

Source Contaminant Control System Design, Operation, and Testing for the Trash Compaction and Processing System

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The Trash Compaction and Processing System (TCPS) aims to reduce volume, biologically safen, physically stabilize, manage effluents, and recover resources from astronaut trash in the International Space Station (ISS). This process involves heating the trash to high temperatures, which in turn releases gaseous contaminants. Effluent management scenarios involve releasing these gases back to the ISS cabin after processing and/or directly venting these gases out to space via the Vacuum Exhaust System (VES). Concerns for recovering the gases back to cabin are crew health, safety, and spacecraft environmental impact. The Heat Melt Compactor (HMC) at NASA Ames Research Center (ARC) serves as a test system that supports TCPS development by conducting risk reduction activities associated with an ISS flight demonstration. Previous gas effluent studies were conducted on the HMC. The results consisted of contaminants from the trash exhaust to exceed Spacecraft Maximum Allowable Concentrations (SMAC), which are selected airborne contaminants that can elicit toxicity symptoms to crewmembers via exposure. The Source Contaminant Control System (SCCS) aims to reduce that risk by converting the contaminants into carbon dioxide (CO₂) and water (H₂O) vapor. The SCCS is composed of a carbon adsorbent bed, to avoid catalyst poisoning, and a catalytic oxidizer (CatOx), which promotes oxidation of the contaminants to CO₂ and H₂O. In turn, the gases coming out of the SCCS should be compatible to the ISS cabin and systems such as the Trace Contaminant Control System (TCCS). Preparation for SCCS testing alongside the HMC Gen 3 are currently underway at ARC. The main objectives are to evaluate CatOx efficiency by CO₂ conversion and characterize effectiveness of removal by comparing contaminant results before and after CatOx. This paper will report on the SCCS design, operation, and testing with results.

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Nomenclature

<i>ARC</i>	= Ames Research Center	<i>NASA</i>	= National Aeronautics and Space Administration
<i>BEN</i>	= benign	<i>NOM</i>	= nominal
<i>CatOx</i>	= catalytic oxidizer	<i>PCI</i>	= Precision Combustion, Inc.
<i>CO</i>	= carbon monoxide	<i>P&ID</i>	= piping & instrumentation diagram
<i>CO₂</i>	= carbon dioxide	<i>psia</i>	= pounds per square inch absolute
<i>ECLSS</i>	= Environmental Control and Life Support System	<i>RH</i>	= relative humidity
<i>FTIR</i>	= Fourier transform infrared spectroscopy	<i>S2S</i>	= Sea to Summit
<i>GCMS</i>	= gas chromatography-mass spectrometry	<i>SLPM</i>	= standard liters per minute
<i>Gen 2</i>	= Generation 2	<i>SMAC</i>	= Spacecraft Maximum Allowable Concentrations
<i>Gen 3</i>	= Generation 3	<i>SCCS</i>	= Source Contaminant Control System
<i>HC</i>	= high cloth	<i>TCCS</i>	= Trace Contaminant Control System
<i>HL</i>	= high liquid	<i>TCPS</i>	= Trash Compaction and Processing System
<i>HMC</i>	= Heat Melt Compactor	<i>TEC</i>	= thermoelectric cooler
<i>ISS</i>	= International Space Station	<i>VES</i>	= Vacuum Exhaust System
<i>JSC</i>	= Johnson Space Center	<i>vol%</i>	= volume percentage unit
<i>H₂O</i>	= water		
<i>MSFC</i>	= Marshall Space Flight Center		

I. Introduction

THE Trash Compaction and Processing System (TCPS) uses pressure and heat via compaction to reduce astronaut trash volume, physically and biologically stabilize trash, and manage liquid and gaseous effluents.¹ During TCPS operation, water vapor and multiple gaseous compounds evolve as a result of trash processing. Upon resource recovery and venting of these effluents, the TCPS must be compatible with the International Space Station (ISS) Environmental Control and Life Support System (ECLSS). The operating scenarios of gas effluent management include gas recovery for crew use via interfacing with the ISS cabin air processor, or, if the gases are deemed irrecoverable, they may be disposed to space via the ISS Vacuum Exhaust System (VES). The Heat Melt Compactor (HMC) Generation 3 (Gen 3) at NASA Ames Research Center (ARC) serves as a TCPS ground test system for validating TCPS technology, operation, performance, and conducts risk reduction activities associated with an ISS flight demonstration.

Under this effort, one of the Solid Waste Management group's risk reduction activities of focus is the catalytic oxidation of effluents for ISS cabin venting. Cabin venting requires meeting Spacecraft Maximum Allowable Concentrations (SMAC), relevant to atmospheric contamination.² The scope of this paper will focus on the gas effluent treatment to remove undesirable contaminants and converting those into useful and safe gases, specifically carbon dioxide (CO₂) and water (H₂O) vapor, that may return to the cabin via a Source Contaminant Control System (SCCS). In addition, an SCCS is needed to prevent additional contaminant load onto the ISS Trace Contaminant Control System (TCCS), which controls trace contaminants from the cabin atmosphere.

A test campaign was conducted to investigate the SCCS and evaluate its effectiveness to reduce contaminant concentrations and convert contaminants into carbon dioxide and water vapor. The SCCS consists of two major components: a pre-filter carbon adsorbent bed and a catalytic oxidizer (CatOx). The Solid Waste Management group is currently in possession of a Generation 2 (Gen 2) catalytic oxidizer that was supplied by Marshall Space Flight Center (MSFC) and developed by Precision Combustion, Inc (PCI).³ The adsorbent bed and CatOx are currently integrated downstream of the HMC Gen 3 test system, so that the trash gas output becomes the input for the SCCS.

II. Methods

A test campaign was conducted to characterize the effectiveness of the SCCS to remove pollutants from the trash exhaust gases. Trash was processed in the HMC Gen 3 and the generated gases will flow into the SCCS, which is also analyzed by a Gasmet Fourier transform infrared spectroscopy (FTIR). Figure 1 shows a picture of both subsystems on respective carts and currently at ARC.

