Heat Melt Compactor Gas Contaminants from Single Waste Materials

John W. Fisher[1] and Jeffrey M. Lee[2]
NASA Ames Research Center, Moffett Field, CA, 94035

Johannes Goeser[3]
Technical University of Munich, 85748 Garching, Germany

and

Oscar Monje[4]
AECOM, NASA Kennedy Space Center, FL, 32899

A Heat Melt Compactor (HMC) has been under development by NASA in recent years as a technology for processing space mission trash. The HMC compacts the trash, heats the trash to 150 °C, sterilizes the trash, and recovers the water from the trash. The heating causes volatile contaminants to be released from the trash, and these contaminants can either be vented to space or oxidized so that the air containing the contaminants can be recycled to the habitat. Characterization of the contaminants has been conducted in the past on the average mixed trash stream. However, every waste batch on a mission will not contain exactly the average overall composition; consequently, it is of value to understand the contribution of each of the components of the trash. This paper provides a summary of the major contaminants produced by components of the trash heated on a temperature profile such as trash experiences in the HMC.

Nomenclature

ARC	=	Ames Research Center
a_w	=	water activity
CM	=	Crew member
ECLS	=	Environmental Control and Life Support
Gen1	=	1st generation HMC
Gen2	=	2nd generation HMC
HMC	=	Heat Melt Compactor
JSC	=	Johnson Space Center
KSC	=	Kennedy Space Center
MAG	=	maximum absorbency garment
PE	=	polyethylene
PET	=	polyethylene terephthalate
TOC	=	total organic carbon
TDS	=	total dissolved solids
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly

[1] Lead Engineer (Retired), Bioengineering Branch, MS239-15, NASA Ames, Moffett Field, CA, 94035
[2] Research Engineer, Bioengineering Branch, MS239-15, NASA Ames, Moffett Field, CA, 94035
[3] Visiting Researcher, Institute of Astronautics, Boltzmannstr. 15, 85748 Garching, Germany
[4] Scientist, AECOM, NASA Kennedy Space Center, FL 32899

I. Introduction

As on earth, humans in space produce trash and waste. This includes packaging materials, plastic foils, wipes, food residues or other everyday used products. Studies have estimated the amount of trash (not including metabolic waste) for future long duration space missions is about 1 kg per crewmember per day.[1] Currently trash is hand compacted and either returned to earth or discarded to a re-supply vehicle, which is later incinerated while entering Earth's atmosphere.[2] Although this is satisfactory for the International Space Station (ISS), a better solution for future long duration missions beyond low earth orbit is to recover resources from the trash. The Heat Melt Compactor (HMC) is a device that heats trash to temperatures in the neighborhood of 150 °C, compresses the trash, recovers water, and produces tiles that are 90% as effective as polyethylene for shielding particle radiation.[3] Recent papers provide an overview and update of a NASA developed HMC.[4,5] During the heating process of the HMC, gaseous contaminants are released. Previous experiments have analyzed the gases of mixed batches of trash.[6] Experiments reported in this paper present analysis of gaseous contaminants that are produced by the HMC process for non-mixed, individual trash components.

II. Heat Melt Compactor background

The HMC is a cylinder with a movable ram that compacts the trash. Heaters in the walls heat the trash. After reaching the boiling point, the water in the trash is boiled and leaves the chamber. A sweep gas carries the water vapor from the trash. Outside of the chamber, the water vapor is condensed and collected. At approximately 130 °C, the plastic components in the heated trash begin to melt and start to flow into the trash. After a hold time of 3 hours and at a temperature of 150 °C, which is sufficiently long and hot enough to sterilize the trash, the compacted trash is cooled. The plastic solidifies and a physically stable, compact tile is formed.

During the heating phase, components in the trash release volatiles that were initially present in the trash or are produced by breakdown of the trash due to the increased temperature. These volatiles are gaseous contaminants that may be vented, or may be contained in the condensed water, or may be released to the cabin after processing in a contaminant cleanup system such as a catalytic oxidizer, or may be captured for sequestration in an adsorption device.

During previous development work on the HMC, analyses of the water and the effluent gases was performed.[4] Those experiments confirmed that the process sweep gas and the recovered water must be cleaned before introduction into any Environmental Control and Life Support (ELCS) system. In the sweep gas, over 70 different chemicals were found and the analysis of the recovered water showed a high concentration of Total Organic Carbon (TOC).[7] The TOC in the recovered water is currently expected to be processed in the Water Processor Assembly (WPA) for future space missions. NASA has in place on the Gen2 HMC plans to include catalytic and adsorption cleanup of the HMC effluent gases but testing has yet to be conducted. An alternative to effluent gas cleanup is to vent gaseous contaminants directly to space vacuum. For either method it is important to know the effluent contributions of individual trash components so as to understand what processes and operations are needed in order to satisfy spacecraft requirements.

III. Objectives

The overall objectives of this work are to identify the characteristic compounds that are outgassed by the individual trash components, to determine the approximate concentrations of those compounds, and to determine when during the processing most of the gases are produced. This information can be useful in predicting what will be produced in various different trash compositions and also useful in perhaps avoiding those trash ingredients that produce unacceptable off-gassing contaminants. To accomplish this a test rig was assembled to capture gases of individual trash materials during a representative HMC processing cycle. The captured gases were then analyzed for composition. The trash components were based on a previous trash model described in the next section.

In order to achieve the characterization of the contaminants from individual trash components, a number of test objectives were identified. These test objectives included: 1. design and assembly of a test rig that simulates the operation of the HMC and produces representative outgassing from trash materials and recovered water; 2. selection of suitable components; 3. definition of the test procedure; 4. performance of the test runs and analysis of the test samples; and 5. evaluation of the test results.

IV. Experimental Setup

To meet experimental objectives and to accurately measure the contaminants released from the different trash components it was decided that the experimental system would need to meet the following requirements:

temperature control, nonleaking hardware, a reasonably sized processing volume, sweep gas flow control, condensation only in the condenser, a cleanable system, and provisions for sampling and safety.

The test rig schematic can be seen in Figure 1 and a picture of the actual hardware is shown in Figure 2. During a run room air is drawn into the system as a sweep gas and passes through a flow meter. In the vacuum oven the room air and the trash are heated up, the trash outgases, and water boils off. The hot gas mixture of air, effluent trash gases, and water vapor exits the oven and is routed to the condenser. There the gas mixture is cooled and the water vapor condenses. The subsequent water separator collects liquid water. A pump is located at the end of the system to pull the sweep gas through the system. A second flow meter at the end is used to compare the entering and exiting gas flow rates. With those two flow meters, leaks in the system can be detected. Uncontrolled and unintended leaks have to be avoided because they could influence and falsify the gas composition. After the contaminated air passes the second flow meter, it is either directed for sampling into a Tedlar Bag or is vented to a fume hood. The flow rate that is displayed by the second flow meter is used to calculate the air volume that fills a Tedlar Bag.

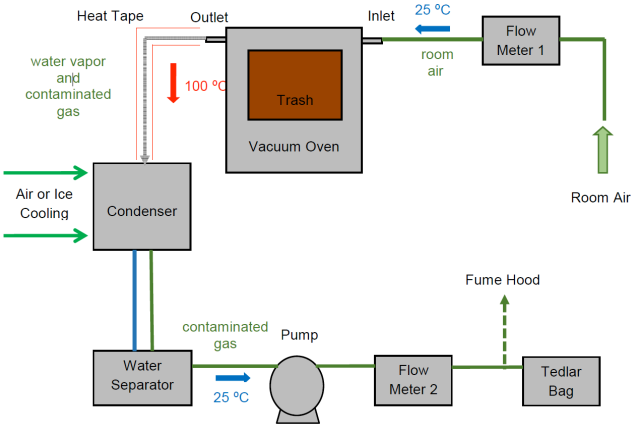

Figure 1. Diagram of experimental system.

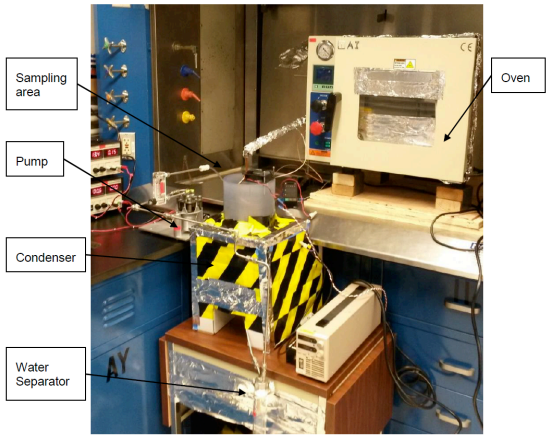

Figure 2. Image of system

V. Procedure

A. Trash components

The components of the experimental trash model were derived from the logistic items described in a recent paper.[8] A total of 40 items made up the trash materials. These 40 items were grouped into the two broad categories consisting of food and non-food items. The breakdown by weight for non-food items is: Cotton T shirt = 19.8%, towels = 8.6%, computer paper + food packaging paper = 1.6%, dry lab chem wipes = 3.4%, Huggies™ diapers to represent EVA maximum absorbency garment (MAG) = 6.8%, nitrile gloves = 2.6%, shampoo - on the towels = 0.8%, toothpaste - on the towels = 0.4%, PET (polyethylene terephthalate) = 0.4%, chewing gum = 0.8%, duct tape = 0.4%, Disinfectant wipes = 0.6%, Bite size pouch = 3.6%, Thermo pouch = 6.4%, Beverage pouch = 2.1%, Septum = 0.9%, Septum adapter = 0.7%, rehydration pouch = 7.3%, Overwrap = 7.9%, Velcro (nylon) = 0.5%, Iron packs = 0.7%, Paper = 0.8%, BOB (Bulk Overwrap Bags)= 3.3%, salt - sodium chloride on T-shirt = 2.0%. The breakdown by food items (Total = 17.4%) is: Sausage Patty = 1.48%, Dried Apricots = 0.69%, Scrambled Eggs = 1.38%, Orange-Pine drink = 0.00%, Apple Cider = 0.00%, Pineapple Drink = 0.00%, Frankfurter = 1.41%, Mac & Cheese = 1.76%, Tortilla = 1.71%, Peaches = 1.58%, Macadamia nuts = 1.00%, Sweet Sour Chicken = 2.78%, Rice with butter = 1.58%, Cream Spinach = 0.86%, Strawberries = 0.10%, Vanilla Pudding = 1.10%. Figure 3 shows the simulant waste materials used for the testing.

Figure 3. Trash components.

Due to various constraints including time and availability of analytical support, it was not possible to run each one of the 40 components separately. Therefore, it was decided to group some of the trash components to reduce the number of tests to 20. Table 1 shows how the single components in the waste model were grouped.

