

Microlith[®]-based Catalytic Reactor for Air Quality and Trace Contaminant Control Applications

Saurabh Vilekar¹, Kyle Hawley², Christian Junaedi³, Bruce Crowder⁴, Julian Prada⁵, and Richard Mastanduno⁶
Precision Combustion, Inc., North Haven, CT, 06473

and

Jay L. Perry⁷ and Matthew J. Kayatin⁸
NASA George C. Marshall Space Flight Center, Huntsville, AL, 35812

Traditionally, gaseous compounds such as methane, carbon monoxide, and trace contaminants have posed challenges for maintaining clean air in enclosed spaces such as crewed spacecraft cabins as they are hazardous to humans and are often difficult to remove by conventional adsorption technology. Catalytic oxidizers have provided a reliable and robust means of disposing of even trace levels of these compounds by converting them into carbon dioxide and water. Precision Combustion, Inc. (PCI) and NASA – Marshall (MSFC) have been developing, characterizing, and optimizing high temperature catalytic oxidizers (HTCO) based on PCI's patented Microlith[®] technology to meet the requirements of future extended human spaceflight explorations. Current efforts have focused on integrating the HTCO unit with a compact, simple recuperative heat exchanger to reduce the overall system size and weight while also reducing its energy requirements. Previous efforts relied on external heat exchangers to recover the waste heat and recycle it to the oxidizer to minimize the system's power requirements; however, these units contribute weight and volume burdens to the overall system. They also result in excess heat loss due to the separation of the HTCO and the heat recuperator, resulting in lower overall efficiency. Improvements in the recuperative efficiency and close coupling of HTCO and heat recuperator lead to reductions in system energy requirements and startup time. Results from testing HTCO units integrated with heat recuperators at a variety of scales for cabin air quality control and heat melt compactor applications are reported and their benefits over previous iterations of the HTCO and heat recuperator assembly are quantified in this paper.

¹ Senior Research Engineer, Microlith[®] Products, 410 Sackett Point Rd., North Haven, CT 06473.

² Lead Development Engineer, Microlith[®] Products, 410 Sackett Point Rd., North Haven, CT 06473.

³ Manager, Microlith[®] Research, 410 Sackett Point Rd., North Haven, CT 06473.

⁴ Senior Mechanical Design Engineer, 410 Sackett Point Rd., North Haven, CT 06473.

⁵ Mechanical Design Engineer, 410 Sackett Point Rd., North Haven, CT 06473.

⁶ Director of the Engineering and Design Group, 410 Sackett Point Rd., North Haven, CT 06473.

⁷ Lead Aerospace Engineer, Space Systems Dept., NASA-MSFC/ES62, Huntsville, AL 35812.

⁸ Aerospace Engineer, Space Systems Dept., NASA-MSFC/ES62, Huntsville, AL 35812.

Nomenclature

$^{\circ}C$	= degree Celsius	<i>PCI</i>	= Precision Combustion, Inc.
<i>GSA</i>	= geometric surface area	<i>ppm_v</i>	= parts per million by volume
<i>hrs</i>	= hours	<i>psia</i>	= pound per square inch absolute
<i>HMC</i>	= heat melt compactor	<i>MSFC</i>	= Marshall Space Flight Center
<i>HTCO</i>	= high temperature catalytic oxidizer	<i>SLPM</i>	= standard liter per minute (21°C, 14.7 psia)
<i>in</i>	= inch	<i>SMAC</i>	= spacecraft maximum allowable concentration
<i>kg</i>	= kilogram	<i>TCCS</i>	= Trace Contaminant Control System
<i>kPa</i>	= kilopascal	<i>VDC</i>	= voltage (direct current)
<i>L</i>	= liter	<i>VOC</i>	= volatile organic compounds
<i>m</i>	= meter	<i>W</i>	= watts
<i>mm</i>	= millimeter		
<i>min</i>	= minute		
<i>Pa</i>	= Pascal		

I. Introduction

CONTAMINATED air is a universal problem which affects applications ranging from terrestrial buildings to space travel. Sources of contamination include offgassing of materials along with industrial and metabolic processes. Traditionally, spacecraft cabin air quality control is accomplished via physical and chemical adsorption of contaminants on pellet based adsorption media such as activated carbon and zeolites. While these methods are effective at removing a variety of volatile compounds, they are often less effective at removing light hydrocarbons (e.g. methane), alcohols, and carbon monoxide.¹ To overcome these limitations thermal catalytic oxidation has been proposed and demonstrated to be a viable addition to trace contaminant control systems (TCCS). A schematic of the TCCS with the catalytic oxidizer is shown in Figure 1.

