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Oxygen Penalty for Waste Oxidation in an Advanced Life Support System - A Systems Approach

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ABSTRACT

Oxidation is one of a number of technologies that are being considered for waste management and resource recovery from waste materials generated on board space missions. Oxidation processes are a very effective and efficient means of clean and complete conversion of waste materials to sterile products. However, because oxidation uses oxygen there is an "oxygen penalty" associated either with resupply of oxygen or with recycling oxygen from some other source. This paper is a systems approach to the issue of oxygen penalty in life support systems and presents findings on the oxygen penalty associated with an integrated oxidation-Sabatier-Oxygen Generation System (OGS) for waste management in an Advanced Life Support System. The findings reveal that such an integrated system can be operated to form a variety of useful products without a significant oxygen penalty.

INTRODUCTION

Solid waste management is important for any human mission, whether it is a near term mission such as the ISS or a long duration mission such as an exploration mission to Mars or the moon. Appropriate methods to manage wastes are important to meet the constraints of space and resources to provide for crew safety. Waste management systems will vary depending on the duration of the mission. A short duration or involving regular re-supply would be different from a long-term mission, where self-sufficiency is desirable because of resupply constraints. A wide array of potential technologies exists and the development of technologies will depend on their efficiencies, crosscutting nature, products, safety, operational reliability and other factors. The choice of technologies to develop will depend on the return on research dollar and on the capability to reduce mission cost. At the same time all the constraints and requirements of the mission and waste processing must be met. To this end, the advanced life support community has been involved in developing a criteria list and identifying mission requirements to focus on development of technologies that are the most promising (Levri, et al., 2001).

Oxidation has been the subject of study for waste management for several years as the most promising technology because it completely oxidizes waste material to benign products such as carbon dioxide, water and inorganic ash. Thus it reduces storage space required, removes the biohazards associated with storage of biohazardous material, recovers water, and recovers inorganic plant growth nutrients. On the other hand, oxidation also requires oxygen, an important resource on any mission. Previous studies (Lee, 2001; Maxwell and Drysdale 2001) have imposed a significant oxygen penalty on the use of oxidation technologies for waste management. This reduces its competitiveness as a promising technology compared to other waste management technologies that do not need oxygen. This study examines the oxygen penalty associated with an oxidation system when it is considered as part of the overall advanced life support system.

PRIOR SYSTEMS ANALYSIS

Systems analysis work on waste processing in the last few years has resulted in reports or papers by Gertner (Gertner, 1999), Lee (Lee, 2001), and Maxwell (Maxwell and Drysdale, 2001). The Gertner report evaluated competing oxidative technologies, Supercritical Water oxidation (SCWO) and incineration and concluded that Incineration and SCWO are equally effective and efficient for long term human space missions, on an ESM (Equivalent System Mass) basis. The Lee report was a detailed systems analysis of several waste treatment technologies for sterilization and water recovery. This report, which focused on sterilization and water recovery on intermediate term missions such as Mars Transit, showed that incineration had the lowest ESM followed by autoclaving-lyophilization. However, the report also showed a large oxygen resupply requirement for incineration that could make it very unattractive. The autoclave-lyophilization system has the lowest ESM if the oxygen must be supplied without recycle for the incineration process.

The approach of the Lee analysis was to treat all the waste without segregation. Lee considered a total waste stream that contains polyethylene plastic packages, tapes and filters, which formed 83% of the total dry weight of the wastes processed. Polyethene packages, tapes, and filer contain roughly only 20% by weight of water to be recovered and do not contain much oxygen that can be utilized in its oxidation.