Table 1. Grouping of waste types

Group	Items in the group
1	Shampoo – on towel; Toothpaste – on towel
2	Computer paper +food packaging paper; Paper
3	Cotton T-shirt; Salt- sodium chloride on T-shirt
4	Sweet Sour Chicken; Rice
5	Orange-Pine; Apple Cider; Pineapple Drink
6	Fruits: Dried Apricots; Peaches; Strawberries
7	Sauage Patty; Frankfurter sausage
8	Beverage Pouch; Septum; Septum adapter
9	Plastics: rehydration pouch; Overwrap; BOB (Bulk Overwrap); Bite size pouch
10	Thermo pouch
11	Nitrile gloves
12	Disinfectant wipes; Dry chem lab wipes; Huggies (Diaper)
13	PET-bottle
14	Tortilla; Peanuts
15	Scrambled eggs
16	Chopped Spinach
17	Vanila Pudding (or chocolate pudding)
18	Chewing Gum
19	Velcro; Duct tape
20	Mac & Cheese

Generally the groups were made of related items. For example, group 8 includes the beverage pouch, the septum, and the septum adapter. All of these items together comprise the drink container, and they will probably always occur together in the trash. Further examples for this kind of grouping are group 1 and group 3. A number of trash groups were composed of just one trash component. Multicomponent groups were grouped with the expectation that components would probably produce the same or similar gases. For example, for group 2 the computer paper and normal paper probably produces similar gases. The same is valid for group 9 that groups all the plastic components. Similarly, group 7 includes both the sausage patty and the frankfurter sausage.

B. Additional Tests

In addition to the main tests of the trash groups, some additional tests were conducted. For example, tests were run to show whether the released gases of a multi-component test are equal to the sum of the released gases of the single components. Discrepancies might indicate the creation (destruction) of new (existing) gases. These "interaction" tests were performed by first processing two components separately and then processing both of these components together.

Furthermore, mass dependency tests were conducted. Such tests can show how the quantity of off gassing is related to the quantity of waste and shows the ability of the test rig and procedures to produce precise, accurate, and reproducible results.

C. Development of a Temperature Profile and Sampling Times

To obtain results are representative of the HMC process, the temperature (heating) profiles of the single group tests should be the same as for an HMC process. However, some adjustments to the original temperature profile were necessary. The mean duration of a HMC run is about 11 to 12 hours. Much of this time is associated with hold time for boiling off water, sterilization hold time, and cool down time. Sterilization was not necessary for the off-gassing runs. The time to boil off the water is shorter because the samples are smaller and more exposed than compacted waste in the HMC. And complete cool down to room temperature is also not necessary since the last sample is taken at a temperature that is higher than room temperature. Figure 4 shows the temperature profile used for the tests. Each hexagon is located at the time when a sample is taken and the numbers inside a hexagon show first the temperature and second the sample number at that temperature (except for the first sample, where 0_1 is sample 1 at 25 °C).

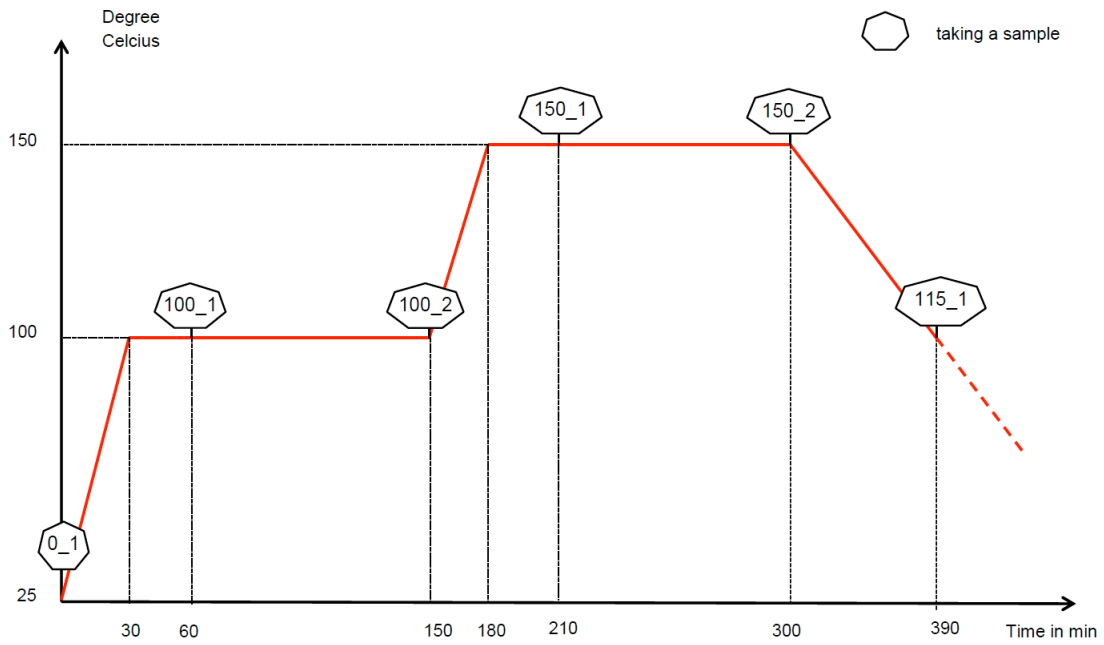

Figure 4. Temperature profile of outgassing test runs.

The general profile is still very similar to the one of the HMC process. There are two holding times at 100 °C and at 150 °C, respectively, and a cooling period at the end. However, the hold times of the constant temperature levels were decreased to 120 min (2 hours) each, instead of holding them for 3 or even 4 hours. Besides the two holding phases, the cooling period was shortened by finishing the test after 90 minutes of cooling. A total of 6 air samples were taken during each test run. The first air sample is taken before the start of the test run. This sample provides a baseline for each test. The baseline sample can be helpful in detecting cross contamination that can be caused by possible waste deposits of previous runs. The next two samples are collected at the 100 °C level; one after 30 minutes and the other after 120 minutes. Those two samples show, first, whether the temperature increase from 25 °C to 100 °C changes the sweep gas composition and second, whether the holding time at that temperature level has an affect. The same sampling pattern is applied for the 150 °C level. A last air sample is collected at 115 °C after the oven has been turned off for 90 minutes. The last air sample provides information and a trend about the outgassing during the cooling phase.

D. Selection of an Appropriate Flow Rate

For a number of reasons a constant sweep gas rate of 0.4 L/min was chosen. It was reasonable to restrict the sweep gas flow to the range of 0.1 to 1 L/min in order to stay within the range of the sweep gas rates used during development of the HMC. In addition, the flow rate should not be too low because the sweep gas assists in water transport from the processed trash. A low flow can cause undesireable condensation of the water vapor in the tube line between the oven and the condenser. The rate also determines the residence time of gas in the vacuum oven. For the 25.5 L oven a flow of 0.4 L/min produces a residence time of 64 minutes. Longer residence times would compromise the time value of samples. High flows and shorter space times produce low contaminant concentrations, which can cause analytical problems. Consequently, the sweep gas flow rate of 0.4 L/min was chosen as a reasonable compromise.

For analytical purposes, 2L Tedlar bags were chosen for sampling. At a flow rate of 0.4 L/min, the time to fill each bag is 5 min. However, because a completely filled and stretched bag can be easily damaged during storage and air transport to the gas analysis center at Kennedy Space Center (KSC), sampling time was set to 3:40 min per bag, which corresponds to a filling of 73% of the maximum filling volume. During the remaining test time of the test run, the released gases were vented to the fume hood.

E. Considerations about the Processed Batch Trash Mass

To avoid concentrations of effluent compounds from being too low for analysis, a sample batch large enough to produce results needs to be collected. For example, if just 4 g of chewing gum (the amount in a 500 g full waste

model run) are processed in the vacuum oven with a consistent sweep gas flow rate of 0.4 L/min, it was expected that no significant changes of the gas composition would be detected in the 6 gas samples of the test run. Constant batch size is also advantageous for comparison purposes because it becomes apparent which trash components produce higher concentrations of gases and which produce lower concentrations.

It was decided to use a constant trash mass of 100 g per test run. Within the groups, the mass ratios of the waste model were approximately applied, to scale the masses of the single components. For example, the processed trash batch of group 14 is composed of 50 g of peanuts and 50 g of tortillas which is consistent with the proportions in the derived trash model.

F. Test Procedure

A detailed test procedure was used with 27 steps.[9] The general steps were: check system cleanliness, prepare and input waste sample, establish air flow, run the temperature profile, take air samples according to the time and temperature schedule in Fig. 4, take water samples at the end, and shut down.

G. Fourier Transform Infrared Spectroscopy (FTIR)

The air/effluent gas samples were analyzed using a qualitative method using an FTIR spectrometer developed at KSC. The method[10] is only a qualitative measure of the effluent gases in the HMC because some compounds may have leaked though the Tedlar bag or adhered to the bag walls during the time the samples were taken and transferred to KSC for analysis. FTIR was used due to a readily available library for the gases expected that was developed from previous offgas studies [Ref. 3]. This method enables the identification and the quantitative measurement of the gaseous compounds in an gaseous sample.[11,12] The FTIR used was the Gasmet DX4030. The FTIR's computer uses a reference library to determine the presence and concentration of compounds that are chosen by the user. Analysis can be performed for 25 chosen gases simultaneously. The Gasmet analyzes for chosen gases only and not general unknowns.[13] Compounds were selected for analysis if they had been among the highest concentration substances found in the previous offgas studies, or if they were considered criticial (such as catalyst poisoning sulfur compounds). The compounds must also be in the FTIR's library. The compounds chosen for analysis were: water, acetaldehyde, carbon disulfide, carbon dioxide, acetone, dimethyl sulfide, carbon monoxide, ethan, 2-butanol, nitrous oxide, sulfur dioxide, nitric oxide, methane, 3-methyl-butanal, hexanal, ammonia, nonanal, furfural, formaldehyde, pentane, 5-methyl-2-furfural, toluene, methanol, 2,3-pentanedione, and butanal. An advantage of the FTIR is that the produced Fourier transform spectrum of each sample can be saved and analyzed for other molecules in the future. If there is interest in looking for another chemical compound that may have been produced during one of the tests, then the saved data can be re-evaluated using the updated library.

Water analysis of the collected samples was conducted at Ames and included the following: Na+, Cl-, NH^{4+}, NO^{2-}, TOC, K+, Br-, TDS, Mg^{2+}, NO^{3-}, TDS, Ca^{2+}, PO_4^{3-}, Sulfite (SO_3^{2-}), SO_4^{2-} and pH

VI. Results

Table 2 shows a summary of all the runs made. For the main tests there were 20 groups with 6 samples per group. However, Group 5 was not tested because it consisted of fruit juices and it was established by the systems analysis group that astronauts on future long-endurance missions will most likely consume all juice drink; therefore, partially consumed drinks will not be present in the trash. Hence, there were 114 main tests instead of 120.

Between the test runs the system was cleaned with distilled water to remove possible deposits. Samples of the water were retained, but not analyzed.

Mass dependency was evaluated, for example, by first processing 25g of gloves and afterwards processing 75g of gloves. For the material interaction test, two different trash components were processed individually first and together afterwards. The interaction test was conducted to evaluate whether the results of single tests can be used estimate the outgassing of any mixed batch based on the trash components and their quantity.

Table 2. Summary of runs

Test	Air Samples	Water Samples
Functionality tests	12	4
Main tests: HMC-similar test run for the trash groups	114	12
Cleaning run	0	7
Mass dependency tests	12	0
Interaction of components tests	18	4
Repeatability tests	28	2
Blank test	3	0
FTIR verification test	4	0
Sum	191	29

The other runs included on Table 2 were verification tests. Some tests of the main test regiment were repeated to evaluate the precision of the results. Some "blank" air samples were also captured in the Tedlar bags and tested. This was done to see if room air itself could affect the results. Last, to check the precision and accuracy of the FTIR analytical methods, some air samples with 50 ppm of methane were analyzed.