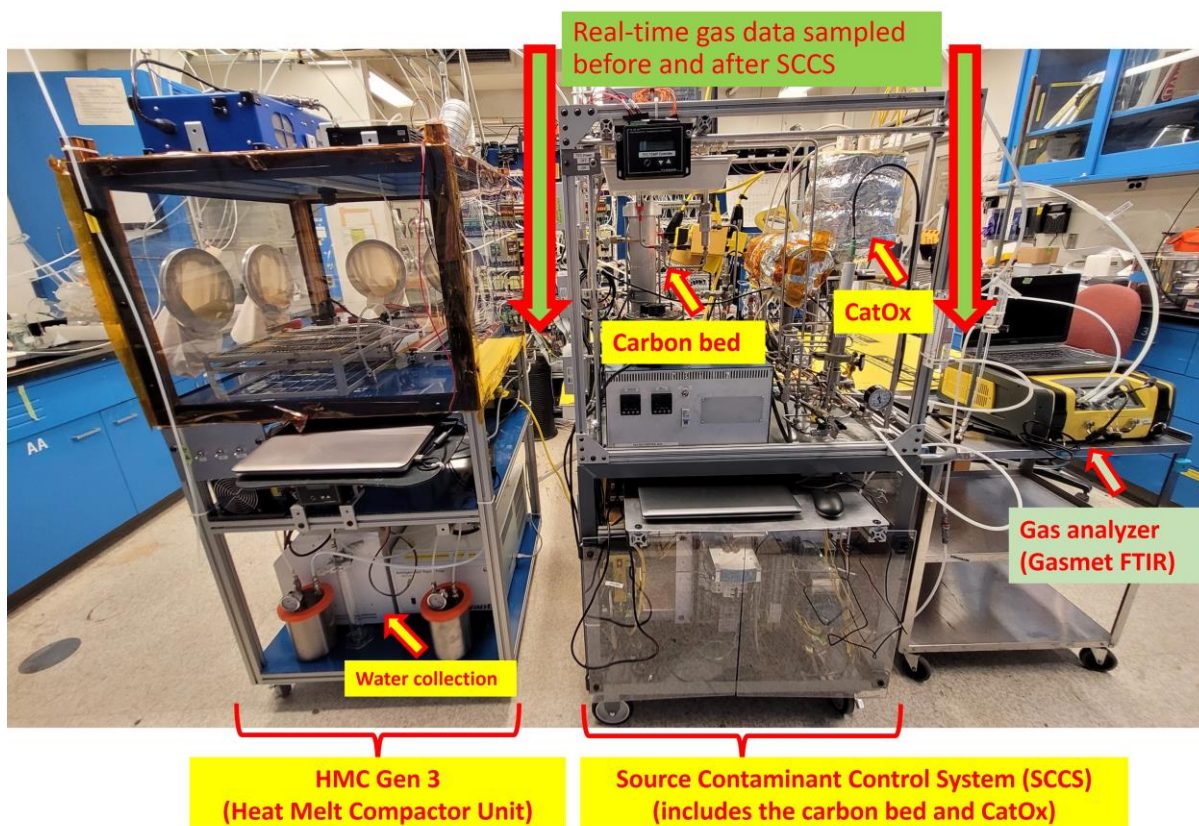


Figure 1. HMC Gen 3 and SCCS subsystems, along with the Gasmet FTIR DX4040 gas analyzer.
The HMC unit is within a glovebox as particulate monitoring of the produced tile will also be evaluated, however, this topic will not be discussed in this paper.

A. HMC Gen 3 Trash Processing Overview

In terms of trash processing, this test campaign aims to reduce the 12-hour operational cycle and investigate if a high percentage of water removal and trash safening can be achieved with a reduced processing time. The method includes bypassing the low-temperature step and immediately jumping to the high temperature step. Originally, the process is similar to what was used in HMC Gen 2, in which the system is operating under vacuum pressures and a two-step temperature process within a 12-hour operational cycle. Trash is loaded into the HMC chamber and the process initiates by pulling vacuum to pressure around 0.3 psia via a vacuum pump. No compaction is introduced and the heaters from the chamber walls and piston are set to 60 °C. This low-temperature step allows for the removal of free or loosely bound water from the trash, as water reaches its boiling point at vacuum pressures. Gas effluent departs the chamber and water vapor is condensed by a thermoelectric cooler (TEC) and collected in a graduated cylinder. After this approximately 4-hour period and water removal, compaction pressure is applied and the temperature is set to 150 °C, in which the heaters on the lid of the chamber are turned on. This high-temperature step allows for sterilization, plasticization, and the release of more volatile gases from the trash. After the trash remains heated and compacted into a tile for a sufficient hold time of around 3 to 4 hours, the trash and system enters a cooling period. The HMC Gen 3's cooling system eliminates the overnight cooling from Gen 2. Once the average temperatures of the piston and lid are 40 °C, which is defined as touch temperature, then the trash tile can be extracted.

Figure 2 shows a P&ID of both HMC and SCCS subsystems. Water from the trash processing is also collected via a graduated cylinder as water condenses through the TEC. A vapor trap of -20 °C and a cold trap are located after to collect any remaining water so it will not enter and damage the vacuum pump downstream. A vacuum pump is located between the HMC and SCCS carts, also seen in Figure 2. The pump's purpose is to pull vacuum within the HMC unit and its outlet flow will be directed to the SCCS. An add-air and bleed-air circuit is also positioned after the vacuum pump, with the purpose of providing the proper air flow rate into the SCCS. The add-air circuit exists to increase the flow rate, if too little, and the bleed-air circuit exists to decrease the flow rate, if too much.

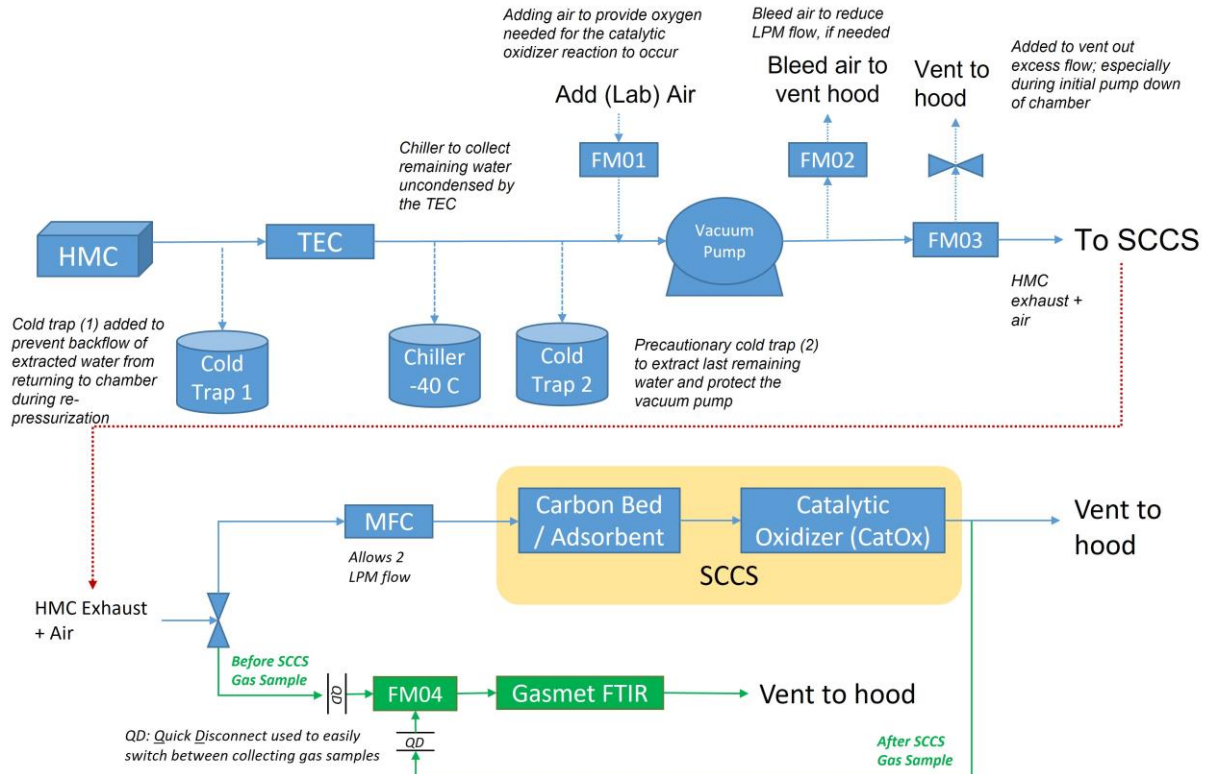


Figure 2. HMC Gen 3 and SCCS process flow diagram with Gaset FTIR gas sampling locations.
FM represents a flow meter and MFC represents a mass flow controller.

B. SCCS Process Overview

The main purpose of the SCCS is to treat the gas effluents released from trash processing and to comply with ISS and habitable, spacecraft cabin air requirements. As mentioned, the SCCS consists of two main components: a carbon adsorbent bed and the catalytic oxidizer. The exhaust gases from the HMC will first enter the carbon bed, which serves as a pre-filter to avoid catalyst poisoning. The filtered gases will then enter the CatOx, promoting oxidation of the contaminants to CO₂ and H₂O vapor.

1. Adsorbent Bed

The carbon adsorbent bed is composed of Chemsorb® 1000, which is a high-grade activated carbon for organic vapor adsorption and utilized for filtration applications.⁴ Characteristics include a mesh size of 4 x 8 and an average bulk density of 0.43 g/mL. Its main design drivers are to remove sulfur compounds and dichloromethane, which may cause poisoning to the CatOx catalyst. Contaminant removal occurs via physisorption, in which the contaminants adsorb onto the exterior of the carbon granules then into the pores, while the gas stream passes through the sorbent.⁵ Optimal operating conditions are adsorption at 25 °C, 60% relative humidity (RH), and a flow rate of up to 2 standard liters per minute (SLPM). SLPM refers to conditions at around room temperature and atmospheric pressure. The packed adsorbent bed is 30 cm long with a length-to-diameter ratio of 4 and an internal diameter of about 7.4 cm.