The Lee analysis did not look in detail for ways to reduce the oxygen penalty. The ways to reduce the oxygen penalty include segregating portions of the waste for separate treatment and/or integrating the oxidation processor with other life support processors to recover oxygen. Feces, for instance, is very appropriate for oxidation because it contains a large amount of oxygen and water, and because feces is already separated from other wastes. Integration with other life support processors means taking advantage of processors that clearly will already be present in advanced support systems such as Sabatier and OGS, or adding other processors such as the carbon formation reactor (CFR). A CFR can take the methane produced by a Sabatier and convert it to carbon. When oxygen and hydrogen are both scarce in a life support system, a CFR conserves these elements by keeping them from being bound to waste carbon. The ways to reduce the oxygen penalty involve sending the right waste to the right processor and using processors that integrate in a manner that leaves the ultimate waste (carbon, carbon dioxide, methane, etc.) in a form that best conserves system resources.

The Maxwell analysis was a comparison of a number of waste technologies based on ESM. The oxidation technologies in this analysis were burdened with oxidation penalties that were not optimized by the method discussed in this paper. As such, the relative ESM of oxidation technologies such as incineration and supercritical water oxidation will fare much better when compared with other technologies when methods of oxygen penalty reduction and water reclamation are included.

APPROACH

The systems analysis approach in this study was based on several factors that were incompletely considered or missing in previous reports.

1. Oxidation recovers water. It is especially good at water recovery when it is integrated with Sabatier and OGS. Water is an important resource to be recovered for any long duration human mission scenario. Water recovery is of limited value only when a mission is "water rich." "Water rich" means that the mission has so much water available that reclamation of water is unnecessary. There are numerous ways that water is gained and lost on a mission, and it is the overall balance of sources and sinks that determines whether a mission is water rich. Calculation of the balance of the sources and sinks for water is uncertain, and flexibility in the system would appear to be very valuable. In addition, the cost of bringing along a large enough store of water to make the whole mission water rich would be very high.

   With transportation costs for a round trip to Mars approaching $2,000,000 per kg of payload (based on the commonly used $20,000 per kg to low Earth orbit and the multiplying propulsion factor for a round trip to and from Mars of about 100 kg of propulsion per kg of payload (Larsen, et al.)), it is hard to imagine systems that will be water rich. Unnecessary water will be eliminated from the initial payload mass whenever possible to reduce costs. Even if the cost of extra water is deemed psychologically necessary, in hydrated food for instance, only portions of a mission are likely to be water rich (parts of missions with significant EVA will not be water rich). Additionally, the water would be contained in stored food. Water in stored food is not available to meet the demands for water during contingencies or when there is an immediate demand for significant amounts of water. Recovery of water during a mission means that less water supply is necessary initially, and this significantly reduces mission cost.

2. Oxidation makes very good sense for feces because oxidation renders a noxious waste nonbiohazardous and chemically inert, because feces contains significant amounts of oxygen that aid oxidation, and because water can be recovered from feces by oxidation.

3. Plastic packaging may not need oxidation processing because it contains limited resources such as oxygen or water to be recovered and because plastic is not nearly as biohazardous as feces. A CFR can be used to keep the ESM low for oxidation of plastics. A CFR is useful because the low oxygen and water in the plastics probably requires conversion of at least some of the carbon in the plastic to pure carbon (via CFR) in order to avoid loss of valuable water or oxygen. Use of a CFR is not discussed in detail in this paper because its use adds some complexity to the description of the integrated

system without changing the fundamental point that oxidation can be conducted without a large penalty.

4. Advanced life support systems make use of the Sabatier process and the oxygen generation system to recover oxygen from carbon dioxide. In this paper an integrated oxidation-Sabatier-OGS system is considered for waste management analysis. The oxygen penalty associated with such an integrated system is considered for an intermediate term mission such as a Mars transit mission. The "oxygen penalty" is the increase in size and power of the Sabatier and OGS system to handle the gas streams from the solid waste processing system.

5. The components of waste can be segregated at the collection point. Consequently, two different waste streams are considered for comparison. The two waste streams considered are: 1) Wet feces only. 2) Feces and the other wet wastes generated in an advanced life support system for an intermediate mission such as Mars transit, for a six person crew, with the exception of plastic packaging and tapes.