H. Air Sample Results

Following are presented air sample results of group tests that illustrate the important findings of this study. The important categories of the trash include hygiene products, package materials, and food residuals. The results of a range of very active to less active trash groups are shown.

The following results summarize the results and show the 25 gaseous compounds analyzed for each test. The diagrams list all the compounds. Gas concentrations are generally shown in ppm. Exceptions are the water vapor and the carbon dioxide, which are given in vol-%.

1. Group 8 (Beverage Pouch, Septum, Septum Adapter)

Figure 5 shows group 8, which comprises the beverage pouch, the septum and the septum adapter. The trash components of this group are weighted before and after processing. It can be seen that the trash mass did not change during the test run. It can also be seen that the septum adapter and parts of the septum melted.

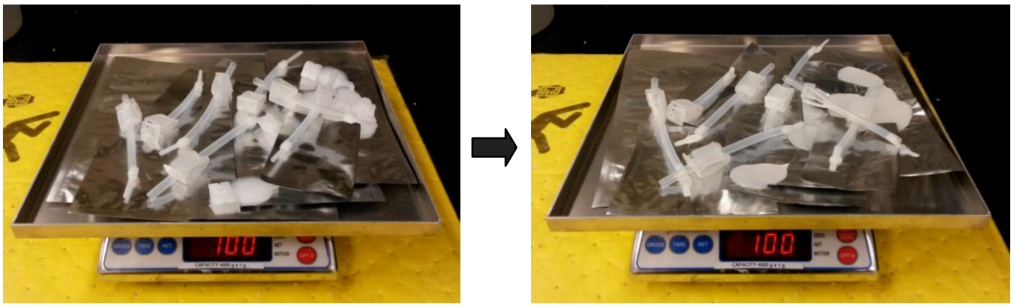

Figure 5. Group 8 beverage pouch, septum, and septum adapter before and after process.

The results of the air samples that were collected during this process are shown in Figure 6. There were four gases, including 2,3-pentanedione, ethanol, pentane and 2-butanol, that were outgassed with higher concentrations compared to the other gases. In the baseline air sample, which was collected right before the HMC temperature profile was started, no significant gases were detected. Concentrations increased and peaked at the first 150 °C sample and then declined.

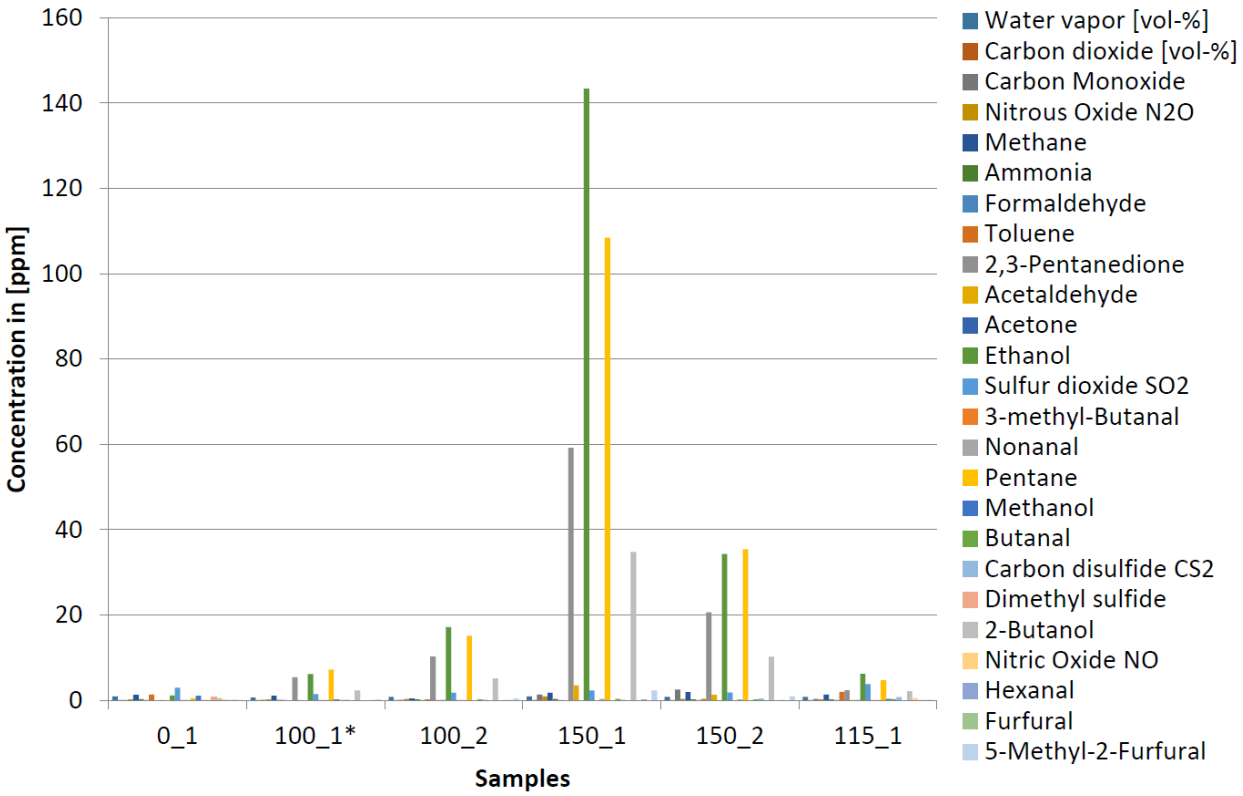

Figure 6. Effluent gases (G8) beverage pouch, septum, and septum adapter.

2. Group 11 (Nitrile gloves)

The single trash component of this group was the nitrile gloves. In Figure 7, they are shown before and after being processed in the test rig. After processing the gloves were discolored.

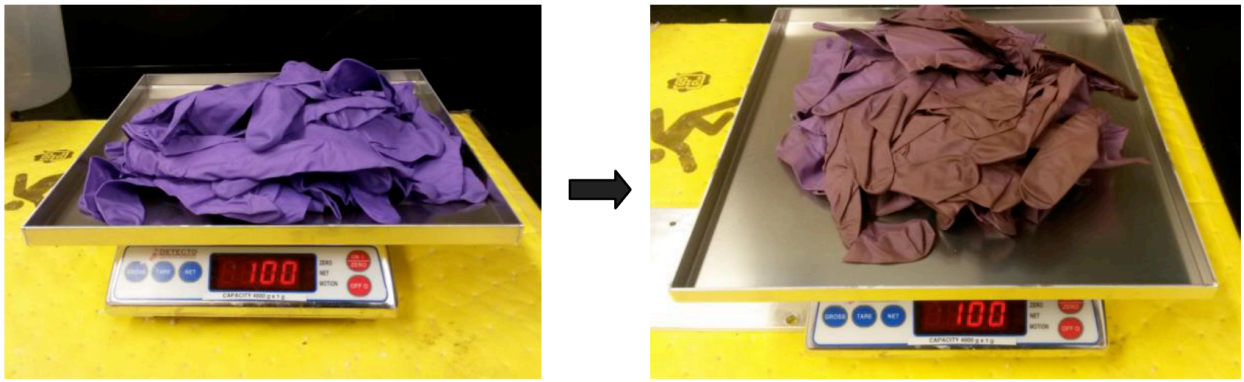

Figure 7. Group 11 nitrile gloves components before and after process.

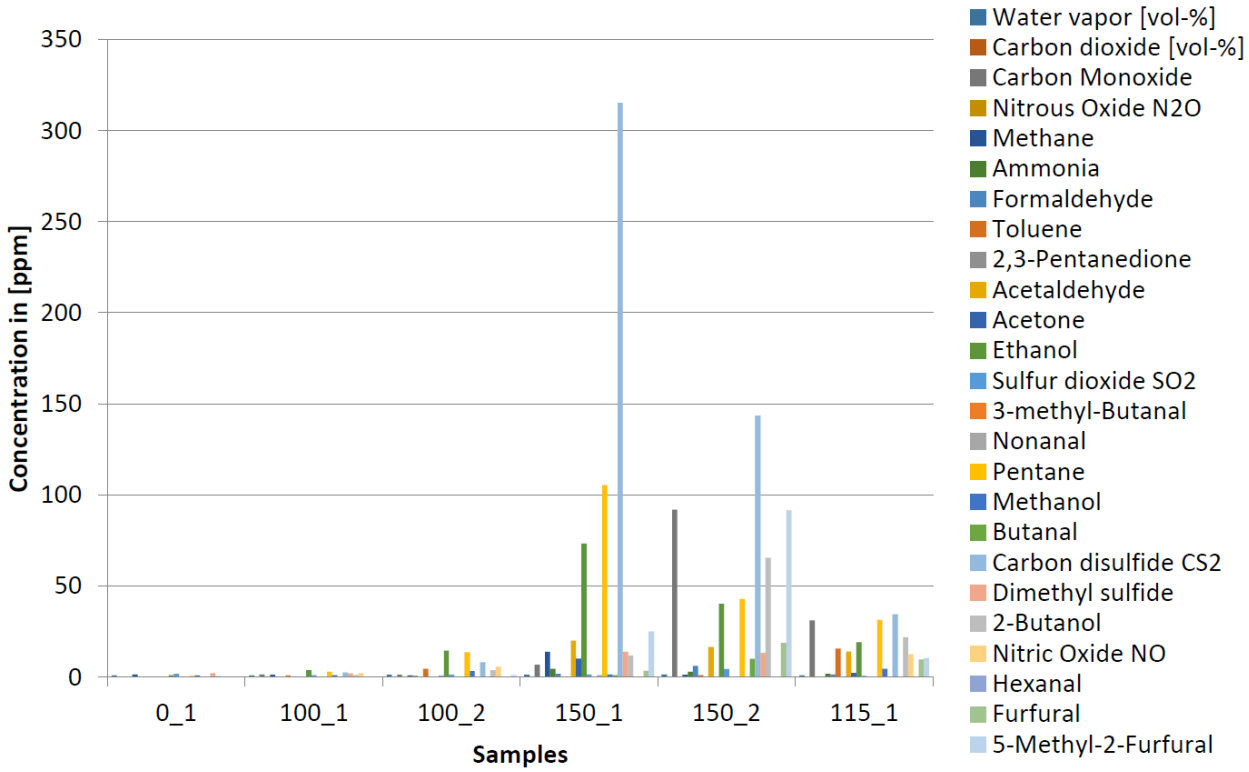

Figure 8. Effluent gases group 11 nitrile gloves.

The results of Figure 8 for effluent gases show that very high concentrations of carbon disulfide were outgassed during the test. Especially in the air sample that was collected after 30 min at 150 °C a peak concentration of around 320 ppm of carbon disulfide was found. Other significant gases that were released during processing of the nitrile gloves included carbon monoxide, ethanol, pentane and 2-butanal.

3. Group 12 (Diaper, Wet disinfectant wipes, Dry lab wipes)

This group consisted of the disinfectant wipes and the dry lab wipes. To obtain the overall mass of 100g, 60g of diaper, 30g of dry wipes and 10g of disinfectant wipes were used. These mass ratios were derived from the overall waste model. To increase the probability that outgassing from the disinfectant wipes could be detected, the mass fraction of this trash component was a bit higher for the group test than it is in the overall trash model. It was found in the overall trash model that about 70% of the diaper mass is assumed to be water. To maintain realistic mass ratios within the group and to enable the production of a realistic mass of water, about 40g of water was added to 20g of dry diaper to arrive at the 60g of diaper mass. This was the only time that any water was added to a trash component. Usually urine is responsible for the high water fraction of the diaper. Figure 9 shows the trash components before and after the process.

