosen as the standard determining point; an example is provided in Figures 2 and 3. This resulted in all of the PF test runs having shorter half-cycle times than its correstponding PW test run. The resulting Performance Optimization Test Parameter Matrix is shown in Table 2. Please note that we were unable to test at 59.5 m/h^3 (35 SCMF) and 4 torr ppCO_2. The resulting half-cycle time was too short to allow the adsorbent beds to reach the required temperature of 204°C (400°F).

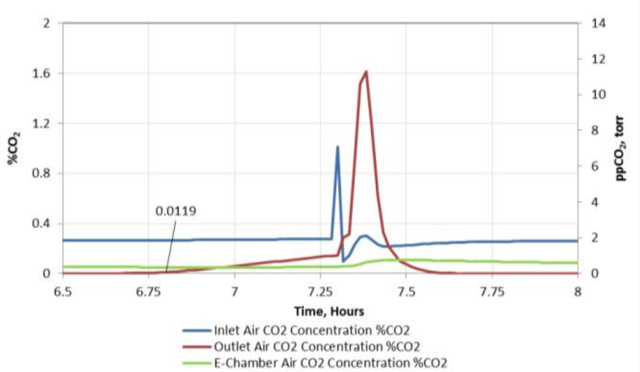


Figure 2. Representative Breakthrough Curve. The graph depicts a sample breakthrough curve taken from one of the Power Minimization test runs.

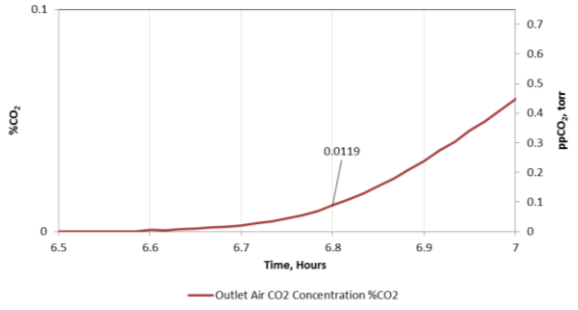


Figure 3. Representative Breakthrough Curve—Zoomed View. The data label indicates the point at which the half-cycle time was determined for the companion performance optimization test.

Table 2. Performance Optimization Test Parameter Matrix

Half-Cycle Time for Performance Optimization, minutes			
Flowrate, m^3/h (SCFM)	**CO_2 Partial Pressure, torr**		
	2	**3**	**4**
34 (20)	195	140	110
42.5 (25)	154	123	104
51 (30)	124	106	93
59.5 (35)	96	79	n/a

A. Results and discussion

The results discussed here are specific to the set of tests performed and serve to provide insight and data anchoring for the 1-D model and simulation development. Additionally, each plot shown in Figures 4-7 have an uncontrolled variable, flow rate in Figures 4 and 7 and half cycle time in Figures 5 and 6. Thus, generalized conclusions are not appropriate given the data set. Other contributing factors such as heat and mass transfer and low pressure fluid dynamics must be taken into account for true optimization to be achieved.

Tabulated results for both tests are shown in Table 3. The PW test data is on the right and the corresponding PF test in on the left. Power utilization is directly related to half-cycle time. For all data points, the longer half-cycle times require less power. This can be seen in Figure 4. This is an expected outcome because the heaters are cycled less often during longer half-cycles. The graph also indicates that there is little variation in power utilization with respect to inlet ppCO_2, with lower partial pressure requiring slightly less power utilization.

Table 3. Test Results

Power Minimization						
PW HC (min.)	PW Inlet ppCO2 (torr)	PW Inlet Flow (scfm)	PW Inlet %CO2	PW HC Efficiency	PW Removal Rate kg/day	PW Average Power
215	2	20	0.265	77.9%	3.17	461
172	2	25	0.253	78.3%	4.06	524
144	2	30	0.267	74.0%	4.85	585
123	2	34	0.262	71.2%	5.19	637
177	3	20	0.396	77.2%	4.78	522
142	3	25	0.394	78.2%	6.29	605
118	3	30	0.390	75.1%	7.33	687
101	3	35	0.399	72.5%	7.93	748
154	4	20	0.537	77.4%	6.410	583
123	4	25	0.533	76.0%	8.31	679
103	4	30	0.536	75.6%	9.86	759
88	4	35	0.538	72.0%	10.71	838