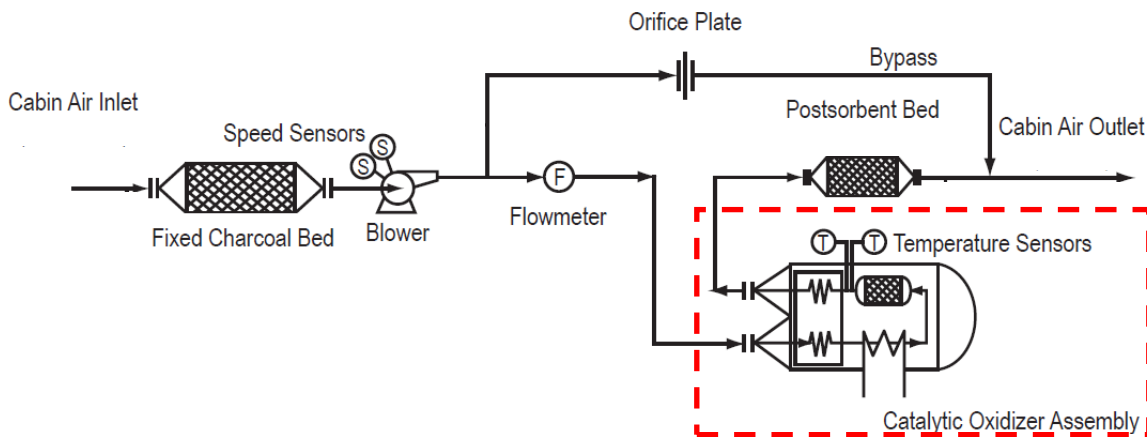


Figure 1. Schematic of the current TCCS system with integrated catalytic oxidizer subsystem.¹

Thermal catalytic oxidation involves heating a process stream in the presence of catalyst to convert contaminants into carbon dioxide and water. The viability of this technology hinges on its safety, reliability, and power consumption. In recent years, Precision Combustion, Inc. (PCI) has developed prototype catalytic oxidizers based on its patented ultra-short channel length Microlith[®] technology for NASA – Marshall (MSFC) and other commercial companies.^{1,2} These prototypes consisted of only one of the two components necessary for the catalytic oxidation subsystem. In order to be viable and reduce its energy requirements, a catalytic oxidizer must be thermally-integrated with a secondary heat exchanger/recuperator to recycle the waste heat back to the oxidizer. While it is possible to couple the oxidizer and the recuperator as two separate units, significant size and weight benefits can be realized by integrating these components into a single unit. In addition, a separate heat exchanger limits the efficiency of the overall system due to its larger surface area and increased heat loss. In pursuit of this goal, PCI has designed and tested catalytic oxidizer systems with integrated recuperators which overcome many of these limitations.

In addition to targeting size, weight, and efficiency improvements, the design drivers for trace contaminant control have been evaluated for deep space exploration missions. The primary compounds that have the greatest influence on TCCS equipment flow rate are ammonia and formaldehyde. Ammonia drives not only the flow rate for the adsorbent fixed bed component in TCCS equipment architecture, but also determines the size of the bed. Compounds such as dichloromethane and siloxanes, which are secondary design drivers for the adsorbent fixed bed size, are incompatible with thermal catalytic oxidation processes due to either acid gas production or catalyst fouling risks.

The design driving compounds for an HTOCO component have typically consisted of methane and carbon monoxide. For the International Space Station TCCS HTOCO unit, achieving >95% single pass methane oxidation efficiency sets the catalyst bed operating temperature while the carbon monoxide generation rate sets the flow rate. In 2008, the cabin air quality standard for carbon monoxide was relaxed by 50% from 10 ppm_v to 15 ppm_v. As well, International Space Station flight operations and improved materials screening methods have provided greater insight on formaldehyde generation. As a result, formaldehyde has replaced carbon monoxide as the flow rate driver for a TCCS HTOCO component. The objective is to operate an HTOCO unit at a temperature condition to achieve >95% single pass methane oxidation efficiency and to provide sufficient process air flow through the HTOCO unit to provide a formaldehyde concentration <35% of its spacecraft maximum allowable concentration (SMAC). The <35% SMAC target not only provides adequate formaldehyde control, but also contributes to maintaining the overall trace contaminant load for TCCS equipment design below a toxic hazard threshold for that specific mixture of compounds.³ To provide the necessary performance, an HTOCO unit designed for deep space exploration missions that support four crewmembers and accommodate offgassing from 15,000 kg of equipment must treat at least 24 SLPM at a catalyst bed temperature of 400°C. The flow rate increases to 40 SPLM to accommodate a crew of six and offgassing up to 75,000 kg. To accommodate the uncertainty that exists regarding future exploration mission objectives, crew size, and vehicle design, the higher, more challenging flow condition has been recommended as the design goal for an HTOCO unit.