2. CatOx System

The catalytic oxidizer-recuperator design was developed by PCI and uses a patented Microlith® technology as its catalyst.⁶ Operating temperatures of the CatOx are from 250 to 400 °C. To achieve at least a 95% removal efficiency, the operating temperature must be at least 350 °C. Current preliminary testing of the CatOx shows the ramp-up period to 250 °C takes 30 minutes. Operating flow rate is between 1 to 2 SLPM.

Fiberglass is insulated around the CatOx to maintain heating temperatures, avoid heat loss, and safety as it reaches high temperatures. Another TEC is located downstream of the CatOx, its purpose is to condense any water vapor that is produced before venting the gas stream to the fume hood.

For SCCS operation, we find that operating at 2 SLPM is needed to heat up the CatOx to around 400 °C. Within this 2 SLPM, 1 LPM is the trash exhaust from the HMC and the other 1 LPM is the lab air, which supplies the necessary oxygen to proceed the CatOx reaction. The carbon bed is a filter so no preparation is needed. For our tests, we heat up the CatOx between 380 to 400 °C before running, while during the test the temperature range decreases to 350 to 380 °C for the run.

C. Sample Monitoring Method

The in-line Gasmet FTIR DX4040 does continuous monitoring and provides real-time contaminant concentrations over time. Two sampling locations are present: (#1) before SCCS and (#2) after SCCS. Since the FTIR only has a single sampling port, quick disconnects were used to switch between monitoring “before and after SCCS” samples. 10-minute intervals were used to switch between each before and after sample to allow sufficient monitoring time. The sampling time configured in the Gasmet software is every 20 seconds. Figure 2 includes how the Gasmet FTIR is incorporated for sample monitoring.

Samples #1 and #2 should cover the gas composition at the HMC exhaust (before SCCS) and after the SCCS to test for contaminant reduction and contaminant conversion to CO₂ and water vapor. If a particular contaminant has noticeably less concentration after the SCCS and with CO₂ data from the CO₂ sensors to support, then this may lead to SCCS conversion. Comparing the before and after SCCS (inlet vs. outlet) can evaluate efficiency:

$$SCCS \text{ efficiency} = \frac{(\text{inlet concentration} - \text{outlet concentration})}{\text{inlet concentration}} \quad (1)$$

While the advantage of FTIR is real-time monitoring, we are only limited to analyzing 24 components. The selected components (aside from water vapor and carbon dioxide) are known contaminants, which were identified in previous contaminant control studies, and are listed in Table 1 in the results section.

D. Method for Calculating Contaminant Load

The Gasmet FTIR collects concentration data over time. With this data, concentration-time curves for each contaminant can be created. As a result, the area under the curve can be calculated to find the accumulated total concentration of a contaminant that the SCCS is exposed to (before SCCS) and the total concentration of a contaminant that exited the SCCS (after SCCS). This can be associated as the contaminant loads “before SCCS” and “after SCCS.”

There are several techniques to numerically evaluate integrals: the simplest and most approximate is the trapezoidal rule, where it uses the integrand evaluated at the limits of integrations:

$$\int_{X_0}^{X_n} f(X) dX = \frac{h}{2} [f(X_0) + f(X_n)] \quad (2)$$

when $h = X_n - X_0$. The sum of all the area of the trapezoids will equal to the total concentration load. This is also relatively the easiest method, as we have all the data points of concentration over time. The limits of integration are the sampling time, which is every 20 seconds.

The other technique can be to fit the concentration data in a polynomial function. However, this will require getting the polynomial equation for each curve and integrating them. This polynomial fitting technique can be used as a reference to compare contaminant load from the trapezoidal method.

E. Trash Models and Containment Bags

In this test campaign, 2.2-kilogram batches will be used and three standard types of trash models, which are the nominal, high liquid, and benign (excludes food and drink components, with the assumption that food and drink residues are small enough to be negligible). The list of components and its respective mass, for each model is in

Appendix A. A trash containment bag will also be used, specifically 8-Liter Sea to Summit (S2S) bags, which store wet trash in the ISS. Both the trash and the bag are compacted in the HMC.

III. Results

Concentration data is collected over time for each of the three trash models: nominal (NOM), high liquid (HL), and benign (BEN). With each trash model there are two cases: (1) trash with no bag (NB) and (2) trash contained in a Sea to Summit (S2S) bag, resulting in 6 tests overall. Table 1 shows the concentration range of all 24 chemical components analyzed by the FTIR over the sampling time before and after the SCCS. The units of concentration are in parts per million, ppm, for all chemical components, except for water vapor, which is in a volume percentage unit, vol%. (1 vol% = 10,000 ppm). In addition, the tables in Appendix B show all component concentration loads before and after the SCCS, the total contaminant load (without water vapor and carbon dioxide) before and after the SCCS, and the calculated SCCS efficiency (%). For results and analysis, we will be highlighting selected components, carbon dioxide, and water vapor. Most of the selected components are compounds that have a known SMAC value.

A. Carbon Monoxide

The release of carbon monoxide (CO) from trash processing is expected because the reaction of hydrocarbons with the oxygen from air tends to produce carbon monoxide and hydrogen gas.



The highest peaks in the concentration-time curves occur when the trash is processed at 150 °C and the catalytic oxidizer temperature is at 400 °C. We also know that CO is not coming from the lab air as none were detected via FTIR sampling of the lab air. From the concentration-time curves, carbon monoxide does not exceed the 24-hr SMAC of 100 ppm nor the 1-hr SMAC of 425 ppm. Comparing the concentration loads (which is the area under the curve) before and after the SCCS, the SCCS shows on average a 93% efficiency, ranging from 88% to near 100%.

B. Methane

The release of methane from trash processing is another compound to be expected. Methane can be produced by pyrolysis of mixed solid wastes. From the concentration-time curves, methane does not exceed the 24-hr & 1-hr SMAC of 5000 ppm. On average, there is about 2 ppm of methane in lab air. Comparing the concentration loads before and after the SCCS, the SCCS shows an average efficiency of 79% (a range from 74 – 81%).

C. Ammonia

In previous studies, the release of ammonia is observed in trash models. This is also a concern for the CatOx as it can possibly produce nitrogen oxides. The concentration-time curves do not exceed the 24-hr SMAC of 20 ppm nor 1-hr SMAC of 30 ppm. Ammonia is barely existent in lab air, ranging from 0 to 0.1 ppm at most. So the only source of ammonia will be from the trash. The concentration load shows an average of 52% efficiency, ranging from 27 to 85%. This wide range is due to low concentration loads: the concentration load of ammonia (which is the accumulated concentration of the processing period) before SCCS is on average 20 ppm, while the concentration load after the SCCS is as low as 2.5 to 11 ppm.

D. Benzene and Toluene (Aromatics)

The concentration-time curves for benzene exceeds the 24-hr SMAC of 3 ppm and 1-hr SMAC of 10 ppm during the temperature ramp-up period of trash for the benign model. The concentration eventually decreases to less than SMAC. The rest of the trash models do not exhibit this behavior. Comparing the contaminant loads before and after the SCCS for benzene, the SCCS shows a low efficiency of 20%. Like the same case with formaldehyde, the SCCS efficiency is difficult to describe due to the relative low amounts of concentration (refer to benzene concentration range in Table 1).

For toluene, the concentration-time curve does not exceed the 24-hr and 1-hr SMAC of 16 ppm. Comparing the concentration loads of toluene before and after the SCCS, the SCCS show little to no conversion. However, a range 0.2 to 0.3 ppm of toluene is detected in lab air. In conclusion, this compound is not a concern for the overall trash processing. Overall, for the aromatic compounds such as benzene and toluene, there is some removal by the SCCS, although there is not much to remove to begin with.

