

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

**James A. Nabity, Erik W. Andersen, Jeffrey R. Engel**  
TDA Research, Inc., 12345 W. 52<sup>nd</sup> Ave, Wheat Ridge, CO 80033

**David T. Wickham**  
Reaction Systems LLC, Golden, CO 80401

**John W. Fisher**  
NASA Ames Research Center, Moffett Field, CA 94035

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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 CO<sub>2</sub> and H<sub>2</sub>O. 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 CO<sub>2</sub> and H<sub>2</sub>O 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 missions<sup>1</sup>. 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/m<sup>3</sup>, a space of approximately 28.5 m<sup>3</sup> would be required to contain this waste<sup>2</sup>. 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<sup>3,4,5,6</sup>. 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 (O<sub>3</sub>) 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 described<sup>7</sup>. 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 Wignarajah<sup>8</sup> was also used during the reactor optimization tests. Active dry yeast was substituted for the E. Coli and the inorganic portion was eliminated.

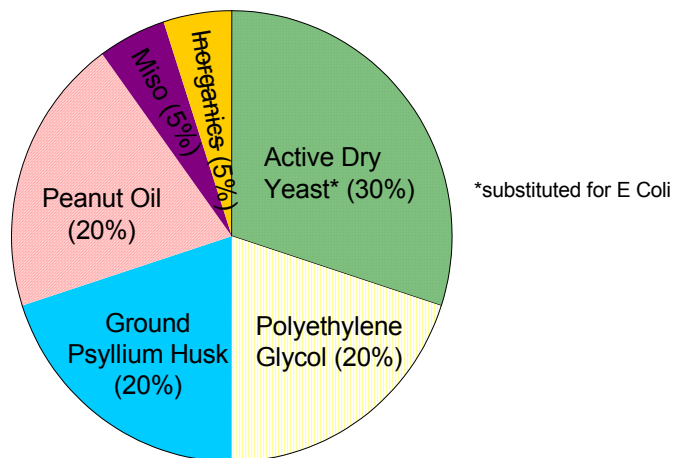


Figure 1. Modified fecal simulant recipe used during reactor optimization tests taken from Wignarajah<sup>8</sup>.

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 CO<sub>2</sub> 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 experiments<sup>9</sup> 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.

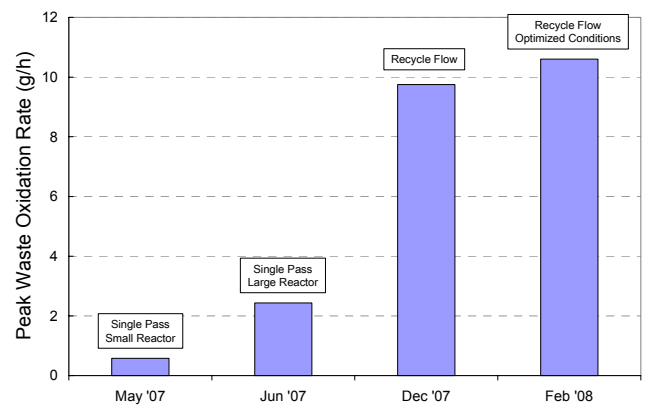


Figure 2. Waste oxidation peak rate results obtained with the modified fecal simulant during process development.

The overall objective of this project is to develop a low temperature waste oxidation process and then scale 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<sub>2</sub> and H<sub>2</sub>O.

## 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<sub>3</sub>/O<sub>2</sub> 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.

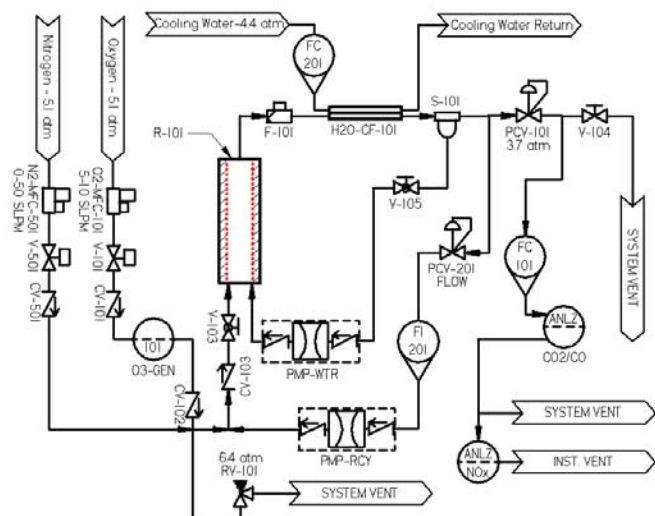


Figure 3. Phase II waste treatment system.

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<sub>2</sub>, CO (Model 602 NDIR analyzer from California Analytical), O<sub>3</sub> (Model OLA ozone analyzer from Ozone Services) and NO<sub>x</sub> (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<sub>2</sub> 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.

