

Development Status of Amine-based, Combined Humidity, CO₂, and Trace Contaminant Control System for CEV

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Abstract

Under a NASA-sponsored technology development project, a multi-disciplinary team consisting of industry, academia, and government organizations lead by Hamilton Sundstrand is developing an amine-based humidity and CO₂ removal process and prototype equipment for Vision for Space Exploration (VSE) applications. Originally this project sought to research enhanced amine formulations and incorporate a trace contaminant control capability into the sorbent. In October 2005, NASA re-directed the project team to accelerate the delivery of hardware by approximately one year and emphasize deployment on board the Crew Exploration Vehicle (CEV) as the near-term developmental goal. Preliminary performance requirements were defined based on nominal and off-nominal conditions and the design effort was initiated using the baseline amine sorbent, SA9T. As part of the original project effort, basic sorbent development was continued with the University of Connecticut and dynamic equilibrium trace contaminant adsorption characteristics were evaluated by NASA. This paper summarizes the University sorbent research effort, the basic trace contaminant loading characteristics of the SA9T sorbent, design support testing, and the status of the full-scale system hardware design and manufacturing effort.

Introduction

Long-duration crewed space explorations missions benefit significantly from using regenerable process technologies to minimize re-supply logistics. Current methods of CO₂ removal for aerospace life support systems include non-regenerable lithium hydroxide (LiOH) and regenerable systems that employ silver oxide, solid amines, or molecular sieves. In 2004, a 3-year rapid technology development project was initiated with the objective of delivering a prototype regenerable, amine-based system that combines CO₂, humidity, and trace contaminant (TC) control within a single processing unit operation. The project team includes members from industry, academia, and NASA.

In October 2005, the trace contaminant control component of the project was cut short after acquiring basic dynamic equilibrium capacity data. No immediate plans to evaluate dynamic working capacity have been defined for the redefined project scope because the observed dynamic equilibrium capacity data indicate a dedicated trace contaminant control process is required. In addition, the prototype equipment delivery date was accelerated by approximately one year, from August 2007 to June 2006. As a result of the acceleration, the most mature amine-based sorbent, SA9T, was selected for the accelerated project.

Basic research on amine chemistry continued at the University of Connecticut and the effects of sorbent bed aspect ratio on performance are being investigated further at the University of Hartford to complete some of the original project objectives.

Whereas the original program was to deliver a system sized for Extravehicular Activity, the acceleration effort redirected the hardware deliverable to be a system sized for the CEV. The deliverable hardware consists of a canister assembly with two thermally linked sorbent beds, a spool valve to direct the process air to the adsorbing bed, while simultaneously exposing the desorbing beds to vacuum, a commercial actuator to actuate the spool valve, and an actuator interface control box. Additionally, a vacuum duct adaptor will be provided which provides a single interface for vacuum source attachment and numerous test ports. After delivery to NASA, specific performance testing to advance the process technology to readiness level 6 will be conducted.

Background

Hamilton Sundstrand has been developing amine-based sorbents for more than 25 years, including steam and vacuum regenerated systems.¹⁻³ In the early 1990s, the first flight system flew on the Shuttle Extended Duration Orbiter missions, and was referred to as the RCRS – Regenerable Carbon Dioxide Removal System. The current sorbent, referred to as SA9T, is an enhanced amine formulation with approximately eight times the usable capacity of the amine used in the RCRS.⁴

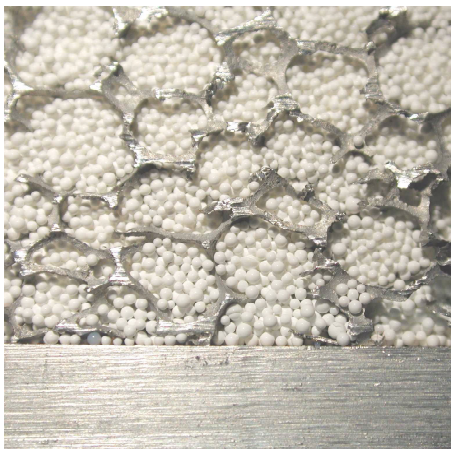


Figure 1 Solid Amine Sorbent in Thermally Conductive Metal Foam

The physical embodiment of the solid amine-based process consists of loading the sorbent in aluminum foam sections which are assembled in multiple, alternating layers to contain the amine sorbent and also promote heat transfer between adjacent beds. A section of amine filled metal foam is shown in Figure 1. The sorbent layers are configured as alternate beds which are connected internally through a series of manifold ports. The

