

# Energy Efficient Microlith<sup>®</sup>-based Catalytic Reactor and Recuperator for Air Quality Control Applications

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Precision Combustion, Inc. (PCI) and NASA's Marshall Space Flight Center (MSFC) have been developing, characterizing, and optimizing high temperature catalytic oxidizers (HTCO) based on PCI's patented Microlith<sup>®</sup> technology to meet the requirements of future extended human spaceflight explorations. Previous efforts focused on integrating PCI's HTCO unit with a compact, simple recuperative heat exchanger to reduce the overall system size and weight. Significant improvement was demonstrated over traditional approaches of integrating the HTCO with an external recuperative heat exchanger. While the critical target performance metrics were achieved, the thermal effectiveness of PCI's recuperator remained a potential area of improvement to further reduce the energy requirements of the integrated system. Using the same material combinations and an improved recuperator design, the redesigned prototype has experimentally demonstrated 20 – 30% reduction (flow dependent) in steady state power consumption compared to the earlier prototype without compromising the destruction efficiency of methane and volatile organic compounds (VOCs). Moreover, design modifications and improvements allow our redesigned prototype to be more easily manufactured compared to traditional brazed plate-fin recuperator designs. The redesigned prototype was delivered to MSFC for validation testing. Here, we report and discuss the performance of the improved prototype HTCO unit with a high efficiency recuperative heat exchanger based on testing at PCI and MSFC. The device is expected to provide a reliable and robust means of disposing of trace levels of methane and VOCs by oxidizing them into carbon dioxide and water in order to maintain clean air in enclosed spaces, such as crewed spacecraft cabins.

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## Nomenclature

$^{\circ}\text{C}$	= degree Celsius	<i>PCI</i>	= Precision Combustion, Inc.
<i>CFD</i>	= Computational Fluid Dynamics	<i>ppm<sub>v</sub></i>	= parts per million by volume
cm	= centimeter	<i>psia</i>	= pound per square inch absolute
GHSV	= gas hourly space velocity	<i>MSFC</i>	= Marshall Space Flight Center
<i>GSA</i>	= geometric surface area	<i>SEM</i>	= scanning electron microscopy
<i>HTCO</i>	= high temperature catalytic oxidizer	<i>SLPM</i>	= standard liter per minute (21 $^{\circ}\text{C}$ , 14.7 psia)
<i>ISS</i>	= International Space Station	<i>SCFM</i>	= standard cubic feet per minute
<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>VOC</i>	= volatile organic compounds
<i>L</i>	= liter	<i>W</i>	= watts
<i>m</i>	= meter		
<i>min</i>	= minute		

## I. Introduction

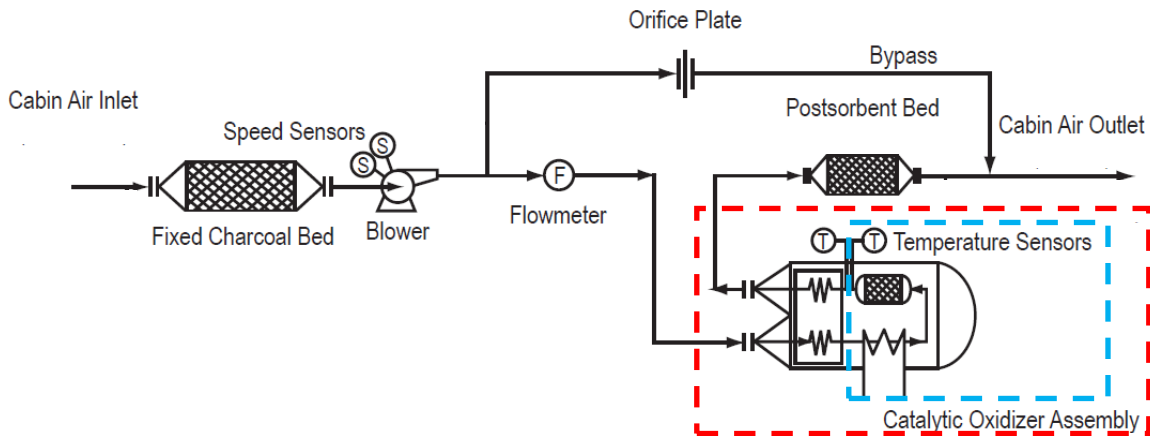
CONTAMINATED air is a universal problem which affects applications ranging from terrestrial buildings to space travel. Sources of contamination include offgassing of materials along with industrial and metabolic processes. Traditionally, spacecraft cabin air quality control is accomplished via physical 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.<sup>1</sup> To overcome these limitations thermal catalytic oxidation has been proposed and demonstrated to be a viable addition to trace contaminant control systems (TCCS). Thermal catalytic oxidation involves heating a process stream in the presence of catalyst to convert contaminants into carbon dioxide and water. In order to be viable and reduce its energy requirements, a high temperature catalytic oxidizer (HTCO) must be thermally-integrated with a secondary heat exchanger/recuperator to recycle the waste heat back to the oxidizer.