Performance Optimization						
PF HC (min.)	PF Inlet ppCO2 (torr)	PF Inlet Flow (scfm)	PF Inlet %CO2	PF HC Efficiency	PF Removal Rate kg/day	PF Average Power
195	2	20	0.263	81.3%	3.49	486
154	2	25	0.254	81.1%	4.20	556
124	2	30	0.263	78.0%	5.13	646
96	2	34	0.261	81.4%	5.69	747
140	3	20	0.396	83.7%	5.10	586
123	3	25	0.401	80.7%	6.54	659
106	3	30	0.396	80.0%	7.77	714
79	3	34	0.393	79.8%	8.72	852
110	4	20	0.536	83.1%	6.83	710
104	4	25	0.526	79.5%	8.60	737
93	4	30	0.532	79.6%	10.41	795
n/a	n/a	n/a	n/a	n/a	n/a	n/a

CO_2 removal efficiency tended to decrease with increasing flow overall as shown in Figure 5. The decrease in efficiency at higher flow rates could be attributed to increased CO_2 hold up in the desiccant bed relative to the sorbent beds, as the higher velocities would increase wall channeling in the narrow heater core channels in the adsorbing beds. Further investigation is needed to determine the exact reason for this phenomenom. It should be noted that all of the PF runs produced higher efficiency compared to the corresponding PW runs indicating that efficiency decreases with longer half-cycle times.

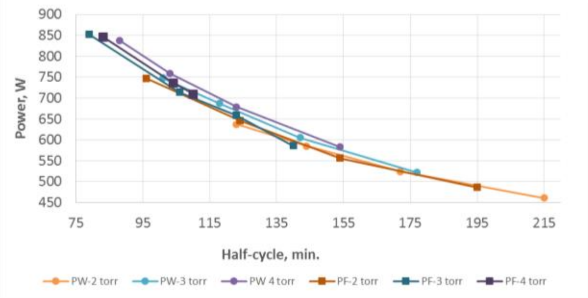


Figure 4. Power vs. Half-Cycle Time. Data are plotted for both the PW and PF tests at each inlet $ppCO_2$.

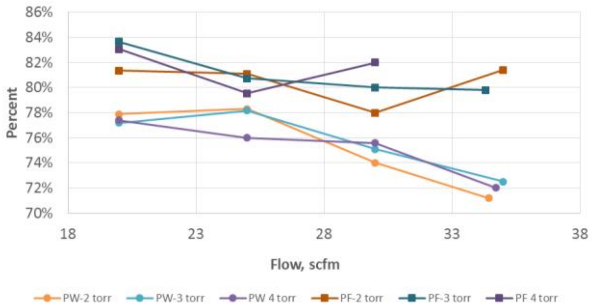


Figure 5. Efficiency vs. Flow Rate. Data are plotted for both the PW and PF tests at each inlet $ppCO_2$.

Removal rate has a direct correlation between both inlet $ppCO_2$ and flow rate and the results are as expected as shown in Figure 6. Longer half-cycles have slightly reduced removal rates when comparing between the PW and PF runs; note however that the HC is not constant for this data so direct conclusions are limited. Removal rates also decrease with increasing cycle times as indicated in Figure 7, however since flow rate is not constant, direct conclusions are limited here as well.

This data provides insight into optimization of the CDRA power and removal efficiency for a range of flow rates and CO_2 partial pressures, as well as baseline data for CDRA simulation validation.