Table 1. Concentration range of all 24 chemical components analyzed by FTIR over the trash processing time.

Trash Model & Bag/No Bag Case	Nominal - No Bag	Nominal - S2S Bag	High Liquid - No Bag	High Liquid - S2S Bag	Benign - No Bag	Benign - S2S Bag
Components [Units]	Concentration Range (Red = Before SCCS, Blue = After SCCS)					
Water vapor [vol%]	0.14 - 1.32 0.76 - 1.38	0.08 - 1.37 0.62 - 1.44	0.75 - 1.98 0.75 - 2.06	0.62 - 1.8 0.98 - 1.52	0.42 - 1.39 0.79 - 1.38	0.53 - 2.08 0.53 - 1.24
Carbon dioxide [ppm]	127 - 2679 121 - 742	167 - 3279 206 - 2577	117 - 785 104 - 798	176 - 2429 165 - 2072	114 - 748 111 - 763	242 - 1501 220 - 670
Carbon monoxide [ppm]	0 - 21.9 0 - 3.35	0 - 54.55 0 - 37.5	0 - 5.1 0 - 4.26	0 - 49.59 0 - 42.03	0 - 22.45 0 - 23.12	0 - 26.76 0 - 0.97
Methane [ppm]	0 - 3.67 0 - 2.34	0 - 4.53 0 - 3.37	0 - 7.48 0 - 5.92	0 - 6.22 0 - 3.85	0 - 2.81 0 - 2.86	0 - 5.24 0 - 1.95
Ammonia [ppm]	0 - 1.16 0 - 0.24	0 - 3.37 0 - 0.21	0 - 0.32 0 - 3.81	0 - 2 0 - 1.42	0 - 0.38 0 - 0.87	0 - 0.28 0 - 0.18
Formaldehyde [ppm]	0 - 1.23 0 - 0.45	0 - 1.1 0 - 1.09	0 - 3.54 0 - 3.3	0 - 2.97 0 - 1.13	0 - 1.28 0 - 2.07	0 - 2.39 0 - 0.71
Benzene [ppm]	0 - 1.63 0.33 - 1.27	0 - 1.17 0 - 1.13	0 - 5.35 0 - 5.05	0 - 5.45 0 - 1.41	0 - 1.17 0 - 1.09	0 - 17.91 0 - 5.88
Toluene [ppm]	0 - 0.95 0 - 0.76	0 - 1.04 0 - 0.69	0 - 1.07 0 - 1	0 - 1.41 0 - 0.74	0 - 1.17 0 - 0.65	0 - 0.98 0 - 1.12
Carbon disulfide [ppm]	0 - 247.83 0 - 33.16	0 - 143.69 0 - 104.63	0 - 9.79 0 - 9.43	0 - 100.23 0 - 117.99	0 - 7.94 0 - 4.01	0 - 32.76 0 - 2.47
Acetone [ppm]	0 - 1.59 0.00	0 - 14.96 0 - 11.04	0 - 1.47 0 - 1.58	0 - 1.57 0 - 1.33	0 - 1.25 0 - 1.01	0 - 13.51 0 - 2.66
Dichloromethane [ppm]	0 - 57.29 0 - 21.66	0 - 121.83 0 - 121.57	0 - 197.72 0 - 193.38	0 - 200.96 0 - 53.1	0 - 198.78 0 - 204.62	
Ethylene [ppm]	0 - 7.07 0 - 0.55	0 - 2.76 0 - 1.19	0 - 2.86 0 - 1.58	0 - 13 0 - 1	0 - 3.22 0 - 2.08	0 - 1.74 0 - 0.55
Acetic acid [ppm]	0 - 20.26 0 - 2.68	0 - 15.93 0 - 15.49	0 - 14.05 0 - 15.24	0 - 39.41 0 - 21.06	0 - 14.39 0 - 15.56	
Acetaldehyde [ppm]	0.3 - 36.95 0.3 - 10.3	0.3 - 17.77 0.3 - 16.78	0.3 - 14.71 0.3 - 11.63	0.3 - 16.37 0.3 - 16.26	0.3 - 12.9 0.3 - 13.22	0.3 - 6.41 0.3 - 2.24
Methyl ethyl ketone [ppm]	0 - 1.22 0 - 0.21	0 - 2.48 0 - 1.28	0 - 9.79 0 - 9.54	0 - 3.23 0 - 2.77	0 - 3.12 0 - 3.15	0 - 1.93 0 - 0.02
Ethanol [ppm]	0 - 69.84 0 - 31.4	0 - 109.84 0 - 120.48	0 - 179 0 - 162.53	0 - 172.27 0 - 72.41	0 - 143.27 0 - 140.92	0 - 67.38 0 - 24.57
Isopropanol [ppm]	0 - 7.82 0 - 2.35	0 - 10.8 0 - 7.58	0 - 27.54 0 - 22.67	0 - 34.73 0 - 7.41	0 - 15.15 0 - 15.06	0 - 16.6 0 - 4.33
Heptane [ppm]	0 - 6.03 0 - 2.89	0 - 0.98 0 - 0.91	0 - 7.65 0 - 12.67	0 - 13.25 0 - 4.53	0 - 9.77 0 - 10.62	0 - 9.32 0 - 3.5
Pentane [ppm]	0 - 15.91 0 - 5.68	0 - 36.64 0 - 33.33	0 - 102.18 0 - 97.57	0 - 73.69 0 - 14.82	0 - 39.31 0 - 39.79	
Acrolein [ppm]	0 - 3.68 0.14 - 1.68	0.12 - 13.12 0.06 - 4.59	0.17 - 18.49 0.1 - 7.95	0 - 5.68 0.67 - 1.18	0.1 - 7.34 0.06 - 5.51	0.34 - 5.81 0.69 - 1.92
Furan [ppm]	0 - 7.04 0 - 4.32	0 - 39.3 0 - 40.76	0 - 7.1 0 - 16.47	0 - 38.08 0 - 11.89	0 - 32.6 0 - 46.2	
Dimethyl sulfide [ppm]	0 - 1.79 0 - 1.64	0 - 1.32 0 - 1.02	0 - 1.8 0 - 1.77	0 - 6.49 0 - 1.41	0 - 1.49 0 - 1.47	
Acrylonitrile [ppm]	0 - 41.26 0 - 14.01	0 - 82.48 0 - 44.18	0 - 25.4 0 - 50.75	0 - 115.7 0 - 37.48	0 - 87.6 0 - 38.05	0 - 93.49 0 - 27.51
Propyl acetate [ppm]	0 - 2.21 0 - 0.55	0 - 0.97 0 - 0.79	0 - 0.38 0 - 3.45	0 - 4 0 - 2	0 - 1.12 0 - 1.03	

E. Formaldehyde and Acetaldehyde (Aldehydes)

Formaldehyde was a concern because it is also a secondary design driver that influences the CatOx stage flow and temperature. The concentration-time curve exceeds the 24-hr SMAC of 0.5 ppm and 1-hr of 0.1 ppm during the temperature ramp-up the trash, noticeably between 50 °C to 90 °C. However, decreases to less than the SMAC after a few minutes. This suggests there could be leftover contaminants in the trash processing chamber (e.g. as odor and gaseous species can linger in the chamber and chamber walls) which would account for the initial spike in concentration. The SCCS efficiency is difficult to describe due to the low concentrations of formaldehyde coming into the SCCS: the temperature ramp-up period has a concentration of 3 ppm and decreases to on average 0.05 ppm (refer to formaldehyde concentration range in Table 1). No formaldehyde is present in lab air, so the formaldehyde detected is from the trash processing. In conclusion, this compound is not a concern in the overall process.