### A. Spacecraft TCCS Performance Needs

The National Aeronautics and Space Administration's (NASA) deep space exploration objectives for a HTCO include the ability to operate at a temperature condition to achieve >95% single pass methane oxidation efficiency and to provide sufficient process air flow through the HTCO 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 the specific mixture of compounds.<sup>2</sup> To provide the necessary performance, an HTCO unit designed for deep space exploration missions that supports four crewmembers and accommodates offgassing from 15,000 kg of equipment must treat at least 24 standard liters per minute (SLPM) at a catalyst bed temperature of 400  $^{\circ}\text{C}$ . 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 HTCO unit. NASA also seeks a heat recuperator to recover heat from the exit stream of the HTCO reactor with a thermal effectiveness of  $\geq 80\%$  to minimize the steady state power consumption.

### B. HTCO Developmental Progression and Testing

The NASA's Marshall Space Flight Center (MSFC) has been involved with TCCS and HTCO technology development, testing, and flight operations since the 1970s Skylab program. A schematic of the International Space Station's (ISS) TCCS with the catalytic oxidizer is shown in Fig. 1. Developmental support for Precision Combustion, Inc.'s (PCI) Microlith<sup>®</sup>-based HTCO concepts began in 1994 under a Small Business Innovative Research (SBIR) Phase I project. The proof-of-concept demonstrated that a 0.23 L (7.62 cm diameter  $\times$  5.08 cm long) reactor containing <100 grams of Microlith media could achieve >99% methane oxidation at space velocities >40,000  $\text{hr}^{-1}$ . The reactor exhibited a pressure drop <0.062 kPa for a process air flow of 283 L/min. Development continued through 1998 under a SBIR Phase II project which produced a directly-heated prototype reactor assembly suitable for integration with NASA's existing plate-fin recuperator assembly. This developmental phase demonstrated >99% oxidation efficiency for the spectrum of volatile organic compounds (VOCs) that are commonly



**Figure 1. Schematic of the ISS TCCS with integrated catalytic oxidizer subsystem.<sup>1</sup> The blue outline encloses the components integrated into the 1<sup>st</sup> Generation Alpha Microlith<sup>®</sup>-based HTCO prototype. The red outline encloses the components integrated into the 2<sup>nd</sup> Generation Beta Microlith<sup>®</sup>-based HTCO prototypes.**

observed in crewed spacecraft cabin environments. The continued catalyst formulation development yielded a thermally durable and poisoning resistant catalyst. Thermal cycling for 16 hours between 750 °C and 920 °C resulted in <10% loss in activity in a propylene light-off test. The Phase II project delivered a full scale HTCO reactor to NASA for test and evaluation.

After delivery to NASA, under sponsorship by the ISS Program's Engineering Research and Technology (ERT) program, the SBIR Phase II prototype HTCO reactor was integrated with an existing plate-fin heat recuperator assembly for test and evaluation.<sup>3</sup> The testing series demonstrated physical integration and evaluated performance relating to thermal transient response, power-saving mode operations, methane and VOC oxidation over the flow range of 28 SLPM to 67 SLPM, oxidation reaction light-off, launch random vibration spectrum, and performance after vibration exposure. The SBIR prototype HTCO reactor testing and evaluation indicated that the Microlith-based technology could provide 77% reduction in catalytic oxidizer assembly startup time, 50% reduction in assembly pressure drop, and functional operation 64% earlier after cold startup than conventional indirectly-heated pellet catalyst reactors. The design also demonstrated durability on exposure to 3.1-g root mean square (RMS) 3-axis random vibration loads by exhibiting no performance loss after the vibration test.

