Design and Assembly of an integrated Metabolic heat regenerated Temperature Swing Adsorption (MTSA) Subassembly Engineering Development Unit

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Metabolic heat regenerated Temperature Swing Adsorption (MTSA) technology is being developed for thermal and carbon dioxide (CO_2) control for a Portable Life Support System (PLSS), as well as water recycling. The core of the MTSA technology is a sorbent bed that removes CO_2 from the PLSS ventilation loop gas via a temperature swing. A Condensing Icing Heat eXchanger (CIHX) is used to warm the sorbent while also removing water from the ventilation loop gas. A Sublimation Heat eXchanger (SHX) is used to cool the sorbent. Research was performed to explore an MTSA designed for both lunar and Martian operations. Previously the sorbent bed, CIHX, and SHX had been built and tested individually on a scale relevant to PLSS operations, but they had not been done so as an integrated subassembly. Design and analysis of an integrated subassembly was performed based on this prior experience and an updated transient system model. Focus was on optimizing the design for Martian operations, but the design can also be used in lunar operations. An Engineering Development Unit (EDU) of an integrated MTSA subassembly was assembled based on the design.

Nomenclature

°C	=	degrees Celsius
CIHX	=	Condensing Icing Heat eXchanger
CO_2	=	Carbon Dioxide
ECLSS	=	Environmental Control and Life Support System
EVA	=	Extra Vehicular Activity
EDU	=	Engineering Development Unit
EBM	=	Electron Beam Melting
EHF	=	ECLSS Human Rated Facility
g	=	grams
H_2O	=	Water
in^3	=	cubic inches
IR&D	=	Internal Research and Development
K	=	Kelvin
kPa	=	kilopascal
LCO_2	=	Liquid CO_2
LCVG	=	liquid cooling ventilation garment

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mg/s	=	milligrams per second
MTSAS	=	MTSA Subassembly
N_2	=	Nitrogen
O_2	=	Oxygen
PLSS	=	Portable Life Support System
$PPCO_2$	=	Partial Pressure CO_2
PPI	=	Pores Per Inch
s	=	Seconds
SHX	=	Sublimation Heat eXchanger
W	=	Watts

I. Introduction

Metabolic heat-regenerated Temperature Swing Adsorption (MTSA) is patent-pending (USPTO 61222208) technology, being developed for Portable Life Support Subsystem (PLSS) carbon dioxide (CO_2) removal and rejection as well as thermal regulation and humidity control. The metabolically-produced CO_2 present in the ventilation loop gas of a PLSS is collected using a CO_2-selective sorbent via temperature swing adsorption. The temperature swing is achieved through cooling using Martian extracted liquid CO_2 (LCO_2) and warming using heat from ventilation loop gas used by the astronaut. Figure 1 illustrates how an MTSA system would be operated in a PLSS using two sorbent beds. Each bed is cycled between adsorb and desorb mode. The concept and its development history has been described previously in detail,[1, 2, 3, 4] but is summarized briefly here as well.

A schematic demonstrating how the MTSA can be employed in a PLSS is shown in Figure 1. Ventilation gas returning from the astronaut enters the PLSS. Metabolic heat and humidity are first removed from the ventilation loop (on the left) via the Condensing Icing Heat eXchanger (CIHX) in contact with the cold sorbent bed fully loaded with metabolically-produced CO_2. Water condenses out of the ventilation gas and initially freezes. The trapped metabolically-produced CO_2 in the sorbent is rejected to ambient as the bed is warmed (straight red arrow pointing down on left). Meanwhile, as the bed continues to warm (to ~280 K), the ice thaws inside the CIHX and condensate is saved.

The ventilation gas exiting the CIHX is now cooler and drier. A recuperative membrane and desiccant will be required to remove any remaining moisture (water can limit a sorbent's CO_2-loading capacity). Passing through the second bed, metabolically-produced CO_2 is removed from the ventilation gas by the sorbent. To increase the capacity of the sorbent in the second bed, the sorbent is cooled with coolant via the Sublimation Heat eXchanger (SHX) (blue lines pointing up on right). Coolant gas exhaust is further used with the liquid cooling ventilation garment (LCVG) for thermal control before being rejected to the mostly-CO_2 Martian atmosphere.