alternate layers are either adsorbing or desorbing at any time. A diverter valve directs airflow to one bed while simultaneously exposing the other bed to space vacuum. After a predetermined interval, the valve position changes to expose the regenerated bed to airflow and the saturated bed to space vacuum as shown schematically in Figure 2.

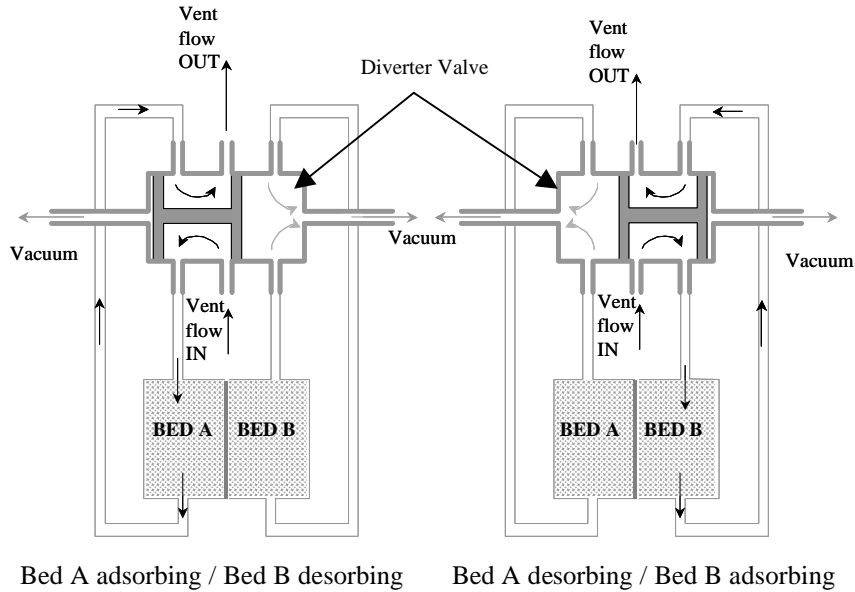


Figure 2 – Operational Schematic of Spool Valve

The exothermic heat of reaction of the adsorbing bed is transferred to the adjacent desorbing bed which, when combined with exposure to vacuum, provides the energy necessary for desorption. By transferring the heat between adjacent sorbent beds, no additional energy is required to regenerate the sorbent. The current packaging concept for the canister and integrated valve assembly are shown below in figure 3. Note in the current design that the sorbent bed assembly consists of a total of eight layers of sorbent, four alternating layers per bed.

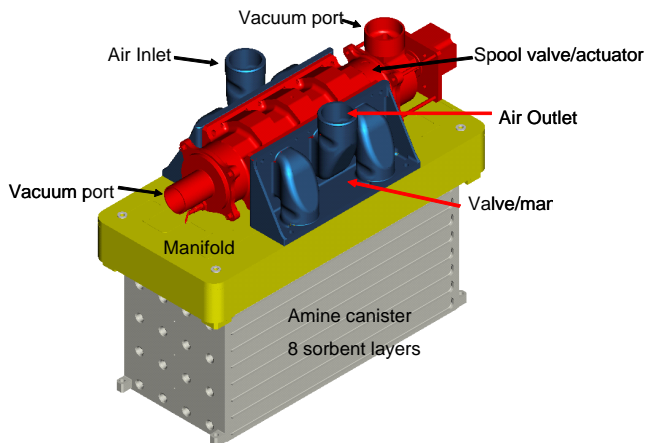


Figure 3 - Amine Sorbent Assembly

Research Effort

Emphasis during the project's first year (August 2004 – July 2005) was on basic research to investigate alternate sorbent configurations. This included alternate amines and substrate materials. The primary goal of the investigation into alternate amines was aimed at enhanced sorbent capacity, while the alternate substrate materials were investigated as potential methods of enhancing the trace contaminant control capability of the sorbent.⁵⁻⁶