II. Microlith[®] Substrate and Catalytic Technology

The development efforts described here are based on PCI's patented Microlith technology (trademarked by PCI).⁴ The Microlith substrate consists of a series of ultra-short-channel-length, catalytically coated metal meshes with very small channel diameters (Figure 2). The mesh-like substrates provide very high heat and mass transfer coefficients, low thermal mass, and extremely high reaction rates. The use of this kind of reactor, where the reacting stream is passed through the catalyst at extremely high space velocity, is generically termed as short contact time approach. Whereas in a conventional honeycomb monolith, a fully developed boundary layer is present over a considerable length of the device, the ultra-short-channel-length Microlith substrate minimizes boundary layer buildup, resulting in remarkably high heat and mass transfer coefficients compared to other substrates (e.g., monoliths, foams, and pellets). In PCI's catalytic oxidizer units, the unique metal mesh substrate permits direct resistive heating of the elements. This enables a highly uniform temperature distribution throughout the catalyst bed eliminating local hot spots and temperature excursions, preventing catalyst deactivation due to metal sintering. Additionally, it lessens reactant bypassing, if any, by eliminating any local cold spots. The Microlith substrate also provides about three times higher geometric surface area (GSA) over conventional monolith reactors with equivalent volume and open frontal area (i.e., low pressure drop for the same flow rate).

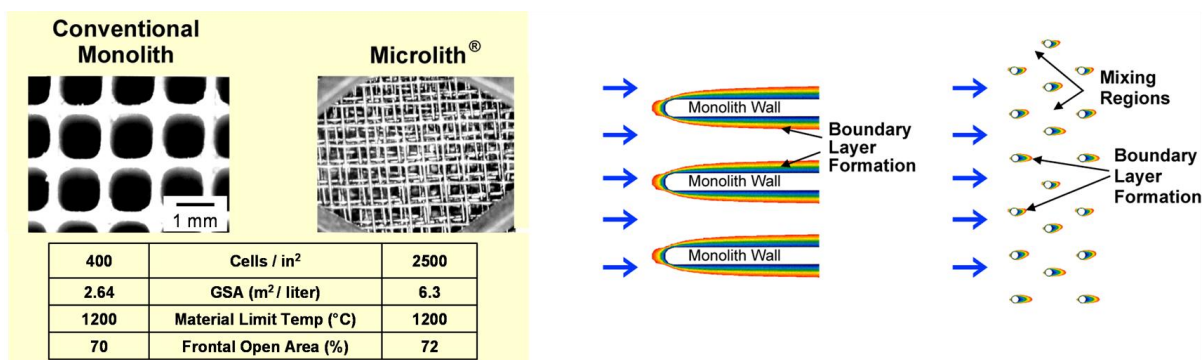


Figure 2. Physical characteristics of conventional, long honeycomb monolith and Microlith substrates, and CFD analysis of boundary layer formation for a conventional monolith and three Microlith screens.

The heat and mass transfer coefficients depend on the boundary layer thickness. For a conventional long channel honeycomb monolith, a fully developed boundary layer is present over a considerable length of the catalytic surface, thus limiting the rate of reactant transport to the surface of active sites. This is avoided when short channel length catalytic screens are used. A Computational Fluid Dynamics (CFD) analysis (Figure 2) illustrates the difference in boundary layer formation between a monolith and Microlith screens. Finally, PCI's proprietary catalyst coating formulations and application methods, with high surface area washcoats, allow for very low catalyst usage with rigorously demonstrated long-term mechanical, thermal, and performance durability.

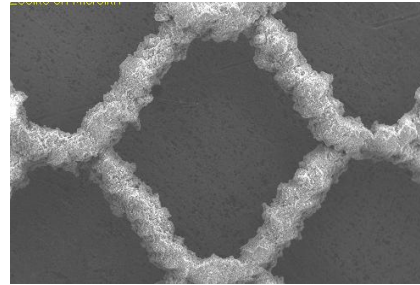


Figure 3. Surface-scan SEM micrograph of the coated Microlith substrate.

The use of catalyst substrates with high heat and mass transfer rates, high surface area, and low pressure drop has a significant impact on reactor performance and size as compared to pellet or monolith based units. The effectiveness of the Microlith technology and long-term durability of PCI's proprietary catalyst coatings have been systematically demonstrated in different applications. These include exhaust post-treatment,⁵ trace contaminant control,^{6,7} catalytic combustion,⁸ partial oxidation of methane,^{9,10} liquid fuel reforming,¹¹ CO preferential oxidation, and water gas shift reactors.¹² A scanning electron microscopy (SEM) micrograph of the coated Microlith substrate is shown in Figure 3. SEM analysis indicates uniform catalyst coatings on the substrate with complete coverage.