For acetaldehyde, this contaminant appears consistently and high concentrations usually appear at 130 to 150 °C. Previous studies show acetaldehyde offgas are from fruits as it is used as preservatives, flavoring agents, and trace amounts are present in ripe fruit. The concentration-time curve exceeds the 24-hr SMAC of 6 ppm and 1-hr SMAC of 10 ppm during the temperature ramp-up stage and more on the high temperature phase. Comparing the contaminant loads of acetaldehyde before and after the SCCS, the SCCS shows an average efficiency of 68%, ranging from 53 to 82%

F. Acetone and Methyl Ethyl Ketone (Ketones)

For acetone, the concentration-time curve does not exceed the 24-hr SMAC of 200 ppm nor the 1-hr SMAC of 500 ppm. Comparing the acetone concentration loads before and after the SCCS, the SCCS shows a high average efficiency of 92%, ranging from 79% to near 100%. No acetone was detected in the lab air sample, meaning the acetone detected is from the trash processing.

Methyl ethyl ketone shows similar results, in which the concentration curve does not exceed the 24-hr and 1-hr SMAC of 500 ppm. Comparing its concentration loads before and after the SCCS, the SCCS shows a good average efficiency of 89%, ranging from 70% to near 100%. No methyl ethyl ketone was detected in the lab air, which means the methyl ethyl ketone detected is from the trash processing.

G. Dichloromethane

Dichloromethane is an important contaminant that is a design driver for the adsorbent bed size. Concentration-time curve exceeds its 24-hr SMAC of 35 ppm and 1-hr SMAC of 100 ppm during the initial temperature ramp-up period between 80 – 90°C, however decreases over time. Comparing the concentration loads before and after the SCCS, the SCCS show a good average efficiency of 75%, ranging from 59 to 93%. On average, 0.2 ppm of dichloromethane is detected in lab air.

H. Ethanol and Isopropanol (Alcohols)

For ethanol, the concentration-time curve does not exceed its 24-hr and 1-hr SMAC of 5000 ppm. Ethanol offgassing occurs during the initial temperature ramp-up period, from 50 to 100 °C. Comparing the ethanol contaminant loads before and after SCCS, the SCCS shows an average 70% efficiency, ranging from 54 to 89%. About 0 to 0.2 ppm of ethanol is detected in lab air, meaning the ethanol detected is from the trash processing.

For isopropanol, the concentration-time curve does not exceed the 24-hr SMAC of 100 ppm nor the 1-hr SMAC of 400 ppm. Similar behavior to ethanol where highest concentration of offgassing occurs during the temperature ramp-up period. There is also additional offgassing at the 150 °C high temperature phase. Comparing the isopropanol concentration loads before and after SCCS, the SCCS shows an average efficiency of 89%, ranging from 76 to 96%. About 0 to 0.1 ppm of isopropanol is detected in lab air, meaning the isopropanol detected is from the trash processing.

Overall, the amount of ethanol and isopropanol are not concerns in the overall trash and gas processing.

I. Carbon Disulfide

The concentration-time curves for carbon disulfide show high concentrations during the high temperature phase. Comparing the contaminant loads before and after SCCS, the carbon disulfide contaminant is removed almost completely by the SCCS, resulting in an average efficiency of 93%. The peaks shown in Figures 3 for the “after SCCS” concentration curves are most likely residual readings from the “before SCCS” sample because the carbon disulfide concentration decreases after.

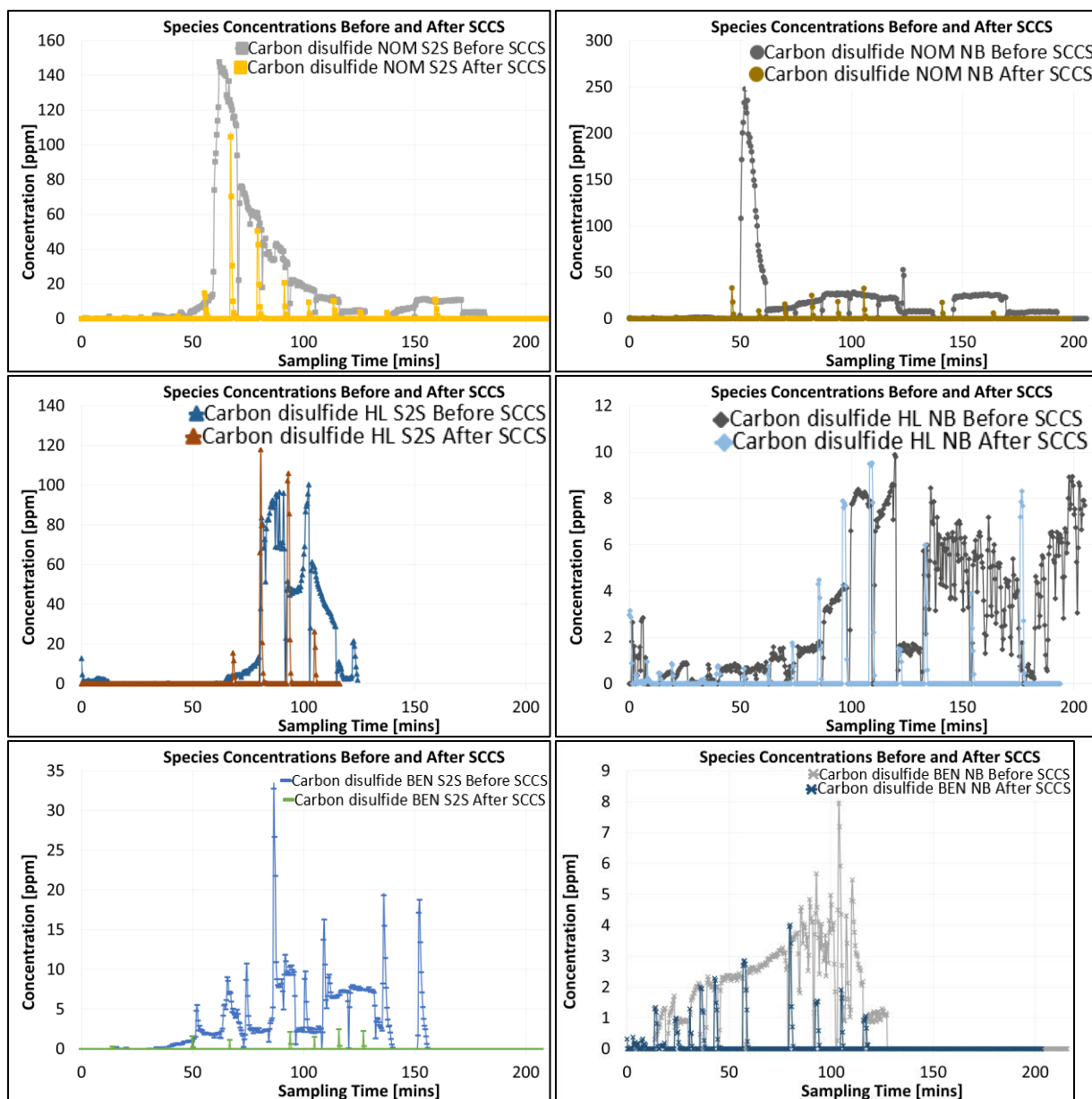


Figure 3. Carbon disulfide concentration-time curves, before and after the SCCS, for each trash model (nominal NOM, high liquid HL, benign BEN) and bag (S2S) & no bag (NB) case.

J. Heptane and Pentane (Alkanes)

For heptane, the concentration-time curve does not exceed its 24-hr SMAC of 80 ppm and 1-hr SMAC of 150 ppm. Comparing the heptane concentration loads before and after SCCS, the SCCS shows an average efficiency of 43%, ranging from 7 to 80%. About 0 to 0.1 ppm of heptane is detected in lab air.

For pentane, the concentration-time curve exceeds its 24-hr SMAC of 80 ppm and 1-hr SMAC of 150 ppm, during the initial heating stage, but decreases over time. Comparing the pentane concentration loads before and after SCCS, the SCCS shows an average efficiency of 80%, ranging from 71 to 92%.