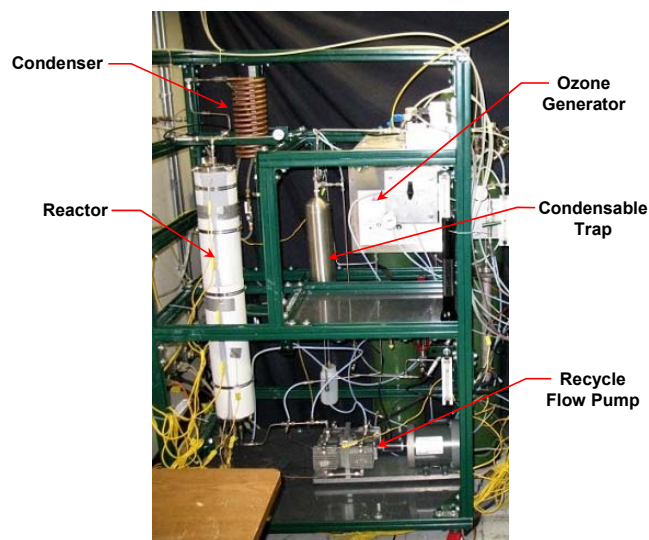


Figure 4. Photograph of waste oxidation apparatus.

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 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

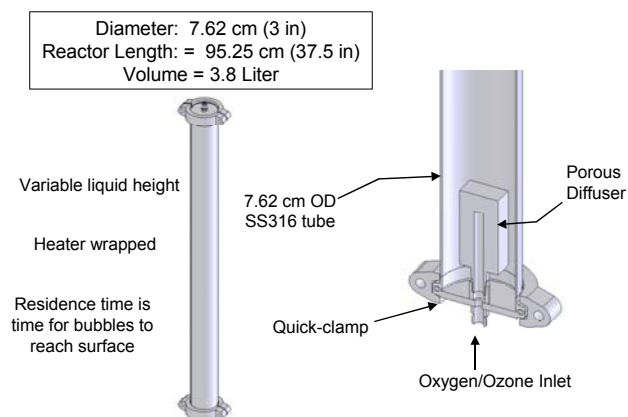


Figure 5. 3-D model showing wet oxidation reactor and porous diffuser for ozone distribution.

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 Phadke<sup>9</sup> 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.

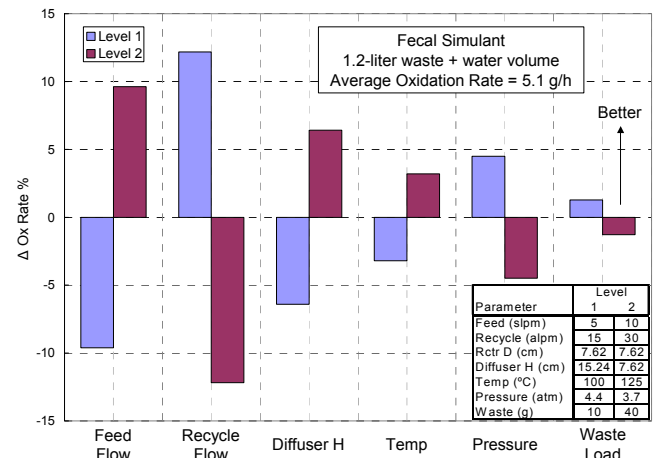


Figure 6. Sensitivity results of the six parameters varied during the set of eight design of experiments testing.

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.

The oxygen feed flow to the ozone generator was set to a constant value of 5, 7.5 and 10 slpm and the recycle flow was increased from 0 alpm up to 20 alpm in 5 alpm increments at each feed flow. The system was held at constant conditions until the system was at steady state for 10 minutes at each flow condition before moving on to the next recycle flow. Once the oxidation rate data was obtained at 20 alpm recycle flow the recycle flow rates were then decreased back down to 5 alpm to obtain repeatability data.

The results of these experiments can be seen in Figure 7. The waste oxidation rates in the figure were calculated as the average rate over the 10-minute steady state period at each condition. The figure shows the highest waste oxidation rate of 10.3 g/h was achieved with a feed flow of 7.5 slpm (red squares) and at a recycle flow of 10 alpm. The figure also shows that during the latter part of the run the oxidation rates were generally twice those during the early part of the run. The oxidation rate of the fecal simulant increase over time during steady state operation had been previously observed. Explanations for this hysteresis could include that one or more of the components in the fecal simulant may initially be more resistant to the oxidation process and once the resistive barrier is eroded away the oxidation rate increases or once the larger particles in the waste are reduced in size the rate increases.

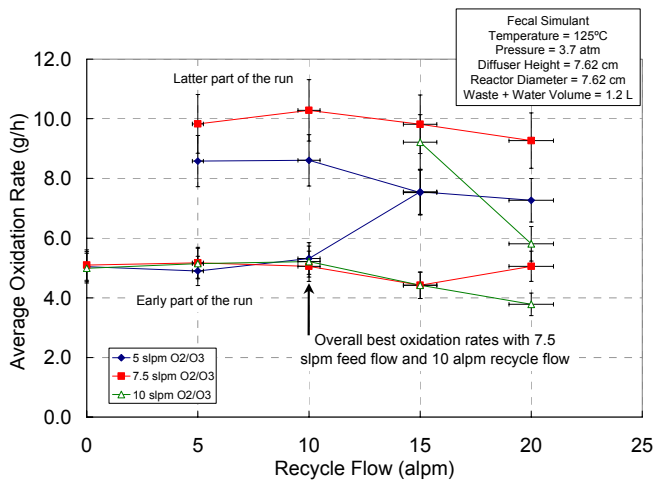


Figure 7. Waste oxidation rates obtained during optimization experiments.