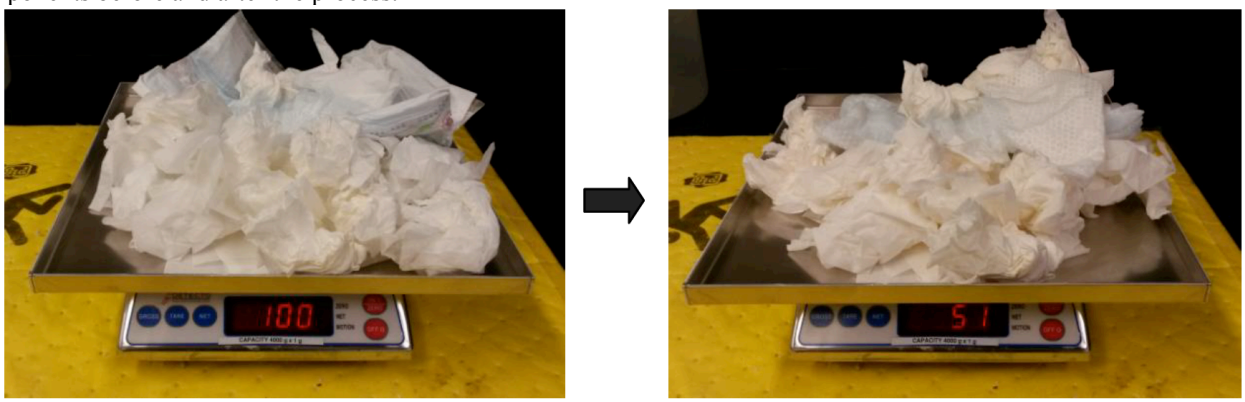

Figure 9. Group 12 diaper/disinfectant wipes/dry wipes before and after process.

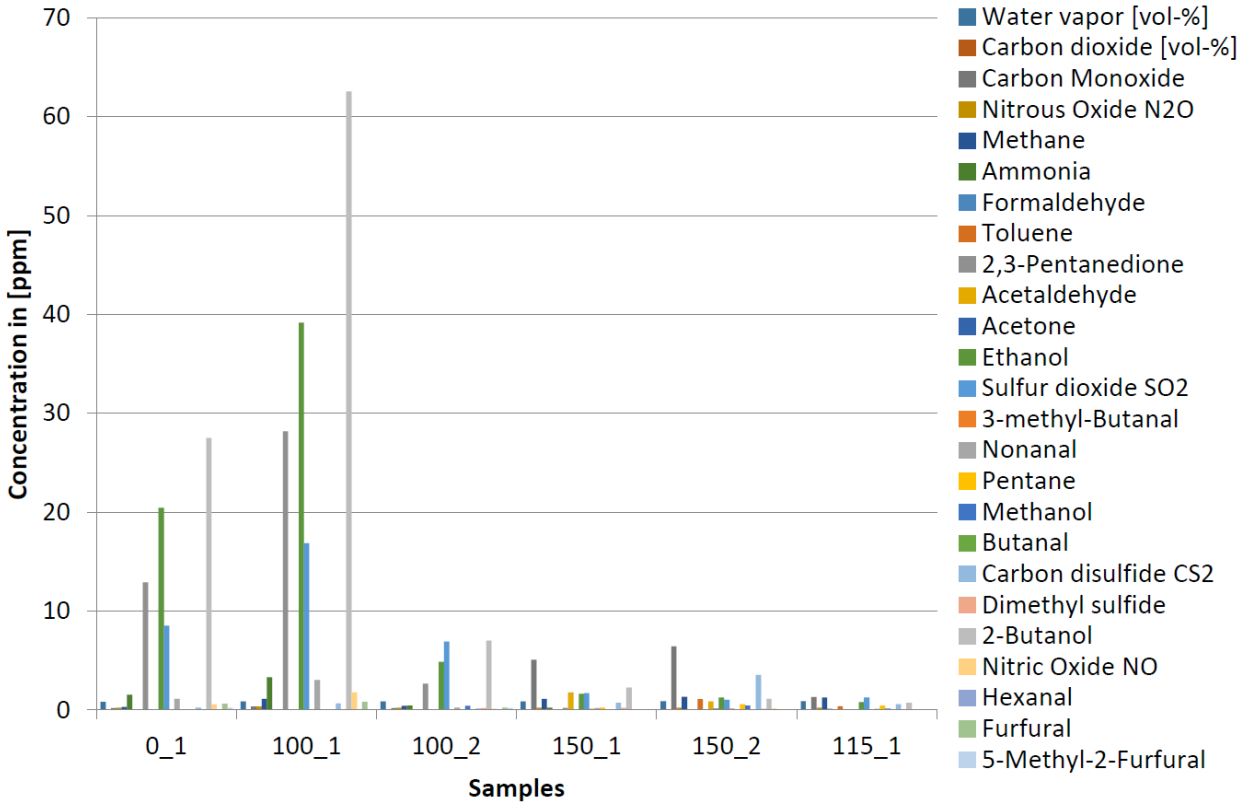

Figure 10. Effluent gases (G12) diaper, disinfectant wipes and dry wipes.

The effluent gases of this trash group shown in Figure 10 had a completely different outgassing behavior than the other groups. Right from the beginning, high concentrations of 2,3-pentanedione, ethanol and 2-butanol were detected in air samples. Even in the baseline sample 0_1, these gases occurred with a significant concentration. The highest concentrations were found in the first 100 °C sample. After that outgassing was minimal.

4. Group 7 (Sausage Patty, Frankfurter)

This group comprises a sausage patty and a frankfurter. The input sample was 50g of sausage patty and 50g of frankfurter. In Figure 11, the initial and the final products of this test run are shown.

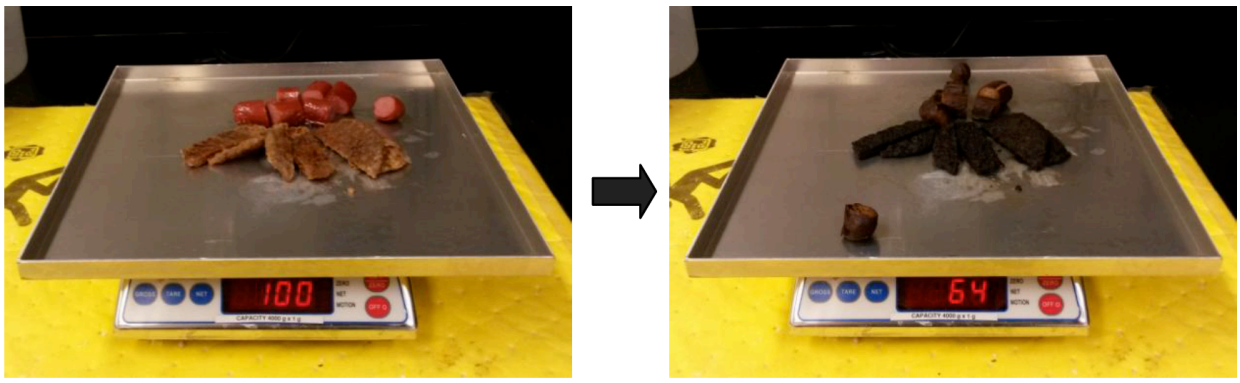

Figure 11. Group 7 sausage patty and frankfurter before and after process.

Beside the significant weight loss, it can be seen that the processed components became black and charred. The impact of this kind of charring on the compound of the sweep gas flow can be assessed from Figure 12.

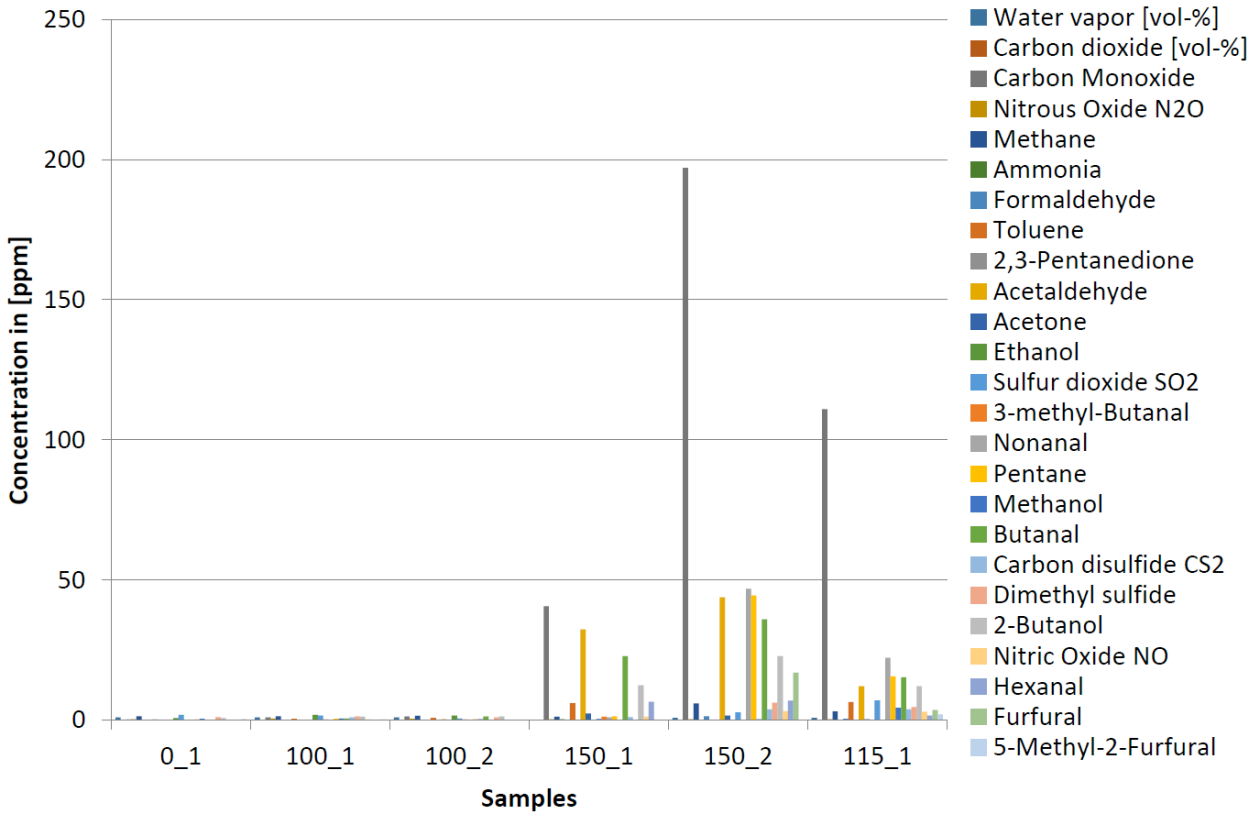

Figure 12. Effluent gases (G7) sausage patty and frankfurter.