K. Acrolein (also an aldehyde)

The concentration-time curve of acrolein exceeds its 24-hr SMAC of 0.035 ppm and 1-hr SMAC of 0.075 ppm. Acrolein offgassing occurs during the temperature ramp-up period and some peaks during the high temperature phase. Comparing the acrolein concentration loads before and after SCCS, the SCCS shows an average efficiency of 20%,

ranging from 6 to 30%. A concern is ~ 1 ppm of acrolein was detected in lab air, which is consistent in acrolein's concentration-time curves. Future work includes investigating and distinguishing what amount of acrolein is coming from the trash processing compared to what is present in the lab air.

L. Water Vapor

The concentration-time curves in Figure 4 show the production of water vapor after the SCCS, indicated by the observed higher concentration. Also comparing the water vapor concentration load data before and after the SCCS, the SCCS efficiency showed a negative percentage, which indicates the more water vapor exited the SCCS than what came in. The amount of water vapor detected in the lab air ranges from 0.86 vol% to 1.37 vol%. There is a range because the amount of water vapor is dependent on the temperature and relative humidity of the lab. The detection limit of water vapor in the Gasetm FTIR is 3 vol%.

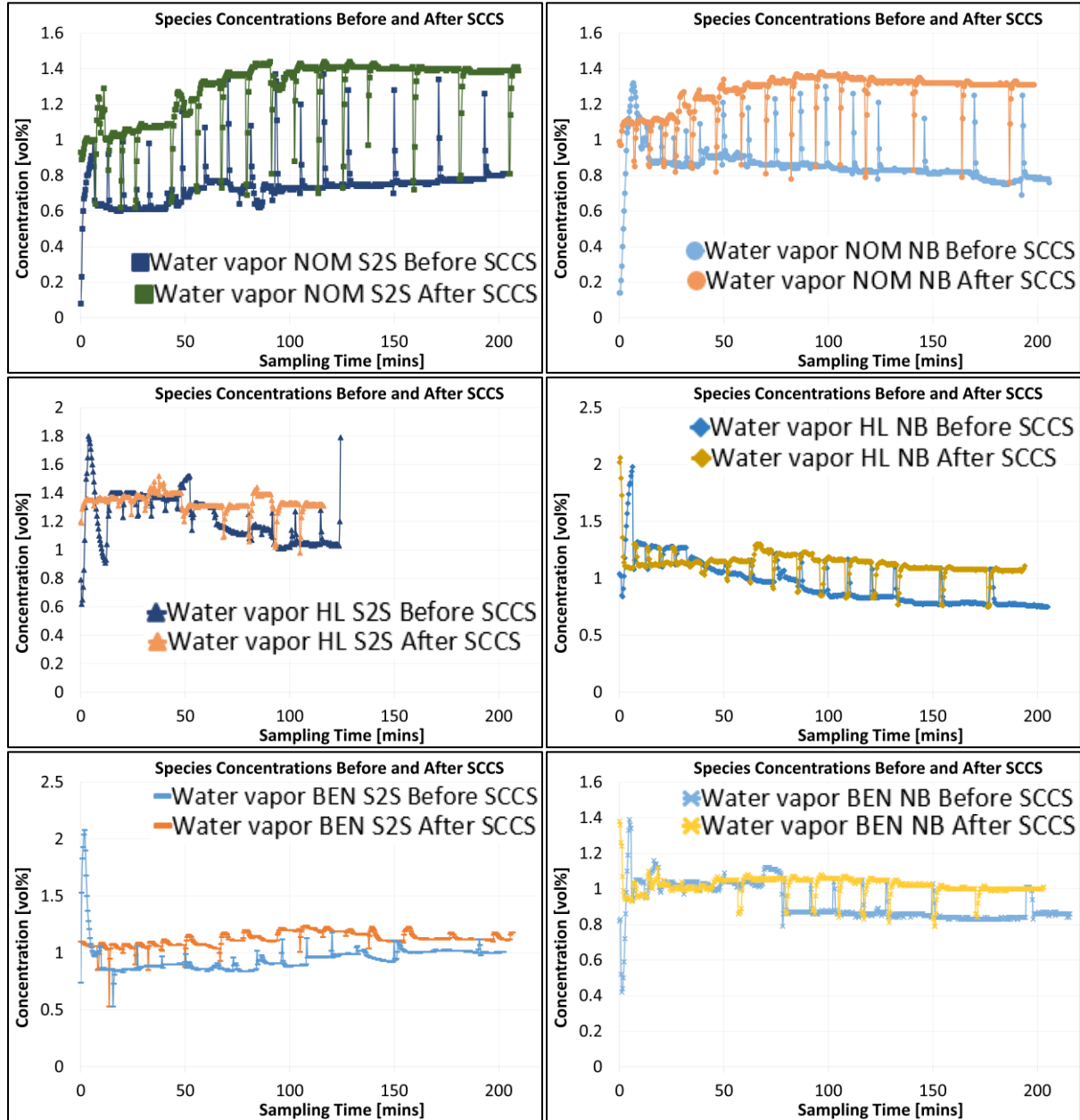


Figure 4. Water vapor concentration-time curves, before and after the SCCS, for each trash model (nominal NOM, high liquid HL, benign BEN) and bag (S2S) & no bag (NB) case.

M. Carbon Dioxide

The concentration-time curves in Figures 5 show the amount of carbon dioxide after the SCCS is less than before the SCCS, which initially seems contradictory to what we expect for contaminant conversion. However, note that with the addition of lab air, the amount of carbon dioxide detected in lab air ranges from 430 to 530 ppm, so a calculation calls for subtracting the carbon dioxide of the lab air baseline from the carbon dioxide monitored. After this calculation, based on the “before SCCS” curves in Figure 5, the average amount of carbon dioxide before the SCCS will be less than after the SCCS, suggesting possible contaminant conversion.

The detection limit of CO₂ in the Gasmet FTIR is 2000 ppm, so any data point above that limit is low in confidence. Based on observation, the points where CO₂ is greater than 2000 ppm occur when the HMC is not venting (e.g. when the HMC program is briefly and temporarily paused to adjust operational sequence, in which the pause causes the internal HMC pump to stop as well). Future work includes more investigation on the actual amount of CO₂, without the lab air baseline, entering the SCCS and in-depth analysis on contaminant conversion to CO₂.