Crew time is not included in this analysis. The systems discussed can be automated to the point that crew time is negligible. Other assumptions included in this analysis: trace contaminant control is included in the oxidation ESM, no credit is assumed for reuse of combustion heat, cooling and condensation of the hot combustion gas is included.

A spreadsheet model was created for the integrated oxidation-sabatier-OGS system. The system was modeled to maximize water and oxygen recovery and minimized for carbon dioxide formation. The feed values and component values, water content, crew-size, batch size can be readily changed to evaluate the effect of these variables on the integrated system. The model can also evaluate the effect of a carbon formation reactor. ESM values for the Sabatier, OGS system and the ESM conversion factors were taken from the BVAD document (Drysdale and Hanford, 1999). ESM values based on mass, power, cooling, and volume for the oxidation system and the lyophilizer were taken from the Lee report.

Figure 1 shows a simplified conceptual version of the system design. The system considers an oxidation system in conjunction with a Sabatier and an oxygen generation system (OGS). Sabatier and OGS are assumed to be a part of an Advanced Life Support System (BVAD, 1999). The diagram implies that by appropriate sizing of the internal flow streams, that the input stream can be converted to any combination of the output streams so long as an elemental balance can be made. Note that if a Carbon Formation Reactor (CFR) were to be included in this system, then C (carbon) could be included in the exit materials, further enhancing the flexibility of the system. The relevant reactions are below. The formula for the waste below was developed from the ratio of the components for combined feces and wet wastes without plastic. It was normalized with respect to the carbon in the waste. See table 1 (Appendix) for more details on the breakdown of the waste.

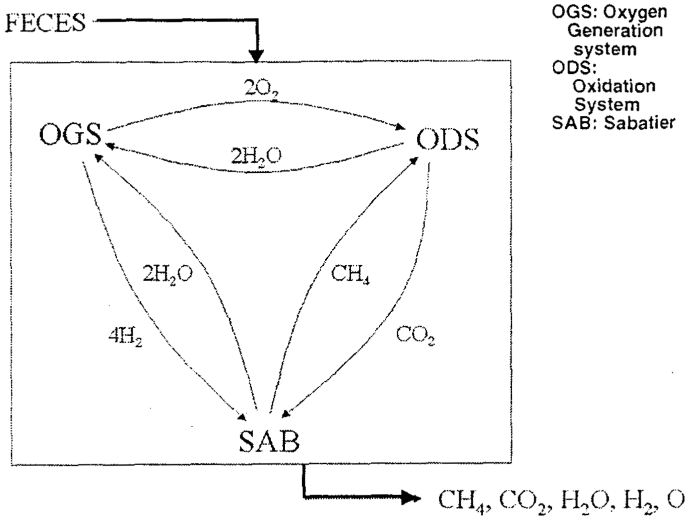

Figure 1, Simplified schematic of the oxidation-Sabatier-OGS system

Oxidation:

$C_1H_{20.2}O_{10.1}N_{0.17} + O_2 = CO_2 + 10.1\ H_2O + 0.085N_2$

Sabatier: $CO_2 + 4H_2 = CH_4 + 2H_2O$

OGS: $2H_2O = 2H_2 + O_2$

The three formulas and the associated processors can be combined to produce a number of different overall results. These two examples illustrate this flexibility:

Overall balance to produce maximum methane without oxygen resupply:

$C_1H_{20.2}O_{10.1}N_{0.17} = CH_4 + 8.1\ H_2O + O_2 + 0.085N_2$

Overall balance to produce maximum carbon dioxide without oxygen resupply:

$C_1H_{20.2}O_{10.1}N_{0.17} = CO_2 + 8.1\ H_2O + 2H_2 + 0.085N_2$

Figure 1 above focuses on the integration with the oxidation system. However, the OGS and the Sabatier in an overall life support system take in water and carbon dioxide from other sources, and the streams from the other sources are much larger than the streams required to handle feces oxidation. In other words, the integration of the oxidation system with the Sabatier and OGS only increases the sizes of the Sabatier and OGS a small amount – approximately 10%.