Figure 12 shows that during the early stages of the test run, no significant changes in the gas compounds were detected. As can be seen, sample 0_1, 100_1 and 100_2 did not contain higher concentrations of the 25 gases that were analyzed. However, at the 150 °C level, the two meat components had very active outgassing. In particular, carbon monoxide was detected at about 45 ppm at the first 150 °C sample point (150_1) and increased to almost 200 ppm at the second 150 °C sample point (150_2). Significant detection of carbon dioxide was also detected at 150 °C. As the proportions of water vapor and carbon dioxide were measured in vol-%, changes cannot be really seen in the diagram that is shown. However, the concentration of carbon dioxide increased from usually around 0.06 vol-% to an average value of 0.145 vol-% in the samples 150_1 and 150_2, which is more than a doubling of the concentration. During the cooling phase, when the oven was already turned off, there was still a lot of carbon monoxide and carbon dioxide that was outgassed by the two meat components. However, compared to the sample 150_2 the quantity decreased again. About 110 ppm of carbon monoxide was found and 0.11 vol-% of carbon dioxide. Other elements that were detected with a considerable concentration during the active period at 150 °C were acetaldehyde, butanal and 2-butanol.

5. Group 9 (Plastics)

The last trash group that is presented is group 9, which combines the rehydration pouch, the overwrap, the bulb overwrap bag and the bite size pouch. All of these components are made of plastic. As can be seen from Figure 13, the plastic components did not lose measurable mass during the process. However, as within the HMC, the plastics melted while the HMC characteristic temperature profile was run.

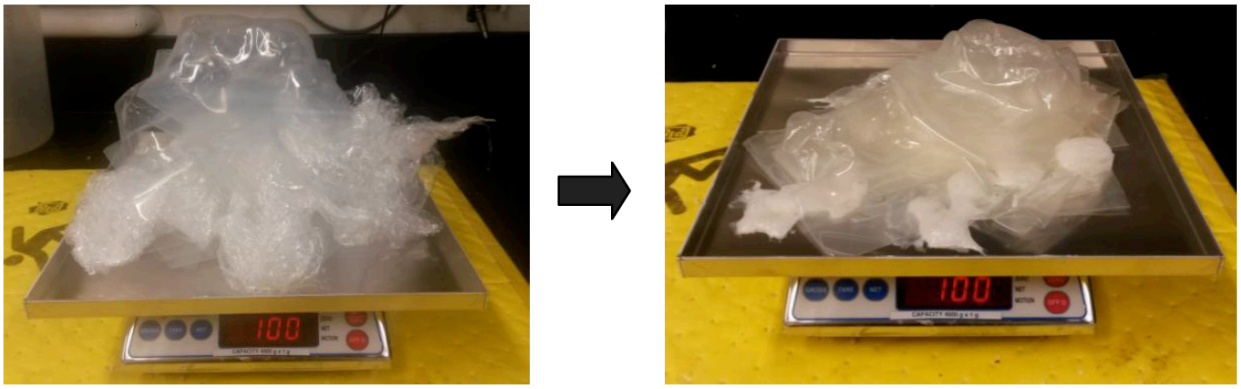

Figure 13. Group 9 plastic trash components before and after process.

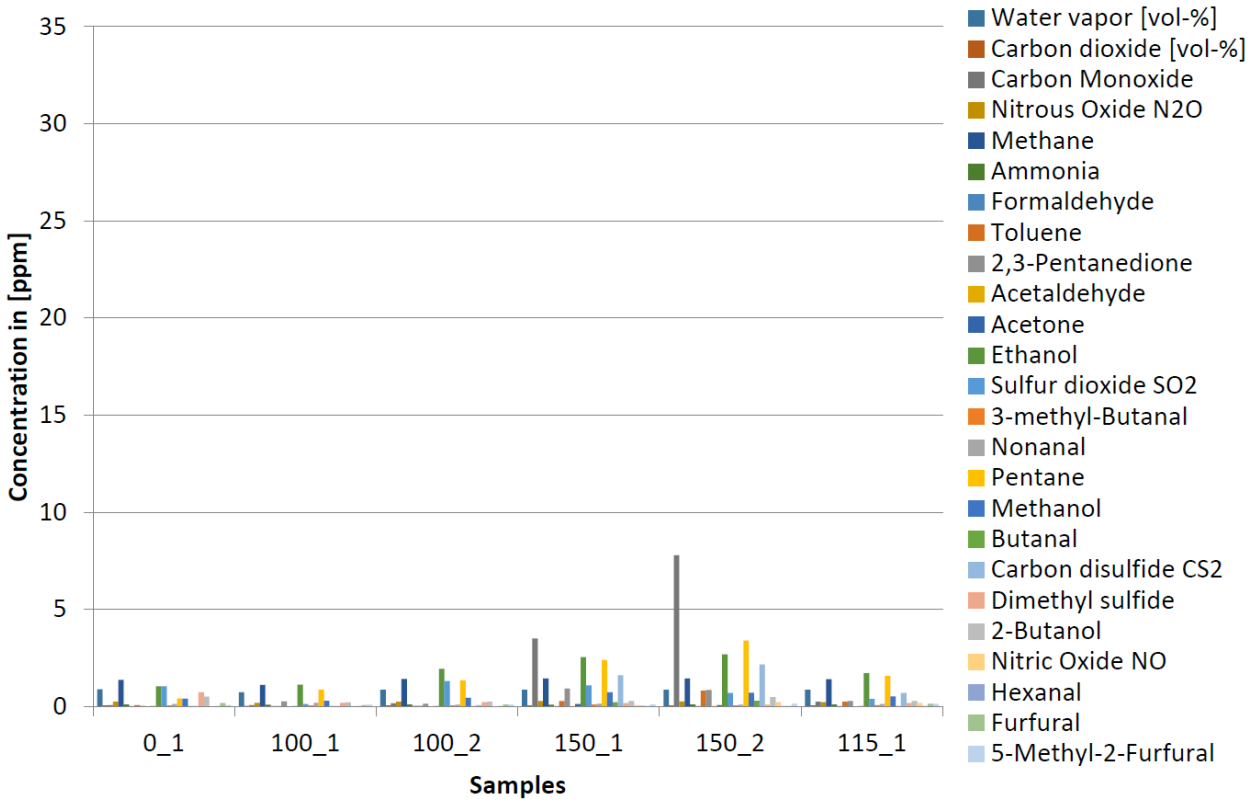

Figure 14. Effluent gases (G9) plastics.

Figure 14 shows the gas components during the process. It can be seen that the plastic components showed very little outgassing activity. Despite the fact that the plastics started melting, the trapped gas concentrations in the samples are fairly low. Beside the carbon monoxide concentration in sample 150_2, no gas concentrations were detected with values over 5 ppm.

Overall the test results identified key trash components corresponding to higher concentrations of contaminants. Carbon disulfide primarily comes from nitrile gloves, carbon monoxide from meats, and ethanol, 2,3-pentanedione, and 2-butanol from diaper wipes and from septum adapters and beverage pouches. Also at higher temperatures one can expect higher amounts of out-gassing with peak levels during the 150 °C hold period. However, for diaper wipes the release of hydrocarbon vapors occurs below 100 °C with a significant decrease at the higher temperatures after the 100 °C hold time.

I. Water Sample Results

Water samples for each run were collected over the length of the run and then analyzed for several different ions as well as for pH, TOC, and TDS.

1. Collected Water Fractions

Each test was performed with a constant overall trash mass of 100g. If various components belonged to a group, the overall mass of 100g was spread over the single components by approximately applying the ratios in the trash model. The values of collected water are shown in Figure 15.

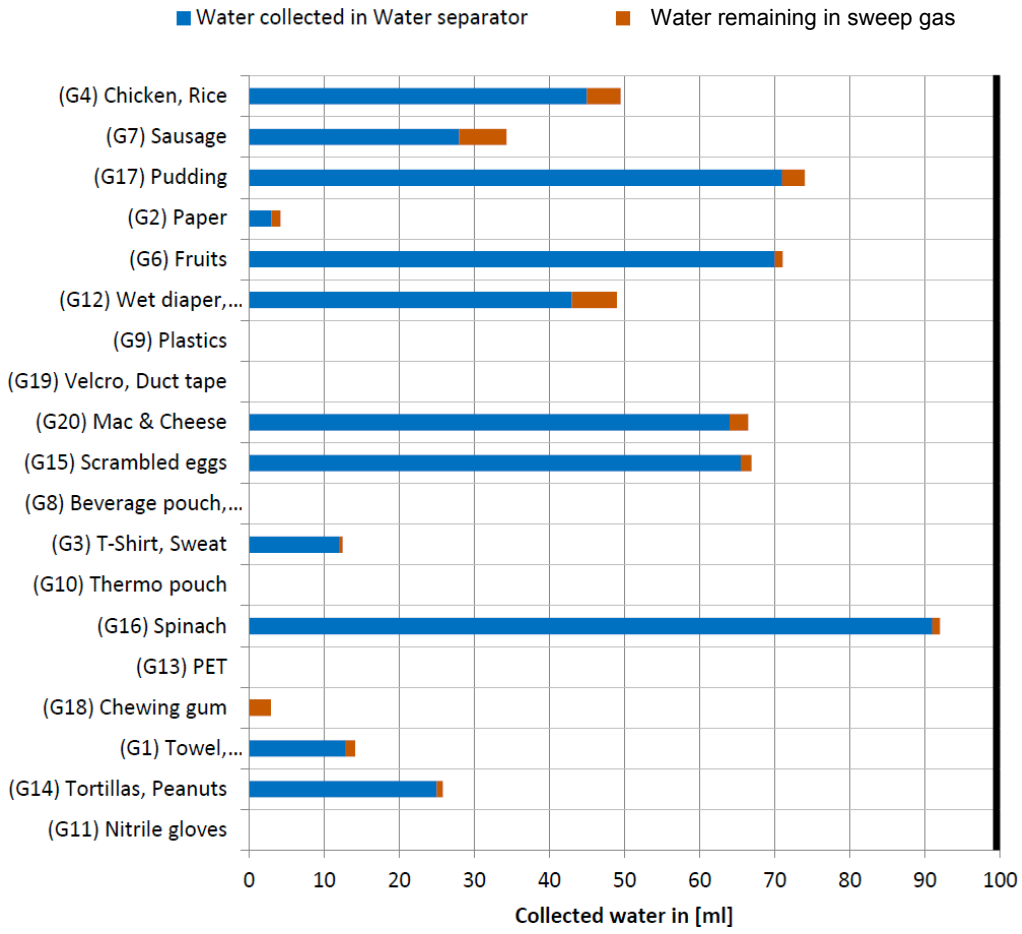

Figure 15. Collected water of the trash groups (initial mass 100g).

As might be expected, water recovery varied significantly depending on the nature of the trash component. It is interesting that the chewing gum produced a small amount of water, but its very viscous water stayed in the tube system and the oven walls and did not make it to the water separator. Generally most of the water fractions that stayed in the system had a high viscous consistency.

2. Water Results

During the analysis of the samples, it was found out that none of the samples contained any considerable concentration of K^+, Mg^{2+}, Ca^{2+}, Cal^-, NO^{2-}, Br^-, NO^{3-} and PO_4^{3-}. Beside one exception, when 1 ppm of Cl^- and 1 ppm of K^+ were detected in the recovered water of group 2 (paper), the detection limit of 0.5 ppm was never exceeded for these compounds. Detectable concentrations of ions, TOC, and TDS, and pH are summarized in Table 3.