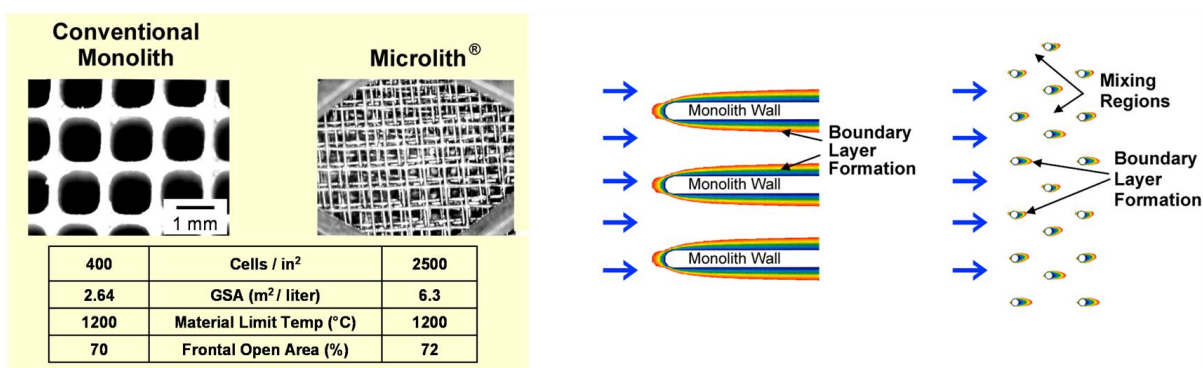
Based on the successful HTCO reactor SBIR prototype testing and evaluation, the ISS Program continued to sponsor development under the ERT program in 1999. Under this project, PCI designed, assembled, and delivered a 1<sup>st</sup> generation Alpha prototype HTCO unit. On delivery to NASA in August 2000, the Alpha prototype HTCO unit was integrated with an existing heat recuperator and began testing and evaluation in 2002 under NASA Center Director's Discretionary Fund (CDDF) sponsorship.<sup>4</sup> Similar testing as the SBIR Phase II prototype unit was conducted on the Alpha prototype unit to evaluate performance over the process air flow rate range between 28 SLPM and 98 SLPM. At the conclusion of the performance evaluation testing, the Alpha prototype HTCO unit was subjected to a 2-year endurance test which was conducted from March 2003 through April 2005. The endurance testing was conducted at process air flow of 77 SLPM and 400 °C reactor temperature. Methane oxidation efficiency was tested regularly during the test and found to average 97.6%.

As a result of the development, testing, and evaluation beginning in 1994 and concluding in 2005, the Microlith-based HTCO technology demonstrated its utility and viability as a core trace contaminant control technology for future crewed deep space exploration missions. As exploration mission life support architectures were developed under NASA's exploration technologies programs between 2005 and the present, the Alpha prototype HTCO reactor was used successfully in exploration life support system architecture testing.<sup>5,6</sup>

In recent years, application of the Microlith-based HTCO technology to other contamination control applications, such as thermal trash management for NASA and other commercial companies, resulted in the development of an advanced heat recuperator design.<sup>1,7,8</sup> While the Alpha prototype of the catalytic oxidizer with integrated recuperator met all the primary design targets, as well as providing size, weight, and power consumption reductions compared to earlier iterations with decoupled heat exchangers, the recuperator thermal effectiveness remained a potential area of improvement to further optimize the average steady state power consumption. This opportunity led to developing a 2<sup>nd</sup> generation Beta HTCO unit consisting of tightly integrated heat recuperator and Microlith-based reactor components. This Beta design has been subjected to two design iterations.

## II. Microlith® Substrate and Catalytic Technology

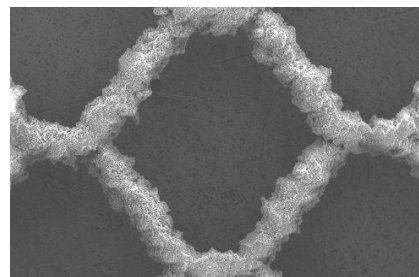
The development efforts described here are based on PCI's patented Microlith technology (trademarked by PCI).<sup>9</sup> The Microlith substrate consists of a series of ultra-short-channel-length, catalytically coated metal meshes with very small channel diameters (Fig. 2). The mesh-like substrates 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 a 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. Pressure drop was found to be comparable between the Microlith substrate and conventional monolith for the same flow conditions suggesting that the reduction in boundary layer formation counteracted the effect of the additional turbulence in the Microlith substrates.



**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 (Fig. 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.

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,<sup>10</sup> trace contaminant control,<sup>11,12</sup> catalytic combustion,<sup>13</sup> partial oxidation of methane,<sup>14,15</sup> liquid fuel reforming,<sup>16,17</sup> CO preferential oxidation, and water gas shift reactors.<sup>18</sup> A scanning electron microscopy (SEM) micrograph of the coated Microlith substrate is shown in Fig. 3. SEM analysis indicates uniform catalyst coatings on the substrate with complete coverage.