III. Results and Discussion

A. Trace Contaminant Control System (TCCS)

1. First Generation HTCO for TCCS

Previous development efforts performed by PCI resulted in a high temperature catalytic oxidizer (HTCO) designed, fabricated, and delivered to NASA-MSFC for performance evaluation and validation with their existing external recuperator test fixture.¹ This unit was designed to meet the original performance targets of >95% methane single pass destruction efficiency and a flow rate sufficient to control carbon monoxide to <50% SMAC for a trace contaminant load produced by up to six crewmembers and offgassing from 75,000 kg of equipment. The process air flow condition necessary to control this load was ~76 SLPM and the catalytic reactor temperature was 400°C. The unit, once integrated with the heat exchanger/recuperator, weighed approximately 5.6 kg and had a volume of approximately 7.3 L (assuming 6.25 inch flange diameter and 14.5 inch total length). The external casing and insulation, individually added ~2.7 kg to the assembly. Testing at NASA-MSFC yielded a maximum pressure drop of ~1.4 kPa for the HTCO-Recuperator subsystem at process air flow rate of 100 SLPM. The HTCO prototype logged >17,000 hrs of endurance testing with a steady methane oxidation efficiency averaging >97%.¹

In order to examine the power requirements and efficiency of HTCO systems, it is necessary to first define a couple of terms. For catalytic oxidizers, methane is usually one of the more difficult contaminants to remove and it requires a higher catalyst temperature to fully oxidize. Therefore, methane was used as the design basis for PCI's HTCO systems to ensure the unit would meet or exceed the target destruction efficiency for other VOCs. Testing at NASA-MSFC determined methane lightoff to occur at ~250°C and the >95% destruction efficiency target was achieved at catalyst temperatures of ~300 – 400°C. Based on this data, this paper will define functional startup as the point in time when the catalyst first exceeds 250°C. The catalytic oxidizer is considered to be at temperature when the catalyst reaches 400°C (the targeted catalyst operating temperature), and the subsystem is considered to be at steady state when all of the temperatures (including those in the recuperator) are stable and the average power consumption is constant. The startup times for the previous HTCO/recuperator prototype were studied while flowing the design target of ~76 SLPM of process air. Due to the on-off control strategy, all power requirements are stated as averages and the peak power in all cases was 176 W. The subsystem required approximately 1.5 hrs to achieve functional startup when supplied with an average power of 90 W and only 38 min when supplied with an average power of 120 W. The catalyst achieved its steady operating temperature after 3.5 hrs when supplied with an average power of 160 W. Once at steady state, the HTCO system required an average power of 112 W to maintain the catalyst at 400°C. These performance metrics provided the baseline for the next iteration prototype with its integrated recuperator. More detail description on the first generation HTCO design can be found in Reference 1.

2. Thermally-Integrated HTCO Prototype

Based on the revised design driver for the TCCS system in which formaldehyde destruction sufficient to achieve <35% SMAC for a 6-crewmember exploration mission is required the overall flow rate through the HTCO component of a TCCS was reduced from ~76 SLPM to 40 SLPM.³ Taking this into account, PCI designed,

fabricated, and assembled a catalytic oxidizer for this application. Additionally, a thermally-integrated design, where the HTCO was close coupled with a recuperative heat exchanger within one housing was developed. A photograph of the integrated HTCO-Recuperator unit is shown in Figure 4. The integrated system had a volume of 3 L (flange diameter of 4.8 inch and total length of 10.2 inch) and a mass of 4.3 kg. This translates into a 23% reduction in weight and a 59% reduction in volume as compared to the first generation unit discussed above. Note that the reported weight of 4.3 kg includes the instrumentation and Swagelok fittings for the prototype. The 1 inch Swagelok elbow at the inlet and outlet, each weigh ~0.28 kg. Thus, there is potential to further optimize the weight of a flight-ready HTCO-Recuperator assembly. The test matrix developed to evaluate this system at PCI is outlined in Table 1. The feed flow rate and methane concentration were controlled via mass flow controllers from Brooks Instruments.