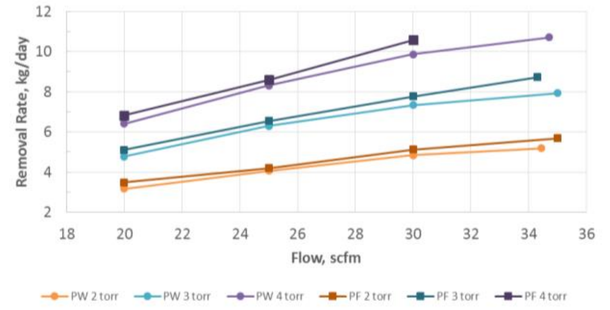


Figure 6. Removal Rate vs. Flow Rate. Data are plotted for both the PW and PF tests at each inlet ppCO2.

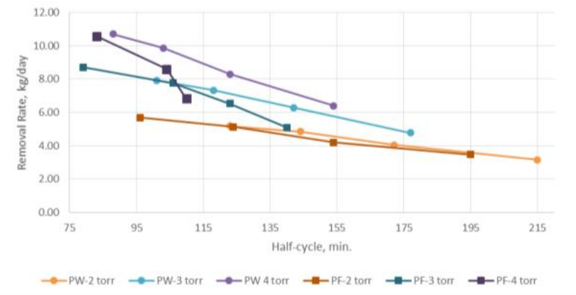


Figure 7. Removal Rate vs. Cycle Time. Data are plotted for both the PW and PF tests at each inlet ppCO$_2$.

In order to gain a clear understanding of the effects of varying operating parameters on both power and performance, a computer simulation will be used. To interpolate between tested data points for nearer term results, we have started using Minitab 17®, a statistical software package, to aid in determining optimal operating conditions. In particular we have begun working with the Response Optimizer tool where multiple variables can be used to determine optimal operating parameters. We used the tool to determine the maximum CO$_2$ removal efficiency and removal rates at 3 torr inlet ppCO$_2$ for varied cases. The selected flow rates represent the nominal CDRA flow rate 34.7 m^3/h (20.4 SCFM), the estimated CDRA flow rate when the blower speed is increased by 5000rpm 36.2 m^3/h (21.3 SCFM), and a high flow rate 42.5 m^3/h (25 SCFM). For cases 4, 5, 6 and 7, 90 minute half-cycles were selected to match the current half-cycles used on the ISS. We performed two test runs as a check to gage the correlation between the analysis and the test data. The test results suggest a correlation between the test data and the analysis, but further testing will be required to make a definitive claim. The test cases are described below followed by the results listed in Table 4:

1. Maximize CO$_2$ removal rate and determine half-cycle time at 34.7 m^3/h (20.4 SCFM) flow rate.
2. Maximize CO$_2$removal rate and determine half-cycle time at 36.2 m^3/h (21.3 SCFM) flow rate.
3. Maximum CO$_2$ removal rate with variable half-cycle time and flow rate.
4. Test data—90 minute half-cycle and 34.7 m^3/h (20.4 SCFM) flow rate.
5. Determine CO$_2$ removal rate and removal efficiency at 90 minute half-cycle and 34.7 m^3/h (20.4 SCFM) flow rate.
6. Test data—90 minute half-cycle and 36.2 m^3/h (21.3 SCFM) flow rate
7. Determine CO$_2$ removal rate and removal efficiency at 90 minute half-cycle and 36.2 m^3/h (21.3 SCFM) flow rate.
8. Determine half-cycle time for maximum removal rate at 42.5 m^3/h (25 SCFM) flow rate.
9. Determine half-cycle time for maximum removal efficiency at 42.5 m^3/h (25 SCFM) flow rate.
10. Maximize removal efficiency at variable half-cycle time and flow rate.
11. Maximize removal efficiency and determine half-cycle time at 34.7 m^3/h (20.4 SCFM) flow rate.
12. Maximize removal efficiency and determine half-cycle time at 36.2 m^3/h (21.3 SCFM) flow rate.