Table 3. Water sample results (ions, TOC, and TDS in ppm)

Sample I.D.	Na^+	NH_4^+	$SO4^{2-}$	pH	TOC	TDS	SO_3^{2-}
(G14) Tortillas, Peanuts	0.9	5.3	21.5	3.5	3314	1400	<0.5
(G1) Towel, Shampoo, Toothpaste	1.2	11.2	<0.5	5.1	1683	1700	<0.5
(G16) Spinach	0.52	7.14	0.64	4.9	290	270	<0.5
(G3) T-Shirt, Sweat	0.72	71.4	1.37	8.8	128	QNS	<0.5
(G15) Scramble Eggs	<0.5	211	6.18	9.4	282	340	<0.5
(G20) Mac & Cheese	0.6	31.7	0.6	5.6	195	390	<0.5
(G12) Wet Diaper, Dry Wipes, Disinfectant Wipes	0.5	4.4	<0.5	5.7	3410	100	<0.5
(G6) Fruits	0.9	2.3	202	3.1	1860	980	133
(G2) Paper	4.0	6.4	1.8	4.8	199	QNS	2.3
(G17) Pudding	0.7	17.8	2.8	3.8	697	260	<0.5
(G7) Sausage	0.9	4.0	5.7	3.6	3460	2300	<0.5
(G4) Chicken, Rice	0.7	22.6	<0.5	4.3	1140	1800	<0.5

Generally one would not expect inorganic ions to be collected in the water because these inorganic compounds are not very volatile. The presence of low concentrations of sodium ions in the water is likely a result of small amounts of particulate entrainment from the tested materials. Organics exhibit significant volatility and that is the likely source of the TOC and TDS numbers. Ammonia and some acids such as sulfuric acid can have significant volatility, which can explain the presence of their ions in the collected water.

J. Other Results

1. Comparison of Air and Water Sample Results

Volatile chemical compounds equilibrate between vapor and liquid water when the vapor and liquid phases are in contact. Because the vapor and the water phases are in close contact in the condenser, it is expected that high concentrations of compounds in the vapor will produce corresponding high concentrations of the compounds in the water. A rough way of checking whether the data supports this expectation is to compare the TOC of the water samples with the sum of the contaminants (most of them are organic) found in the air samples. Figure 16 shows the results for the 12 groups that produced water during the processing.

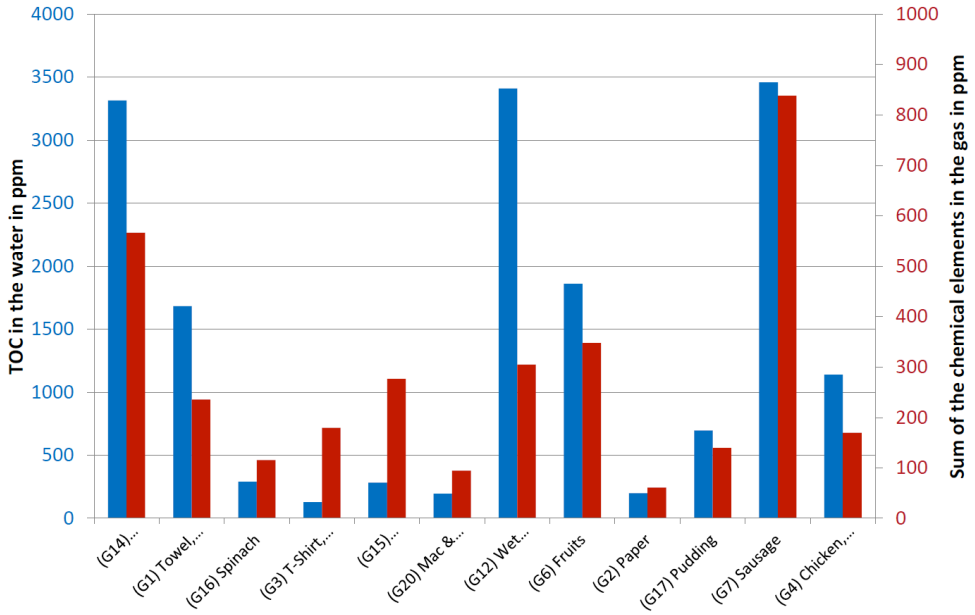

Figure 16. Comparison of water and air contamination.

Figure 16 shows that there is a definite correlation between concentration between contaminants in the air and the water. The biggest difference can be seen for group 12, when high TOC water was produced but gas concentrations were not exceptionally high. Examination of Figure 10 reveals that group 12 has an unusually high 2-butanol peak on one gas sample. Perhaps strong partioning of 2-butanol to the water phase is responsible for the high TOC. Since the relative partitioning of compounds between gas and liquid varies significantly, only a rough relationship between gaseous concentrations and TOC was expected. Here it is rather clear that when the concentrations of contaminants in the air are high, so is the TOC in the water, and vice versa.

2. Results of the Mass Dependency Tests

The mass dependency tests were conducted to determine whether the size of the sample would correlate with the amount of contaminants offgased. Two tests were conducted, one with apricots and one with nitrile gloves. The materials were heated to 150 °C, held for 90 minutes, and then gas sampled. Sweep gas airflow was the same (0.4 L/min) for all mass dependency runs. For the apricots samples of 25g and 75g were used.

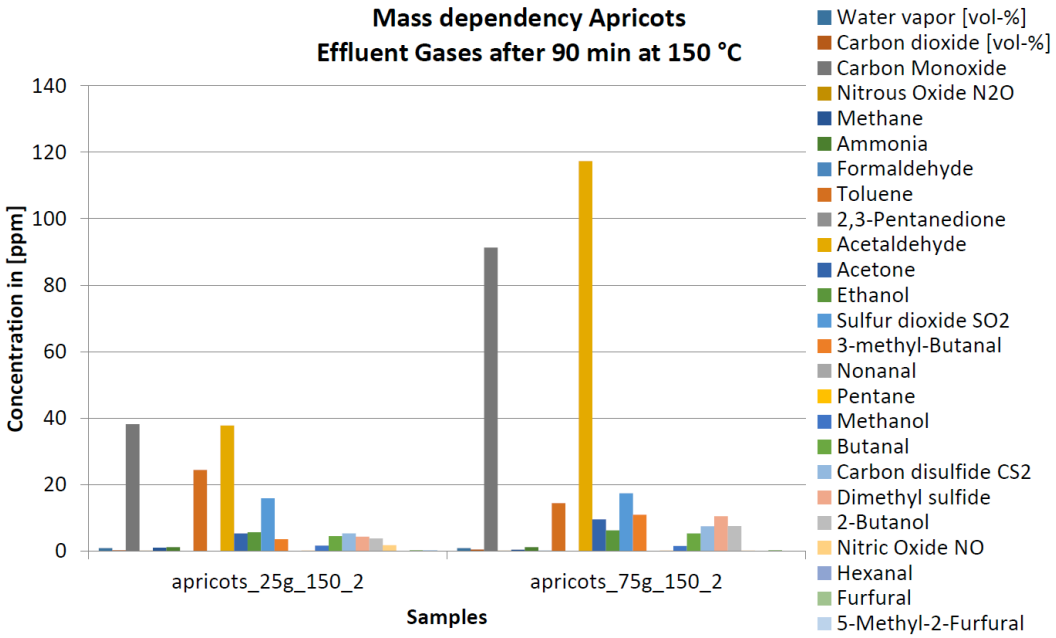

Figure 17. Mass dependency of apricot sample and effluent gases after 90 minutes at 150 °C

Figure 17 shows that tripling the trash batch size clearly increased the concentration of compounds in the vapor. Carbon monoxide and acetaldehyde have the highest concentrations in each sample and increased by a factor of 2.4 and 3.0 respectively – close to the 3.0 increase in batch size. However, compounds with lower concentrations showed the same concentrations or even lower concentrations at the higher batch size. Perhaps at lower concentrations loss of material to adsorption in the hardware or to a water phase can have more significant impacts. The behavior of the major components seems to confirm the expectation that higher batch size means more contaminant production.

A similar test was performed for the nitrile gloves. This component does not produce water. Test masses of 25 g and 75 g were used. In order to see how consistent the results of the air sample analysis are, the test with 75 g of gloves was performed twice.

Figure 18 shows that the different masses of gloves influenced the concentrations of the collected air samples. The concentration of carbon disulfide, which is the most characteristic detected gas of the glove tests, increased by factors of 2.1 and 3.6 for a tripling of batch mass. Ethanol and pentane increased by factors of 3.3. Overall a three factor increase in batch mass increased many of the most significant offgas contaminants by factors of roughly three, but there were also significant fluctuations.

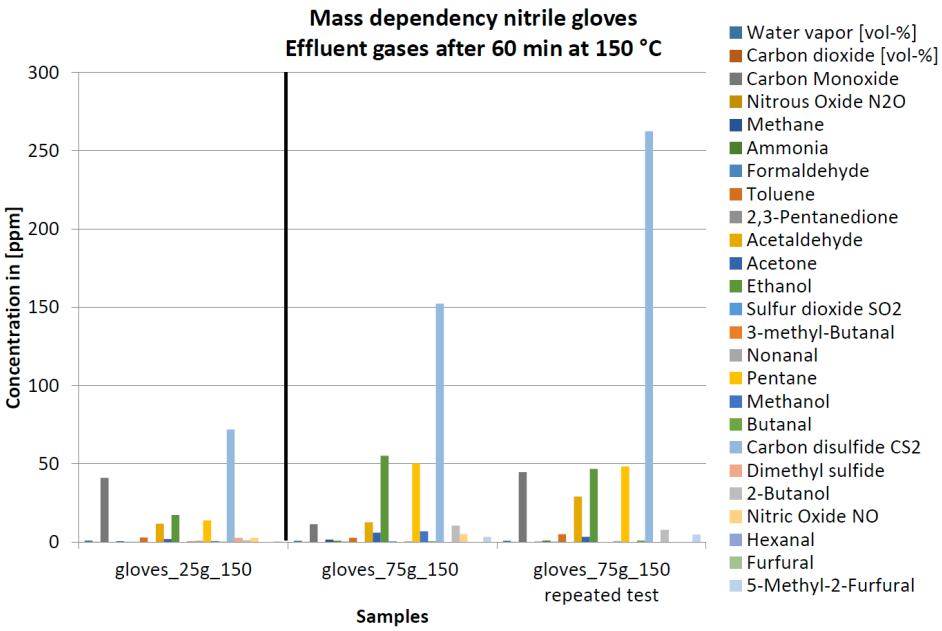

Figure 18. Mass dependency of nitrile gloves and effluent gases after 60 minutes at 150 °C

3. Results of the Material Interaction Tests

The material interaction tests were done to evaluate whether the offgasing from mixtures of waste components would produce off-gas concentrations that were the sum of the waste inputs. Similar to the mass dependency tests, dried apricots and nitrile gloves were used as test components. First, 100g of dried apricots were heated in the vacuum oven to 150 °C and held there for 60 min before sampling. The same small test was performed with 100g of gloves. Finally, this test procedure was conducted again, but now with 100g of dried apricots and 100g of gloves together. As defined, the detected gas compounds of the single component tests were finally summed up and compared to the gas compound of the combo test sample.

Figure 19 shows that the gas compound of the combo test and the sum of the gas compounds of the single tests are almost identical. Beside some minor differences, the same gases were detected in summed amounts. No other significant concentrations of other gases were detected during the combo test.