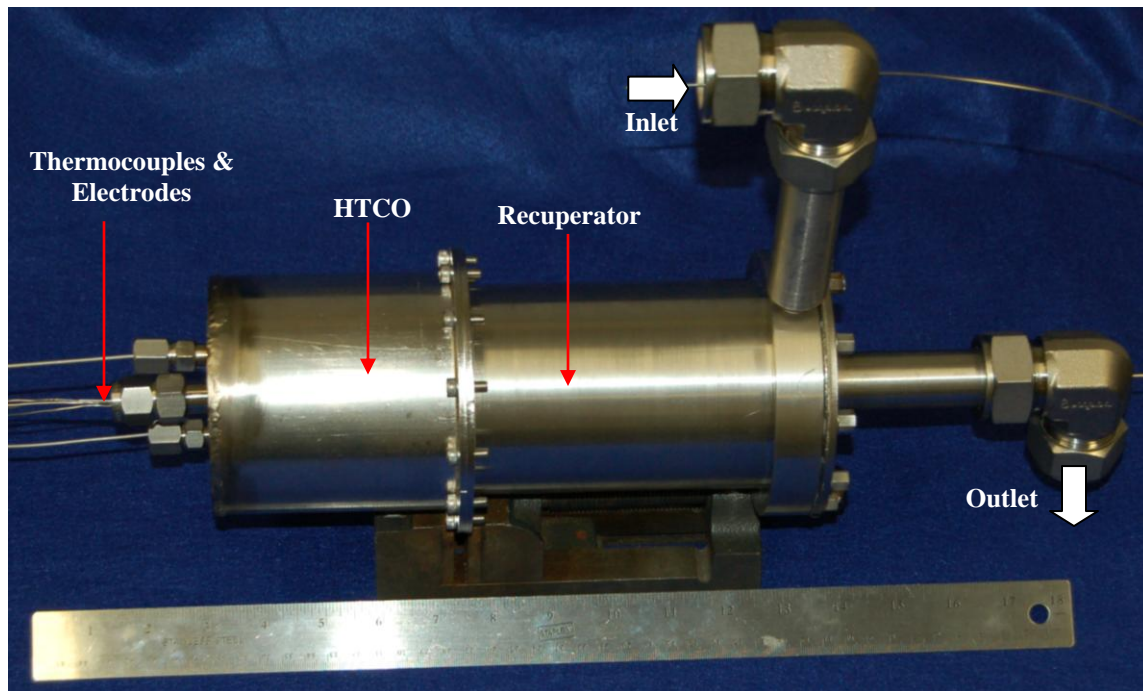


Figure 4. A photograph of the HTCO integrated with a finned recuperator for 6-crew TCCS applications. An 18 inch ruler is shown next to the unit to provide relative dimensions.

Table 1. Test matrix for the TCCS HTCO with integrated recuperator subsystem.

Parameters	Targets
Bulk contaminant load	~100 ppm _v
Flow rate	25 (4-Crew) – 40 (6-Crew) SLPM
Inlet process air temp.	20 – 25°C
HTCO operating temp.	350 – 400°C

The targeted and achieved performance metrics are summarized in Table 2. Discussions with NASA-MSFC determined that the VOC destruction efficiency and power consumption were the primary design targets for this prototype while the pressure drop and recuperator thermal effectiveness were deemed to be secondary objectives. While NASA’s targeted methane single pass destruction efficiency remains >95%, this level of efficiency removes significantly more methane than is required to meet the SMAC. Therefore, based on discussions with NASA-MSFC, a methane single pass destruction efficiency of >50% was used as an initial target for this prototype to ensure methane remains below SMAC while also minimizing the unit’s size and weight. To evaluate the prototype’s performance, the testing performed at PCI involved substituting the VOC destruction efficiency target with a more stringent methane destruction efficiency target of ≥90% which, if achieved, should ensure the unit’s ability to exceed the VOC destruction efficiency target. The actual VOC destruction efficiency will be evaluated at NASA-MSFC in the near future. Destruction efficiency was measured by comparing the methane concentration before and after the catalytic oxidizer via a gas chromatograph equipped with a flame ionization detector. Based on testing at PCI, the integrated HTCO-Recuperator prototype (shown in Figure 4) met or exceeded all of its primary

performance targets. The unit also nearly achieved NASA’s current single pass methane destruction efficiency target of >95% and, if desired, only minor design revisions would be required to achieve the >95% target.

Table 2. Performance targets and achieved results for the TCCS HTCO with integrated recuperator subsystem.