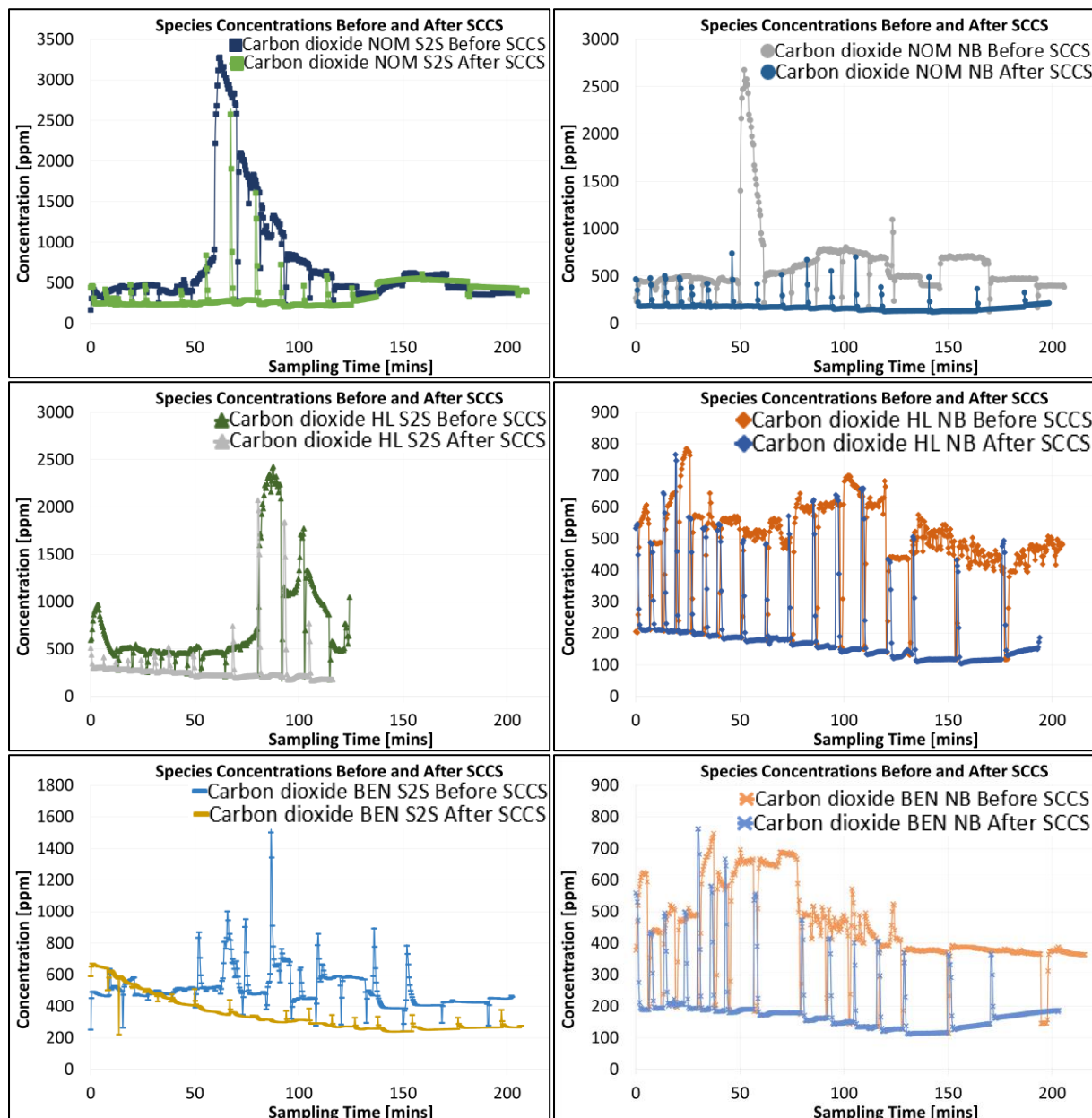


Figure 5. Carbon dioxide concentration-time curves, before and after the SCCS, for each trash model (nominal NOM, high liquid HL, benign BEN) and bag (S2S) & no bag (NB) case.

IV. Conclusion

Comparing the contaminant loads before and after SCCS (inlet vs. outlet) can evaluate the efficiency. Overall, there is a reduction in total contaminant load (without water vapor and CO_2) when the trash exhaust gases are treated in the SCCS. Carbon adsorbent bed is effective for dichloromethane and carbon disulfide. Problem contaminants such as acrolein seem to be ineffective by SCCS removal. Future work includes individually evaluating the carbon bed and CatOx, to understand what components the carbon bed removes and what contaminants are converted in the CatOx. Some issues and observations are identified: The recuperator / heat exchanger component of the CatOx is not working. Trash processed with a S2S bag shows no significant containment of contaminant release compared to trash processed with no bag. The advantage of a S2S bag containments is for easier trash loading and tile unloading from the HMC chamber.

One issue of the sampling method is the “before SCCS” and “after SCCS” sample cannot be measured simultaneously, so we must switch between “before and after samples” after particular intervals (usually every 10 minutes). In most cases, this results in the “after SCCS” samples having “spikes” in concentration, which can indicate residual gas from the “before SCCS” sample that is still in the Gasmet FTIR sample cell. Refer to Figure 6 for examples. In turn, this can affect the “after SCCS” concentration range data (Table 1) and concentration load calculations (Appendix B) to include larger concentrations than what is present.

Another issue is most offgassing that exceeds SMAC occurs during the initial heating / temperature ramp-up period of the trash process. Refer to Figure 7 for examples. This also affects the concentration range data and concentration load calculations to include larger concentrations than what is present from the trash processing. Future work includes investigating if there are leftover gasses from previous runs or gaseous species linger within the chamber walls.

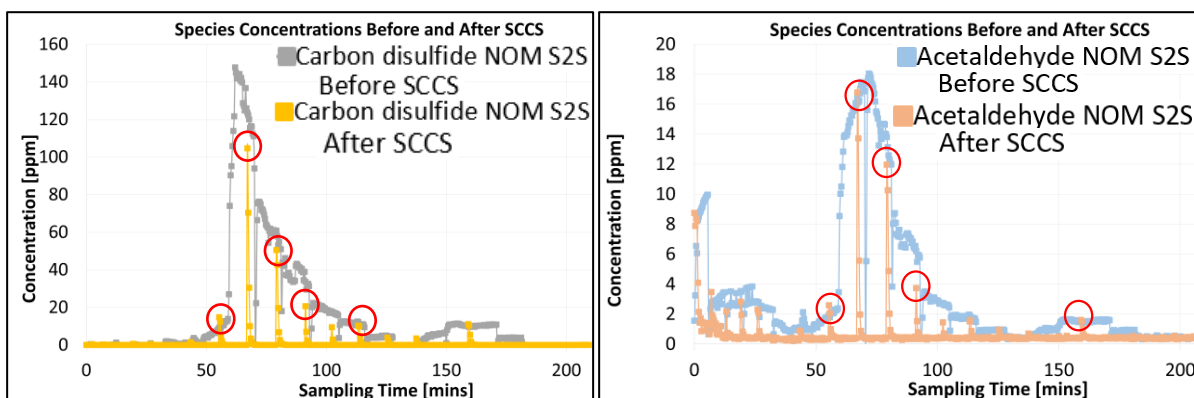


Figure 6. Examples of concentration-time curves with “spiked” concentrations in the after SCCS curve.

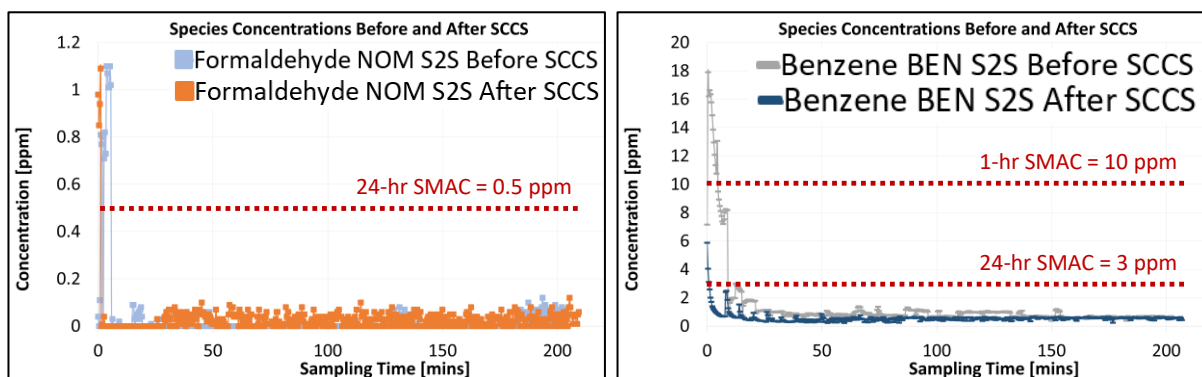


Figure 7. Examples of concentration-time curves where offgassing occurs during initial heating / temperature ramp-up period.