The University of Hartford and the University of Connecticut supported the project in the investigation of various amine synthesis routes as alternates to the baseline amine; however, preliminary results showed much lower CO₂ capacity than previous formulations. As a result of the accelerated re-scoped effort, it was decided that the University of Connecticut would continue basic research in amine synthesis while the University of Hartford would support the evaluation of amine bed aspect ratio as it relates to vacuum regeneration efficiency.

NASA's Marshall Space Flight Center (MSFC) defined the trace contaminant challenge, test protocol, and analytical techniques during the first year, in addition to modifying and checking out the test rig used for dynamic equilibrium trace contaminant control testing during the second year.

Hamilton Sundstrand concentrated on alternate substrates for the amine with a goal of potentially increasing performance as well as enhancing the trace contaminant loading characteristics through the incorporation of carbon based support materials. Approximately 15 carbons from TDA Research, along with 10 commercially available carbons were tested during the first year of the program. In addition to carbons, alternate polymeric and inorganic supports were also evaluated as potential support materials. In preliminary screening tests, the maximum CO₂ capacity measured was approximately 70% of the baseline sorbent for all of the alternate support materials tested. As a result of the reduced capacity of the alternate materials, and the acceleration of the program, the SA9T baseline sorbent was selected at the conclusion of the year one effort.

Current Program Status

Program Acceleration - In the beginning of the second year of the project, NASA accelerated the schedule to concentrate on process equipment design, manufacturing, and testing to address near-term VSE needs. Specifically, these needs are dictated by the CEV's development. The University of Hartford effort focused on the impact of sorbent bed geometry on regeneration efficiency, while basic amine chemistry research continued at the University of Connecticut. These efforts are on-going and will be completed in mid

2006 and reported at a later date. MSFC completed single and multi-component dynamic equilibrium contaminant adsorption tests using the SA9T sorbent.

As a result of the new emphasis on CEV-based application, a preliminary performance specification was generated based on our understanding of the CEV's mission requirements. This includes basic requirements and derived requirements based on engineering judgment and previous systems experience. The basic requirements are listed below in Table 1.

Table 1 – Preliminary Performance Requirements				
Crew Size	CO ₂ Removal Rate, lbs/hr	H ₂ O Removal Rate, lbs/hr	Nominal Air Flow Rate, cfm	Nominal Pressure Drop, inches H ₂ O
6	0.5-0.7	1.0-1.2	26	< 4.0

In addition to the preliminary performance requirements, assumptions relative to reliability were also considered in defining the system size. The current sizing approach assumes a two-fault tolerant system design, where a degraded operation is considered acceptable upon the second failure. In this scenario, we sized the system to accommodate a crew size of 3 by using a total of 3 parallel sorbent assemblies on board the CEV. In this scenario if the second sorbent assembly fails, the remaining assembly must be able to accommodate the full crew size of 6, but degraded operation is allowed – in this case we assumed the partial pressure of CO₂ could increase to approximately 7.6 mmHg and that the dew point could increase to approximately 65°F.

Design Support Testing - To support our analysis, extensive testing has been conducted using the ½ scale test article shown in Figure 4. Additionally, numerous mock ups were built and tested to validate pressure drop and flow distribution of the various elements in the system - including full scale canister, valve and manifold. Figures 5 and 6 show the water and CO₂ removal rate data obtained with the ½ scale test article. These results are used to validate our sizing for the full scale system. When extrapolating to full scale performance, note that the removal rate and process flow rate double. Based on the ½ scale performance extrapolated to full scale, the total sorbent volume required is approximately 400 cubic inches, 200 cubic inches per bed.

