

Development and Design of a Low Temperature Solid Waste Oxidation and Water Recovery System

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ABSTRACT

In February 2004 NASA released "The Vision for Space Exploration." The goals outlined in this document include extending the human presence in the solar system, culminating in the exploration of Mars. A key requirement for this effort is to identify a safe and effective method to process waste. Methods currently under consideration include incineration, microbial oxidation, pyrolysis, drying, and compaction. Although each has advantages, no single method has yet been developed that is safe, recovers valuable resources including oxygen and water, and has low energy and space requirements. Thus, the objective of this work is to develop a low temperature oxidation process to convert waste cleanly and rapidly to carbon dioxide and water.

Previously, TDA Research, Inc. demonstrated the potential of a low temperature dry oxidation process using ozone in a small laboratory reactor. Currently, TDA and NASA Ames Research Center are developing a pilot scale low temperature ozone oxidation system to convert organic waste to CO₂ and H₂O. The system also disinfects the waste and remaining water, and recovers not only the water content of the waste but also generates additional water that can be utilized by the crew. Tests are being conducted with model wastes in a reactor design that maximizes the contact between the reactants by mixing the waste with water, which also makes the oxidation process extremely selective to CO₂ and H₂O and mitigates the rapid combustion events that were seen in the dry oxidation reactor. An ozone recycle loop was recently added to the system, which significantly increased the waste oxidation rates. The reactor operating conditions were then optimized using

the design of experiments technique to maximize the waste oxidation rate. Currently, a pilot scale, fully automated system is being designed that will be capable of handling many different types of waste. The waste oxidation rates achieved to date, along with current waste generation rate models, indicate that all of the waste from a single crew member in one day can be processed in a vessel ranging in size from 8.2 liters (2.2 gallons) for a short term mission to 9.9 liters (2.6 gallons) for a long term mission. In addition, if the system were used solely as a fecal matter oxidizer the reactor size would be only 0.7 liters. At the conclusion of the project the system will be delivered to NASA Ames for evaluation.

INTRODUCTION

A critical need for space missions is an effective method to control solid waste. The current estimates of solid waste generation rates are about 1.69 kg/CMD (kilograms per crew member day) for long duration space missions and 1.39 kg/CMD for short term missions¹. If one assumes that a 180 day mission to Mars will include six crew, a total of 1825 kg of waste will be generated. Without processing and using the highest densities that have been achieved to date of 64 kg/m³, a space of approximately 28.5 m³ would be required to contain this waste². In addition to occupying valuable space, leaving waste unprocessed could cause the crew to be exposed to odors and biohazards, which would be a serious threat to their health and morale.

Moreover, since leaving waste on the surface of Mars is undesirable, all waste generated on the way to the planet along with that produced during the surface stay is to be transported back. Thus, the additional launch

weight could be well over 1300 kg, requiring that extra fuel be carried from Earth. Finally, if the waste is not processed, neither the oxygen nor the water contained in the waste will be recovered. Thus, in addition to the extra weight that must be returned from the planet, makeup water would also need to be included in the launch. Therefore, identifying an effective waste processing method would reduce original and return launch weights, eliminate the storage volume required on the transit vehicle, and avoid crew exposure to odors and biological hazards.

The waste treatment method for long term missions needs to meet difficult and demanding criteria: it must be safe, reliable, have low energy and space requirements, ideally recover the water and oxygen contained in the waste, and most importantly, not produce toxic compounds in the process. Waste treatment methods that have received consideration include incineration, microbial oxidation, pyrolysis, and compaction^{3,4,5,6}. Unfortunately, although each method has certain advantages, no single process has been developed that meets all of these demanding criteria.

In the past year, TDA developed a low temperature wet oxidation process, utilizing ozone (O₃) as the oxidant and found that the method meets all of the criteria for a successful waste treatment process. In the initial Phase II tests TDA used a model waste stream that was previously described⁷. Cellulose was used to represent waste paper, wheat straw to represent food scraps, low-density polyethylene (LDPE) for plastic and plastic wrapping, methionine to represent feces, and urea for other biological waste. A modified fecal simulant (Figure 1) described by Wignarajah⁸ was also used during the reactor optimization tests. Active dry yeast was substituted for the E. Coli and the inorganic portion was eliminated.