Regenerated, pure oxygen ventilation gas exits the sorbent bed. A recuperative heat exchanger is used to warm the ventilation gas prior to return to the astronaut. Lastly, the dry line is humidified with the membrane recuperative humidifier.

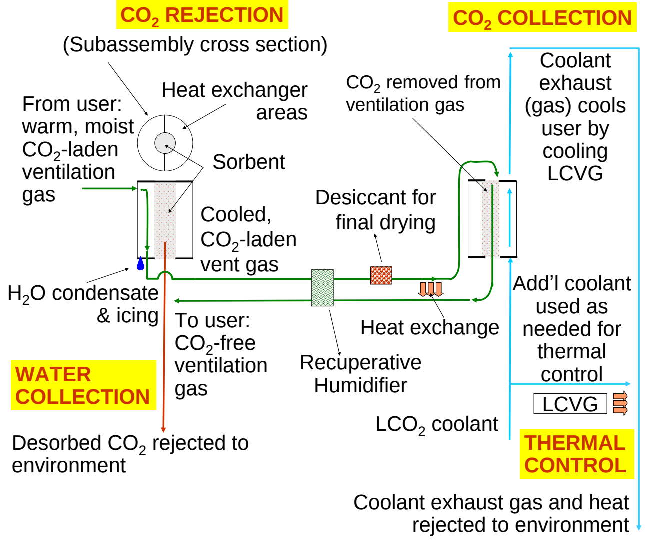

Figure 1. Two bed MTSA system operation.

Continuous removal of metabolically-produced CO_2 is achieved using two beds that cycle between desorb mode (CO_2 rejection) and adsorb mode (CO_2 collection). Each bed will perform the same loading and unloading cycles as shown in Figure 2. Figure 2 (left side of the figure) demonstrates how each bed works in adsorb and desorb modes to ensure continuous CO_2 removal. Figure 2 (right side) demonstrates how the CO_2 loading changes with temperature and pressure within a given bed for a Martian application.

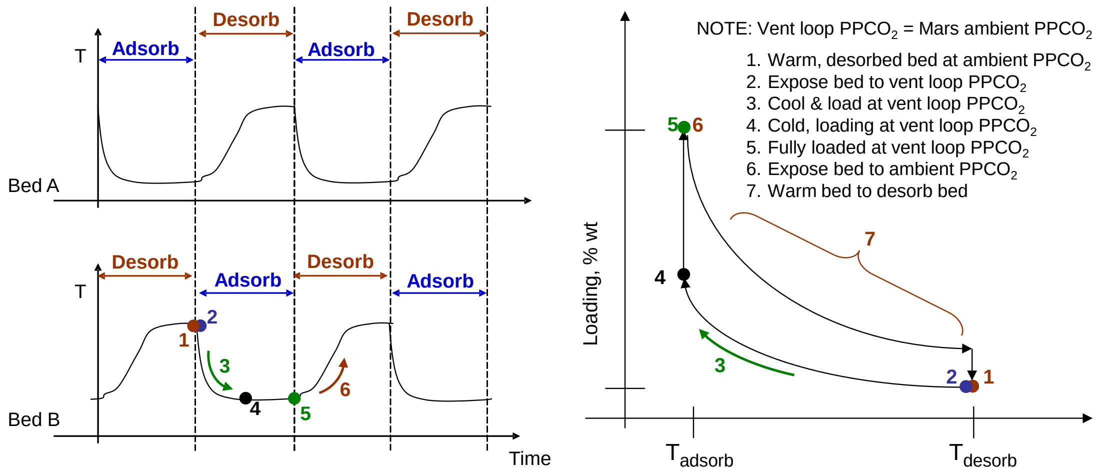

Figure 2. (Left) Loading cycles (temperature vs time); (right) % Loading changes vs. temperature.

