Updated Effluent Analysis of the Heat Melt Compactor: Water Quality and Dewpoint Simulation of Gas Effluent

Janine Young[1]
KBR, Houston, TX, 77002

Jurek Parodi[2]
Bionetics Corporation, Yorktown, VA, 23693

Serena Trieu[3]
Logyx LLC, Mountain View, CA, 94043

Tra-My Justine Richardson[4], Steven A. Sepka[5], Jeffrey M. Lee[6], Kevin R. Martin[7]
NASA Ames Research Center, Moffett Field, CA, 94035

Gregory S. Pace[8]
KBR, Houston, TX, 77002

and

Mary Lou Nadeau[9]
Aerodyne Industries, Houston, TX, 77058

The Trash Compaction and Processing System (TCPS) processes astronaut trash through volume reduction, biological safening, trash stabilization, effluent management, and resource recovery. TCPS development for the International Space Station (ISS) and risk reduction activities are supported by testing the Heat Melt Compactor (HMC) at NASA Ames Research Center (ARC). Processing trash extracts water vapor that can be recovered and releases volatile gases that must be managed. Part of the effluent is condensed and collected for analysis. The evaluation of the liquid effluent includes total organic carbon (TOC) concentrations, which provide a general indication of overall water quality, other defining characteristics such as pH and conductivity, and identified chemical components. On the other hand, the gas effluent may be recovered through a contaminant control system and vented to ISS cabin or vented overboard into space through the ISS Vacuum Exhaust System (VES). In the latter venting scenario, a constraint is the dewpoint of the gases disposed into the VES must be less than 15.5 °C. With simulations using Aspen Plus® and the HMC gas effluent results, flash calculations were conducted in the modeling study to calculate feed temperature and dewpoint at fixed pressures. Saturated vapor curves were also produced and provide a preliminary result on optimal feed conditions that satisfy the dewpoint and vapor-phase only requirements upon venting to VES. This paper serves as an update on the ongoing liquid and gas effluent analysis of the HMC/TCPS.

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[1] Chemical Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[2] Aerospace Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[3] Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[4] Research Physical Scientist, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[5] Solid Waste Management Lead, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[6] Solid Waste Management Advisor, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[7] Science Payload Project Manager, Flight Systems Implementation Branch, M/S 240A-3, NASA ARC, Moffett Field, CA 94035.
[8] Senior Mechanical Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[9] Modeling and Simulation Chemical Engineer, 2224 Bay Area Blvd, Houston, TX 77058/JE-5EA.

Nomenclature

ARC = Ames Research Center
ASW = Aspen Simulation Workbook®
C_i = concentration of component or species *i*
C_{total} = total concentration of mixture
ECLSS = Environmental Control and Life Support System
FTIR = Fourier transform infrared spectroscopy
Gen 1 = Generation 1
Gen 2 = Generation 2
GCMS = gas chromatography-mass spectrometry
HMC = Heat Melt Compactor
i = species
ISS = International Space Station
JSC = Johnson Space Center
mol% = mole percent
NASA = National Aeronautics and Space Administration
NRTL-HOC = Non-Random Two-Liquid Hayden O'Connell
O_2 = oxygen
P&ID = piping & instrumentation diagram
P_i = partial pressure of a gas mixture component
P_{total} = total pressure of mixture
ppm = parts per million
psia = pounds per square inch absolute
Q = Quality (also known as molar vapor fraction)
SMAC = spacecraft maximum allowable concentrations
TCPS = Trash Compaction and Processing System
TDS = total dissolved solids
TEC = thermoelectric cooler
TOC = total organic carbon
UPA = Urine Processing Assembly
VES = Vacuum Exhaust System
VOCs = volatile organic compounds
WPA = Water Processing Assembly
x% = mol% of water vapor
y_i = molar fractions

I. Introduction

THE Trash Compaction and Processing System (TCPS) uses pressure and heat via compaction to reduce trash volume, physically and biologically stabilize trash, and manage liquid and gaseous effluents.[1] During the TCPS operation, water vapor and multicomponent gas mixtures evolve as a result of trash processing. Upon resource recovery and venting, the TCPS must be compatible with the International Space Station (ISS) Environmental Control and Life Support System (ECLSS). Water removal is important for two reasons: (1) the recovered water can be recycled for crew use and (2) stabilizes the trash as a preventative measure for microbial growth. Conversely, if permissible, the gas effluent can be recovered for crew use via interfacing with the cabin air processor or, if the gases are deemed irrecoverable, they may be disposed to space via the ISS Vacuum Exhaust System (VES). The feasibility of these recovery and venting scenarios rely on characterization and extensive analysis of the liquid and gas effluent produced by trash processing. The Heat Melt Compactor (HMC) Generation 2 (Gen 2) at National Aeronautics and Space Administration (NASA) Ames Research Center (ARC) serves as a ground test system for validating TCPS technology, operation, performance, and conducts risk reduction activities associated with an ISS flight demonstration.[2,3]

Under this effort, a test campaign was conducted to address risks associated with trash tile quality and effluent analysis. The test campaign consisted of 18 separate trash processing runs with controlled measures, standardized trash models, and standardized gas collection and analytical methods. Some of the culminating activities were the analysis and characterization of the captured water and gas effluent contaminants from the HMC Gen 2. Liquid water was condensed and collected downstream of the HMC via a thermoelectric cooler (TEC) throughout the operation cycle. These water samples were analyzed by gas chromatography-mass spectrometry (GCMS), ion chromatography (IC), and other methods which will be further discussed. Gas samples were collected via grab and continuous sampling and analyzed by GCMS and Fourier-transform infrared (FTIR) spectroscopy.[4] The gas results identified and quantified component concentrations coming off the trash at specific operational conditions.

Effluent studies have previously been done on the preceding system of HMC Gen 2, which is HMC Generation 1 (Gen 1). A water characterization effort on standardized and altered trash models were conducted on HMC Gen 1 and resulted on identified chemical ions, pH, and total organic carbon (TOC) to expect in the HMC product water.[5] Similarly, a gas characterization effort identified and quantified contaminant concentrations via GCMS, which provided a baseline on expected volatiles and chemical classes from standardized and altered trash models.[6] Contaminant characterization of gas and water extracted from individual and group trash components were also conducted to identify sources of contamination and water contribution (e.g. carbon disulfide are from nitrile gloves, plastic components do not produce water).[7] In terms of HMC operation between Gen 1 and Gen 2, the compaction, heating, and condensation elements remain similar. However, the operational conditions differ in pressure and temperature profiles that have developed over time. HMC Gen 1 was developed to test waste management capability by trash compaction in a spacecraft environment, while HMC Gen 2 is a relatively improved unit that included resource recovery and repurposed as a basis test system for ISS technology demonstration. In addition, the composition of the trash models have evolved as well, reaching closer to a representative of astronaut and space mission waste.

With a general characterization of the TCPS effluent, the next step is to investigate the compatibility of the liquid and gas effluent with ISS systems:

It is expected that the "wet" gas effluent will be condensed to liquid and transferred to a spacecraft water processing system (e.g. Urine Processing Assembly (UPA), Water Processing Assembly (WPA) on the ISS to name a few). The objectives of the liquid effluent analysis are to identify chemical components in the water sample, evaluate water quality, and assess compatibility with ISS water processing systems. Identification of chemical components include volatile organic compounds (VOCs), anions, cations, and trace metals. The evaluation of water quality includes total organic carbon (TOC) concentrations, which provide a general indication of overall water quality, and other defining characteristics such as pH, conductivity, and total dissolved solids (TDS).