**RESULTS OF WASTE OXIDATION EXPERIMENTS CONDUCTED AT THE OPTIMUM CONDITIONS** - Once the conditions were determined that produced the highest fecal simulant oxidation rates, a test with 37.5 grams of the fecal simulant was conducted. The experiment was allowed to continue until the CO<sub>2</sub> level exiting the reactor dropped to less than 0.1%, indicating that the oxidation reaction was no longer occurring.

Figure 8 shows the reactor temperatures and pressure during the test as well as the calculated instantaneous oxidation rate from the CO<sub>2</sub> data. The figure shows that the test ran for 8 hours during which the temperatures and pressure were extremely stable, verifying that this

process is both safe and controllable. The small perturbations seen in the temperature profile were caused from the condenser water being periodically pumped back into the reactor.

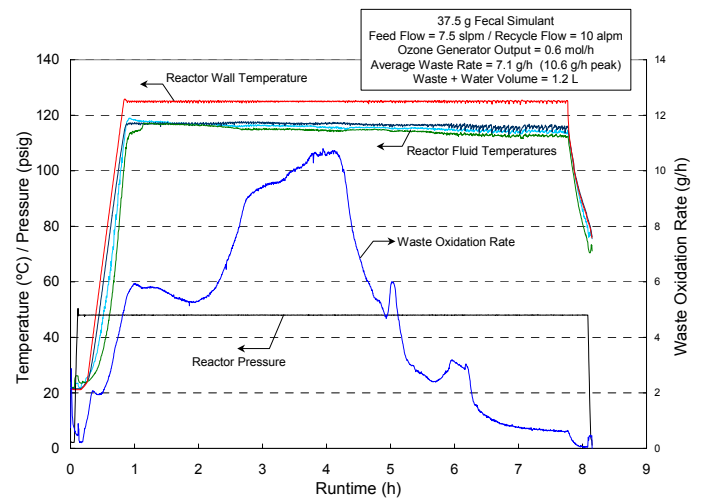


Figure 8. Run data showing process stability during an 8-hour full oxidation test of fecal simulant.

The figure also shows that the instantaneous oxidation rate (blue line) increased from the beginning of the run to a maximum of 10.6 g/h at a runtime of 4.1 hours and then declined to less than 2 g/h at 6.2 hours and finally to less than 0.5 g/h at 7.7 hours. The shape of the instantaneous rate curve suggests that the majority of the waste is being oxidized in a much shorter time period than 8 hours and therefore an average oxidation rate was calculated based on the time it takes to oxidize the majority of the waste.

Figure 9 shows the integrated mass fraction of the fecal simulant oxidized during the course of the 8-hour test. The time interval required to oxidize the majority of the waste was determined from this figure. The start time was determined when the reactor reached the desired operating temperature (0.9 hours runtime and 5% of the waste oxidized). The stop time was determined by the intersection of a tangent line to the slope of the integrated mass curve during the bulk of the oxidation

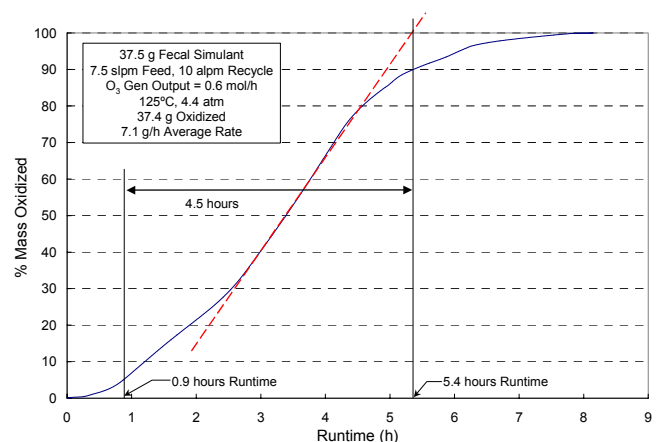


Figure 9. Fecal simulant mass fraction oxidized during 8 hour test.

(dashed red line) with the 100% oxidized axis line (5.4 hours runtime and 90% of the waste oxidized). The result of this analysis indicates that 85% (31.8 g) of the waste had been oxidized in 4.5 hours, resulting in an average oxidation rate of 7.1 g/h.

Figure 10 shows photographs taken of the fecal simulant before, during and after full treatment in the oxidation reactor. Note the progression of photographs from dirty to clean showing the effectiveness of the ozone oxidation system at processing the waste. The picture on the left of the brown water shows the fresh fecal simulant and water mixture prior to loading in the reactor. The middle picture shows significant improvement in the mixture after operating the oxidation reactor for 2.75 hours and the picture on the right shows a very clean reactor residue after the 8 hour test. Two samples of the reactor residue after 8 hours of runtime were sent to Huffman Analytical Laboratories for total organic carbon (TOC) analysis. The results of the TOC analysis on both samples was less than 100 ppm TOC, which indicates that the residue from the reactor after the oxidation step could potentially be sent directly to the waste water treatment unit on board of the spacecraft which can typically handle up to 5000 ppm TOC's.



Figure 10. Photographs of fecal simulant and water mixture before and after treatment in the low temperature wet oxidation system.