MTSA was originally designed for Mars using LCO_2 coolant derived from the Martian atmosphere. Production of LCO_2 on Mars from the readily available CO_2 atmosphere can be achieved for relatively low power using the cold Martian nights to facilitate the process. This is a tremendous mass savings and reduction in mission risk because missions do not have to rely on the coolant being launched from Earth. Additionally, as LCO_2 is not cryogenic, reserves of LCO_2 can be stored on the surface of Mars with no risk of boil-off. To extend an EVA or obtain emergency cooling, it is only necessary to switch out or refill the LCO_2 tank. Finally, as the cooling capacity of the LCO_2 is consumed, its exhaust can be safely expelled to the Martian atmosphere where it does not contaminate the surrounding environment (the Martian atmosphere is 95% CO_2). Thus, a Martian PLSS that uses MTSA will not interfere with scientific investigations by contaminating samples with water vapor as its coolant (the Martian-derived CO_2) is sublimated for heat rejection.

MTSA is also a means for risk mitigation because it does not have technologies in common with the current spacesuit PLSS baseline. This means heat rejection and ventilation loop CO_2 and humidity control are all handled completely differently than the current baseline. As MTSA technology addresses well the challenges posed by missions performed in the unique environment of Mars, with very limited accessibility from Earth, pursuing MTSA is sound justification for mitigating PLSS development risk.

Such a system would be ideally suited for use on Mars where LCO_2 may be produced with relative ease and would not risk contamination of the environment. However, the same hardware may also permit removal of metabolic CO_2 in a lunar environment solely through a vacuum swing on the sorbent. Thus the primary considerations for the technology may be made for a Mars focused design without need for modification for use on the moon.

In addition, the design can theoretically be used on the Moon with no modifications to the sorbent bed. The lunar vacuum can be used to regenerate the sorbent bed alone via a vacuum swing. This reduces the amount of coolant required and uses the Moon as a test bed for furthering Mars technology development, but will require an as of yet unidentified means of drying the ventilation loop gas. Previous testing had always been performed in a Martian environment,[4] and the current effort designed and built an Engineering Development Unit (EDU) to the Martian requirements that can also be used in a lunar environment.

A. Objective

The objective of this paper is to describe the MTSA subassembly (MTSAS) EDU design, capable of being tested in Paragon's ECLSS Human-rating Facility (EHF). The design enables operation on Mars, even though near term testing would be performed in a lunar simulated environment. This will show that a Martian design can work on the Moon. Finally, fabrication of the full scale MTSAS EDU will be discussed.

II. MTSAS Engineering Development Unit Design

A. Martian Design Scenario and Parameters

A fully functional MTSAS is comprised of a sorbent bed (for CO_2 removal), the SHX (for cooling), and the CIHX (for moisture removal and warming). In the Martian configuration the system is reliant on a minimum level of sorbent performance. This is driven by the temperature cycling that must be done to adsorb CO_2 and to regenerate the bed. There is a fixed amount of metabolic heat available from the ventilation loop gas to warm the sorbent bed. Any MTSAS structure / mass other than the sorbent needs to be minimized as it diverts precious heat away from the sorbent that needs to be warmed to desorb the adsorbed, metabolic CO_2. While LCO_2 used for cooling affects mass of the system, it can be easily regenerated in the Martian environment, so it is not as limiting as warming supplied by the ventilation loop gas.

B. Lunar Design Scenario and Parameters
Thermal Desktop® and SINDA/FLUINT models developed previously[6] were used to elucidate lunar operations of the MTSAS. Lunar operation is not limited by the operation of a warming or cooling device, only on the sorbent capacity. In this mode of operation, cycles are no longer tied to how long it takes the CIHX to warm the bed. Instead, the cycle can be operated purely based on the time it takes for breakthrough to occur in the sorbent bed assuming the same amount of time is sufficient to desorb. Reduced sorbent density in the bed shortens cycle time and can increase ventilation gas losses as the system switches to expose the sorbent bed to the lunar vacuum environment for metabolic CO_2 desorption. The vacuum swing, at assumed constant temperature, that drives the adsorption / desorption cycle, cycles between the 0.1 psi $PPCO_2$ (4.3 psia total pressure) PLSS ventilation pressure and the lunar vacuum. As a bed, currently in adsorb mode, reaches breakthrough the system switches it to desorb mode where it can be vented and reconditioned. For an operational temperature of 298 K, a maximum delta capacity of about 5% mass loading of CO_2 per mass of sorbent is possible. Based on previous experience,[4] only about 2% loading is expected because the bed cannot be fully reconditioned by vacuum swing alone, but this reduced cycling capacity should be sufficient for lunar operations.