Appendix A. 2.2-kilogram Trash Models

General Category	HMC Batch Constituent	Nominal	High Cloth	High Liquid	Benign
		Component Mass/batch [grams]			
Cloths	Cotton T-shirts	421.6	940.5	333.5	525.3
	Towels	201.9	413.0	146.4	230.7
Wipes	Huggies Simply Clean Wipes Fragrance Free	201.9	64.8	115.1	181.3
	Dry lab. Chem Wipes	72.7	32.4	57.5	90.6
	Disinfectant Wipes	51.1	5.0	8.9	13.9
Personal Hygiene	Nitrile Gloves	57.2	25.5	45.2	71.2
	Shampoo on Towels	17.8	7.9	14.0	22.1
	Toothpaste on Towels	9.0	4.0	7.1	11.2
	PET plastic	9.0	4.0	7.1	11.2
	Chewing Gum	17.8	7.9	14.0	22.1
	Deodorant	48.7	0.0	0.0	0.0
Paper	Computer Paper, food & packaging paper	20.7	21.9	38.9	61.2
Adhesives	Duct Tape	5.1	2.3	4.0	6.4
	Kapton Tape	3.9	1.7	3.1	4.8
	Velcro	12.2	5.4	9.6	15.2
Food Packaging and Storage	Bite size pouch	77.4	34.5	61.2	96.4
	Thermo pouch	137.0	61.0	108.3	170.7
	beverage pouch	44.5	19.8	35.2	55.5
	straw assembly	19.9	8.9	15.8	24.9
	septum adapter assembly	15.1	6.7	11.9	18.8
	rehydrateable pouch	155.7	69.3	123.2	194.0
	overwrap (white laminate food packaging)	168.6	75.1	133.4	210.1
	dessicant	15.6	6.9	12.3	19.4
	BOB	71.0	31.6	56.2	88.5
Sweat Solids	Sodium Chloride	43.8	19.5	34.6	54.6
Foods & Drinks	Beef Pattie	15.2	9.7	17.2	0.0
	Scrambled Eggs	14.2	9.0	16.0	0.0
	Beef Franks	14.5	9.3	16.4	0.0
	Macaroni & Cheese	18.1	11.5	20.5	0.0
	Tortilla	17.6	11.2	19.9	0.0
	Rice pilaf	16.3	10.3	18.4	0.0
	Sweet & Sour Chicken	28.6	18.2	32.4	0.0
	Creamed Spinach	8.8	5.6	10.0	0.0
	Orange-Pineapple Drink	26.8	17.4	102.9	0.0
	Apple Cider Drink	26.8	17.2	101.7	0.0
	Pineapple Drink	26.8	17.7	104.8	0.0
	Dried Apricots	7.1	4.5	8.0	0.0
	Peaches	16.3	10.3	18.4	0.0
	Macadamia Nuts	10.3	6.6	11.7	0.0
	Strawberries	1.03	0.66	1.2	0.0
	Vanilla Pudding	11.3	7.2	12.8	0.0
Flight Packaging Materials	Reclosable Bag	20.7	81.9	145.5	0.0
	ESD Bubble Wrap	20.7	81.9	145.5	0.0
Total Mass (g)		2200	2200	2200	2200

Appendix B. Concentration Loads (Before and After SCCS) and SCCS Efficiency %

Components	Nominal – No Bag			Nominal – S2S Bag			High Liquid – No Bag		
	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)
Water vapor [vol%]	177.09	250.23	-41%	151.51	266.56	-76%	197.27	217.90	-10%
Carbon dioxide	125265	35689	72%	146800	74778	49%	100840	39445	61%
Carbon monoxide	334.93	7.26	98%	989.41	53.84	95%	278.50	30.84	89%
Methane	414.06	78.68	81%	416.87	77.97	81%	411.91	105.57	74%
Ammonia	17.24	2.570	85%	11.81	8.67	27%	21.48	10.868	49%
Formaldehyde	6.618	3.434	48%	6.164	5.852	5%	13.76	6.930	50%
Benzene	164.15	140.77	14%	121.77	127.99	-5%	155.75	133.42	14%
Toluene	64.51	60.93	6%	51.12	53.80	-5%	74.83	60.41	19%
Carbon disulfide	3651.99	93.06	97%	3207.04	183.67	94%	596.71	69.41	88%
Acetone	11.31	0.0000	100%	309.36	19.57	94%	18.77	3.938	79%
Dichloromethane	653.63	84.16	87%	992.41	266.86	73%	974.61	350.91	64%
Ethylene	31.29	15.14	52%	44.69	27.89	38%	45.10	28.85	36%
Acetic acid	110.84	13.23	88%	133.22	41.06	69%	95.60	42.61	55%
Acetaldehyde	619.84	111.51	82%	676.77	139.43	79%	277.35	129.99	53%
Methyl ethyl ketone	7.24	0.906	87%	31.99	0.990	97%	32.12	9.51	70%
Ethanol	817.27	184.86	77%	1057.91	374.45	65%	1218.57	450.59	63%
Isopropanol	124.17	5.502	96%	201.07	18.21	91%	161.49	32.70	80%
Heptane	125.10	51.45	59%	42.01	38.87	7%	63.93	56.22	12%
Pentane	257.65	29.00	89%	428.54	97.43	77%	580.48	162.77	72%
Acrolein	231.85	187.06	19%	224.36	163.47	27%	229.65	178.78	22%
Furan	38.97	20.46	48%	161.86	79.13	51%	13.13	45.20	-244%
Dimethyl sulfide	136.48	156.01	-14%	88.78	148.73	-68%	202.47	153.21	24%
Acrylonitrile	341.04	110.80	68%	421.34	176.72	58%	207.99	203.67	2%
Propyl acetate	33.55	1.670	95%	22.43	1.276	94%	3.548	5.825	-64%
Total Contaminant Load (w/o Water Vapor & CO ₂)	8194	1358	83%	9641	2106	78%	5678	2272	60%

Components	High Liquid – S2S Bag			Benign – No Bag			Benign – S2S Bag		
	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)	Concentration Load (Before SCCS)	Concentration Load (After SCCS)	SCCS Efficiency (%)
Water vapor [vol%]	152.03	155.21	-2%	199.51	206.64	-4%	193.03	231.94	-20%
Carbon dioxide	95535	32723	66%	95435	39160	59%	102593	71372	30%
Carbon monoxide	732.31	63.72	91%	655.89	78.85	88%	356.61	1.041	100%
Methane	271.77	51.94	81%	393.13	90.99	77%	435.57	81.76	81%
Ammonia	17.50	6.347	64%	20.96	9.63	54%	14.73	9.88	33%
Formaldehyde	10.95	0.838	92%	5.066	5.392	-6%	2.653	0.1852	93%
Benzene	117.99	81.55	31%	141.91	128.38	10%	266.74	118.16	56%

Toluene	22.23	22.82	-3%	66.79	61.30	8%	38.67	88.16	-128%
Carbon disulfide	2164.61	256.87	88%	246.96	27.40	89%	509.99	4.829	99%
Acetone	22.11	2.196	90%	33.44	2.277	93%	169.64	2.471	99%
Dichloromethane	1737.14	125.94	93%	885.02	359.27	59%			
Ethylene	48.45	9.81	80%	72.90	31.06	57%	60.17	59.06	2%
Acetic acid	182.61	21.09	88%	105.54	44.11	58%			
Acetaldehyde	600.63	98.13	84%	269.13	120.66	55%	238.80	101.26	58%
Methyl ethyl ketone	80.77	5.599	93%	60.47	7.36	88%	32.62	0.00733	100%
Ethanol	2009.91	227.09	89%	932.32	427.32	54%	594.36	177.73	70%
Isopropanol	344.18	13.17	96%	122.83	29.05	76%	163.29	5.058	97%
Heptane	153.34	31.19	80%	94.56	66.42	30%	118.20	33.95	71%
Pentane	741.15	59.54	92%	315.16	92.68	71%			
Acrolein	149.21	104.05	30%	219.56	185.26	16%	183.17	171.63	6%
Furan	229.27	34.14	85%	115.50	72.97	37%			
Dimethyl sulfide	61.86	86.80	-40%	137.23	165.64	-21%			
Acrylonitrile	620.46	152.09	75%	393.99	202.15	49%	731.71	157.90	78%
Propyl acetate	34.36	3.377	90%	16.31	2.911	82%			
Total Contaminant Load (w/o Water Vapor & CO ₂)	10353	1458	86%	5305	2211	58%	3917	1013	74%

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