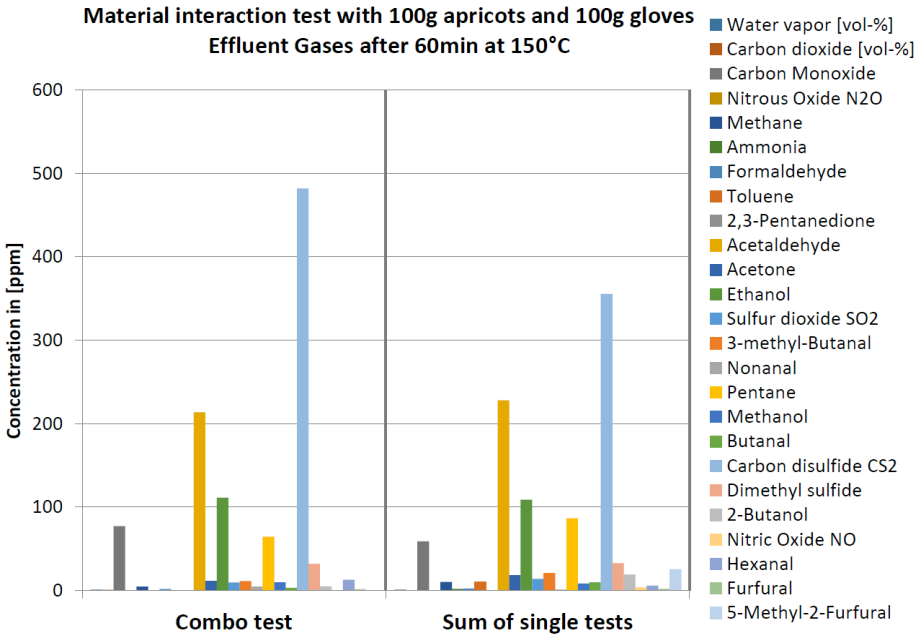

Figure 19. Results of the material interaction test with dried apricots and nitrile gloves.

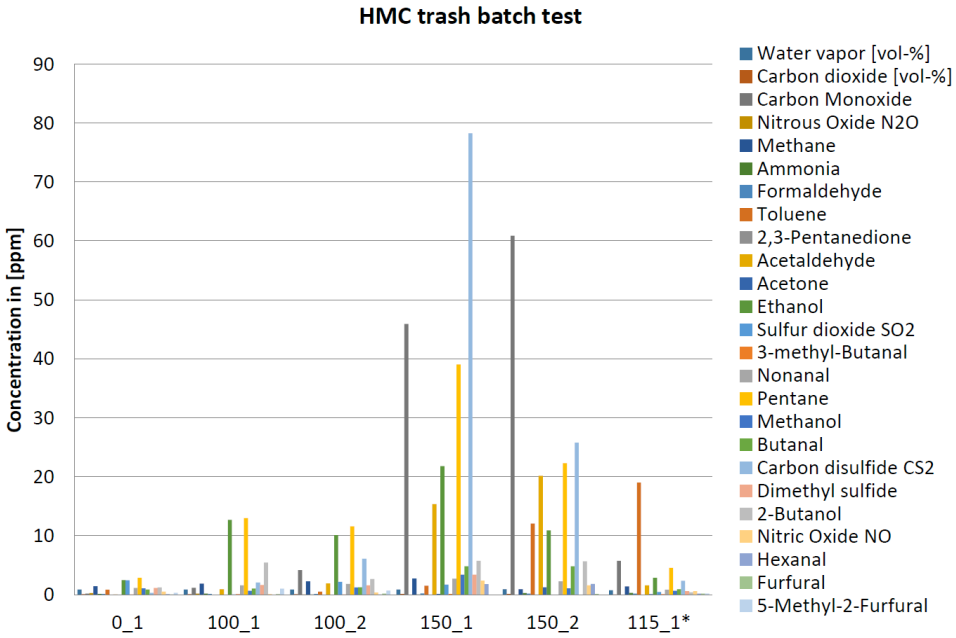

Figure 20. Effluent gas results of HMC trash batch test 457 grams sample.

The last mass dependency tests was a test run with an almost complete HMC trash model batch. The trash batch contained almost every component of the trash model with the same masses that are defined in the trash model. Other than the spinach, the peaches, the scrambled eggs, and the salty sweat on the T-shirt, all components were processed. The missing food components were not available for this test run. Because of that the processed trash mass was not 500 g, as defined in the trash model, but 457 g. The results of the test run are shown in Figure 20.

It can be seen that carbon disulfide, carbon monoxide, pentane, acetaldehyde and ethanol were the highest concentrated gases that occurred. Similar to the single group tests, the 150 °C level was the most active outgassing period. Generally, it can be said that all four tests detected the same characteristic gases and the same outgassing pattern over the samples of the respective test runs as during the first tests. Note that the high concentration of carbon disulfide has not been observed in previous HMC offgas testing. From the individual component tests, it appears that the source is the nitrile gloves.

4. Results of the Replication Tests

To evaluate the repeatability of the results some of the group tests were redone. Figure 21 shows the results of the repeated test of group 8, which comprises the beverage pouch, the septum and the septum adapter.

The results of the first test (Fig. 6) and the repeated test (Fig. 21) look very similar. Compounds including 2,3-pentanedione, ethanol, pentane and 2-butanol were the most characteristic gases that were found in both tests. The patterns of the rise and fall of concentrations with time in the runs are similar. The patterns of major and minor compounds are also similar. The absolute values of the concentrations show significant fluctuations. In one of the more extreme examples of fluctuations - on the first 150 °C sample - the ethanol values were 90 and 144. Generally speaking then, the use of the experimental results can be expected to provide one significant digit of accuracy for use in calculations.

Numerous air samples were taken during the testing and these showed very low concentration of compounds in the gas. Therefore contributions of background compounds from the lab air did not contribute to the results of the tests.

At the end of the test campaign, a test was conducted of how accurate the FTIR was in measuring gas concentrations in general. This was checked by filling air with a known concentration of 50 ppm of methane in some Tedlar bags. Four of these samples were produced and they all contained the same volume of this air mixture. The FTIR detected methane concentrations of 32 ppm, 32 ppm, 33 ppm and 36 ppm in the samples. The precision was fairly close, but the accuracy was off a bit.

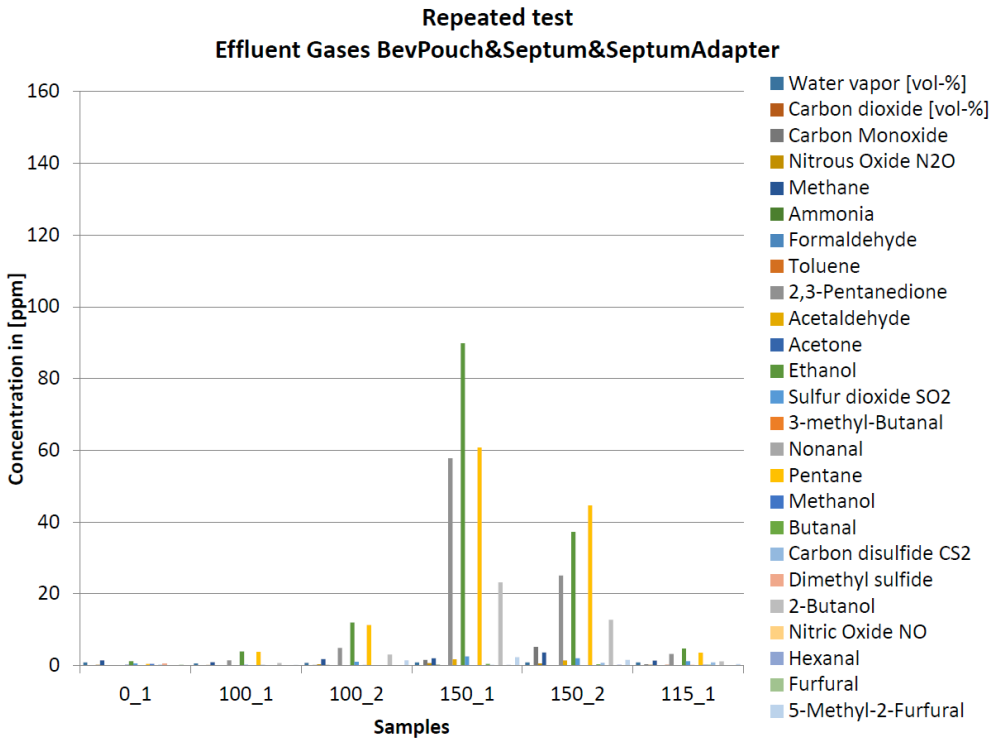

Figure 21. Repeated Group 8 test - effluent gases for bev pouch, septum and septum adapter.

VII. Discussion

The air sample results of the single group tests of the main test campaign provide a lot of interesting information. General findings of single group tests are first examined, followed by detection of an outgassing pattern, and then disruptive factors during the sampling and analysis are discussed.

A. Discussion of General Findings

One of the most general findings is that there are trash components that highly contribute to the contamination of the air and there are others that are inconspicuous. For example, the HMC-similar heat processing of the plastic components of group 9 did not produce any higher gas concentrations in all the samples that were collected during the test run. The results of this group were shown in Fig. 14. A similar inconspicuous outgassing behavior was detected for some other groups, too, which are not presented here. Those groups are group 2, 10, 13, 16 and 20, which comprise paper, thermo pouches, PET-bottles, spinach and mac&cheese, respectively. In particular for all the plastic components, which also includes the PET-bottles, this is an interesting finding because plastics are a major component of the trash batch of the HMC. Concerns about the fact that the processing and melting of the plastics could highly contaminate the sweep gas flow, could not be confirmed during this study. To the contrary, they seem to be very inactive when outgassing is considered.

Other trash components are the major polluters of the air. Other than the spinach and mac&cheese, the food residues showed a high outgassing activity. The group of sausage components and the fruits produced the highest single gas concentrations of all food residues. Carbon monoxide was highly outgassed by the sausage components and acetaldehyde by the fruits. Other major polluters are groups 8 and 11, which are composed of the beverage pouch components and the nitrile gloves. The high concentration of carbon disulfide that was outgassed by the gloves was very significant. Sulfide components can damage catalysts in catalytic oxidizers. Adsorbent beds preceding an oxidizer can protect the oxidizer, but the amount of adsorbent can become prohibitive if significant amounts of sulfur compounds need to be removed. Alternatives are to vent sulfides directly to space vacuum, or to simply not use nitrile gloves. Organic compounds such as acetaldehyde and inorganic carbon monoxide are not as much of a concern because these can be readily oxidized in a catalytic oxidizer.

B. Detection of an Outgassing Pattern

Generally, it was observed that each group has very characteristic off gases, which means that usually the same gases were produced over the entire test run, however with a different concentration depending on temperature and time. As is expected, for most of the groups, the 150 °C level was the most active outgassing period of the test run, which means that during the high temperature part of an HMC run the highest sweep gas contamination can be expected. Peak concentrations were observed either at the beginning or the end of the 150 °C hold time. The behavior at the 150 °C level was more dependent on the chemical compound rather than on the trash group. For example, the carbon monoxide concentration usually increased the longer the trash component was exposed to 150 °C whereas other gas concentrations, for example ethanol or pentane, usually reached the peak concentrations in the first 150 °C sample and showed a decreased concentration in the second 150 °C sample. The continuously increasing carbon monoxide concentrations on some tests may be explained by progressive charring of the trash components. During the cooling phase, the outgassing concentrations decreased for all test runs.