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

### III. Results and Discussion

An advanced 2<sup>nd</sup> generation Beta HTCO reactor and integral heat recuperator was designed and fabricated by PCI. The Beta prototype has been subjected to two design iterations. The integrated unit resulting from the second design iteration was tested at PCI and NASA facilities. Results from these tests are presented and discussed.

#### A. High Temperature Catalytic Oxidizer Testing at PCI Facility

Testing before delivery to MSFC is presented and opportunities for design improvement are presented and discussed by the following narrative.

##### 1. Second Generation HTCO Beta Prototype with Integrated Recuperator

Based on the performance data from testing an earlier version of the 2<sup>nd</sup> Generation HTCO-Recuperator Beta prototype (Beta-1), appropriate design modifications were evaluated to improve the overall recuperator thermal effectiveness and lower the steady state power consumption. PCI's heat transfer model was revised based on the experimental test data from performance mapping of the earlier Beta-1 prototype. Recuperator sizing calculations for the revised Beta-2 prototype were completed to target ~75-80% thermal effectiveness at total air flow rate of 40 SLPM. In comparison to the earlier design, the updated Beta-2 prototype's recuperator diameter and the overall length were respectively increased from 8.25 cm (3.25 inches) to 10.2 cm (4 inches) and from 25.9 cm (10.2 inches) to 29.5 cm (11.6 inches). The design changes also reduced the number of parts which made it

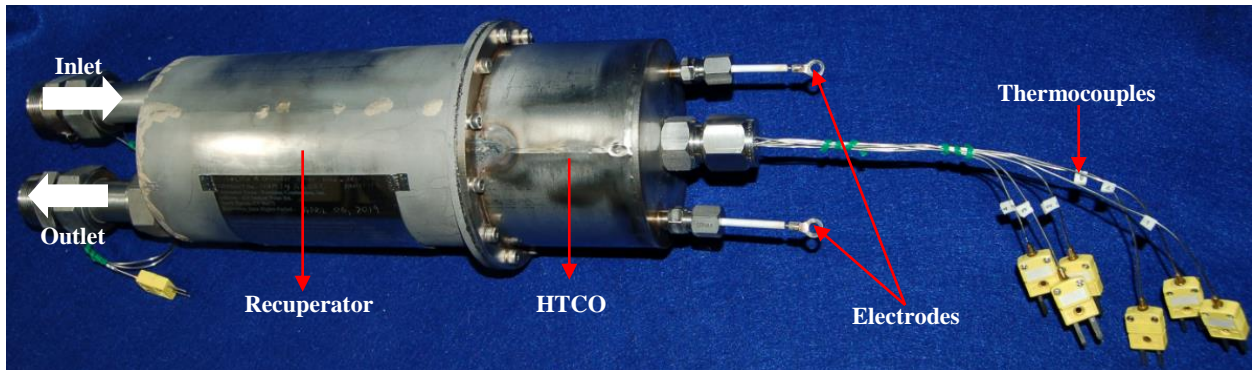


Figure 4. A photograph of the HTCO integrated with a recuperator Beta-2 prototype.