C. Design Methods
A detailed look at design concepts and fabrication considerations for the MTSAS EDU was undertaken during this effort. Design tools previously built using Mathcad and Excel for individual component and system level analyses[7] were reexamined, modified, and/or reworked to apply to the EDU design. The tools as-built compile a large number of thermodynamic, heat transfer, and fluid flow equations, but further texts were also consulted and equations used to develop the design. This resulted in a Mathcad model that was used to guide the design for an EDU of the MTSAS.

The team first revisited the approach and results of previous efforts, extending back nearly to the inception of work on MTSA[8]. From this a list of features / considerations was compiled and each individual team member then brainstormed concepts for the EDU general design. The result was essentially a single conceptual design of the EDU despite the individual assessments made. In large part this was due to the recognition by all parties of the significant mass sensitivity of the design as it pertains to transient heat transfer. The concept centers on a cylindrical sorbent bed within a tube that contains the vent-loop flow. This, in turn, has small diameter tubing attached to the outside to function as the SHX and then a surrounding CIHX shell. It was recognized that it may not be desirable / necessary to fully encapsulate the assembly with the CIHX because the benefit of the added heat transfer area is negated by the added mass. A mass to heat exchanger area optimization dictates that the CIHX only needs to attach to a portion of the sorbent bed. A rough potential cross-section view is shown in Figure 3.

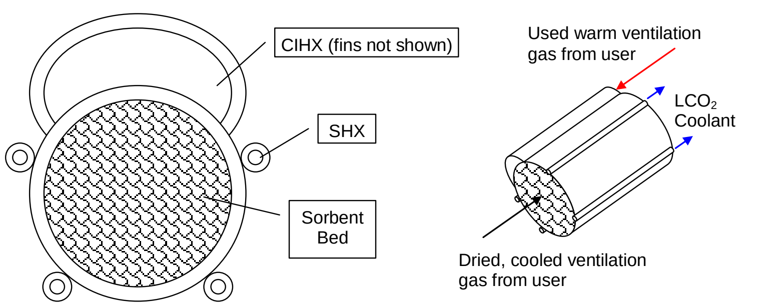

Figure 3: Conceptual Illustration of the EDU MTSAS (Left) Cross-Section & (Right) Side View

With a new geometry concept chosen there was interest in exploring the potential system effects that arose from the design change (original design concept summarized in previous work[4]). The tool generated for the most recent system impact study[7] was updated to use the radial geometry in place of the rectangular geometry originally established. The tool was also rearranged to allow the sorbent bed volume to be automatically determined based on the metabolic rate of CO_2 produced, weight loading of CO_2 on the sorbent, a multiplier of 1.1 on volume to account for degradation of the sorbent performance over time, and the amount of sorbent that can be washcoated onto a unit amount of foam.

D. Design and Fabrication Considerations

The key driver to the final design is the expected change in weight loading capacity over the temperature swing. In prior work,[9] tests with sorbent pellets resulted in a weight loading of approximately 11% under loading conditions relevant to the EDU design (under Martian simulated conditions). This compares to a maximum value of 7.6% demonstrated using sorbent washcoated foam (explored for higher heat transfer rates and lower pressure drop).[5] This could be seen as a risky assumption, but for the EDU, it is expected that performance will be more like that of the pellets since the EDU is able to attain more even coating of the sorbent with less of the pore bridging thought to prevent full utilization of the bed in prior testing. In addition to this, the EDU bed is longer and of greater cross section than the previous washcoated test articles resulting in greater dwell times in the sorbent bed. Thus an 11% change in capacity over a range of 210 K to 280 K is used in the design of the EDU. This input, coupled with the washcoat density achieved in the washcoat test articles (~1.35 g of sorbent per in^3), requires an assumption of CIHX energy extraction efficiency and design mass metric, which results in the EDU design. In this design the system requires that 190 g of sorbent be used in the EDU article.