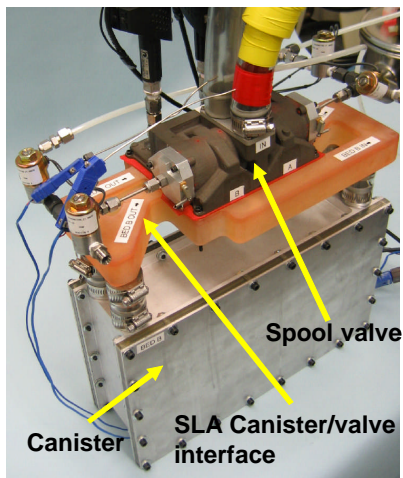


Figure 4 – ½ Scale Design Support Test Article

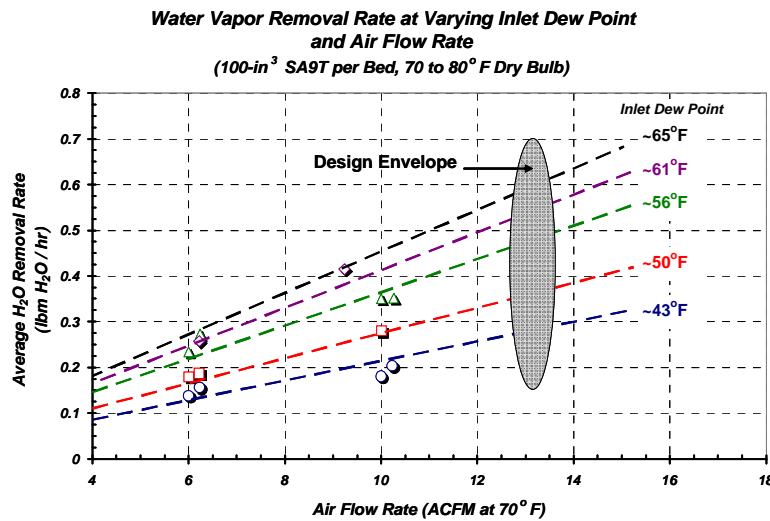


Figure 5 Water Removal Performance Data using the ½ Scale Test Article

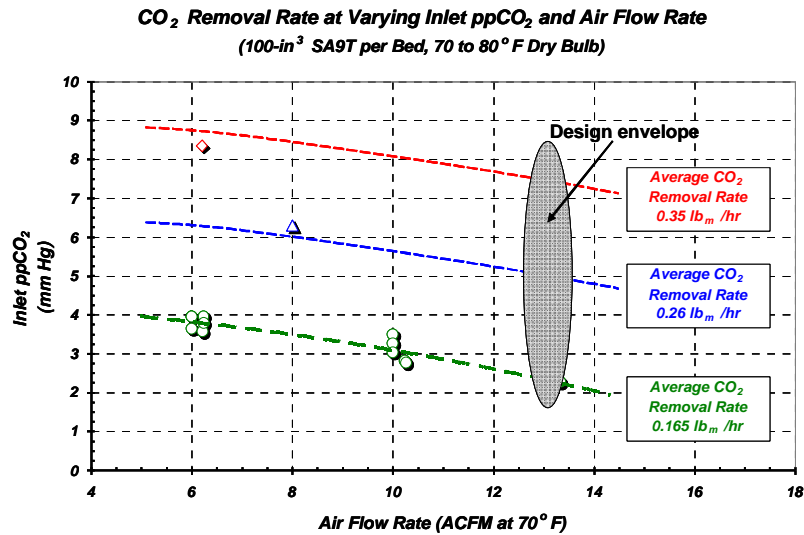


Figure 6 CO₂ Removal Performance using the ½ Scale Test Article

Manufacturing Status – The spool valve is currently in the process of assembly, while the canister core has been manufactured and is currently in the process of being assembled and loaded with sorbent. The canister consists of eight layers, with four layers per bed. Each layer consists of 4 parallel metal foam sections as shown in Figure 7. After assembly the foam is loaded with sorbent material through fill ports at the end of each section. The

entire eight layer brazed assembly in shown in Figure 8.