Parameters	Targets	Achieved
<i>Primary Objectives</i>		
VOC destruction efficiency	>90%	TBD
CH ₄ destruction efficiency	>50%	90 – 94 %
Power consumption	<150 W	80 – 125 W avg. ≤150 W peak
<i>Secondary Objectives</i>		
Acceptable pressure drop	< 1.5 kPa	0.6 – 1.2 kPa
Recuperator thermal effectiveness	>80%	~70%
Preferred exit temp.	~45°C	100 - 120°C

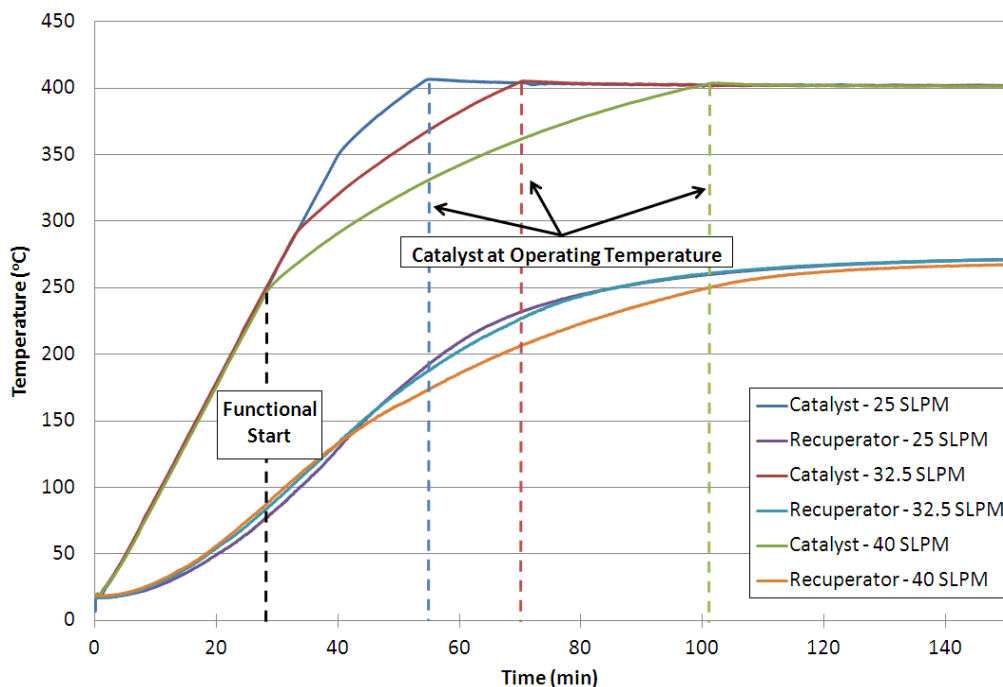


Figure 5. Cold startup and thermal transient response profiles for the TCCS HTCO with integrated recuperator prototype.

To quantify the efficiency of the system the cold startup thermal response (from room temperature to target operating temperature) of the HTCO-Recuperator prototype was monitored at air flow rates of 25, 32.5, and 40 SLPM. As seen in Figure 5, the initial thermal transient response of the HTCO-Recuperator prototype was limited by the ramp rate (~9°C/min) programmed by PCI in the temperature controller. The prototype approached the functional temperature of ~250°C after ~30 min for all three flow rates. After achieving functional startup the thermal response of the system differed depending on the air flow rate. When flowing 25 SLPM of air, the system continued to be limited by the PCI programmed ramp rate for another ~10 min (total of ~40 min) after which the system became limited by the thermal transient response of the recuperator component. The HTCO reactor catalyst reached the target operating temperature of ~400°C after ~55 min. The thermal response of the recuperator component approached steady state after ~140 min. When flowing 32.5 SLPM of air, the system continued to be limited by the PCI programmed ramp rate for another ~4 min (total of ~33 min) after which the system became limited by the thermal transient response of the recuperator component. The HTCO reactor catalyst reached the target operating temperature of ~400°C after ~70 min. The thermal response of the recuperator component approached steady state after ~140 min. When flowing 40 SLPM of air, the system became recuperator limited around the same time as achieving functional startup (~30 min). The HTCO reactor catalyst reached the target

operating temperature of ~400°C after ~100 min. The thermal response of the recuperator component approached steady state after ~150 min. These startup times are summarized in Table 3.

Table 3. Cold startup thermal transient response times for the TCCS HTCO with integrated recuperator prototype.

Flow (slpm)	Time to Achieve (min):		
	Functional Start	Catalyst Operating Temp.	Steady State
25	30	55	140
32.5	30	70	140
40	30	100	150

The power consumption of the system depended on both the flow rate and whether the system was limited by the ramp rate programmed in the temperature controller or the thermal transient response of the recuperator component. During the initial, temperature controller-limited warmup regime, the system's power consumption was automatically adjusted by the temperature controller. While the process was recuperator limited, the system was maintained at peak power (~145 W). Thereafter, the temperature controller appropriately adjusted the input power to maintain the target catalyst operating temperature of ~400°C with no temperature overshoot or cycling. The steady state power consumption for the system was 81 W, 100 W, and 123 W when flowing 25, 32.5, and 40 SLPM air flow rate, respectively. It should be noted that during prototype testing, the available peak power was limited to ~145 W since the power supply for the HTCO heater elements was fixed at ~77 VDC. Any change in the peak power could result in different transient thermal behavior than that reported here.