For the gaseous effluent, venting gases to the ISS cabin requires meeting the Spacecraft Maximum Allowable Concentrations (SMAC)[8]. On the other hand, venting gases directly to space requires meeting the VES[9] requirements such as the disposed gases into the VES must have an input pressure of ≤ 40 psia, an initial temperature of 16 – 45 °C, an initial dewpoint of ≤ 16 °C, approved exhaust gas compounds, and an acceptable mass flow rate. The gas effluent analysis will focus on examining the gas effluent conditions when vented to VES within the scope of meeting the dewpoint requirement. A model in Aspen Plus® was created to determine the dewpoints at various low pressures for a multicomponent gas mixture that is representative of the TCPS effluent. The scope of this analysis is to determine the thermodynamic conditions of the effluent, in particular if condensation does or does not occur.

This paper will focus on examining two aspects of the HMC/TCPS effluent: an assessment of water quality from HMC Gen 2 water samples and a dewpoint analysis on the HMC gas analytical results. Overall, this paper serves as an update on the ongoing effluent analysis.

II. HMC Gen 2 Process Overview and TCPS Description

The HMC process is a closed system operating under vacuum pressure and a two-step temperature process within a 24-hour operational cycle. Figure 1 provides a schematic of the HMC Gen 2 system and a theoretical temperature profile over time is in Figure 3. Trash is loaded into the HMC chamber and the process initiates by pulling vacuum to pressures around 0.3 psia via a vacuum pump. Compaction via the ram and heating from heaters along the ram, lid and chamber walls are also initiated until approximately 60 °C is reached. This low-temperature period 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 and collected in a graduated cylinder. After water removal, the trash continues to be compacted and heated until approximately 150 °C. This high-temperature period allows for sterilization, plasticization, and the release of volatile gases from the trash. After the trash remains heated and compacted into a tile for a sufficient hold time of around 3 hours, the trash and system enters an overnight cooling period and finally trash tile removal occurs the following day at room temperature.

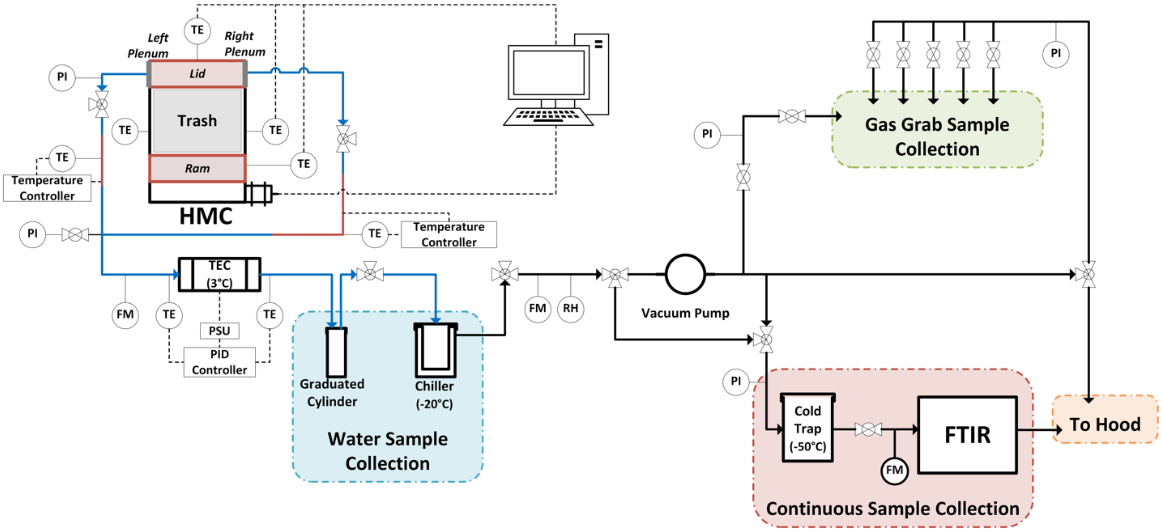


Figure 1. P&ID Schematic of HMC Gen 2 System.

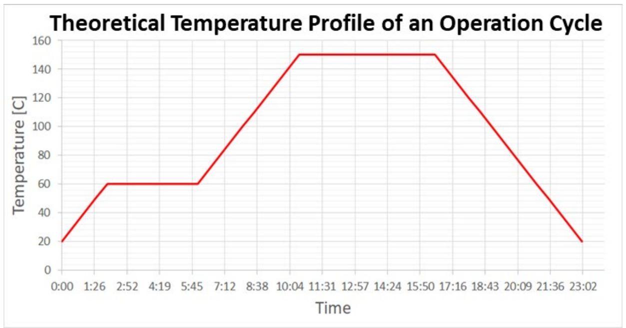


Figure 3. The theoretical temperature profile of the HMC Gen 2 operation.

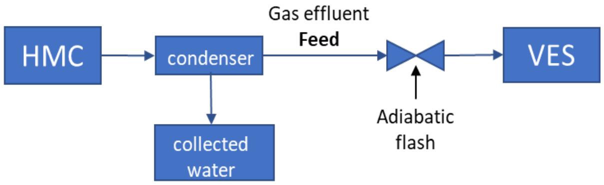


Figure 2. Overview diagram of HMC gas effluent venting scenario. *Feed is the HMC gas effluent to the valve that enters the VES. Note, there is no gas processor or source contaminant control system.*

The standardized trash models are a set of commonly generated trash components in the ISS. There are three types of models: nominal, high-liquid, and high-cloth. High-liquid model represents wet trash with high water and sugar content from fruit drinks. High-cloth represents dry trash with low liquid and higher content of cloth components like t-shirts and towels. The specific compositions and amounts of trash components are reported in a previous paper.[3]

In a TCPS operation, water recovery and gas management subsystems will be present downstream of the trash compactor subsystem. The HMC is used as a test system to explore trash compaction and processing capabilities. Eventually, when the liquid is managed, it can be released to an ECLSS water processor. On the other hand, managed gases can be vented back to the ISS cabin and/or the VES. For this paper, the venting to VES scenario will be the focus (Figure 2).

III. Water Collection and Analysis Method

The water recovery subsystem on the HMC was initially composed of an external condenser made of a copper coil submerged in an ice bath and connected to a graduated cylinder. The chemical analysis of water samples collected during preliminary test runs using both trash and deionized water indicated the presence of copper oxide, which was caused by corrosion of the copper coil. Moreover, the maximum water recovery rate never exceeded 70% in this configuration. Thus, the ice bath condenser has been replaced by a two-stage water recovery subsystem composed of a TEC followed in series by a chiller (Figure 1).

The TEC consists of a cold-plate cooler with a stainless steel heat exchanger. A programmable temperature controller with two thermistors regulates the output power to the TEC using pulse-width modulation. The temperature of the TEC is manually set at 4 °C to prevent deposition of ice within the heat exchanger when the gas flow is saturated with steam, which reduces the diameter and eventually completely blocks the orifice, thus interrupting the gas flow. The temperature of the benchtop chiller cannot be controlled and thus the second stage operates at -20 °C. About 75% of all the water is collected in the graduated cylinder located after the TEC, while the remaining volume is collected in the benchtop chiller as seen in Figure 1. The two stages combined allow approximately 100% recovery of the theoretical volume of water contained in each trash model.

A. Collection of HMC water effluent samples over the operational cycle

Three water samples are collected during each trash run: two from the graduated cylinder after the TEC respectively at the end of the low-temperature phase and at the end of the high-temperature phase, and one from the chiller at the end of the run (Figure 4).