The input quantities of the various wastes were obtained from the Lee report and are shown in table 1 (Appendix). As can be seen from tables 3 and 4 (Appendix) all the carbon in the waste is turned into CH_4. The oxygen in the waste is either converted to water or released as oxygen. In addition, the water in the waste is recovered as water. For dry wastes such as plastic, the system can be run with a carbon formation reactor added to fully reduce the carbon in the waste to form solid carbon.

The flow diagram used to model the integrated oxidation-Sabatier-OGS system is as shown in figure 2 (Appendix). Input and output quantities are listed in the tables 3 and 4 (Appendix). The amount of the various outputs such as O_2, water, CH_4, and CO_2 are a function of the input C, H, and O; the spreadsheet was modeled to study the effects of differing input ratios to the output quantities. Internal streams (shown in the flow diagram of figure 2 (Appendix)) were calculated by unit operations mass balance (a unit operation is the Sabatier for instance). The ESM values (based on mass, power, cooling, and volume) for the oxidizer, Sabatier, oxygen generation system, and the autoclave-lyophilizer were based on the detailed analysis from the Lee report and the assumptions in the BVAD document and were scaled linearly from those documents for the present analysis.

RESULTS AND DISCUSSION

The ESM values calculated from the spreadsheet model indicate that the oxidation-Sabatier-Oxidation system does not incur a large oxygen penalty as previously estimated (Lee, 2001, Maxwell and Drysdale, 2001). The integrated system is capable of converting all the carbon in the waste to form CH_4 and recovering the valuable resources such as water and oxygen. For example, no resupply is needed for the wet wastes with moisture content over 4.5%. Furthermore, the integrated system is very flexible. The operation of the system can be manipulated to vary the products – trading carbon dioxide for methane was illustrated above. The analysis and results for the wet mixed wastes and feces are as shown in tables 5 and 6 (Appendix). For both cases, the primary output streams are water and oxygen. The extra water generated over 600 days for a Mars transit mission in comparison with the next best process i.e. autoclave/lyophilization is 52.87 kgs for the wet feces case and 465.71 kgs for the total wet waste case. If water is considered a valuable resource this results in a negative ESM. The amount of water recovered during the course of the mission more than makes up for the extra mass, power, and volume required for the incinerator, Sabatier, and OGS.

All of this water should be very valuable because, as previously mentioned, with mass worth $2,000,000 per kg on a Mars mission, there is little reason to think that extra water would be taken on a such a mission (i.e. that a mission would be "water rich"). However, even in the case of a water rich portion of a mission, this processor would be a valuable asset that would provide resiliency and make-up for periodic water shortages, which in the absence of such a processor might be trapped in stored food. The rationale for choosing the oxidation-Sabatier-OGS system is further strengthened if the whole mission is considered, including portions when there would be extra demand for water such as during the surface stay of the mission, where there would be regular EVA activities.

The plastic packaging waste has an insignificant amount of recoverable resources, and a simple stabilization procedure may be a more appropriate way of managing the plastic wastes generated.

In this report, lyophilization-autoclaving is considered with and without venting to space. Venting means releasing contaminant volatiles formed during autoclaving to space. The ESM for contaminant cleanup increases the autoclave ESM if contaminant venting is not allowed. The oxidation system always includes contaminant cleanup and does not incur additional ESM for no venting cases. Without venting the ESM values for lyophilization/autoclaving increases by 37.3 kg for the feces only case and by 280 kg when the entire wet wastes are considered.

CONCLUSIONS

An oxidation system such as an incinerator does not incur a large oxygen penalty as previously estimated when operated in conjunction with other subsystems such as the Sabatier and the oxygen generation system. The integrated system can be applied to near term as well as long term manned missions. The oxidation-Sabatier-OGS system had the lowest ESM for water recovery when compared to the other waste management systems for intermediate missions such as a Mars transit mission. The oxygen penalty estimated in the previous analysis reports was unnecessarily increased by the inclusion of significant amounts of supplied oxygen to oxidize plastic packaging, a waste with no resources to be recovered.