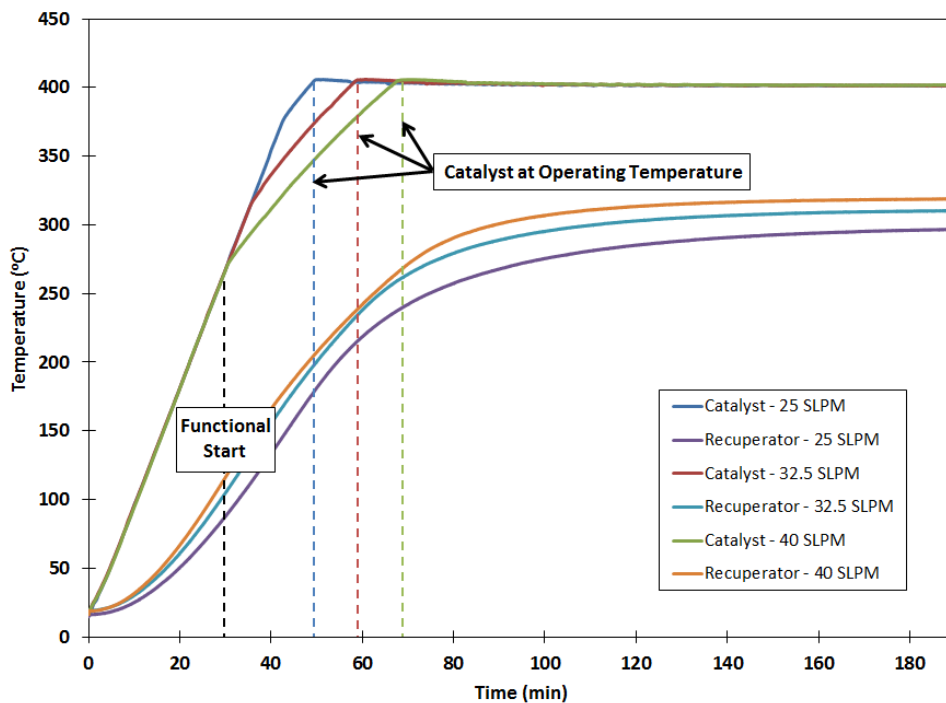
easier to manufacture and repair the recuperator component of the assembly (if needed). An improved manufacturing process for the recuperator fins was identified that produced twice the fin density compared to that employed in the earlier Beta-1 prototype. Compared to the Beta-1 design, higher fin density and larger recuperator diameter were expected to provide additional heat transfer area for improved thermal effectiveness while maintaining a reasonable pressure drop for the Beta-2 prototype. The fully assembled and instrumented Beta-2 HTCO-Recuperator prototype is shown in Fig. 4. The integrated system had a volume envelope of ~4 L based on a flange diameter of 13.2 cm (5.2 inches) and total length of 29.5 cm (11.6 inches) and a mass of ~5.1 kg (including inlet/outlet Swagelok fittings that weighed ~0.6 kg). The total weight of the unit, including the insulation, was 6.7 kg. Eliminating the flanged design will reduce the prototype volume to ~2.8 L. There is potential to further optimize the volume and weight of a flight-ready HTCO-Recuperator assembly by eliminating the thicker flange as well as the Swagelok and Conax compression fittings. 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 calibrated mass flow controllers from Brooks Instruments.

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

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



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. It is advantageous to minimize the cold startup transient time as this is the most power intensive stage of the unit's operation. The unit will consume maximum power until thermal steady state is achieved and the recuperator is operating at the maximum possible thermal effectiveness. In addition, due to the limited availability of power and reduced VOC emissions (as crewmembers are sleeping) during the night cycle, the unit could be turned off to conserve power. Therefore a faster startup transient is advantageous because the unit can be shutdown for longer duration, further conserving power. As seen in Fig. 5, the initial thermal transient response of the HTCO-Recuperator prototype was limited by the ramp rate ( $\sim 9\text{ }^{\circ}\text{C}/\text{min}$ ) programmed by PCI in the temperature controller. The prototype approached the functional temperature of  $\sim 250\text{ }^{\circ}\text{C}$  after  $\sim 30$  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  $\sim 12$  min (total of  $\sim 42$  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  $\sim 400\text{ }^{\circ}\text{C}$  after  $\sim 50$  min. The thermal response of the recuperator component approached steady state (within  $3\text{ }^{\circ}\text{C}$  of the steady state temperature) after  $\sim 180$  min. When flowing 32.5 SLPM of air, the system continued to be limited by the PCI programmed ramp rate for another  $\sim 6$  min (total of  $\sim 36$  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  $\sim 400\text{ }^{\circ}\text{C}$  after  $\sim 60$  min. The thermal response of the recuperator component approached steady state (within  $3\text{ }^{\circ}\text{C}$  of the steady state temperature) after  $\sim 150$  min. When flowing 40 SLPM of air, the system became recuperator limited around the same time as achieving functional startup ( $\sim 30$  min). The HTCO reactor catalyst reached the target operating temperature of  $\sim 400\text{ }^{\circ}\text{C}$  after  $\sim 70$  min. The thermal response of the recuperator component approached steady state (within  $3\text{ }^{\circ}\text{C}$  of the steady state temperature) after  $\sim 130$  min. These startup times are summarized in Table 2. Insulation surface temperature during the prototype testing was observed to be  $<38\text{ }^{\circ}\text{C}$  (less than touch temperature requirement of  $\sim 40\text{ }^{\circ}\text{C}$ ), indicating minimal heat loss and safety compliance.



**Figure 5. Cold startup and thermal transient response profiles for the TCCS HTCO with integrated recuperator Beta-2 prototype.** The catalyst temperature was measured at the exit of the catalyst bed. The recuperator temperature is the gas temperature measured between the recuperator and inlet to the catalyst bed.