The water samples are refrigerated and analyzed by two facilities. The first analysis is supported by the in-house analytical lab at ARC. The water sample's pH, total organic carbon (TOC), total dissolved solids (TDS), conductivity, and ion concentrations are analyzed. Ions are detected by ion chromatography via the Dionex ICS-1500 for cations and ICS-1600 for anions. The following ions are analyzed: Na^+, NH_4^+,

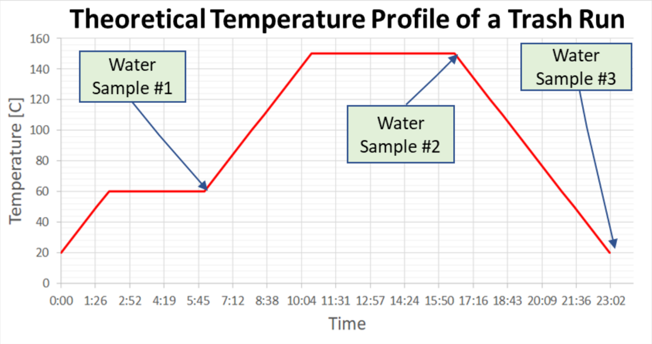


Figure 4. The theoretical temperature profile for the HMC operation with water sample points.

K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2}. The second analysis is supported by JSC's Water Quality Laboratory. Water samples are shipped with cold packs. The laboratory requires 200 – 300 mL of volume sample and, due to the low sample volume produced by the HMC (varies 100 - 200 mL), the laboratory combines them into a single water sample for analysis. JSC analyzes a more comprehensive amount of contaminants via GCMS and ion chromatography, resulting in detecting volatile, semi-volatile, and non-volatile organics, acids and bases/neutrals, and classes of compounds (e.g. alcohols, acetone, glycols, carboxylates, amines, and aldehydes).

IV. Dewpoint Analysis and Modeling Approach

As stated in a previous work,[4] the HMC gas effluent was collected and analyzed via grab and continuous sampling (Figure 1). This is the feed input for the phase equilibrium model in this study. The grab sample data was used to determine what feed conditions will result in meeting the VES dewpoint requirement for a given mixture after flashing across a valve (Figure 2). The continuous sample data was used to determine whether at any time throughout the operation cycle the HMC violates the dewpoint requirement.

Composition information about the gas effluent (concentration, mole fraction, flow rate etc.) are loaded into a flash separator (Flash2 block) in Aspen Plus®. Flash2 is a two outlet flash separator; one outlet being vapor and the other liquid. The flash model determines the thermal and phase conditions of a mixture and performs a phase equilibrium flash calculation based on its specifications. The thermodynamic condition of the feed stream is specified by any two combination of temperature, pressure, or molar vapor fraction. To determine the dewpoint of a mixture, the molar vapor fraction, also known as Q for quality, is set to 1. Aspen Plus® performs the phase equilibrium flash calculation throughout a simulation run. The property method used for the simulation environment is the Non-Random Two-Liquid Hayden O'Connell (NRTL-HOC), which is suitable for nonideal liquids and nonideal gases. In this simulation, the point at which the feed enters the flash separator represents a throttle valve and the VES is the flash subsystem (Figure 6). The flash specifications are the temperature 15.5 ºC and the molar vapor fraction, Q = 1.

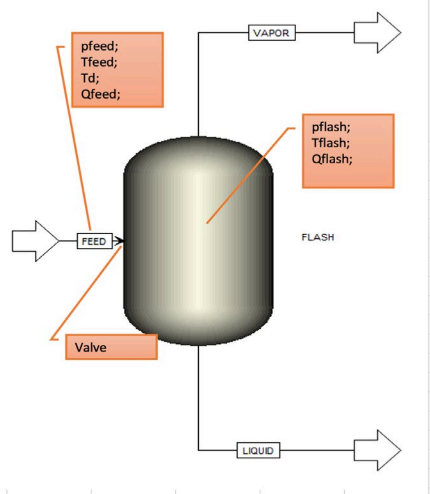


Figure 6. Flash separator block (Flash2) in Aspen Plus®.

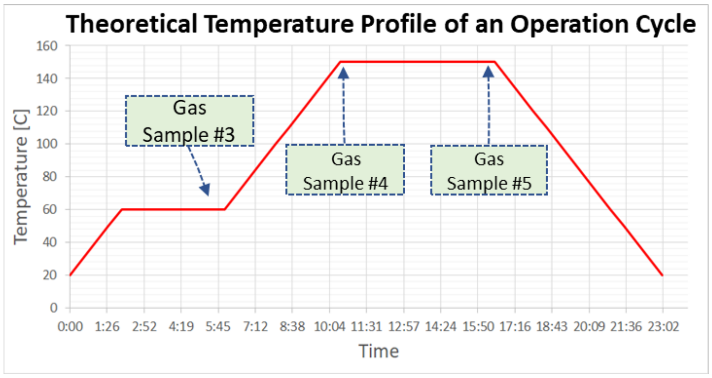


Figure 5. The theoretical temperature profile of the HMC operation with gas sample points. *Sample point 3 is the end of the low-temperature phase at 60 °C and end of the water recovery stage. Sample points 4 and 5 are the beginning and end of the high-temperature melting phase at 150 °C.*

A. Evaluation of optimal feed stream conditions to VES via grab sample data

With the grab sample data, the feed conditions to the VES were analyzed, in which the feed temperatures are calculated at fixed feed pressures. Grab sample data of sample points 3, 4, and 5 for each trash model were used. In the HMC operational cycle, these three sample points produce the most offgassing and ideally encompasses most, if not all, gas contaminants present in the trash (Figure 5).

In the flash separator equilibrium model, gas effluent concentrations of 35 abundant components, including water vapor, were specified in the feed stream as mole flows. Simulations were run at 0 mol%, 1 mol%, 2.5 mol% and 5 mol% water vapor for each sample to analyze its effect on dewpoint. The amount of water vapor in the feed is calculated by:

$$water\ vapor\ in\ feed = \frac{x\% \times \sum C_i}{1 - x\%} \tag{1}$$

where C_i is the concentration of component or species i and $x\%$ is the mol% of water vapor (0%, 1%, 2.5%, and 5%). The simulation produces temperature-pressure curves for each sample point, which describes the feed conditions that lead the sample to meet the VES requirements after flashing across the valve.

B. Dewpoint analysis of HMC gas effluent over operational cycle via continuous sample data

A similar simulation was conducted for the continuous data with additional work in a Microsoft® Excel® add-in called Aspen Simulation Workbook® (ASW). The continuous data consists of real-time concentrations of components from the HMC and includes the effect of air leakage into the HMC. The gas effluent components and concentrations analyzed by the FTIR are in ppm (parts-per-million) amounts as a function of time. In order to analyze the dewpoint temperatures of the gas effluent at different total pressures (30 – 760 Torr), the ppm amounts were converted to partial pressure units. Molar fractions y_i can be found via component concentration and total concentration:

$$y_i = \frac{component\ concentration = f(time\ t)}{total\ concentration} = \frac{C_i(t)}{C_{total}} \tag{1}$$

The total concentration of the mixture must normalize to 1 million or 10^6 ppm, so the remainder is assumed to be leakage air (79% nitrogen N_2 and 21% oxygen O_2) where:

$$C_{total} = 10^6\ ppm \tag{2}$$

$$C_{total} = \sum C_i(t) + 0.79 * \left(10^6 - \sum C_i(t)\right) + 0.21 * \left(10^6 - \sum C_i(t)\right) \tag{3}$$

Since the total pressure at which the concentrations were measured is known, which is at atmospheric pressure (760 Torr), the partial pressure of a gas mixture component was calculated via the relationship:

$$P_i = y_i P_{total} \tag{4}$$

With the partial pressures, the molar fractions of components in different total pressures (30, 76, 228 Torr) can be calculated as well. The molar fractions are then loaded into the simulation, flashing the mixtures at constant pressure to determine the dewpoint temperature. The flash separator has the same temperature and molar vapor fraction specifications. Since this is continuous data, the dewpoint temperature over time (the operational cycle) can be evaluated. ASW was used to generate a dewpoint temperature as a function of partial pressure, total system pressure, and vapor fraction at each time point for a given gas composition.