Figure 11 shows the  $O_3$  and  $CO_2$  flow data for the 8-hour test presented in Figure 8. The figure shows that up to a runtime of 0.7 hours and again after a runtime of 7.7 hours the output of the  $O_3$  generator was measured (blue line) to be 0.62 mol/h at the beginning and 0.60 mol/h at the end. Between the runtimes of 0.7 and 7.7 hours the  $O_3$  flow exiting the system was measured while the  $CO_2$  (red line) was measured at the outlet of the system for the entire runtime. The figure shows that at the peak oxidation rate (runtime of 4.1 hours) the  $O_3$  and  $CO_2$  flows exiting the reactor were 0.05 and 0.43 mol/h, respectively, which gives 90%  $O_3$  utilization and indicates that for every mole of  $O_3$  entering the reactor 0.78 moles of  $CO_2$  are produced.

Figure 12 shows the  $NO_x$  and CO levels recorded during the 40 g fecal simulant 8-hour oxidation test. The figure shows that the  $NO_x$  level observed during the majority of the run was less than 2 ppm and peaked at 5.6 ppm at

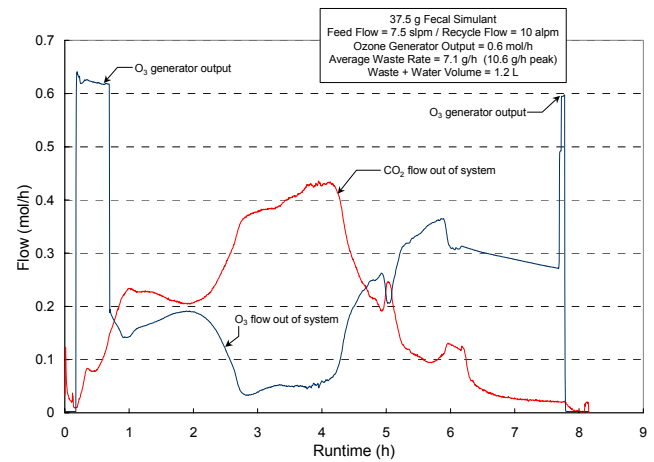


Figure 11. Ozone and carbon dioxide flows exiting the system during the 8-hour fecal simulant experiment.

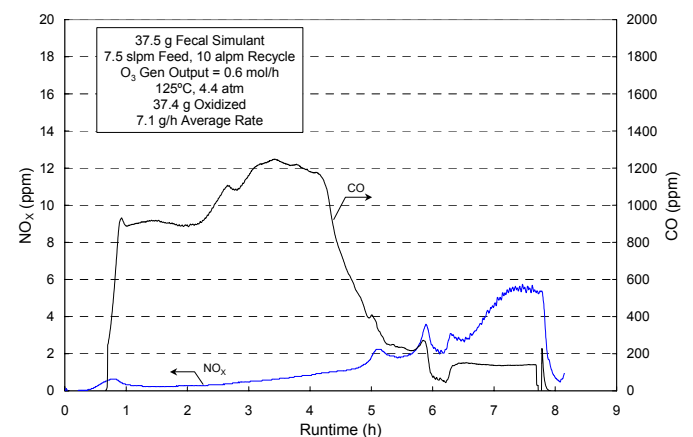


Figure 12.  $NO_x$  and CO data recorded during 8-hour complete oxidation run of 40 g fecal simulant.

7.5 hours runtime. The  $NO_x$  level increased above 2 ppm only after 5 hours of runtime when over 85% of the waste had been oxidized (Figure 9). The highest CO concentration observed was 1243 ppm at 3.5 hours, which by comparison the  $CO_2$  level observed at 3.5 hours was 2.0%, indicating over 94% selectivity to  $CO_2$ . The CO and  $NO_x$  levels are very low and could easily be oxidized or removed downstream of the reactor.

In addition to the fecal simulant, the oxidation rates of the individual components of the fecal simulant and rehydrated instant mashed potatoes were measured. The results of these tests can be seen in Figure 13. The average oxidation rates were calculated for each run in the same manner as described for Figure 9. Each of the runs shown in Figure 13 took between 2.5 and 3 hours to complete except for the 37.5 g fecal simulant test, which took 8 hours to complete. The gravimetric data (maroon bars) for the waste components can also be seen for comparison to the integrated waste consumed data (blue bars). The figure shows that the integrated and gravimetric data agree very well, indicating that the process is very selective to  $CO_2$  and  $H_2O$ . The average rates for the individual components in the fecal simulant range from 3.1 to 7.2 g/h and the peak rates range from

3.5 to 10.4 g/h. The mashed potatoes were completely oxidized at an average rate of 5.7 g/h, peaking at 7.6 g/h.