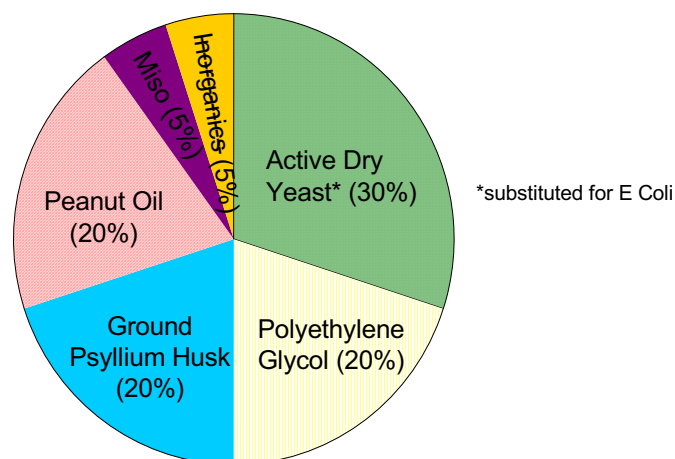


Figure 1. Modified fecal simulant recipe used during reactor optimization tests taken from Wignarajah⁸.

The individual components of the fecal simulant from Figure 1 was submitted to Huffman Laboratories (Golden, CO) for elemental analysis on C, H, N, O and S in order to obtain a more accurate integrated oxidized mass for each test. The results of the analysis can be

found in Table 1. Based on the composition of the fecal simulant and the elemental analysis every gram of CO₂ measured in the effluent is equivalent to 1.95 grams of fecal simulant if the waste is stoichiometrically oxidized.

Table 1. Elemental analysis results of individual fecal simulant components.

Ingredient	Weight %				
	Carbon	Hydrogen	Nitrogen	Oxygen	Sulfur
Yeast	45.16	6.92	6.83	37.99	0.05
Psyllium	40.87	6.33	0.51	50.07	0.05
PEG	49.61	9.45	0.03	40.97	<0.01
Peanut Oil	77.72	11.85	0.03	11.18	<0.01
Miso	29.89	7.21	4.09	46	0.03

The tests were completed in a reactor consisting of a 7.62 cm (3-in) O.D. x 95.25 cm (37.5-in) long stainless steel reactor (total volume = 3.8 L) that contained the solid waste/water mixture. A resistance heat tape was wrapped around the reactor to provide the heat necessary for the experiments. The ozone was introduced through an aeration diffuser at the bottom of the reactor that produced very small bubbles resulting in very good mixing and contact of the reactive mixture during the waste treatment process.

Figure 2 shows a progression of the oxidation rates that have been obtained in the Phase II portion of this project with the wet oxidation reactor. The figure shows that the peak oxidation rate was increased from less than 1.0 gram/hour to 10.6 g/h by increasing the size of the reactor, implementing a recycle loop and utilizing the design of experiments⁹ optimization technique. The recycle loop takes a large portion of the flow exiting the reactor that contains unused ozone and reintroduces it into the bottom of the reactor to increase reactor efficiency and better utilize the ozone during waste oxidation. The highest waste oxidation rates we have achieved indicate that we can oxidize all of the waste generated on a long-term space mission from one crew member in a vessel volume smaller than three gallons.

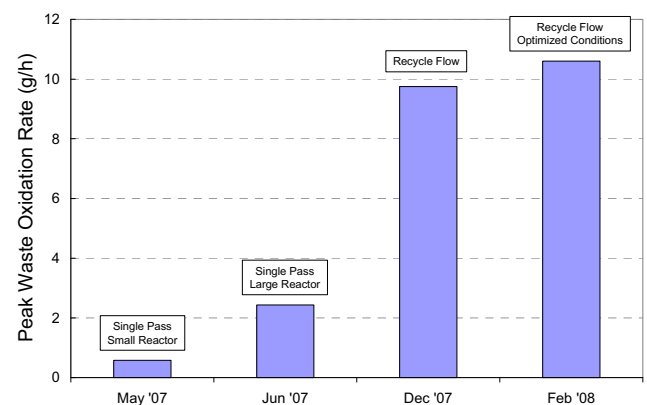


Figure 2. Waste oxidation peak rate results obtained with the modified fecal simulant during process development.