V. Results and Discussion

A. Water Analysis Results

The volume of water recovered has a high variability both between runs and within the runs themselves. The total volume collected on average during nominal trash runs is 93.64 mL, or 89.6% of the total theoretical moisture contained in the trash, with a standard deviation of 21.13 mL. On average, 43.08 ± 14.81 mL and corresponding to 46% of the total, is collected after the TEC at the end of the low-temperature phase, 24.74 ± 20.18 mL and corresponding to 26.4% of the total is collected after the TEC at the end of the high-temperature phase, and 25.82 ± 16.67 mL and corresponding to 27.6% of the total is collected from the cold trap/chiller at the end of the run.

The total volume collected on average during high-liquid trash runs is 140.07 mL, or 94.8% of the total theoretical moisture contained in the trash, with a standard deviation of 5.12 mL. On average, 86.15 ± 6.97 mL and corresponding to 61.5% of the total, is collected after the TEC at the end of the low-temperature phase, 29.93 ± 32.64 mL and corresponding to 21.4% of the total is collected after the TEC at the end of the high-temperature phase, and 23.98 ± 10.72 mL and corresponding to 17.1% of the total is collected from the cold trap/chiller a the end of the run.

The total volume collected on average during high-cloth trash runs is 57.8 mL, or 89.1% of the total theoretical moisture contained in the trash, with a standard deviation of 5.3 mL. On average, 24.13 ± 8.91 mL and corresponding to 41.8% of the total, is collected after the TEC at the end of the low-temperature phase, 7.33 ± 3.09 mL and corresponding to 12.7% of the total is collected after the TEC at the end of the high-temperature phase, and 26.33 ± 8.2 mL and corresponding to 45.6% of the total is collected from the cold trap/chiller a the end of the run.

The variability of water recovery within the run is explained by the way the different trash components are loaded into the chamber. When the "wet" trash components are located closer to the plenums and/or closer to the heating surfaces, more water is collected during the low-temperature phase. When the "wet" trash components are located in the middle of the puck (tile), more water is collected during the high-temperature phase. When the water evaporation rate is higher, part of the vapor bypasses the TEC and condenses in the chiller/cold trap. The variability of water recovery from run to run is mainly due to the condensation of water in non-heated plumbing lines and/or volumes in correspondence of sensors.

Figure 7 summarizes the results obtained from the water samples collected during the testing campaign for nominal, high-liquid, and high-cloth trash runs. All concentrations, except for pH, are reported in ppm. The total organic carbon (TOC) of the water samples collected from nominal trash model runs ranged between 402.3 ppm and 1230.0 ppm, with an average concentration of 624.2 ppm. Samples collected from high-liquid trash runs showed similar results, with values ranging from 363.4 ppm to 1,241.0 ppm, and with an average concentration of 627.6 ppm. On the other hand, the TOC of the water samples collected from high-cloth trash model runs were much lower, ranging between 218.5 ppm and 485.5 ppm, with an average concentration of 334.7 ppm. These results were expected due to the lower mass of food components in the high-cloth trash model (about 1/3) compared to the other two models. Moreover, the TOC concentration measured at the end of the high-temperature phase was generally higher compared to the values measured in samples collected at the end of the low-temperature phase. Finally, the highest TOC concentrations were measured in the water samples collected from the chiller, with an average of 2557.2 ppm. This is also expected since the sub-freezing temperature of the chiller leads to the condensation of volatile organics that are able to bypass the TEC.

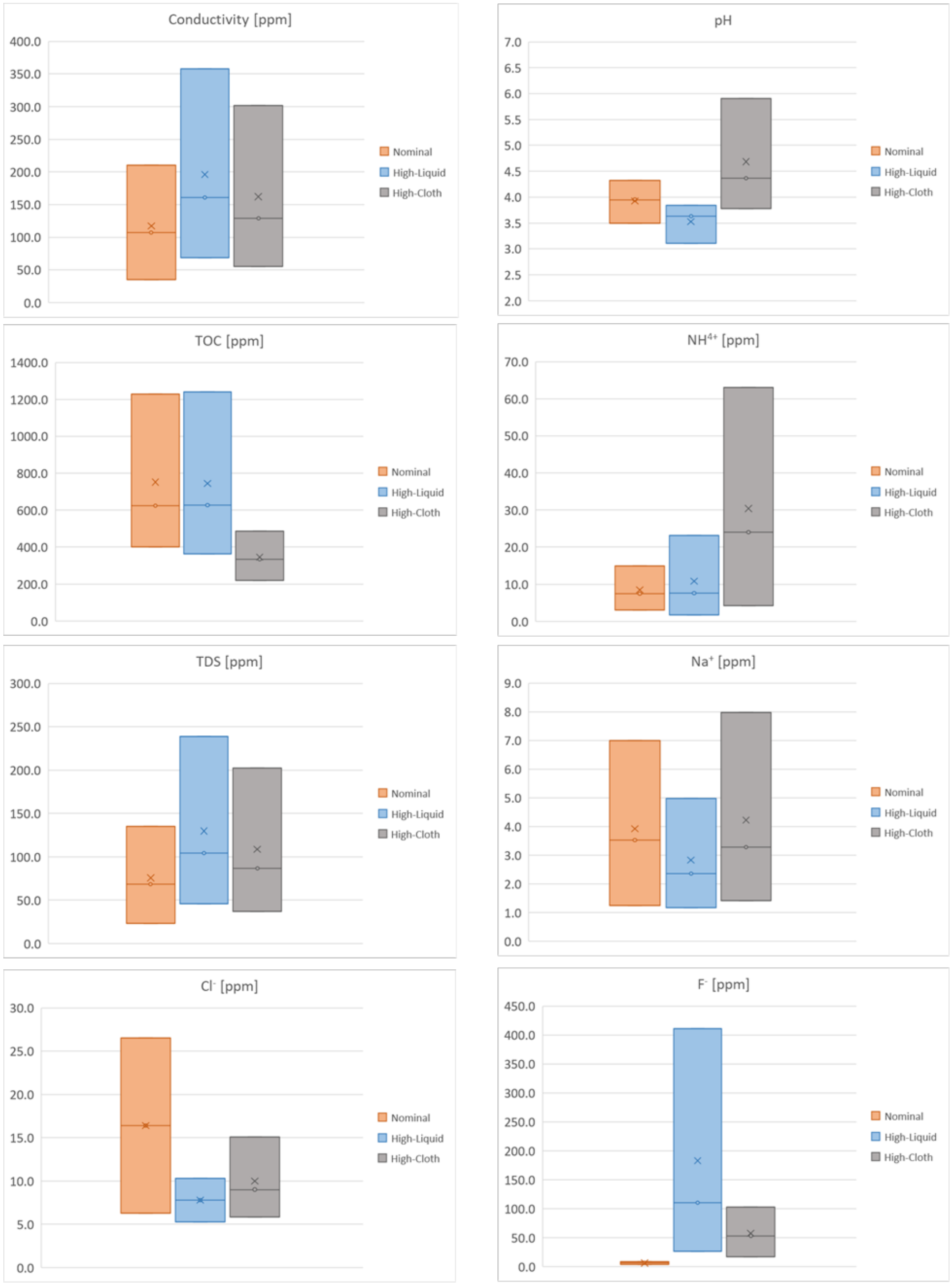


Figure 7. Summary of water analysis results.

The pH of all water samples collected was on average 4.0 with a standard deviation of 0.3 for the nominal trash runs, 3.6 ± 0.2 for the high-liquid model, and 4.4 ± 0.7 for the high-cloth model trash runs. This can be explained by the higher content of fruit juice in the high-liquid model, which makes the water samples more acidic.