One of the more important metrics derived from the modeling effort is the time required to warm the CIHX from 210 K to 283 K (the temperature required to warm the sorbent bed to 280 K). This defines the minimum half cycle time and was calculated to be 890 seconds for the EDU. For this design to close, conservatively assuming the sorbent washcoat density is the same as the previous test articles, the sorbent bed must have a delta loading capacity of about 13% between the cold adsorption condition and the Martian exhaust condition. In theory, the bed can hold a difference of about 17% in these conditions. Since the washcoat density in the EDU article is expected to be about 20% greater than that previously tested[5] the EDU may only require a loading capacity swing of 10.5% to allow a closed cycle. Further, the SHX is expected to perform the required cooling in about 550 seconds[6]. These both indicate performance margin on the EDU.

Taking all the available information into account and considering previous experience, the EDU design pursued a washcoated aluminum foam sorbent bed with an outer case made via wire Electrical Discharge Machining (EDM). This allows the EDU to be built such that each portion of the design is known to be achievable including sorbent loading, pending verification, and casing wall thickness. It requires significant consideration for the incorporation of caps and plumbing connections due to the constant cross-section necessary for the primary component using these fabrication techniques. Detailed design needs to consider characteristics and tolerances for the various assembly processes that will be used to form a single, cohesive unit as well as the order in which the sub-components will be assembled. This approach would minimize the risk associated with fabricating an EDU that will perform as needed and expected.

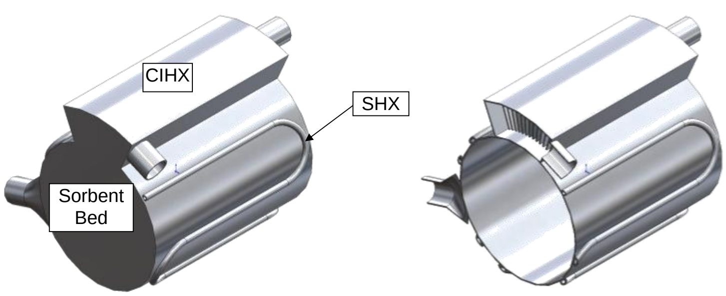

Figure 4: MTSAS EDU Design (Left) MTSAS, assembled. (Right) front end cap removed

It was decided that the foam used within the EDU be 8% relative density and 40 PPI. Paragon and Precision Combustion, Incorporated (PCI) of North Haven, CT are comfortable with this arrangement as it was used within the two test articles manufactured previously. It was tempting to choose a foam that would elicit more surface area in a given volume, but the only potential way to increase the ratio would be with increased density and the same pore characteristic. Increasing the foam density while maintaining PPI would result in a foam with thicker strands and thus smaller overall pore size. This is not desirable as bridging within previous test articles was already suspected to impact performance. In order to reduce the risk of the EDU being coated poorly, dummy beds were given to PCI to coat prior to the EDU which permitted the coating parameters to be optimized prior to coating the EDU.

The preliminary design of the EDU is shown conceptually in Figure 4 through Figure 5. The large central cylinder houses the foam sorbent bed. The top, "Mohawk" feature is the CIHX and the small diameter tubes that are snaked around the outside of the sorbent bed are the SHX.

The plan for building the EDU involves three key vendors that Paragon has worked with in past MTSA efforts. ERG Materials and Aerospace Corp. of Emeryville, CA fabricated the structure of the EDU (this includes the CIHX, the SHX, and the sorbent bed as well as end caps that will seal the EDU). PCI wash coated the partially assembled sorbent bed / foam structure with the sorbent. S-Bond Technologies of Lansdale, PA then attached the end caps to the EDU using their low temperature solder joining process that prevents damage to the sorbent coating applied by PCI. Final integration, assembly into the test bed, and testing was then performed by Paragon at its Tucson facility. Table 1 lists example design parameters of the MTSA EDU.