**Table 2. Cold startup thermal transient response times for the TCCS HTCO with integrated recuperator Beta-2 prototype.**

Flow (SLPM)	Time to Achieve (min):		
	Functional Start	Catalyst Operating Temp.	Steady State
25	30	50	180
32.5	30	60	150
40	30	70	130

Table 3 summarizes the observed performance of the Beta-2 prototype unit relative to target design parameters. The pressure drop across the Beta-2 HTCO-Recuperator was 0.7 kPa, 1 kPa and 1.3 kPa when flowing 25, 32.5, and 40 SLPM of air, respectively. 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 (~148 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 65 W, 73 W, and 83 W when flowing 25, 32.5, and 40 SLPM of air, respectively. In comparison to the Beta-1 prototype, this represented ~20 – 30% reduction in the steady state power consumption.

The recuperator thermal effectiveness was evaluated as a function of air flow rate, and was defined 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 recuperator thermal effectiveness for the Beta-2 prototype was ~76%, ~78% and ~80% when flowing 25, 32.5, and 40 SLPM of air, respectively.

The CH<sub>4</sub> destruction efficiency was also evaluated at a feed concentration of 100 ppm<sub>v</sub>. 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 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

**Table 3. Performance targets and experimentally achieved results for the Beta-1 and Beta-2 TCCS HTCO with integrated recuperator prototypes. Performance was validated using 25 - 40 SLPM of air containing 100 ppm<sub>v</sub> CH<sub>4</sub>.**

Parameters	Design Parameters	Actual Performance	
		Beta-1 Prototype	Beta-2 Prototype
Acceptable pressure drop	≤1.5 kPa	0.6 – 1.2 kPa	0.7 – 1.3 kPa
CH <sub>4</sub> destruction efficiency	>50%	90 – 94%	93 – 96%
VOC destruction efficiency	>90%	Projected to be >90% (based on CH <sub>4</sub> testing)	Projected to be >90 (based on CH <sub>4</sub> testing)
Power consumption	≤150 W	≤148 W peak 81 – 123 W average	≤148 W peak 65 – 83 W average
Recuperator thermal effectiveness	≥80%	~69 – 72%	~76 – 80%
Exit temperature	~45 °C	~100 °C	~70 °C
Functional start up time	Not Specified	~30 min.	~30 min.
Time to achieve operating catalyst temperature	Not Specified	~55 – 100 min.	~50 – 70 min.
Time to achieve steady state temperature	~45 min. (Minimum)	~140 – 150 min.	~130 – 180 min.
Volume envelope (assuming flange diameter)	Not Specified	3 L	4 L
Weight	Not Specified	4.3 kg (w/o insulation)	5.1 kg (w/o insulation) 6.7 kg (with insulation)

destruction efficiency target of  $\geq 90\%$  which, if achieved, should ensure the unit's ability to exceed the VOC destruction efficiency target because methane is usually one of the more difficult contaminants to remove and it requires a higher catalyst temperature to fully oxidize. 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. The  $\text{CH}_4$  destruction efficiency for the Beta-2 prototype was  $\sim 96\%$ ,  $\sim 94\%$  and  $\sim 93\%$  when flowing 25, 32.5, and 40 SLPM of air with 100 ppm<sub>v</sub> of  $\text{CH}_4$ , respectively.

Table 3 compares the performance of the Beta-1 and Beta-2 HTCO-Recuperator prototypes with the target design parameters. The results show that the Beta-2 prototype achieved improved performance in comparison to the Beta-1 prototype. All the target performance parameters were met and demonstrated. The unit also nearly achieved NASA's current single pass methane destruction efficiency target of  $>95\%$  at its full scale flow rate and, if desired, only minor design revisions would be required to achieve the  $>95\%$  target. Additional performance mapping, along with long term durability testing will be performed by NASA-MSFC.

## 2. Potential Future Development Efforts

PCI's Beta-2 HTCO-Recuperator prototype succeeded in meeting or exceeding all of the design targets. Optimization of reactor insulation to minimize heat loss is further expected to reduce the steady state power consumption. Elimination of a flanged design as well as bulky Swagelok fittings will lead to a light-weight solution. PCI has also discussed alternate design configurations with NASA-MSFC that has volume and weight savings depending on the desired target metrics.