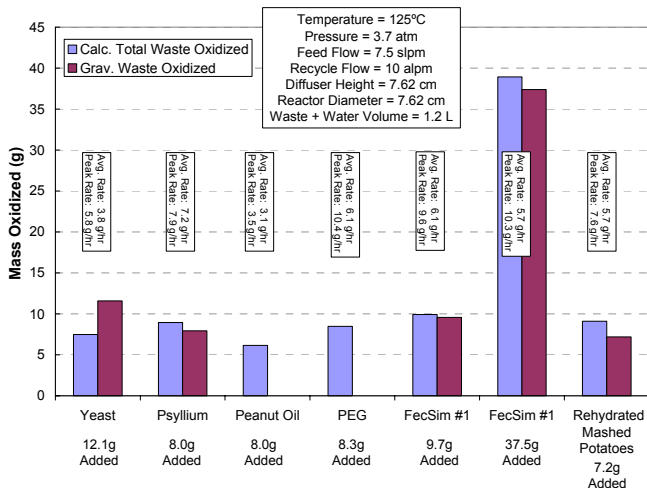


Figure 13. Oxidation results for several types of waste compounds tested at the optimum conditions.

The model waste compounds of cellulose, wheat straw, low-density polyethylene (LDPE), methionine, and urea were also tested in the original, smaller wet oxidation reactor with no recycle loop, previously described<sup>10</sup>. The results of these tests are shown in Figure 14. The figure shows that the low temperature oxidation system is not only effective for a broad range of wastes but also very selective to CO<sub>2</sub>, indicated by the good agreement between the gravimetric and integrated results for all the different types of waste tested.

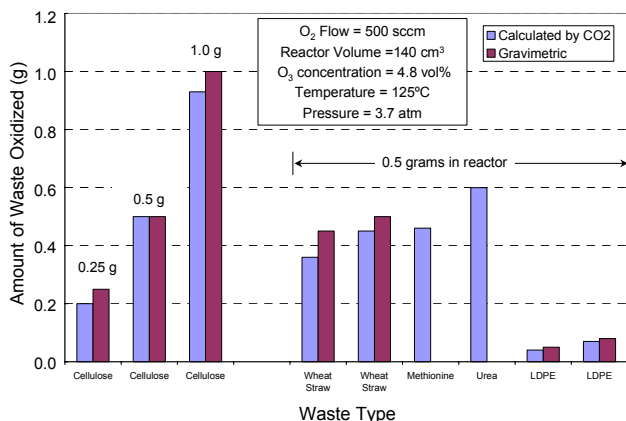


Figure 14. Effectiveness of oxidation with ozone for various model waste compounds.

The improved rates obtained in the oxidation system were compared with rates published for a competing oxidation technology, the solids thermophilic aerobic reactor (STAR)<sup>5</sup>. After an 11 day treatment in the STAR, solid levels were reportedly reduced from 2.95 to 1.71%. Assuming the reactor was filled to its 46 liter capacity, the reactor processed about 575 grams of solids, resulting in a solids processing rate of 0.048 grams/h-L. By comparison, the average rate achieved with the wet oxidation system is 7.1 g/h-L.

## PILOT SCALE SYSTEM DESIGN

At the end of this Phase II project TDA will construct and deliver a pilot scale system to NASA Ames Research Center for testing. The system will be fully automated and will convert the hydrocarbon portion of the waste into H<sub>2</sub>O and CO<sub>2</sub>. The pilot scale process and instrumentation diagram will be identical to our current laboratory scale P&ID shown in Figure 3. The pilot scale apparatus, however, will have a scaled up reactor, as shown in Figure 15.

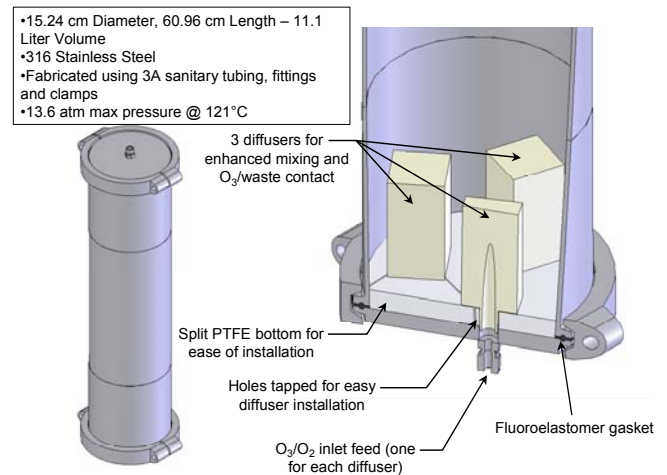


Figure 15. 3-D model of pilot scale wet oxidation reactor design.

The reactor will be 6-inches in diameter and 24-inches long for a total internal volume of 11.1 liters. There will be three diffusers to distribute the O<sub>3</sub> into the waste and water mixture as well as a PTFE spacer in the bottom to prevent waste from settling into small areas of the reactor where there is not good mixing or contact with the O<sub>3</sub>. The reactor will be sealed using quick-clamps, making it very easy to load or access the reactor interior between experiments.

The pilot scale unit will only incorporate the oxidation system. A conceptual process and instrumentation drawing (Figure 16) shows how the oxidation system may fit into the waste processing system on board a manned spacecraft or outpost. The main component of the system would be the ozone oxidation system with the recycle loop (shown inside the dotted line). A portion of the effluent that exhausts the reactor will pass into a series of analyzers to monitor the levels of O<sub>3</sub>, O<sub>2</sub>, CO<sub>2</sub>, CO, and NO<sub>x</sub> in the effluent stream while the majority of the gas will pass through a CO oxidation catalyst, possibly a NO<sub>x</sub> scrubber and into a CO<sub>2</sub> recovery system. The pure oxygen will be resupplied into the ozone generator to replenish the concentration of ozone as needed. A commercially available ozone decomposition catalyst (which are widely used on aircraft cabins) will be utilized to remove any O<sub>3</sub> from the supply of O<sub>2</sub> that exits the closed loop system before being vented. In addition, water from the wet oxidation system condenser could be pumped directly to the on-board water recovery system for purification.