The overall objective of this project is to develop a low temperature waste oxidation process and the results are the

design to a larger pilot rig that will be constructed and delivered to NASA Ames Research Center. The reactor will be part of a fully automated system that will be capable of converting the waste into CO_2 and H_2O .

EXPERIMENTAL SETUP AND PROCEDURES

DESCRIPTION OF THE TEST RIG - A schematic of the low temperature waste oxidation system is shown in Figure 3. The system consists of a gas manifold for the introduction of well-controlled flows of oxygen and nitrogen to the test apparatus. The oxygen flow passes through an ozone generator (Model AE30M80VP from Absolute Ozone, Edmonton, Alberta), capable of producing a total flow of ozone up to 1.0 mol/h (48.0 g/h). The O_3/O_2 mixture is then directed into the test section through a porous diffuser where it contacts and oxidizes the waste. The gases exiting the reactor then pass through a condenser to separate the water from the product stream. A large portion of the exhaust stream is then circulated back into the bottom of the reactor through a diaphragm pump (the recycle flow). Water from the condenser is periodically pumped back into the reactor to maintain the original water level.

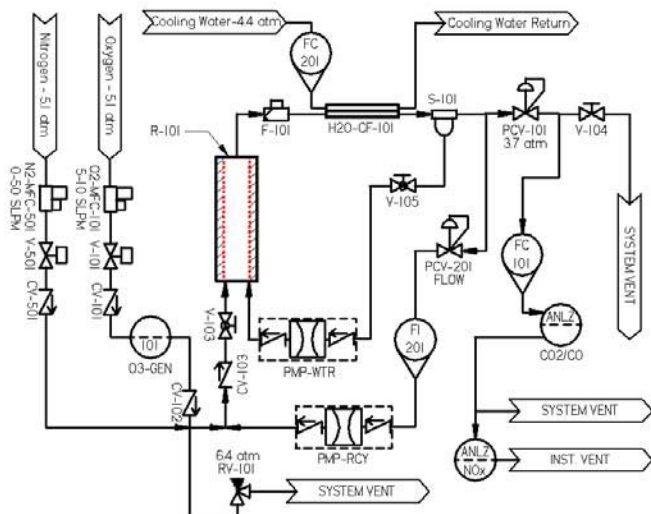


Figure 3. Phase II waste treatment system.

The portion of the exhaust stream not pumped through the recycle loop passes through a pressure control valve (PCV) and finally into a series of analyzers that monitor the concentrations of CO_2 , CO (Model 602 NDIR analyzer from California Analytical), O_3 (Model OLA ozone analyzer from Ozone Services) and NO_x (Model 42C from Thermo Scientific) that are generated during the testing. Finally the effluent passes through a catalyst that reduces the ozone concentration to less than 1 ppm before it is vented. The nitrogen manifold is used for the purging of the reactor in the event of an over-temperature situation. The entire system is interfaced to the control computer running *OPTO Factory Floor*.

The CO , CO_2 concentration and total flow rates along with the chemical formula for the waste are used to

calculate a waste oxidation rate during the testing. In order to calculate the rate it was assumed that the other species in the molecule (mainly H, O and N) were being oxidized into volatile species at the same rate as carbon and therefore calculated the expected weight change based on the total molecular weight, not just the quantity of carbon in the molecule. The amount of waste that had been oxidized gravimetrically was also measured by weighing the samples before they were loaded into the reactor and also after the oxidation test was complete.

Figure 4 shows a photograph of the waste oxidation apparatus. The reactor is visible on the left side of the photograph along with the condenser. The ozone generator, recycle pump and the condensable trap are shown on the right side of the photograph.