The integrated system is very flexible and has many advantages over competing systems. The amount of individual outputs such as CH_4, H_2O and O_2 can be readily varied according to needs. Oxidation systems have the added advantage of rendering the output sterile, in contrast to processes such as lyophilization, for which the products still possess the threat of contamination.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ARC: Ames Research Center
BVAD: Baseline Values and Assumptions Document
CFR: Carbon Formation Reactor
ESM: Equivalent System Mass
JSC: Johnson Space Center
OGS: Oxygen Generation System

APPENDIX

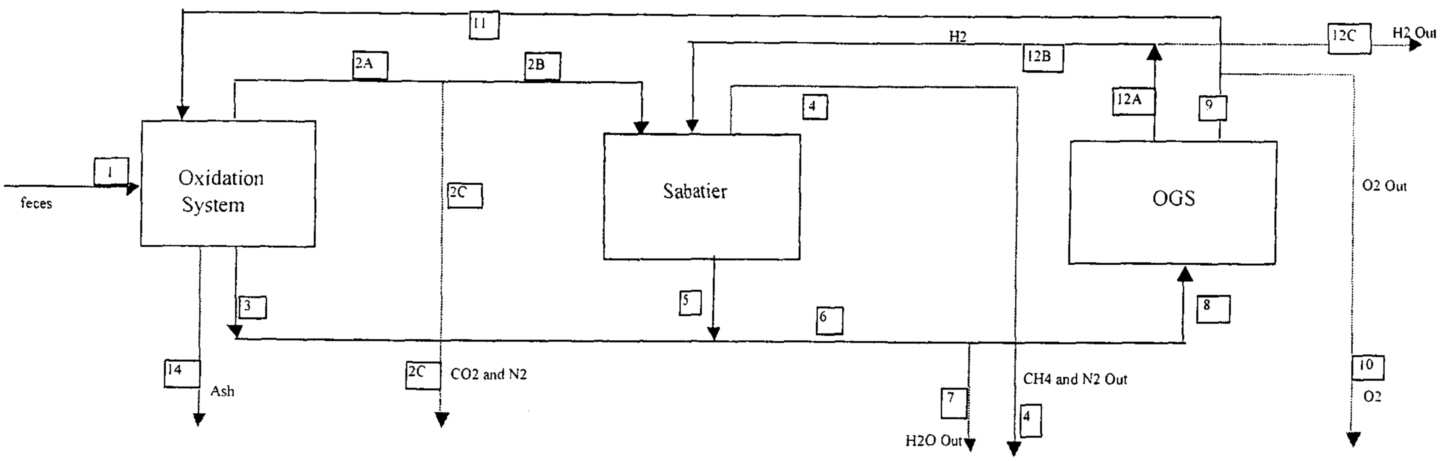

Figure 2, Flow-diagram of the integrated oxidation-Sabatier-OGS system

Table 1, Feed composition. Total for 6 Person Crew. Dry Basis.

			C	H	O	N	
Name	Rate(kg/d)	Formula	a	b	c	d	Mol.Wt
Feces	0.18	$C_{42}H_{69}O_{13}N_5$	42	69	13	5	851
Toilet paper	0.138	$(C_6H_{10}O_5)n$	6	10	5	0	162
Urine solid	0.36	$C_2H_6O_{3.6}N_2$	2	6	3.6	2	115.6
Wash water solid	0.06	$C_{13}H_{28}O_{13}N_2$	13	28	13	2	420
Sweat solid	0.12	$C_{13}H_{28}O_{13}N_2$	13	28	13	2	420
Paper (cellulose)	0.349	$(C_6H_{10}O_5)n$	6	10	5	0	162
Trash (cellulose)	0.245	$(C_6H_{10}O_5)n$	6	10	5	0	162
Values from Lee, 2001 (Ref 5).							