Most ion concentrations are below the detection limit of the instrument, with the exception of chloride (Cl^-), fluoride (F^-), sodium (Na^+), and ammonium (NH_4^+). The concentration of ammonium in the high-cloth trash model runs is about three times higher compared to the nominal and high-liquid trash model runs, with an average concentration of 24 ppm and a peak concentration of 63 ppm. This can be explained by the higher content in cloth components and by the fact that ammonia is largely used in the textile industry to treat white cotton fabrics.

Chemical contaminant concentrations of the liquid effluent are listed in Appendix A. TOC concentrations dominate the sample and a few characteristic contaminants. Phenol, methanol, and formate are contaminants traced back to foods. Trimethylamine, acetone, formaldehyde, caprolactam, and glycols (1,2-ethanediol and 1,2-propanediol) are potentially sourced from plastics and fibers.

Finally, the higher conductivity and TDS concentration in the water samples from high-liquid trash model runs is due to their higher concentrations of fluoride rather than to their concentration of sodium chloride. The higher concentration of fluoride in the water samples from the high-liquid trash model runs can be explained by the exposure to toothpaste of a larger volume of water and water vapor contained in the trash.

B. Optimal Feed Conditions of Gas Effluent to VES

Temperature-pressure curves are generated for sample points 3, 4, and 5 of each trash model. These are phase diagrams where the phase of the mixture can be determined based on temperature and pressure conditions. For example, Figure 8 shows the minimum feed conditions (blue curve) and the optimal feed conditions (orange curve) for the VES. The blue curve describes feed conditions that are Q < 1, meaning it is possible to feed a two-phase (liquid-vapor) flow and still meet the VES dewpoint requirement. The orange curve is the two-phase boundary, but most appropriately called the saturated vapor curve. The area below and to the right of the curve describes the pressure and temperature of vapor-only feed that meet VES requirements. Overall, it is of best interest to focus on only the saturated vapor curves to meet optimal feed conditions.

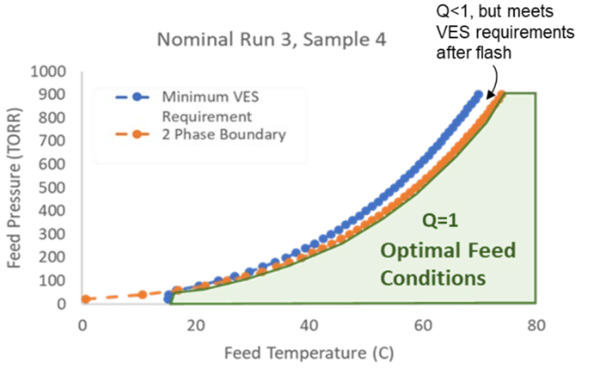


Figure 8. An example of vapor-liquid curves describing feed conditions that meet the VES dewpoint requirement.

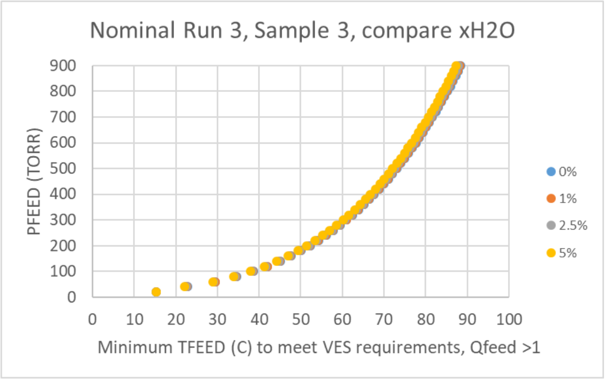


Figure 9. An example of a saturated vapor curve of various mol% amounts of water vapor.

In addition, this also included a sensitivity analysis on dewpoint changes, in which water vapor is added to the feed in various mole percentages. For example, in Figure 9, the sensitivity analysis on the mol% of water vapor does not significantly change the dewpoint. Similar results occur for other sample points in each trash model.

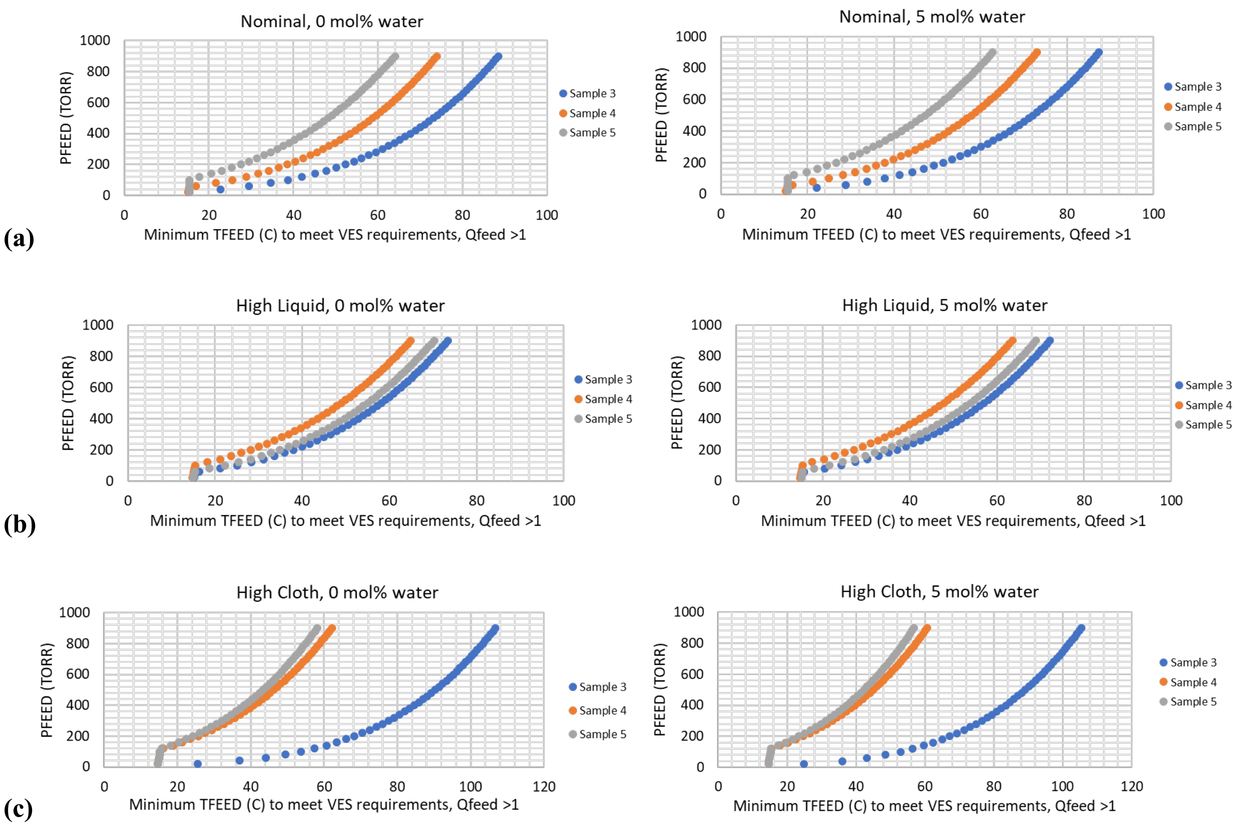


Figure 10. Saturated vapor curves of sample points 3, 4, and 5 for each trash model (a) nominal, (b) high liquid, and (c) high cloth and effect of applying a 0 mol% and 5 mol% of water vapor to the feed.