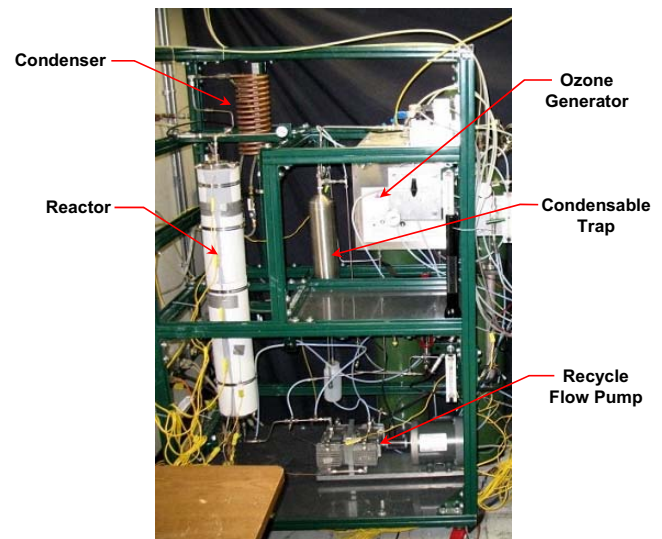


Figure 4. Photograph of waste oxidation apparatus.

Figure 5 shows a 3-D model of the laboratory scale wet oxidation reactor design. The pressure vessel was constructed out of 316 stainless steel quick-clamp tube fittings and was designed to contain 20.6 atm at 200°C . The top and bottom of the reactor is sealed with 316 stainless steel caps, hand tightened quick-clamps and Teflon gaskets. The waste bed was 95.25 cm in height by 7.62 cm in diameter, resulting in a total internal

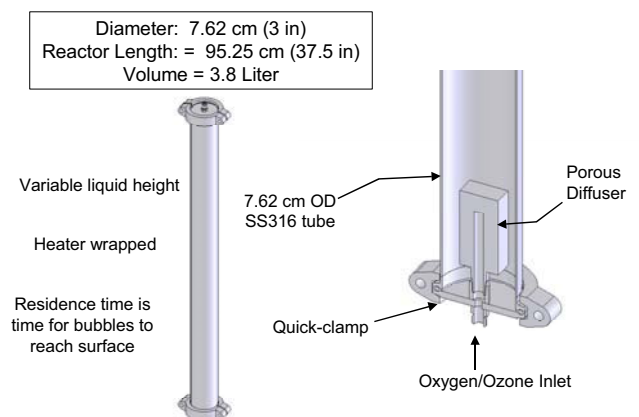


Figure 5. 3-D model showing wet oxidation reactor and porous diffuser for ozone distribution

volume of 3.8 liters. The oxygen/ozone mixture was introduced into the waste bed through a porous diffuser located at the bottom of the waste bed that maximized the contact of the ozone with the waste slurry. The reactor was heated using resistance style heaters (heat tapes) wrapped around the outside of the reactor and insulated to reduce heat loss to the surroundings.

EXPERIMENTAL PROCEDURE - The following procedure was followed during each of the experiments. The reactor was initially loaded with a premixed waste and water slurry and then sealed using the Teflon gaskets and quick-clamps. The oxygen feed flow was then started, the reactor pressurized and the ozone generator activated. The recycle pump was then turned on and the recycle flow established. Once the pressure and flow conditions were stabilized, the reactor was heated to the desired operating temperature. Ozone and carbon dioxide concentrations were continuously monitored throughout the duration of the experiment. Once the desired data had been collected, the ozone generator was powered off, the reactor depressurized and allowed to cool down to ambient temperature before accessing the remaining waste and water mixture.

DESCRIPTION OF THE DESIGN OF EXPERIMENTS TEST MATRIX - In order to optimize the waste oxidation rates that were being obtained for the fecal simulant in the reactor an investigation into what effect varying certain control parameters would have on the overall oxidation rate was performed. The six parameters that warranted investigation were as follows: the feed flow rate of oxygen, recycle loop flow rate, diffuser height, reactor temperature and pressure and the amount of waste loaded into the reactor. Perturbing only one parameter at a time to two different values each would require a minimum of 64 tests. Thus, to simplify the test matrix the design of experiments method by Phadke⁹ was employed and an abbreviated matrix was tested. Additional tests were then conducted where needed to better understand the sensitivity of the performance data to a specific parameter.