Table 2, Input and Output Components (mixed waste stream)

Calculation Basis		
Water in wet mixed wastes(%)	83	%
Batch size:	1	Per day
Mixed Waste dry weight/person/day	242	g
Mixed waste dry weight/batch	1452	g
Number of crew members	6	persons

Mixed waste elemental breakdown (dry weights based on table 1 above)			
wet wastes	wet formula	dry formula	dry wt.%
C	1.00	1.00	35.40
H	20.28	1.89	5.58
O	10.08 1	0.89	42.01
N	0.17	0.17	7.02
ash	* * * *	-->	10.00
total			100.00

Component	Input g/day	Input Stream number in figure 2	Output g/day	Output Stream number in figure 2
Wet waste	8541	1		
CH_4			685	4
H_2O			6275	7
CO_2			0	2C
O_2			1332	10
H_2			0	12C
N_2			101	2C, 4
Ash			145	14
Total	8541		8541	

Table 3, Input and Output Components (feces only waste stream)

Calculation Basis		
Water content in feces(%)	80	%
Batch size:	1	Per day
Feces dry weight/person/day	39	g
feces dry weight/batch	234	g
Number of crew members	6	persons

Feces elemental breakdown (dry weight formula from Carden, 1982)			
feces	wet formula	dry formula	dry w%
C	1.00	1.00	41.89
H	14.69	1.96	6.84
O	6.95	0.59	32.96
N	0.17	0.17	8.31
ash	* * * *	-->	10.00
total			100.00

Component	Input gm/day	Input Stream number in figure 2	Output gm/day	Output Stream number in figure 2
Wet feces	1170	1		
CH_4			130	4
H_2O			786	7
CO_2			0	2C
O_2			210	10
H_2			0	12C
N_2			19	2C, 4
Ash			23	14
Total	1170		1170	

Table 4, Assumptions Used in ESM Calculations

Mars transit ESM Conversion Factors (BVAD, 1999)

Volume(kg/m^3)	16.1
Power(kg/kW)	83.3

Mars Planetary ESM Conversion Factors (BVAD, 1999)

Volume(kg/m^3)	2.083
Power(kg/kW)	86.95

ESM for Sabatier and OGS, crew of six (BVAD, 1999)

	mass	volume(m^3)	power(kW)
Sabatier	182	0.21	0.2
OGS	377	1.1	1.84

Table 5, Partial Breakdown of ESM Values for Oxidation-Sabatier-OGS and Lyophilization - Before Considering Water Recovery Effects

Mars transit

	Wet feces only	All wet trash
	ESM (kg)	ESM (kg)
OGS	52	272
Sabatier	12	62
Oxidation*	61	412
	125	747

* Note: includes heat of combustion cooling

Note: Mars Surface ESM values are essentially the same because the power penalties are roughly the same and the volume penalties are negligible.

Table 6: ESM values for the oxidation-Sabatier-OGS system in comparison with combined Autoclaving-Lyophilization With Water Effects Included.

Note: "Venting" refers to the fact that the autoclave-lyophilization system produces gases that must either be vented overboard or treated for habitat internal release. Treatment for internal release (nonventing) increases the ESM somewhat.

Wet Feces Only, Mars Transit

ESM	OGS-SAB-Oxidation, (kg)	Autoclave-Lyophilization, (kg)
ESM with venting	125	80 (Lee, 2001)
Water recovered/600 days	-597	-544
Total system ESM with venting	-472	-464
Oxidation system has a lower overall ESM by 8 kg.		
Total system ESM for no venting	-472	-427
Oxidation system has a lower overall ESM by 45 kg.		

All Wet Wastes Except Plastic Packaging, Mars Transit

ESM	OGS-SAB-Oxidation, (kg)	Autoclave-Lyophilization, (kg)
ESM with venting	747	550 (Lee, 2001)
Water recovered/600 days	-4591	-4125
Total system ESM	-3843	-3575
Oxidation system has a lower overall ESM by 268 kg.		
System ESM for no venting	-3843	-3295
Oxidation system has a lower overall ESM by 548 kg.		