- Enterococcus faecalis<sup>16</sup>
- Yersinia enterocolitica<sup>16</sup>
- Pseudomonas aeruginosa<sup>16</sup>
- Helicobacter pylori<sup>17</sup>
- Yeast
  - Candida albicans<sup>16</sup>
  - Zygosaccharomyces bailii<sup>16</sup>
- Fungi
  - Aspergillus niger<sup>16</sup>
  - Bacillus subtilis<sup>18,19,28</sup>
  - Clostridium sporogenes<sup>18</sup>
- Protozoans
  - Cryptosporidium parvum Oocysts<sup>20,21</sup>
  - Giardia lamblia Cysts<sup>22</sup>
- Viruses
  - Vesicular stomatitis virus<sup>13</sup>
  - Encephalomyocarditis virus<sup>13</sup>
  - GDVII virus<sup>13</sup>
  - Bacteriophage f2<sup>23</sup>, Bacteriophage MS2<sup>29</sup>
  - Enterovirus<sup>24</sup>
  - Hep-2 cell-associated poliovirus<sup>25</sup>, Poliovirus<sup>1,28,29</sup>
  - Coxsackievirus A9<sup>25</sup>
  - Venezuelan equine encephalomyelitis virus<sup>26</sup>
  - Rotaviruses<sup>27</sup>
  - Hepatitis A virus<sup>28</sup>
  - Norwalk virus<sup>29</sup>

The mechanisms by which microorganisms and viruses are destroyed with ozone are not yet fully understood. However, the mechanism does depend upon the particular organism or virus present in the water and whether or not organic matter is in the solution<sup>12,13,16,18,19</sup>. Yet even with non ideal mixtures comparable to the organic waste-loaded slurry in our reactor, the studies have shown ozone to be very effective. Chlorine compounds, on the other hand, have only limited ability to disinfect (greater concentrations are needed and must be continuously maintained to be effective<sup>15,16,17,20,21</sup>) and may produce carcinogenic compounds and leave an off-taste and odor in the water<sup>16</sup>.

Steam autoclaves are the most common instruments used to kill all micro-organisms for medical equipment and operate at temperatures of 121 to 124°C and pressures of 1.1 to 1.25 bar for a minimum of 15 minutes or at 126 to 129°C and 2.1 to 2.3 bar for a minimum of 3 minutes<sup>31</sup>. The TDA low temperature wet oxidation system operates at 125°C and 3.8 bar for several hours, which, in addition to the benefits of ozone disinfection, is an environment which exceeds that used to disinfect medical instruments.

## CONCLUSIONS

The waste oxidation rates obtained in the Phase II wet oxidation recycle loop reactor show that low temperature

oxidation has excellent potential to be an effective method to control waste in long term space missions. The rates have been increased to a level that will process the waste generated by a single crew member in one day in a reactor size of only 9.5 liters (2.5 gallons). In addition, the reactor configuration TDA has developed is very stable and does not produce any measurable temperature or pressure fluctuations. The following is a list of the conclusions reached so far in this Phase II project.

- Ozone can rapidly oxidize model wastes at temperatures below 150°C with very high selectivity to CO<sub>2</sub> and H<sub>2</sub>O.
- In the current wet oxidation reactor design with the recycle loop, an average waste removal rate of 7.1 grams waste removed per hour was achieved at only 125°C with a maximum rate of 10.6 g/h.
- In addition, the system is very reliable which will require minimal maintenance or attention so the crew time equivalencies are expected to be small.
- TDA is designing a fully automated pilot scale reactor to consume up to 83 g/h of waste that will be delivered to NASA Ames Research Center at the completion of this Phase II project.

A low temperature ozone oxidation process offers many additional benefits to NASA. In addition to the elimination of solid organic waste matter, it also safens the waste and sterilizes the system, and recovers water that can be injected directly into the water purification system without any need for pre-treatment. Given these benefits and the very small volume needed to support each crew member, the low temperature ozone oxidation process will be extremely attractive for use in space stations, spacecraft and lunar and Mars outposts.

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## REFERENCES

1. Hanford, A.J. (2004). Advanced Life Support Baseline Values and Assumptions Document: [http://advlifesupport.jsc.nasa.gov/documents/SIMADocs/CR\\_2004\\_208941.pdf](http://advlifesupport.jsc.nasa.gov/documents/SIMADocs/CR_2004_208941.pdf)
2. Pace, G.S. and J. Fisher (2004). "Development of Plastic Melt Waste Compactor for Space Missions – Experimental and Prototype Design". SAE Paper No. 2004-01-2378, 34th International Conference on Environmental Systems, Colorado Springs, CO.
3. Drysdale, A. (2004). "A Comparison of Waste Systems", SAE Paper No. 2004-01-2581, 34th International Conference on Environmental Systems, Colorado Springs, CO.
4. Serio, M., E. Kroo, E. Florcza, M. Wojtowicz, K. Wignarajah, K. Howard and J. Fisher (2004). "A Hybrid Pyrolysis / Oxidation System for Solid Waste