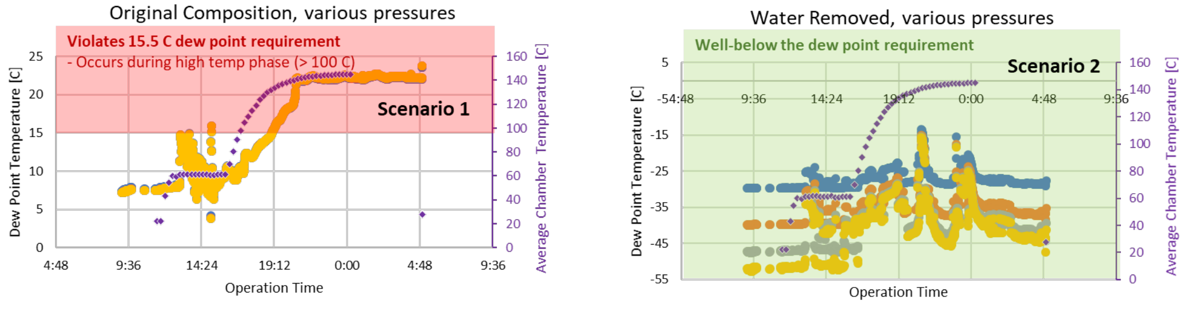
The HMC chamber operates at approximately 0.3 psia, which is roughly 15 Torr. The TCPS exhaust line will likely be close to the operational pressure of the compaction chamber, so the expected pressure range of the gas effluent feed is between 0.3 and 14 psia (15 – 760 Torr). According to the saturated vapor curves in Figure 9, the optimal temperature and pressures of the feed are graphically to the right and below the curves. The blue curves (sample 3) have relatively higher dewpoints than the other sample points because at this stage of the operation, water vapor is released. Higher pressures would require the feed temperature to be higher. According to Figure 10, if the feed is at atmospheric pressure (760 Torr), the minimum feed temperature to meet vapor-phase only flow is > 80 °C for nominal trash, > 70 °C for high-liquid, and > 100 °C for high-cloth. However, VES limits the feed temperatures to 16 – 45 °C and pressures of less than 40 psia (roughly 2070 Torr). While the pressure and vapor-phase only requirements are met, the feed temperatures are not. Limiting the temperature to less than 45 °C would require pressures of at least less than 200 Torr for all sample points and trash models. If the temperature of the exhaust is assumed to be at room temperature and the pressure limited to 15 Torr, then the exhaust will meet the VES venting and dewpoint requirements.

C. Dewpoint vs. Operation Time

This analysis is the continuous sample and depicts dewpoint temperature with respect to the operation cycle time. The dewpoint temperatures of the effluent gas are plotted with respect to different pressures ranging from 30 – 760 Torr. The analysis evaluates two scenarios:

1) effluent gas with a leak coming from lab air, this includes water vapor coming from trash and leak, and
2) completely dry effluent gas where the water vapor content is removed.

Note, that these scenarios are if the exhaust gases from the TCPS are directly vented to the VES without cooling to the 16 – 45 °C requirement range and without going through a contaminant control system. The collection of this gas data did not pass through a cooling subsystem as specified in Figure 1.



(a) **(b)**

Figure 11. Dewpoint vs operation time for a nominal trash model in various operating pressures. *(a) Scenario 1 is the original composition of the gas effluent, which includes water vapor and leak into the system. (b) Scenario 2 is the gas effluent when water is removed. In other words, a dry gas effluent.*

Figure 11 shows that for the continuous sample the dewpoint of the mixture is dependent on the presence of water vapor. The calculated dewpoint temperatures do not change significantly as pressure decreases except when water is removed. This is because the partial pressure of water vapor is at least 3 orders in magnitude greater than the partial pressures of other components. Removing the water will result in a lower dewpoint at lower pressures. In addition, removing water by drying the gas effluent is an advantage because wet steam is not allowed in the VES.

A substantial amount of water vapor leads to a violation in dewpoint and occurs during high temperatures (greater than 100 ºC), as seen in scenario 1. Theoretically, this makes sense because generally higher dewpoint temperatures are associated with relatively greater amount of water vapor present. This scenario is considered a worst case as the leak possibly contributes to a relatively large amount of water vapor.

Scenario 2, which is the completely dry effluent case, is rather unrealistic because not all 100% of water vapor can be removed. However, this is a good case if the water separator prior to the VES is proven in design to have a high efficiency to capture water. This raises the question, how much water can be in the TCPS exhaust as it is fed into the VES to not violate the dewpoint.

This same analysis was also done on the high liquid and high cloth trash models and produced similar results. Additional supplementary analysis included the removal of specific compounds and its effect on the dewpoint. Cases such as the elimination of carbon disulfide only and the elimination of isopropyl alcohol & acetone were conducted. The results showed they did not contribute a significant change on the dewpoint because of the relatively large partial pressure of water vapor.

VI. Conclusion

The quality and contaminant characterization of water samples generated during the processing of trash with a heat-melt-compaction system are successfully assessed. There is a concern with input loading on a spacecraft water processing system due to the high TOC concentration and its effect on the surface tension and adsorption on water treatment or filtration systems. It is observed that TOC concentrations reflect lower mass of food components and chemical contaminants can be traced back to food items, plastics, and fibers. As for a specific TOC concentration requirement for the spacecraft water processing system, the input load is undetermined as it is highly dependent on volume instead. It is possible that the added load will be diluted instead. Although estimates have been developed in the past for acceptable wastewater quality, further investigation and analysis is needed for compatibility.

Dewpoint analysis is only a thermodynamic analysis, thus there is no involvement of kinetics and processes. Saturated vapor curves are useful because it determines the temperature and pressure conditions where the mixture will condensate or remain vaporized and a regime can be identified as to meet the VES dewpoint requirement. The dewpoint of the effluent is dependent on water vapor and removing water will result in lower dewpoints as pressure decreases. Critical future work is to analyze the composition and rate of the leak of air from the cabin into the compaction chamber. Characterizing the leak is important so the amount of water vapor and other contaminants external to the system can be accounted for.

Appendix

Appendix A. Table of chemical contaminants and concentrations from water analysis.