## B. High Temperature Catalytic Oxidizer Testing at NASA-MSFC

Ground testing of the HTCO-Recuperator Beta-2 prototype was carried out by NASA-MSFC. Results are summarized in Figs. 6 and 7. Trace contaminant-free process air was fed to the unit by drawing laboratory air through the MSFC Environmental Chamber's low-flow fixed adsorbent bed packed with approximately 23.5 kg of activated charcoal.<sup>6</sup> Air flow was measured by process flowmeter and feedback controlled by a proportional-integral-derivative (PID) controlled blower using LabView software.  $\text{CH}_4$  was injected into the process air stream using a mass flowmeter manually controlled by needle valve. The  $\text{CH}_4$  source was a K-bottle (Sexton) containing 2%  $\text{CH}_4$  in balance compressed air. The mixed process inlet stream was both measured and verified to contain 100 ppm<sub>v</sub>  $\text{CH}_4$  using a Gasetm DX4040 Fourier transform infrared spectrometer. The sample slip stream flow rate to the spectrometer was 400 standard cm<sup>3</sup>/min and a 1 minute detector sampling time was used. Background  $\text{CH}_4$  levels in

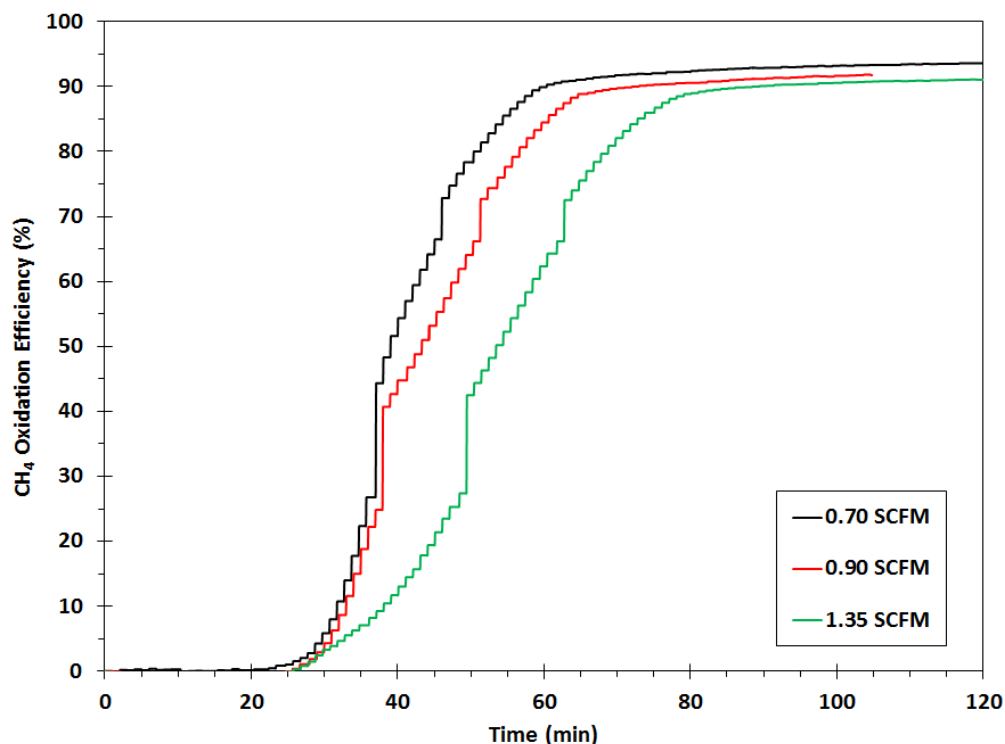
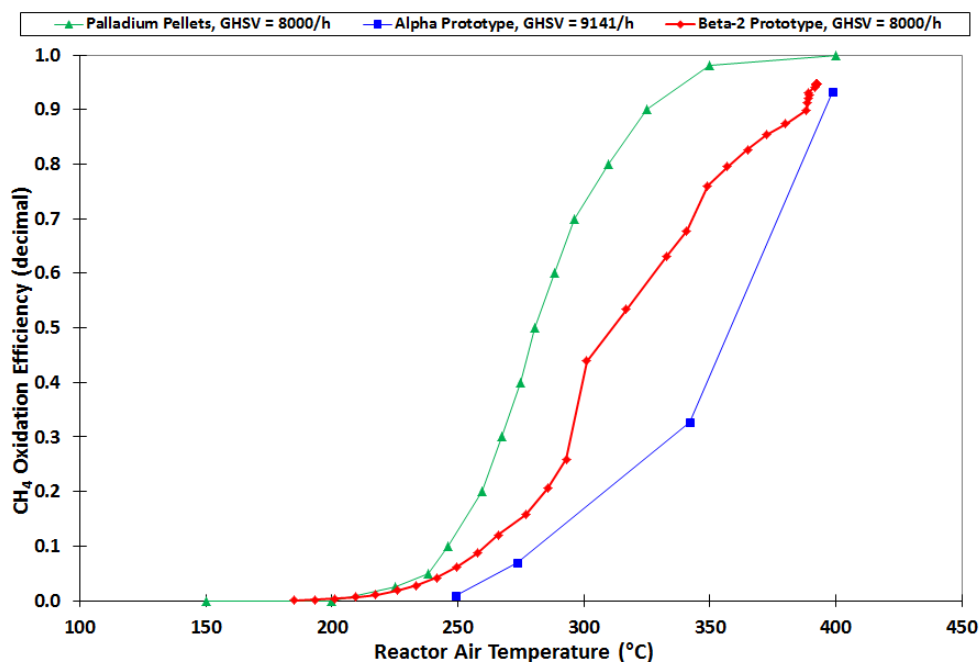