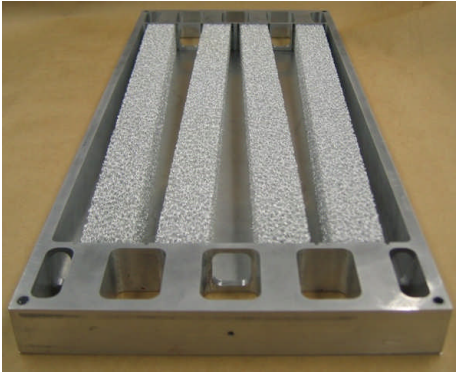


Figure 7 – Single Layer Showing Metal Foam Elements



Figure 8 – Layer, Brazed Canister Assembly

NASA Trace Contaminant Testing of SA9T - As part of the investigation into the feasibility of using the amine based sorbents as a combined system for trace contaminant control, MSFC conducted trace contaminant dynamic equilibrium loading tests on fully regenerated SA9T sorbent beds to obtain data on the loading characteristics of selected compounds of most importance to spacecraft cabin air quality control design. The tests were conducted using completely regenerated SA9T sorbent and consisted of 30-minute adsorption cycles. The representative compounds that were evaluated include dichloromethane, acetone, xylene, methane, ethanol, and acetaldehyde. Testing was conducted for both single components and multi-components under dry and humid conditions. Data analysis indicated the multi-component, humid condition to be the most challenging. Results for the multi-component runs under dry and humid condition are shown by Figures 9 and 10.

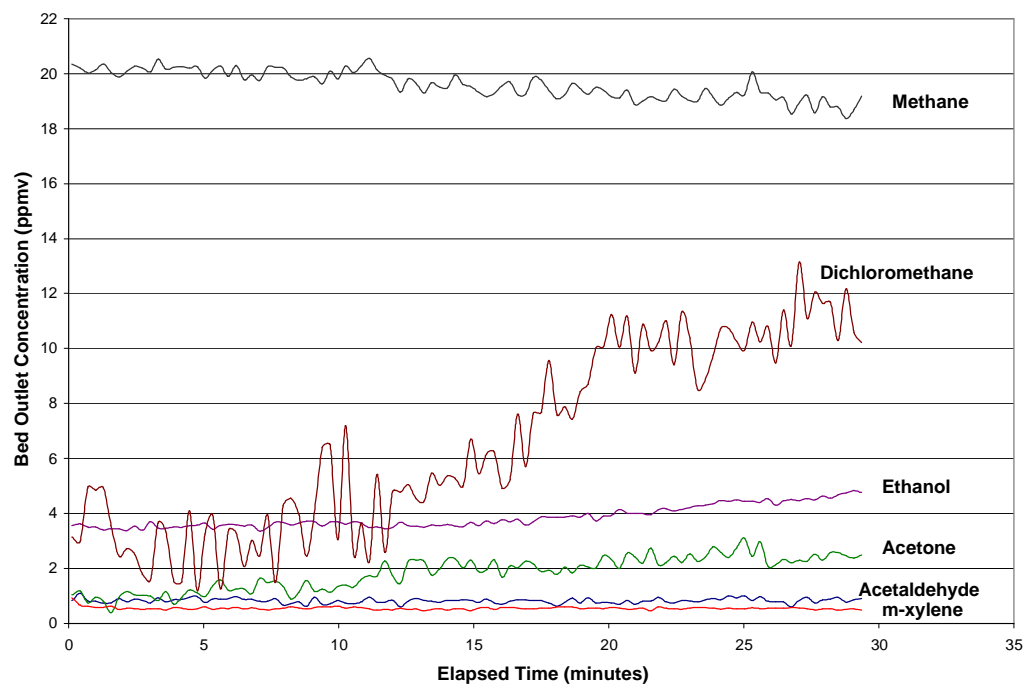


Figure 9. Multi component Dynamic Trace Contaminant Adsorption Under Dry Conditions