	CONCENTRATION [μg/L = mg/m3]							
	Sample is a the combination of wastewater composite, sample point #3 TEC, sample point #6 TEC, & sample point #6 cold trap							
		Nominal #1		**Nominal #4**		**High Liquid #1**		**High Liquid with MMI Bag #2**
		Run #1		Run #4		Run #5		Run #6
		10/17/2019		11/13/2019		12/2/2019		12/5/2019
CHEMICAL CONTAMINANT		JSC		JSC		JSC		JSC
Method								
Total Organic Carbon (TOC)		1230000		511000		480000		480000
Trimethylamine		476		2000		590		1080
N,N-Diethylformamide		190		170		200		860
Neomenthol		18000		12000		5600		3700
Phenethyl alcohol		180		200		230		120
p-Menth-1-en-8-ol (alpha-Terpineol)		500		220		330		250
1,2-Propanediol (Propylene glycol)		60700		50700		42700		45800
Acetate		52900		115000		112000		206000
Formate		7400		14000		16000		16600
Propionate		16600		20500		25700		28400
Formaldehyde (Methanal)		4420		6340		4670		9360
Benzyl alcohol		429		115000		199000		155000
Butyrate		1240		1890		3230		4240
Benzaldehyde		not found		1200		4100		2100
Methanol	<	100000		11300		14600		20200
2-Methylthiobenzothiazole	<	100		44		54		54
2-Ethylhexanoic acid		not found		260		not found		280
Tributyl phosphate		not found		not found		not found		64
Ethanol		114000		39600		71800		73400
Diethylphthalate		198		199		231		107
Di-n-butylphthalate		223		95		111		110
Vanillin		310		120		160		130
2-Butoxyethanol		not found		not found		150		160
2-Phenoxyethanol		not found		69		not found		72
Caprolactam		5130	<	5000		9630	<	5000
Glyoxylate	<	500	<	500		1320	<	500
Methyl 4-hydroxybenzoate		130		93		67		not found
1,2-Ethanediol (Ethylene glycol)		5330		7690	<	25000	<	25000
bis-(2-Ethylhexyl)phthalate		303		119	<	50	<	50
2-Propanol (Isopropanol)		1810000		78300	<	12000	<	12000
bis-(2-Ethylhexyl)adipate	<	100		142	<	50	<	50
Dimethylphthalate	<	100		43	<	50	<	50
Fluoranthene	<	100		54	<	50	<	50
Benzoic acid	<	500		1370	<	250	<	250
2-Hydroxybenzothiazole		not found		120		not found		not found
Butylated hydroxyanisole (BHA)	<	200		86		not found		not found
Isobutyrate (2-Methylpropanoic acid)	<	500		682	<	500	<	500
Total Inorganic Carbon (TIC)			<	15000	<	15000	<	15000
Decamethylcyclopentasiloxane (DMCPS)		126	<	40	<	50	<	50
Dodecamethylcyclohexasiloxane		426	<	40	<	50	<	50
Acetone		822	<	500	<	500	<	500
Phenol		135	<	40	<	50	<	50
Acetone		822	<	500	<	500	<	500
TOC OI								
Volatiles Targets GCMS								
1,1,1,2-Tetrachloroethane	<	500	<	500	<	500	<	500
1,1,1-Trichloroethane	<	500	<	500	<	500	<	500
1,1,2,2-Tetrachloroethane	<	500	<	500	<	500	<	500
1,1,2-Trichloroethane	<	500	<	500	<	500	<	500
1,1-Dichloroethane	<	500	<	500	<	500	<	500
1,1-Dichloroethene	<	500	<	500	<	500	<	500
1,1-Dichloropropanone	<	1000	<	1000	<	1000	<	1000
1,1-Dichloropropene	<	500	<	500	<	500	<	500
1,2,3-Trichlorobenzene	<	500	<	500	<	500	<	500
1,2,3-Trichloropropane	<	500	<	500	<	500	<	500
1,2,4-Trichlorobenzene	<	500	<	500	<	500	<	500
1,2,4-Trimethylbenzene	<	500	<	500	<	500	<	500
1,2-Dibromo-3-chloropropane (DBCP)	<	500	<	500	<	500	<	500
1,2-Dibromoethane (EDB)	<	500	<	500	<	500	<	500
1,2-Dichlorobenzene	<	500	<	500	<	500	<	500
1,2-Dichloroethane	<	500	<	500	<	500	<	500

1,2-Dichloropropane	<	500		<	500		<	500		<	500
1,3,5-Trimethylbenzene	<	500		<	500		<	500		<	500
1,3-Dichlorobenzene	<	500		<	500		<	500		<	500
1,3-Dichloropropane	<	500		<	500		<	500		<	500
1,4-Dichlorobenzene	<	500		<	500		<	500		<	500
1-Chlorobutane (Butyl chloride)	<	500		<	500		<	500		<	500
2,2-Dichloropropane	<	500		<	500		<	500		<	500
2-Butanone (Methyl ethyl ketone)	<	500		<	500		<	500		<	500
2-Chlorotoluene (1-Chloro-2-methylbenzene)	<	500		<	500		<	500		<	500
2-Hexanone	<	500		<	500		<	500		<	500
2-Nitropropane	<	1000		<	1000		<	1000		<	1000
3-Chloropropene (Allyl chloride)	<	500		<	500		<	500		<	500
4-Chlorotoluene	<	500		<	500		<	500		<	500
4-Isopropyltoluene (Cymene)	<	500		<	500		<	500		<	500
4-Methyl-2-pentanone (MIBK)	<	500		<	500		<	500		<	500
Acrylonitrile	<	500		<	500		<	500		<	500
Benzene	<	500		<	500		<	500		<	500
Bromobenzene	<	500		<	500		<	500		<	500
Bromochloromethane	<	500		<	500		<	500		<	500
Bromodichloromethane	<	500		<	500		<	500		<	500
Bromoform	<	500		<	500		<	500		<	500
Bromomethane	<	1000		<	1000		<	1000		<	1000
Carbon disulfide	<	500		<	500		<	500		<	500
Carbon tetrachloride	<	500		<	500		<	500		<	500
Chloroacetonitrile	<	1000		<	1000		<	1000		<	1000
Chlorobenzene	<	500		<	500		<	500		<	500
Chloroethane	<	500		<	500		<	500		<	500
Chloroform	<	500		<	500		<	500		<	500
Chloromethane	<	500		<	500		<	500		<	500
cis-1,2-Dichloroethene	<	500		<	500		<	500		<	500
cis-1,3-Dichloropropene	<	500		<	500		<	500		<	500
Dibromochloromethane	<	500		<	500		<	500		<	500
Dibromomethane	<	500		<	500		<	500		<	500
Diethyl ether	<	500		<	500		<	500		<	500
Ethyl methacrylate	<	500		<	500		<	500		<	500
Ethylbenzene	<	500		<	500		<	500		<	500
Freon 11 (Trichlorofluoromethane)	<	500		<	500		<	500		<	500
Freon 12 (Dichlorodifluoromethane)	<	500		<	500		<	500		<	500
Hexachlorobutadiene	<	1000		<	1000		<	1000		<	1000
Hexachloroethane	<	500		<	500		<	500		<	500
Iodomethane		NA		<	500		<	500		<	500
Isopropylbenzene (Cumene)	<	500		<	500		<	500		<	500
m and p-Xylene	<	1000		<	1000		<	1000		<	1000
Methacrylonitrile	<	500		<	500		<	500		<	500
Methyl acrylate	<	500		<	500		<	500		<	500
Methyl methacrylate	<	500		<	500		<	500		<	500
Methylene chloride (Dichloromethane)	<	500		<	500		<	500		<	500
Methyl-t-butyl ether (MTBE)	<	500		<	500		<	500		<	500
Naphthalene	<	500		<	500		<	500		<	500
n-Butylbenzene	<	1000		<	1000		<	1000		<	1000
Nitrobenzene	<	1000		<	1000		<	1000		<	1000
n-Propylbenzene	<	500		<	500		<	500		<	500
o-Xylene	<	500		<	500		<	500		<	500
Pentachloroethane	<	500		<	500		<	500		<	500
Propanenitrile (Ethyl cyanide)	<	1000		<	1000		<	1000		<	1000
sec-Butylbenzene	<	500		<	500		<	500		<	500
Styrene (Ethenylbenzene)	<	500		<	500		<	500		<	500
tert-Butylbenzene	<	500		<	500		<	500		<	500
Tetrachloroethene (Perchloroethene)	<	500		<	500		<	500		<	500
Tetrahydrofuran (1,4-Epoxybutane)	<	1000		<	1000		<	1000		<	1000
Toluene	<	500		<	500		<	500		<	500
trans-1,2-Dichloroethene	<	500		<	500		<	500		<	500
trans-1,3-Dichloropropene	<	500		<	500		<	500		<	500
trans-1,4-Dichloro-2-butene	<	500		<	500		<	500		<	500
Trichloroethene	<	500		<	500		<	500		<	500
Vinyl acetate	<	1000		<	1000		<	1000		<	1000
Vinyl chloride	<	500		<	500		<	500		<	500
Volatiles SICs GCMS											
Acetaldehyde		not found			not found			not found			not found
Trimethylsilanol		not found			not found			not found			not found
Semi-volatiles Targets GCMS											
Benzothiazole	<	100		<	40		<	50		<	50
Methyl sulfone	<	100		<	40		<	50		<	50
N-n-Butylbenzenesulfonamide	<	100		<	40		<	50		<	50
Octamethylcyclotetrasiloxane (OMCTS)	<	100		<	40		<	50		<	50