- Recovery”, SAE Paper No. 2004-01-2380, 34th International Conference on Environmental Systems, Colorado Springs, CO.
5. Whitaker, D. R. J. W. Lane, J.E. Alleman, and R. Riano (2004). “Solids Thermophilic Aerobic Reactor for Solid Waste Management in Advanced Life Support Systems”, SAE Paper No. 2004-01-2467, 34th International Conference on Environmental Systems, Colorado Springs, CO.
  6. Fisher, J., K. Wignarajah, K. Howard, M. Serio, and E. Kroo (2004). “An Evaluation of a Prototype Dry Pyrolysis System for Destruction of Solid Wastes”, SAE Paper No. 2004-01-2379, 34th International Conference on Environmental Systems, Colorado Springs, CO.
  7. Serio, M., Yonggang Chen, Marek A. Wojtowicz, and E.M. Suuberg (2000). “Pyrolysis Processing for Solid Waste Resource Recovery in Space”, SAE Paper No. 2000-01-2286, 30th International Conference on Environmental Systems, Toulouse France.
  8. Wignarajah, Kanapathipillai, Eric Litwiller, John W. Fisher and John Hogan (2006), “Simulated Human Feces for Testing Human Waste Processing Technologies in Space Systems,” SAE Paper No. 2006-01-2180, 36th International Conference on Environmental Systems, Norfolk, VA.
  9. Phadke, Madhav S. (1989), Quality Engineering Using Robust Design, published by Prentice Hall, 1989
  10. Wickham, D., E. Andersen, J. Engel and M. Jones (2007). “Development of a Pilot Scale Apparatus for control of Solid Waste Using Low Temperature Oxidation”, SAE Paper No. 2007-01-3135, 37th International Conference on Environmental Systems, Chicago, IL.
  11. Tamas, G., C.J. Weschler, J. Toftum, and P.O. Fanger (2006). “Influence of Ozone-Limonene Reactions on Perceived Air Quality”, *Indoor Air*. Volume 16, No.3, pp. 168-178.
  12. Broadwater, W.T., R.C. Hoehn and P.H. King, “Sensitivity of Three Selected Bacterial Species to Ozone,” *Applied and Environmental Microbiology*, Sep 1973, Vol. 26, No. 3, p. 391-393.
  13. Burleson, G., T.M. Murray and M. Pollard, “Inactivation of Viruses and Bacteria by Ozone, With and Without Sonication,” *Applied and Environmental Microbiology*, Mar 1975, Vol. 29, No.3, p. 340-344.
  14. Edelstein, P.H., R.E. Whittaker, R.L. Kreiling and C.L. Howell, “Efficacy of Ozone Eradication of *Legionella pneumophila* from Hospital Plumbing Fixtures,” *Applied and Environmental Microbiology*, Dec 1982, Vol. 44, No. 6, p. 1330-1334.
  15. Muraca, P., J.E. Stout, V.L. Yu, “Comparative Assessment of Chlorine, Heat, Ozone, and UV Light for Killing *Legionella pneumophila* within a Model Plumbing System,” *Applied and Environmental Microbiology*, Feb 1987, Vol. 53, No. 2, p. 447-453.
  16. Restaino, L., E.W. Frampton, J.B. Hemphill and P. Palnikar, “Efficacy of Ozonated Water against Various Food-Related Microorganisms,” *Applied and Environmental Microbiology*, Sep 1995, Vol. 61, No. 9, p. 3471-3475.
  17. Baker, K.H., J.P. Hegarty, B. Redmond, N.A. Reed and D.S. Herson, “Effect of Oxidizing Disinfectants (Chlorine, Monochloramine, and Ozone) on *Helicobacter pylori*,” *Applied and Environmental Microbiology*, Feb 2002, Vol. 68, No. 2, p. 981-984.
  18. Rickloff, J.R., “An Evaluation of the Sporicidal Activity of Ozone,” *Applied and Environmental Microbiology*, Apr 1987, Vol. 53, No. 4, p. 683-686.
  19. Cho, M., H. Chung and J. Yoon, “Disinfection of Water Containing Natural Organic Matter by Using Ozone-Initiated Radical Reactions,” *Applied and Environmental Microbiology*, Apr 2003, Vol. 69, No. 4, p. 2284-2291.
  20. Peeters, P.E., E.A. Mazás, W.J. Masschelein, I.V.M. de Maturana and E. DeBacker, “Effect of Disinfection of Drinking Water with Ozone or Chlorine Dioxide on Survival of *Cryptosporidium parvum* Oocysts,” *Applied and Environmental Microbiology*, Jun 1989, Vol. 55, No. 6, p. 1519-1522.
  21. Korich, D.G., J.R. Mead, M.S. Madore, N.A. Sinclair and C.R. Sterling, “Effects of Ozone, Chlorine Dioxide, Chlorine, and Monochloramine on *Cryptosporidium parvum* Oocyst Viability,” *Applied and Environmental Microbiology*, May 1990, Vol. 56, No. 5, p. 1423-1428.
  22. Finch, G.R., E.K. Black, C.W. Labatiuk, L. Gyürék and M. Belosevic, “Comparison of *Giardia lamblia* and *Giardia muris* Cyst Inactivation by Ozone,” *Applied and Environmental Microbiology*, Nov 1993, Vol. 59, No. 11, p. 3674-3680.
  23. Kim, C.K., D.M. Gentile and O.J. Sproul, “Mechanism of Ozone Inactivation of Bacteriophage f2,” *Applied and Environmental Microbiology*, Jan 1980, Vol. 39, No. 1, p. 210-218.
  24. Roy, D., P.K.Y. Wong, R.S. Engelbrecht and E.S.K. Chian, “Mechanism of Enteroviral Inactivation by Ozone,” *Applied and Environmental Microbiology*, Mar 1981, Vol. 41, No. 3, p. 718-723.
  25. Emerson, M.A., O.J. Sproul and C.E. Buck, “Ozone Inactivation of Cell-Associated Viruses,” *Applied and Environmental Microbiology*, Mar 1982, Vol. 43, No. 3, p. 603-608.
  26. Akey, D.H. and T.E. Walton, “Liquid-Phase Study of Ozone Inactivation of Venezuelan Equine Encephalomyelitis Virus,” *Applied and Environmental Microbiology*, Oct 1985, Vol. 50, No. 4, p. 882-886.
  27. Vaughn, J.M., Y.S. Chen, K. Lindburg and D. Morales, “Inactivation of Human and Simian Rotaviruses by Ozone,” *Applied and Environmental Microbiology*, Sep 1987, Vol. 53, No. 9, p. 2218-2221.
  28. Herbold, K., B. Flehmig and K. Botzenhart, “Comparison of Ozone Inactivation, in Flowing Water, of Hepatitis A Virus, Poliovirus 1, and Indicator Organisms,” *Applied and Environmental Microbiology*, Nov 1989, Vol. 55, No. 11, p. 2949-2953.
  29. Shin, G.A. and M.D. Sobsey, “Reduction of Norwalk Virus, Poliovirus 1, and Bacteriophage MS2 by Ozone Disinfection of Water,” *Applied and Environmental Microbiology*, Jul 2003, Vol. 69, No. 7, p. 3975-3978.
  30. Cuello, J.L., S. Kuwahara, K. Reynolds and C. Gerba, “Synergistic Uv-Ozone Effects on the Treatment of Pathogens in Secondary Effluent,” SAE Paper No 2003-01-2563, 33rd International Conference on Environmental Systems, Vancouver, B.C.
  31. Palenik, C.J., F.J.T. Burke, W.A. Coulter, and S.W. Cheung, “Improving and Monitoring Autoclave Performance in Dental Practice,” *British Dental Journal*, December 1999, Vol 187, No. 11, p. 581-584.