Table 4. MiniTab® 17 Response Optimizer Results

Case Number	Case at $ppCO_2$ = 3 torr	Data Type: Analysis (A) Test (T)	HC (min)	Flow (scfm)	Removal Rate (kg/day	Efficiency (percent)
1	Max RR HC and 20.4 scfm	A	79	20.4	4.42	70.5%
2	Max RR HC and 21.3 scfm	A	79	21.3	4.89	72.6%
3	Max RR, variable HC and FR	A	79	35	8.69	80.1%
4	Test data-90 min. HC and 20.4 scfm	T	90	20.22	4.8	75.3%
5	90 min. HC and 20.4 scfm	A	90	20.4	4.72	74.9%
6	Test data-90 min. HC and 21.3 scfm	T	90	21.3	5.08	76.0%
7	90 min. HC and 21.3 scfm	A	90	21.3	5.14	76.7%
8	HC for Max RR @ 25 scfm	A	133	25	6.287	78.8%
9	HC for Max EFF @ 25 scfm	A	133	25	6.287	78.8%
10	Max EFF, variable HC and FR	A	138	20	5.11	83.5%
11	Max EFF HC and 20.4 scfm	A	138	20.4	5.24	83.3%
12	Max EFF HC and 21.3 scfm	A	138	21.3	5.51	82.8%

Removal Rate (RR) Efficiency (EFF) Half Cycle (HC) Flow Rate (FR)

Selected removal rate data, for cases with CDRA inlet partial pressure controlled to 3 torr, are shown in Figure 8. This figure also shows, as light blue points, the estimated removal rates based on a Minitab correlation. Although the correlation is reasonable when used for interpolation it has questionable consistency when used for extrapolation. It is anticipated that the 1-D CDRA simulation will provide a predictive capability as needed for design optimization where testing is not practical.

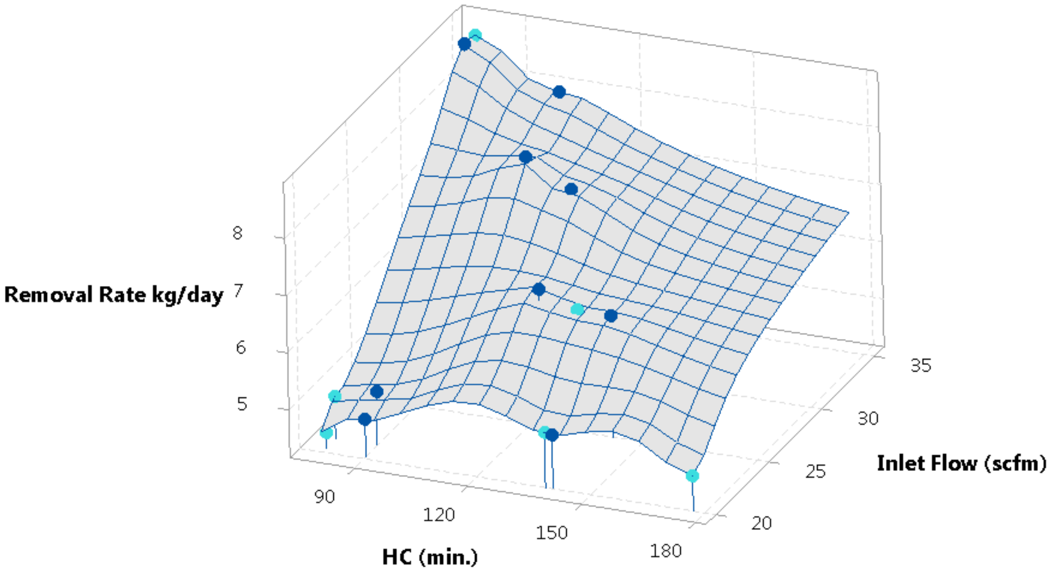


Figure 8. Surface Plot of Removal Rate vs. Inlet Flow and Half Cycle Time for cases with inlet CO_2 partial pressure of 3 torr. Test data points are shown in dark blue; results based on a correlation are shown in light blue.

VI. Conclusion

Exploration and other long term missions dictate that life support systems be required to minimize power utilization while maintaining optimal performance. Understanding the effects of varying CDRA operating parameters is key to optimizing the CDRA to meet the those requirements. Ground testing not only offers valuable data for input to the decision making process, but also provides needed data to support the CDRA modeling and simulation effort. Further optimization will be performed using parametric virtual testing, with final results confirmed by CDRA-4EU tests.

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