Figure 6. Single-pass  $\text{CH}_4$  (feed concentration of 100 ppm<sub>v</sub>) destruction efficiency for the TCCS HTCO with integrated recuperator Beta-2 prototype.





**Figure 7. CH<sub>4</sub> (feed concentration of 100 ppm<sub>v</sub>) oxidation efficiency for alumina pellet-supported catalyst, HTCO Alpha prototype and the HTCO-Recuperator Beta-2 prototype.**

the lab facility air of approximately 2 ppm<sub>v</sub> were taken into account and measured daily before testing. The HTCO-prototype process outlet stream was continuously measured for CH<sub>4</sub> levels during the test in order to calculate the single-pass oxidation efficiency. The inlet condition was also verified from the HTCO-Recuperator prototype's process outlet port at cool catalyst temperatures (i.e. during test start-up and shutdown) to verify absence of upstream leaks.

Figure 6 displays the transient CH<sub>4</sub> destruction efficiency during cold startup at various process flowrates. A methane oxidation efficiency of approximately 92% was observed at the desired nominal process flowrate of 25.5 SLPM (0.90 SCFM). Two repeatable step increases in oxidation efficiency were observed at approximately 25% and 65%, independent of the process flow. The origin of these step changes is unknown but is believed to be related to light-off of the specific catalyst chemistry. Note that the transitions did not occur at the same temperatures and the onset temperature generally increased with increased flowrate.

Historically, thermal catalytic oxidation for TCCS application has been benchmarked at NASA by comparison to the performance of a catalyst bed containing 0.5% Pd on Al<sub>2</sub>O<sub>3</sub> pellets at 8,000 hr<sup>-1</sup> gas hourly space velocity (GHSV). Such a comparison was made for the HTCO Alpha prototype by Perry et al. (2005).<sup>4</sup> Figure 7 overlays the performance for such a catalyst bed against the Microlith<sup>®</sup> HTCO Alpha and the Microlith<sup>®</sup> HTCO with integrated recuperator Beta-2 prototype. Remarkably, the light off behavior of the HTCO-Recuperator Beta-2 prototype mirrors the pellet supported catalyst bed at low temperatures. Additionally, the HTCO catalyst used in the Beta-2 prototype appears to have greater activity than the Alpha prototype unit over the entire temperature range studied.

#### IV. Conclusion

An advanced HTCO-Recuperator Beta prototype was designed, fabricated, and demonstrated to achieve improved performance compared to the HTCO Alpha prototype. A 20 – 30% reduction (flow dependent) in the steady state power consumption was achieved for the Beta-2 prototype in comparison to the Beta-1 prototype. The test results indicated that the HTCO-Recuperator Beta-2 prototype was able to meet all of the targeted performance metrics for 25 – 40 SLPM of air containing 100 ppm<sub>v</sub> of CH<sub>4</sub>:

- 1) CH<sub>4</sub> destruction efficiency of >92%.
- 2) VOC destruction efficiency projected to be >90%.
- 3) Recuperator thermal effectiveness of 76 – 80%.
- 4) Peak power consumption ≤148 W; Average steady state power consumption of 65 – 83 W.
- 5) Pressure drop of 0.7 – 1.3 kPa.

Benchmarking the HTCO-Recuperator Beta-2 prototype against state-of-the-art pelletized oxidation catalyst showed comparable light off performance and improved catalytic activity over the HTCO Alpha prototype unit.

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