Figure 5: MTSASEDU Cross-section, front end cap and inlets removed, view at back wall of subassembly

Table 1. MTSA EDU Design Parameters
(all dimensions in inches unless otherwise noted)

No.	Parameter	Value
1.	Sorbent Bed Dimensions and Sizing	~ 9" in length & 5" in diameter
2.	Foam material	Nominal 8% dense, 40 PPI, 6101 aluminum
3.	Casing material	6061 aluminum
4.	Foam substrate integration	Foam is vacuum brazed to housing
5.	Sorbent bed inlet port orientation	Radial, perpendicular to CIHX center plane
6.	Sorbent bed inlet port placement	No interference with foam substrate is allowed
7.	Sorbent bed outlet port orientation	Axial, centered
8.	CIHX Dimensions and Sizing	~ 1" tall, ~ 8.5" long, with 9 channels
9.	CIHX inlet port orientation	Radial to sorbent bed, inline with CIHX center plane
10.	CIHX inlet port placement	No interference with CIHX fins is allowed
11.	CIHX outlet port orientation	Axial, centered
12.	SHX Dimensions and Sizing	Symetrically spaced around the sorbent bed with 8 passes

III. MTSA Engineering Development Unit Fabrication

The EDU hardware is depicted and labeled in Figure 6. ERG was responsible for fabricating the structure of the EDU as well as brazing of the foam sorbent bed into the structure, attachment of the SHX tubes, and welding on the CIHX end caps and inlet / outlet tube stubs for the flow of gasses through the CIHX and sorbent beds.

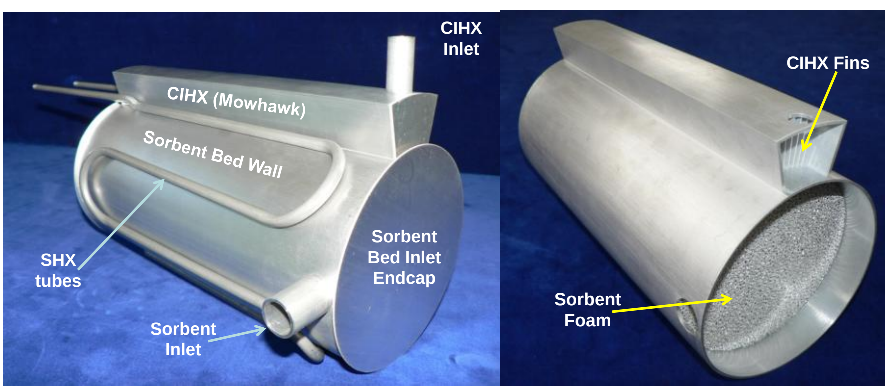

Figure 6. Pre-Braze mock assembly of the MTSAS EDU

In addition to the structure of the MTSAS EDU, ERG also provided three reduced geometry sorbent coating development units. This hardware was comprised of 8% dense 40 PPI aluminum foam (the same as in the MTSAS EDU) that was roughly the same dimensions as used in the MTSAS EDU. The foam was housed inside a cylindrical tube that was cut in half (like a clam shell) along the cylinder axis and held together by band clamps. The foam bed was fabricated in 12 separate, but equal, cylindrical segments. This allowed the sorbent coating vendor (PCI) to develop and verify the sorbent coating process prior to coating of the MTSAS EDU. Because the reduced geometry sorbent coating development units were fabricated in pieces, PCI was able to take the foam out of the cylindrical housing and evaluate the mass and distribution of sorbent in the foam. Figure 7 shows a picture of an assembled reduced geometry sorbent coating development unit as well as one with the top ½-cylindrical clamshell removed to show the 12 foam sections contained within.