The only trash group that did not follow the characteristic outgassing pattern was group 12 (Diaper/Disinfectant wipes/Dry wipes). The likely reason for the immediately detected, high outgassing rate is the presence of the disinfectant wipes, which are wet with volatiles such as ethanol and therefore started outgassing immediately.

C. Discussion of the Detected Water Fractions

Similar to off gassing studies on previous HMC water testing, $NH4^{+}$ and $SO42^{-}$ were the most frequent and highly concentrated ions that were found during the single group tests [Ref. 7]. Whereas ammonium was detected in various water samples in a considerable concentration, SO_4^{2-} was mainly detected in the sample of the fruits. That sample also contained a high concentration of SO_3^{2-}. Other ions that were searched in the samples were negligible. A similar behavior was also detected during the earlier study [Ref. 7]. High TOC in the water can be a concern for the water recycling system. The group of sausage components, the group of tortillas and peanuts, and the group with the diaper and the wet wipes generated water with a very high TOC values over 3000 ppm. The fruits and the group of towels with shampoo and toothpaste also produced water with a significant concentration of TOC. Low producers of TOC included spinach, paper, and mac&cheese, with TOC values of roughly 200 ppm.

The relationship between the TOC in the water with the sum of chemicals in the air can be explained by Henry's law, which defines that in a system, which consists of a liquid and gaseous phase, volatiles distribute in the two phases at equilibrium according to

$$K_H = \frac{c_g}{c_l}$$

Here K_H is the Henry solubility constant, c_g the concentration in the gaseous phase and c_l the concentration in the liquid phase. Since the water and gas are in close contact in the condenser, it is expected near equilibrium conditions exist between the liquid and vapor.

D. Discussion of the Mass Dependency Tests

Just a small number of mass dependency tests were performed. The results of these tests confirmed that the gas concentrations are dependent on the processed trash mass. Higher trash masses generally produced higher gas concentrations. Many of the high concentration compounds showed approximately 3 times increase in concentration with a 3 times increase in batch size. However, the variability of the data as shown between repeat testing is too large to derive a precise mathematical relationship between trash mass and gas concentrations. An extensive test study with many replications would be necessary to determine an average value for the gas concentrations and to reach statistical reliability.

E. Discussion of the Material Interaction Test

The material interaction test in Figure 19 showed that the results of the single trash group tests could be added up to get the approximate concentrations of an overall trash batch. However, similar to the mass dependency tests, the data is not sufficient to provide a precise relationship. High concentrations of carbon disulfide and acetaldehyde shown in Figure 6 and 17 were also detected in an earlier study [Ref. 6]. However, ethanol and pentane, which were detected with high concentrations during this study (Fig. 6), did not show high concentrations in the previous study. From the single group tests, ethanol and pentane were highly outgassed by the beverage pouch, the septum and the septum adapter. A possible explanation for the missing high concentrations of these two gases in the earlier study could be that those components were not part of the processed trash at that time. The data from the previous study is not clear as to the presence of those components.

F. Discussion of the Replication Tests

For the repeated tests, the same characteristic gases and the same outgassing pattern over the single test runs were detected. This is a very important. However, large concentration fluctuations occurred of 50% or more from the initial measurement. There can be several reasons for this. The most important one is that the small volume of the Tedlar bags and the consequently short sampling time of 3:40 min only allows the trapping of a small sample of the current sweep gas flow and therefore just represents a minor time section compared to the overall duration of the test run. It is improbable that the trash components release the exact same number of gaseous elements at each minute of the 7 hour test run. Because of that, concentration fluctuations are possible. In the earlier test study on an HMC when parts of the sweep gas flow were continuously collected during the test run, significant variations of gases occurred [Ref. 6].

Further reasons for concentration fluctuations can be the measurement accuracy of the FTIR itself or a small leak in the system. During the verification tests, small flow rate differences were detected at the flow meter at the inlet and outlet of about 0.05-0.15 L/min. Pump leakage is the likely cause.

In summary, the replication tests results were confirmed. The fluctuations of the gas concentrations in the collected air samples can be explained by the comparatively short sampling time. A small leak and the accuracy of the measurement itself could have influenced the concentration values too.

G. Discussion of the Detected Water Fractions

Concerning the earlier defined equation, which states that the addition of the final trash weight and the recovered water should result in the initial trash weight, if the weight of the outgassed volatiles is neglected, it can be said that that this relation was met throughout the conducted tests. Due to the lower accuracy of the weight scale and the measuring bottle of the water separator, small deviations up to 1g were possible. However, no bigger deviations were detected, which means that deposits and the contamination of the system could be minimized. This was an important requirement of the test rig because deposits could have falsified the results of the single group tests. The fact that the mass balance was always met, confirms that the system could be kept clean during the entire test campaign and therefore disruptive factors could be minimized.

H. Discussion of the Water Contamination Analysis

Water sample analysis were similar to earlier studies in that the recovered water was comparable to that of the Gen 1 HMC [Ref. 7] and that NH^{4+} and SO_4^{2-} were the most highly concentrated ions found during the single group tests. Whereas ammonium was detected in various water samples in a considerable concentration, SO_4^{2-} was mainly detected in the sample of the fruits. That sample also contained a high concentration of SO_3^{2-}. A reason for the high concentrations of sulfur ions in the fruit water sample can be that sulfur dioxide is one of the ingredients of the dried apricots, which are part of the fruit group. Beside the concentrations of NH^{4+}, SO_4^{2-} and SO_3^{2-}, the other ions were negligible. In cases where the detection limit was exceeded, the concentrations were still very low. A similar behavior was also detected during the earlier study. However, the major concern of the earlier test study of the recovered water was the high average TOC value of 2200 ppm, which can be a challenge for the WPA. The problem is that the WPA cannot process water with a TOC value higher than 300 ppm.

I. Future Work

Generally, it can be said, that a lot more tests can be performed, especially concerning the material interaction and mass dependency. Those topics were just marginally investigated during this tests campaign and therefore further tests are necessary to confirm the findings of this study. If exact concentration values or ratios are needed for any tests, they have to be repeated several times, in order to get statistical reliability and counteract the concentration deviations that were detected.

Beside the performance of further tests, the test rig could be modified and improved. First, as mentioned, the air tightness of the currently used pump should be checked. If a constant degradation of the air tightness were detected, the pump would need to be periodically replaced. Beside the presumed degradation of the pump's air tightness after a frequent and long-term usage, a further fact supports the selection and implementation of a new pump. As mentioned above, the pump provides a maximum flow rate of 12 l/min. This is much higher than the flow rate range that is needed and used for the HMC process. The flow rate of 0.4 l/min, which was used during this test campaign, is already close to the lowest possible flow rate that can be sustained with the current pump. A pump with a lower pump capacity would facilitate the flow rate control in the relevant range and furthermore allow the performance of tests with flow rates lower than 0.4 l/min. Further modifications that could be implemented in the future are a trash compaction system and the possibility to perform sub-atmospheric tests. Trash compaction and sub-atmospheric

tests would be more comparable to the real system. However, maintaining a tight vacuum could be problematic both for a test system and for an operational HMC.

The last point is more a recommendation than an actual operation point for the future. For a further test study, it would be advantageous to reactivate the GCMS or the FTIR instrumentation at Ames for on-site sample analysis. This would avoid the transport and the transfer time of the Tedlar bags to KSC and would minimize any possibility of damaged bags during transit.

VIII. Conclusion

A very interesting finding was that processing of the plastic components, which represent a high fraction of the overall trash batch, did not produce high gas concentrations and so can possibly be excluded as a major source of contamination. Regarding the outgassing of active components, the study characterized trash components into groups and correlated characteristic gases released from each group when processed. This correlation makes it easier to trace specific component groupings that are responsible for the gas effluents of undesired compounds. For example, carbon disulfide effluent gas can be directly attributed to nitrile glove thermal processing. Additionally, it was found that the effluent concentrations increased with the amount being processed; tripling the amount of gloves being processed increased the amount of carbon disulfide by about 2.5 times. Another general finding is that over numerous test runs, a similar outgassing pattern was detected with peak concentrations occurring when processing at 150 °C with lower outgassing at lower temperatures for trash components having minimal liquid water. For trash groupings with liquid water and hydrocarbons in aqueous solution, outgassing occurs at and below the boiling point and is significantly reduced when the water evaporates.

The presented information herein highlights just some of the interesting and important results of tests conducted at Ames Research Center in the summer of 2016. The complete set of information and data, and resulting analysis and conclusions can be found in [Ref. 9].

References

[1] Ewert, M.K. and Broyan, J.L., "Mission Benefits Analysis of Logistics Reduction Technologies", ICES, AIAA-2013-3383.

[2] Jones H., Pace G., Fisher J, "Managing Spacecraft Waste Using the Heat Melt Compactor (HMC)," Vail, 2013, AAIA 2013-3362.

[3] Bahadori, A. A., Semones, E. J., Swan B. G., "Heat Melt Compactor Puck Shielding Evaluation," SRAG-COM-RDWK-2015-001, May 29, 2015.

[4] Lee J. M., Fisher, J. W., Pace, G. S., "Heat Melt Compactor Development Progress," 47th International Conference on Environmental Systems, Charleston, South Carolina, ICES-2017-267, 2017.

[5] Turner M., Fisher J., Broyan J., Pace G., "Generation 2 Heat Melt Compactor Development," 44th International Conference on Environmental Systems, Tucson, AZ, July 2014, ICES-2014-024.

[6] Delzeit L., Fisher J., Alba R., Wignarajah K., Harris L., "Chemical Characterization of the Heat Melt Compactor Effluent Gas," Vail, 2013, AAIA 2013-3395

[7] Harris L., Wignarajah K., Alba R., Pace G., Fisher J., "Characterization of Heat Melt Compactor (HMC) Product Water," Vail, 2013, AAIA 2013-3394.

[8] Goodliff, K., Stromgren, C., Ewert, M., Hill, J., Moore, C., "Logistics Needs for Future Human Exploration Beyond Low Earth Orbit," AIAA SPACE and Astronautics Forum and Exposition, 12-14 Sep 2017, Orlando, FL, AIAA 2017-5122.

[9] Goeser, J., "Characterization of the Outgassing Behavior of Various Waste Materials for NASA's Heat Melt Compactor," Master Thesis, RT-MA 20-16/23, Technische Universitat Munchen, 2016.

[10] Harris, L., Alba R., Wignarajah K., Fisher J., Monje O., Maryatt B, Broyan J., and G. Pace, "Processing of Packing Foams using Heat Melt Compactor", 44th International Conference on Environmental Systems, Tucson, AZ, July 2014, ICES-2014-080.

[11] Retrieved from: http://www.gasmet.com/technology/ftir (03.12.2016)

[12] Thermo Nicolet Corporation: *Introduction to Fourier Transform Infrared Spectrometry*, 2001, Madison, Retrieved from: http://www.niu.edu/analyticallab/_pdf/ftir/FTIRintro.pdf (03.12.2016)

[13] Retrieved from: https://chemistry.oregonstate.edu/courses/ch361-464/ch362/irinstrs.htm (03.12.2016)