The design of experiments method assumes that each parameter affects the result independently of every other parameter (i.e. each parameter is orthogonal to the others). Unfortunately, this is rarely the case in practice and interactions between parameters often make interpretation difficult, but the interactions can be estimated by leaving one or more columns out of the matrix. Table 2 shows an L8 matrix of eight experiments that permitted the concurrent evaluation of two levels for up to seven different factors. Of the seven available factors only the six previously mentioned were varied while holding the seventh factor fixed (reactor diameter). The initial matrix of eight experiments determined the sensitivity of the waste oxidation rate to the six factors. Once the best set of run conditions were identified, additional tests were done as needed to better define the reactor performance.

Table 2. Design of experiments L8 matrix used during waste oxidation optimization experiments.

Exp #	Feed (slpm)	Recycle (alpm)	Rctr D (cm)	Diffuser H (cm)	Temp (°C)	Pressure (atm)	Waste (g)
1	5	15	7.62	15.24	100	4.4	10
2	5	15	7.62	7.62	125	3.7	40
3	5	30	7.62	15.24	100	3.7	40
4	5	30	7.62	7.62	125	4.4	10
5	10	15	7.62	15.24	125	4.4	40
6	10	15	7.62	7.62	100	3.7	10
7	10	30	7.62	15.24	125	3.7	10
8	10	30	7.62	7.62	100	4.4	40

EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS FROM THE L8 TEST MATRIX - Figure 6 presents the results from the fecal simulant oxidation L8 matrix testing. The six parameters that we adjusted can be seen in the lower right corner of the figure along with the values we used for the two different levels of testing. The figure shows that changing the recycle flow rate had the largest effect on the waste oxidation rate; specifically the level 1 recycle flow (15 alpm) produced a 12.2% better than average rate and the level 2 flow (30 alpm) produced a 12.2% worse than average rate. The oxygen feed flow rate had the second greatest impact on the oxidation rate, with a +/- 9.6% change from the average between level 1 and level 2. The diffuser height was an important parameter with the level 2 height of 3-inches providing a 6.4% higher than average oxidation rate. The remaining 3 parameters temperature, pressure and waste loading did not have significant impacts on the oxidation rate between the two levels tested.

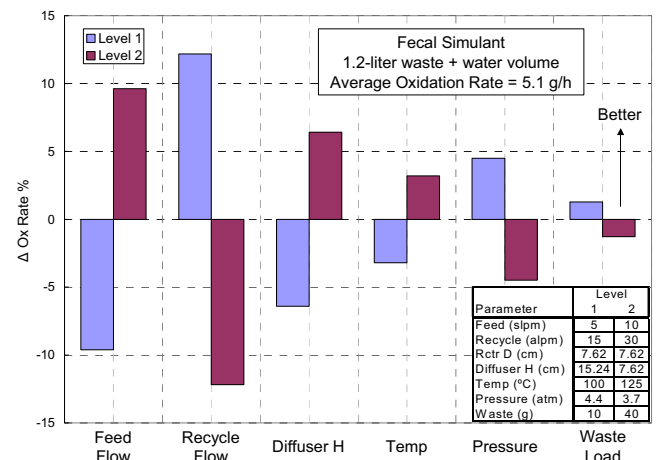


Figure 6. Sensitivity results of the six parameters varied during the set of eight design of experiments testing.

Based on the results shown in Figure 6, the oxygen feed flow rate and the recycle flow were determined to have the largest effect on the oxidation rate and therefore required a more thorough investigation. An additional set of experiments to further optimize the reactor performance was conducted by holding the following parameters constant: diffuser height at 3 inches, reactor temperature at 125°C and the reactor pressure at 40 psig while only varying the feed flow and the recycle flow.