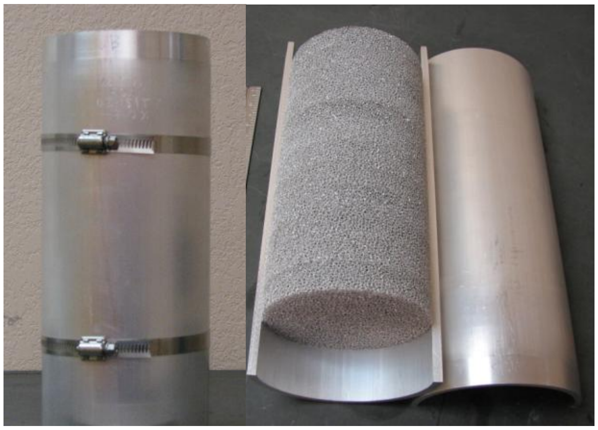

Figure 7. Reduced Geometry Sorbent Coating Development Units

The washcoating of the sorbent onto the three units is shown in Figure 8 (results are normalized to average sorbent mass on an individual foam slice). The second and third units that were coated (units B and C respectively, in Figure 8) showed an increased loading over the first unit (unit A) and allowed PCI to refine their coating process. Sorbent densities (mass of sorbent per volume of foam) achieved for the Reduced Geometry Sorbent Coating Development Units were 1.46, 1.68, and 1.66 g/in^3 for units A, B, and C respectively.

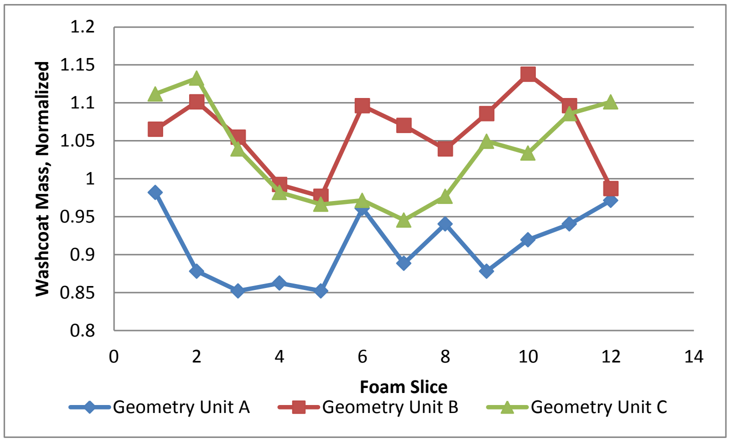

Figure 8. Sorbent Coating of the Reduced Geometry Sorbent Coating Development Units, Mass of Individual Foam Sections (normalized to average sorbent mass on foam slice)

PCI then proceeded to the coating of the MTSAS EDU hardware. This was done rapidly in series so that lessons learned on the coating development units could be freshly leveraged for the delivered hardware. The final coating of the MTSA EDU achieved 1.65 grams of sorbent per cubic inch of foam, which, as shown in Table 2, is on average a 30% increase in sorbent density over previous MTSA efforts;.

Additionally, the coating on the MTSA EDU (left picture in Figure 9) is much more uniform, much more open, and with significantly less sorbent bridging than either of the previously coated test articles[4] (center and right pictures in Figure 9). This should result in more even flow, and greater sorbent utilization.

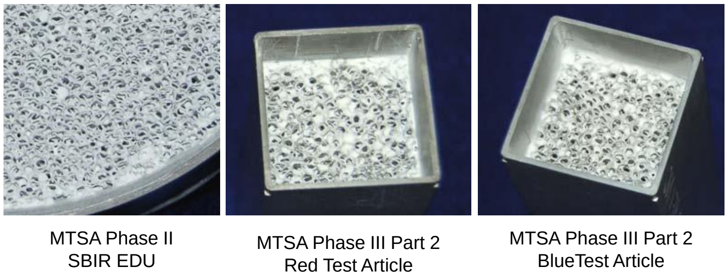

Figure 9. Sorbent Bridging Comparison (Proprietary Wash Coating By Precision Combustion, Inc.)

Final assembly of the MTSA EDU occurred at S-Bond Technologies using their low temperature soldering process to attach the sorbent bed end-caps onto the sorbent bed.