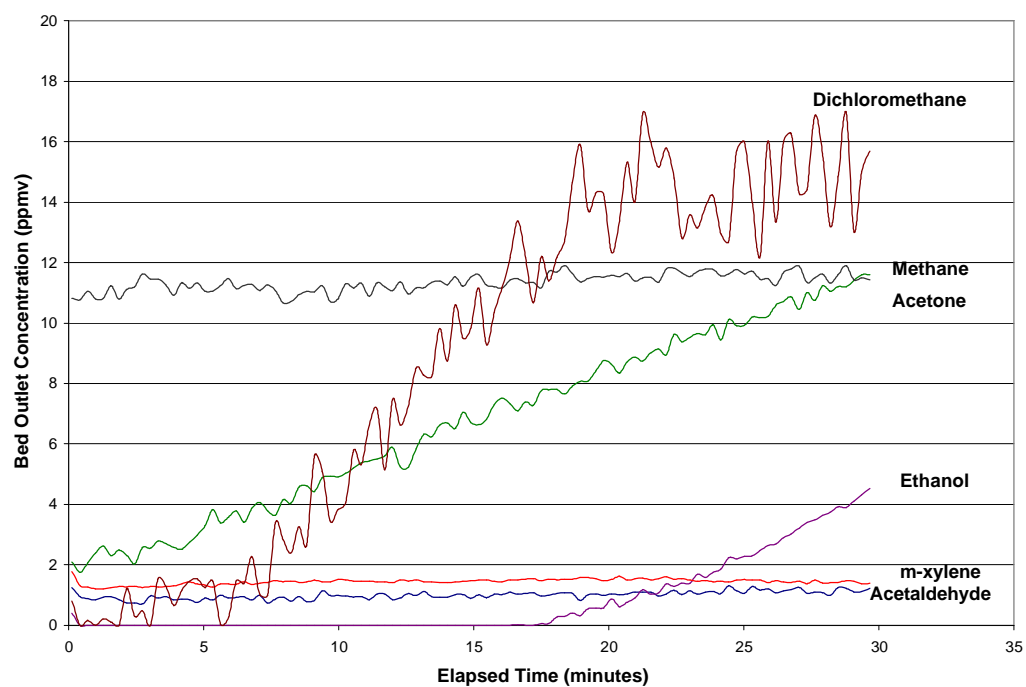


Figure 10. Multi-component Dynamic Trace Contaminant Adsorption Under Wet Condition

For the contaminants tested, there was little impact on the overall loading as a result of the presence of multiple contaminant or water vapor, with the exception of acetone, in which case both water and other contaminants cause a decrease in overall capacity. As indicated by the data, dichloromethane and acetone start to break through relatively early in the run, with approximately 50% removal during the 30-minute test, while methane is not removed at all. Past evaluations have also found that carbon monoxide, a key compound in trace contaminant control design, is also not removed. Approximately 90% of the xylene, acetaldehyde and ethanol was adsorbed.

It must be noted that the experimental runs conducted to date are indicative of performance when complete regeneration is accomplished. Due to limitations imposed on the project, short duration cycles lasting 10 minutes or less have not been evaluated. Therefore the actual working capacity for trace contaminant removal has not been evaluated. Given the observations from this and previous testing with key design-driving trace contaminants, including carbon monoxide, as well as the likelihood that working capacity will diminish over a number of short duration regeneration cycles, it is concluded that dedicated trace contaminant control is required for an air revitalization system where CO₂ removal is accomplished using the SA9T material. Any assist provided by the SA9T should be considered as incidental and not be attributed to TCC design safety margin.

Summary

The combined CO₂ and humidity control project schedule has been accelerated with the primary focus on a design specific to the CEV. Subscale testing using a 1/2 scale test article has been completed and has shown that a total sorbent volume of 400 in³ in a single canister is adequately sized to remove the CO₂ and water for a crew of 3. Two canisters are assumed to operate in parallel which reduces the weight and volume required to meet a two-fault tolerant design. With two failures, testing has demonstrated the ability of a single canister to meet the performance requirements of a crew of six in a slightly degraded mode. The canister assembly has been completed and the valve manufacture is ongoing.

References

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