While the new, thermally-integrated HTCO prototype (Figure 4) met the secondary pressure drop objective, it fell below the targeted recuperator thermal effectiveness and exceeded the preferred exit temperature (both variables are intimately related). For the purposes of this paper, recuperator thermal effectiveness was calculated as $\Delta T_{\text{cold}} / \Delta T_{\text{max}}$ for the recuperator where the cold stream is the room temperature contaminated air entering the recuperator. The primary purpose of this recuperator effectiveness target was to further reduce the system's power consumption. The more energy that can be recovered from the hot oxidizer exhaust and recycled back to the oxidizer, the less energy will be required to maintain the catalyst at its operating temperature. Therefore, while the recuperator effectiveness target was not achieved, it did not prevent the system from achieving the target peak power consumption. Nonetheless, it highlights an area for improvement for future iterations.

3. Potential Future Development Efforts

While the recently developed HTCO-Recuperator prototype succeeded in meeting or exceeding all of the primary design targets as well as providing size and weight reductions, it should be possible to improve upon both of the secondary targets while also further reducing the system's power consumption. Toward this goal, second generation HTCO-Recuperator design and fabrication is currently underway. The design goal is to improve the recuperator thermal effectiveness (and in turn steady state power consumption) by increasing the heat transfer area without compromising the system pressure drop and minimizing any ensuing size/weight increase.

B. Heat Melt Compactor (HMC)

1. Thermally-Integrated HTCO Prototype for HMC

In addition to cabin air TCCS applications, catalytic oxidizers have the capability to benefit other processes aboard spacecraft as well. One such application is the Heat Melt Compaction (HMC) system. Heat melt compaction has the capability to reduce the volume of solid waste (e.g., food packages, wipes, paper, tape, etc.) generated during manned space missions by more than 90% while also recovering much of the water that is typically contained within this trash.¹³ By heating and compacting the solid waste a dry, hardened "tile" is produced which not only saves space, but may also be useful as supplemental radiation shielding. Unfortunately the melting process results in the offgassing of various toxic compounds which must be immediately removed to avoid adversely affecting the crew health and life support system. Standard adsorption methods using activated carbon or similar sorbent materials will remove many of the generated compounds such as VOCs, but others, such as methane, carbon monoxide, and low molecular weight VOCs, are often more difficult to remove.¹⁴ Catalytic oxidation is a viable method of removing these compounds.

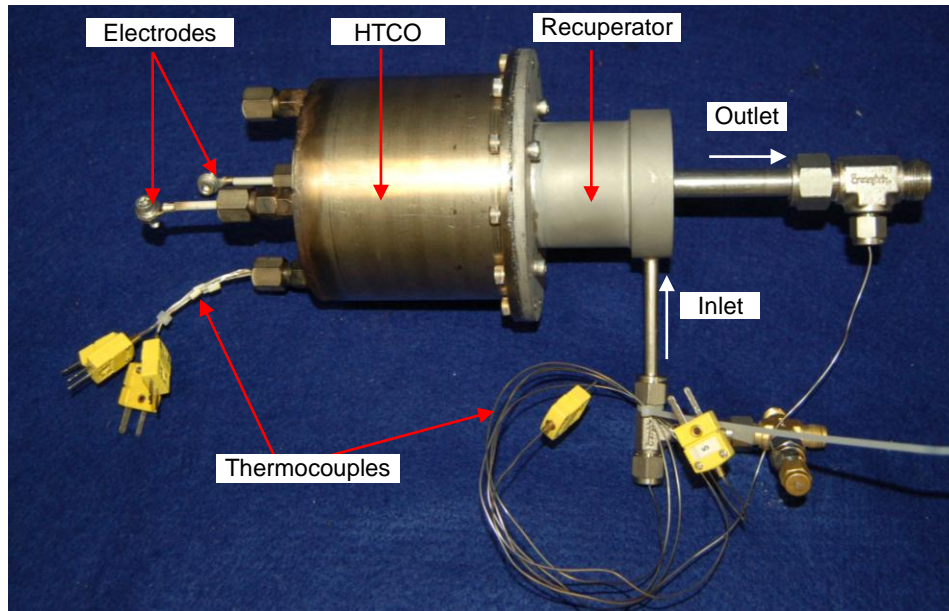


Figure 6. A photograph of the HTCO thermally-integrated with a finned recuperator for HMC applications.