A. Analysis and Discussion

Table 2. MTSA EDU Sorbent Density

	Sorbent Density	
	g/ in^3	g/cc
MTSAS EDU	1.65	0.1005
Previous Test Article "Blue"	1.19	0.0726
Previous Test Article "Red"	1.34	0.0818

The design and instrumentation of the EDU was planned and implemented with the future intent of testing the article in a Martian simulated environment using the CIHX and SHX. Where possible, the EDU contains hardware and sensors that allow smooth transition to that set of tests. Just as in lunar testing, the most important part of the Martian testing is the adequate characterization of the performance of the sorbent bed. Here, however, system feasibility relies on meeting the designed-to sorbent performance. In the lunar testing reduced sorbent bed capacity can be overcome by faster cycle times. In the Martian configuration the system is reliant on a minimum level of sorbent performance. As noted in section II.D, the EDU design assumed 1.35 g of sorbent per in^3 of foam, which required an 11% delta-weight loading on the sorbent. With the 1.65 g/ in^3 of sorbent that is loaded in the EDU, a cycle loading of only 9% is now expected to allow full cycle operation with the current EDU design.

IV. Conclusions

The MTSAS EDU was designed and successfully built. During this effort, the following observations were made:

a. Analysis shows that a single tube SHX is more effective over a finned HX, especially given the thermal sensitivity to thermal mass.
b. Similarly, the CIHX only needs to cover a small portion of the unit.
c. Paragon and NASA's investment in the PCI-recommended reduced geometry sorbent coating development units was a sound investment as PCI was able to achieve 23% more sorbent loading than was previously attained. Visually the EDU has a lot less bridging, despite having higher sorbent density than test articles of prior efforts.
d. Prior work and mass sensitivity drove the design larger than previous efforts (but still within requirements) but developments by PCI now promise further reductions in size. [10]
e. Initially an MTSAS built using Electron-Beam Melting (EBM) was considered. EBM is a type of additive manufacturing, with a lattice substrate that has the potential to be the most desirable solution for fabrication. It has a high relative density for maximum sorbent loading, does not require brazing as it is integrally linked to the structure walls (perfect thermal contact), and would potentially reduce the risk of leaks. However, at the present time such an ideal solution is not possible largely due to the infancy of the EBM technology and lack of multiple data points for sorbent loading on an aluminum lattice structure. Taking such an approach for the EDU was simply too risky at this stage in the development of MTSA.
f. The unit was tested in a simulated lunar vacuum. Despite a seal failure, the performance met requirements (see Ref 10).

V. Future Work

As detailed herein, the work performed helped to greatly develop the MTSAS technology. Additionally it elucidated approaches for future work to mature this technology:

a. Along with integrated Martian testing, independent evaluation of each of the three MTSAS components (sorbent bed, CIHX and SHX) should be performed to allow for independent, parametric characterization and application in future design optimization.
b. Following a full suite of Martian and characterization testing, this data can be leveraged to perform model verification and correlation. With the implementation of improved physics modeling to the existing model, framework model validation can be performed within the MTSA design space to support optimization of the MTSA system.
c. The system analysis model in Mathcad was used to develop an optimized EDU design. This model, when coupled with the more complete physics model (from the previous bullet), will be able to optimize MTSA system around the optimized MTSAS from the Thermal Desktop™ model.
d. Exploration into direct or indirect coupling of the Mathcad system model and MTSAS Thermal Desktop™ model should be explored in order to model to support optimization by reducing iteration time and interface complexity.

e. A water capture system for the CIHX that is tolerant of gravities between zero and 1 g still needs to be developed. The current EDU relies upon gravitational acceleration to remove the water from the CIHX and will not work in a micro-gravity environment.

System considerations are as follows:

f. A desiccant / water removal system, prior to the sorbent bed that augments the water removed by the CIHX needs to be identified and/or designed. Additionally the desiccant bed needs to be designed such that waste heat generated by water removal is dissipated from the bed.
g. Auxiliary components of the MTSA system need to be designed and identified. The following components are of near term interest; ventilation loop switching valve that controls adsorption and desorption and the recuperative heat exchangers.
h. Paragon has been introduced recently to some advanced sorbents that may increase the performance of the MTSA technology. These need to be explored as they could significantly decrease the mass and volume of the system.
i. Additionally an exploration of more dense, greater areal density sorbent substrates and advanced manufacturing technologies (EBM and related technologies) would be worthwhile to determine if additional system optimization is achievable.

VI. Acknowledgments

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