## CONTACTS

James A. Nabity, TDA Research

Dr. Nabity received a BS degree in Mechanical Engineering from the University of Nebraska in 1983 and an MS in Aeronautical Engineering from the Naval Postgraduate School in 1989. Jim earned a Ph.D. in Mechanical Engineering from the University of Colorado in 2007. In 1996, Jim was elected a Naval Air Warfare Center Technical Fellow for his contributions to combustion research. He joined TDA's aerospace technology staff in 1999. Overall, he has 25 years experience in thermal systems, propulsion, combustion, test methods and MEMS research and has published extensively in these areas. Jim may be reached at:

James Nabity, Principal Engineer  
TDA Research, Inc  
12345 W 52nd Ave  
Wheat Ridge, CO 80033  
(303) 940-2313 or nabity@tda.com

John W. Fisher, NASA Ames Research Center

Mr. Fisher received a BS degree in Chemical Engineering from Rutgers University and an MS in Environmental Engineering from Stanford University. He has 15 years of experience as a research and process development engineer for American Cyanamid Co. and Chevron Chemical Co., and 18 years of experience in the development of life support technology at NASA Ames Research Center. He is currently the Waste Management Systems Lead for NASA's Exploration Life Support Project. He has been active as an author and session organizer for the ICES conference for 17 years and received the ICES Award for Technical Excellence in 2006. John can be reached at:

John W. Fisher, Lead Engineer  
Exploration Life Support  
Bioengineering Branch (Code SCB)  
NASA Ames Research Center  
(650) 604-4440 or john.w.fisher@nasa.gov

## DEFINITIONS, ACRONYMS, ABBREVIATIONS

### ACRONYMS

**BVAD:** Baseline Values and Assumptions Document

**LDPE:** Low-density polyethylene

**NDIR:** Non-Dispersive Infrared

**PAQ:** Perceived Air Quality

**PCV:** Pressure Control Valve

**PEG:** Polyethylene glycol

**PTFE:** Polytetrafluoroethylene

**P&ID:** Process and Instrumentation Diagram

**NASA:** National Aeronautics and Space Administration

**STAR:** Solids Thermophilic Aerobic Reactor

**TOC:** Total Organic Carbon

### NOMENCLATURE

ANLZ analyzer

CF concentric tube counter flow heat exchanger

CMD Crew Member Day

CV check valve

D diameter, cm

F filter

FC flow controller

FI flow indicator

GEN generator

H height, cm

MFC Mass Flow Controller

PCV pressure control valve

PMP diaphragm pump

R reactor

Rctr reactor

RCY recycle

RV relief valve

S separator

V valve

WTR water