Tris(2-Chloroethyl)phosphate	<	100		<	40		<	50		<	50
Acid Extractables-EPA 625 list GCMS											
2,4,5-Trichlorophenol	<	100		<	40		<	50		<	50
2,4,6-Trichlorophenol	<	100		<	40		<	50		<	50
2,4-Dichlorophenol	<	100		<	40		<	50		<	50
2,4-Dimethylphenol	<	100		<	40		<	50		<	50
2,4-Dinitrophenol	<	500		<	200		<	250		<	250
2-Chlorophenol	<	100		<	40		<	50		<	50
2-Methylphenol (o-Cresol)	<	100		<	40		<	50		<	50
2-Nitrophenol	<	100		<	40		<	50		<	50
4,6-Dinitro-2-methylphenol	<	100		<	40		<	50		<	50
4-Chloro-3-methylphenol	<	100		<	40		<	50		<	50
4-Methylphenol (p-Cresol)	<	100		<	40		<	50		<	50
4-Nitrophenol	<	200		<	80		<	100		<	100
Pentachlorophenol	<	200		<	80		<	100		<	100
Base and Neutral Extractables-EPA 625 List GCMS											
1,2,4-Trichlorobenzene	<	500		<	500		<	500		<	500
1,2-Dichlorobenzene	<	500		<	500		<	500		<	500
1,3-Dichlorobenzene	<	500		<	500		<	500		<	500
1,4-Dichlorobenzene	<	500		<	500		<	500		<	500
2,4-Dinitrotoluene	<	100		<	40		<	50		<	50
2,6-Dinitrotoluene	<	100		<	40		<	50		<	50
2-Chloronaphthalene	<	100		<	40		<	50		<	50
3,3`-Dichlorobenzidine	<	200		<	80		<	100		<	100
4-Bromophenyl phenyl ether	<	100		<	40		<	50		<	50
4-Chlorophenyl phenyl ether	<	100		<	40		<	50		<	50
Acenaphthene	<	100		<	40		<	50		<	50
Acenaphthylene	<	100		<	40		<	50		<	50
Anthracene	<	100		<	40		<	50		<	50
Benzo(a)anthracene	<	100		<	40		<	50		<	50
Benzo(a)pyrene	<	100		<	40		<	50		<	50
Benzo(b)fluoranthene	<	100		<	40		<	50		<	50
Benzo(g,h,i)perylene	<	100		<	40		<	50		<	50
Benzo(k)fluoranthene	<	100		<	40		<	50		<	50
bis(2-Chloro-1-methylethyl)ether (2,2`-Oxybis(1-chloropropane))	<	100		<	40		<	50		<	50
bis(2-Chloroethoxy)methane	<	100		<	40		<	50		<	50
bis(2-Chloroethyl)ether	<	100		<	40		<	50		<	50
Butylbenzylphthalate	<	100		<	40		<	50		<	50
Chrysene	<	100		<	40		<	50		<	50
Dibenzo(a,h)anthracene	<	100		<	40		<	50		<	50
Di-n-octylphthalate	<	100		<	40		<	50		<	50
Fluorene	<	100		<	40		<	50		<	50
Hexachlorobenzene	<	100		<	40		<	50		<	50
Hexachlorobutadiene	<	1000		<	1000		<	1000		<	1000
Hexachlorocyclopentadiene	<	100		<	40		<	50		<	50
Hexachloroethane	<	500		<	500		<	500		<	500
Indeno(1,2,3-cd)pyrene	<	100		<	40		<	50		<	50
Isophorone	<	100		<	40		<	50		<	50
Naphthalene	<	500		<	500		<	500		<	500
Nitrobenzene	<	1000		<	1000		<	1000		<	1000
N-Nitrosodimethylamine	<	100		<	40		<	50		<	50
N-Nitroso-di-n-propylamine	<	100		<	40		<	50		<	50
N-Nitrosodiphenylamine	<	100		<	40		<	50		<	50
Phenanthrene	<	100		<	40		<	50		<	50
Pyrene	<	100		<	40		<	50		<	50
Semi-volatiles SICs GCMS											
1,3,5-Triallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione		not found			not found			not found			not found
1-Methyl-2-pyrrolidinone		not found		<	160		<	200		<	200
2-(2-Butoxyethoxy)ethanol		not found			not found			not found			not found
2-Ethoxyethanol		not found			not found			not found			not found
2-Ethyl-1-hexanol	<	200			not found			not found			not found
2-Mercaptobenzothiazole		not found			not found			not found			not found
2-Methyl butyric acid		not found			not found			not found			not found
2-Methyl-2,4-pentanediol		not found			not found			not found			not found
2-Phenyl-2-propanol		not found			not found			not found			not found
2-Phenylacetic acid		not found			not found			not found			not found
3-tert-Butylphenol		not found			not found			not found			not found
4-Ethylmorpholine		not found			not found			not found			not found
Acetophenone	<	50			not found			not found			not found
Caffeine		not found			not found			not found			not found
Dibutylamine		not found			not found			not found			not found
Diethylene glycol monoethyl ether		not found			not found			not found			not found
Dipropylene glycol methyl ether		not found			not found			not found			not found
Heptanoic acid		not found			not found			not found			not found
Hexanoic acid (Caprolate)		not found			not found			not found			not found

Ibuprofen		not found			not found			not found			not found
Monomethyl phthalate		not found			not found			not found			not found
N,N-Dimethyl acetamide		not found			not found			not found			not found
N,N-Dimethylbenzylamine		not found			not found			not found			not found
N,N-Dimethylformamide		not found			not found			not found			not found
Nicotine		not found			not found			not found			not found
Nonanoic acid		not found			not found			not found			not found
N-Phenyl-2-naphthylamine		not found			not found			not found			not found
Oxindole		not found			not found			not found			not found
Palmitic acid		not found			not found			not found			not found
Salicylic acid		not found			not found			not found			not found
Tetramethyl thiourea		not found			not found			not found			not found
Thymol		not found			not found		<	120			not found
Tributylamine		not found			not found			not found			not found
Triethyl phosphate		not found			not found			not found			not found
Alcohols and Acetone GCMS											
1-Butanol	<	100000		<	6000		<	12000		<	12000
1-Pentanol (Amyl alcohol)	<	100000		<	6000		<	12000		<	12000
1-Propanol	<	100000		<	6000		<	12000		<	12000
2-Butanol	<	100000		<	6000		<	12000		<	12000
2-Methyl-1-butanol	<	100000		<	6000		<	12000		<	12000
2-Methyl-1-propanol (Isobutanol)	<	100000		<	6000		<	12000		<	12000
2-Methyl-2-butanol	<	100000		<	6000		<	12000		<	12000
2-Methyl-2-propanol	<	100000		<	6000		<	12000		<	12000
2-Pentanol (sec-Amyl alcohol)	<	100000		<	6000		<	12000		<	12000
3-Methyl-1-butanol (Isopentanol)	<	100000		<	6000		<	12000		<	12000
3-Pentanol	<	100000		<	6000		<	12000		<	12000
Glycols GCMS											
Carboxylates IC											
Glycolate	<	1000		<	1000		<	1000		<	1000
Lactate	<	500		<	500		<	500		<	500
Isovalerate (3-Methylbutanoic acid)	<	500		<	500		<	500		<	500
Oxalate	<	500		<	500		<	500		<	500
Valerate (Pentanoic acid)	<	500		<	500		<	500		<	500
Amines IC											
Ethylamine	<	250		<	250		<	250		<	250
Methylamine	<	250		<	250		<	250		<	250
n-Propylamine	<	250		<	250		<	250		<	250
Aldehydes GCMS											
Non-volatiles LC-UVVIS											
Urea	<	8000		<	8000		<	8000		<	8000

Acknowledgments

For the water analysis, many thanks to Jessica Kong from ARC and Dan Gazda, Ed Hudson, and the Water Quality Laboratory in JSC. Many thanks to Mary Lou Nadeau, Kevin Lange, and Tsvetelina Baryakova from JSC for doing the Aspen Plus® modeling and simulations.

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