To meet the needs of this application, a new HTCO reactor thermally-integrated with a recuperative heat exchanger was designed. Unlike the TCCS application discussed above, the air flow rates for the HMC application were considerably smaller, on the order of 1-2 SLPM. However, the total bulk contaminant load was as high as 600 ppm_v with targeted destruction efficiency of >95%. Due to time and budgetary constraints, it was decided to test the prototype with up to 200 ppm_v CH₄. A photograph of the current design is shown in Figure 6. This prototype had a volume of ~1 L (HTCO: 4 inch diameter, 3.6 inch long; recuperator: 2.25 inch diameter, 2.5 inch long). Although the recuperator was correctly sized for the target flow rate of 1-2 SLPM, the catalytic oxidizer portion of the system was oversized by a factor of ~12. This was due to the challenges inherent in scaling previous iterations down to the desired low flows. Based on discussions with NASA, a “lower risk” approach with larger safety factors was chosen as a first attempt to prove the concept feasibility. Size and weight optimization could be addressed in future iterations. Therefore, the size and weight of the current design are not representative of an actual system. In addition, the larger size likely resulted in significantly longer startup times and higher energy requirements due to the added thermal mass and higher heat loss. The test matrix developed to evaluate this unit at PCI is included in Table 4. Testing will continue at the NASA facility, where the HTCO-Recuperator performance evaluation at higher bulk contaminant levels and humidity will be performed to more accurately reflect the conditions present in the HMC system.

Table 4. Test matrix for the HMC HTCO with integrated recuperator subsystem

Parameters	Targets	Tested to Date
Total bulk contaminant load	As high as 600 ppm _v	100 – 200 ppm _v CH ₄
Air flow rate	1 – 2 SLPM	1 – 2 SLPM
Relative humidity	~50%	7%
Inlet temp.	20 – 25°C	20 – 25°C

The targeted and achieved performance metrics are summarized in Table 5. Discussions with NASA-MSFC determined that the destruction efficiency, power consumption, and pressure drop were the primary design targets for this application while the recuperator effectiveness (as measured by the recuperator exit temperature) was deemed to be a secondary objective. Additional secondary objectives included a functional startup time of ~10-15 min and a durability of >1 year. Both of these objectives will be evaluated by NASA. The HMC HTCO-Recuperator prototype was found to meet or exceed all of the primary objectives.

Table 5. Performance targets and achieved results for the HMC HTCO with integrated recuperator subsystem

Parameters	Targets	Achieved/Tested
<i>Primary Objectives</i>		
CH ₄ Destruction efficiency	>95%	>98%
Power limitations	100 W (avg.) or less	46.5 W
Acceptable pressure drop	< 800 Pa (for entire assembly)	25 – 50 Pa (for HTCO + Recuperator)
<i>Secondary Objectives</i>		
Preferred exit temp.	~40°C	170-210°C
Acceptable functional start-up time	~10 – 15 min	TBD
Durability	1+ years	TBD

2. Potential Future Development Efforts

While the functional startup time was not measured at PCI, the system's time to steady state was found to be ~2 hrs. The safety factor built into the HTCO design likely hurt the overall system efficiency which was expected. Once the performance of this unit is validated at the NASA facility, future efforts will focus on scaling the HTCO portion of this assembly to minimize the safety factor and to optimize the size, weight, and energy losses for the prototype. Effort will also be spent on improving the recuperator thermal effectiveness to reduce the exit temperature. These efforts are also likely to further reduce the energy consumption by the HTCO-Recuperator system, making it an even more feasible addition to HMC systems.

IV. Conclusion

Two new Microlith-based high temperature catalytic oxidizer (HTCO) prototype with integrated heat recuperators were developed, tested, and delivered to NASA for further performance validation. The first prototype, intended for 6 crewmember Trace Contaminant Control (TCCS) applications, achieved size, weight, and power consumption reductions compared to the previous iteration of the system with a decoupled heat recuperator. The thermally-integrated HTCO-Recuperator unit achieved >90% methane destruction efficiency, significantly higher than its 50% target, and consumed an average of ~123 W at steady state with a peak power consumption of ~150 W (the target maximum) while processing 40 SLPM of contaminated air. Further reduction in power consumption is expected as the recuperator effectiveness is improved in future iterations. The second prototype, intended for the Heat Melt Compactor applications, exceeded the >95% methane destruction efficiency target and consumed only 46.5 W, significantly below the 100 W target. While this unit achieved the primary design targets, significant size, weight, and efficiency improvements should be possible with further work to scale the system more appropriately to the required flow rates. In summary, Microlith-based HTCO systems are proving to be a viable addition to contaminate removal systems and they provide significant size, weight, and power consumption benefits over state-of-the-art systems.

Acknowledgments

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