

## PYROLYSIS PROCESSING OF MIXED SOLID WASTE STREAMS

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### ABSTRACT

The NASA objective of expanding the human experience into the far reaches of space will require the development of regenerable life support systems. A key element of these systems is a means for solid waste resource recovery. The objective of this work was to examine the feasibility of pyrolysis processing as a method for the conversion of solid waste materials in a Controlled Ecological Life Support System (CELSS). A composite mixture was made consisting of 10% polyethylene, 15% urea, 25% cellulose, 25% wheat straw, 20% Gerepon TC-42 (space soap) and 5% methionine. Pyrolysis of the composite mixture produced light gases as the main products ( $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ ,  $\text{NH}_3$ ) and a reactive carbon-rich char as the main byproduct. Significant amounts of liquid products were formed under less severe pyrolysis conditions, but these were cracked almost completely to gases as the temperature was raised. A primary pyrolysis model was developed for the composite mixture based on an existing model for whole biomass materials.

### INTRODUCTION

A key element of a CELSS is a means for solid waste resource recovery. Solid wastes will include inedible plant biomass (IPB), paper, plastic, cardboard, waste water concentrates, urine concentrates, feces, etc. It would be desirable to recover usable constituents such as  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , hydrogen, nitrogen, nitrogen compounds, and solid inorganics. Any unusable byproducts should be chemically and biologically stable and require minimal amounts of storage volume. Many different processes have been considered for dealing with these wastes: incineration, aerobic and anaerobic biodigestion, wet oxidation, supercritical water oxidation, steam reforming, electrochemical oxidation and catalytic oxidation [1-13]. However, some of these approaches have disadvantages which have prevented their adoption. For example, incineration utilizes a valuable resource, oxygen, and produces undesirable byproducts such as oxides of sulfur and nitrogen. Incineration also will immediately convert all of the waste carbon to  $\text{CO}_2$ , which will require storing excess  $\text{CO}_2$ .

"Pyrolysis," in the context of this paper, is defined as thermal decomposition in an oxygen free environment. Primary pyrolysis reactions are those which occur in the initial stages of thermal decomposition, while secondary pyrolysis reactions are those which occur upon further heat treatment. A pyrolysis based process has several advantages when compared to other possible approaches for solid waste resource recovery: 1) it can be used for all types of solid products and can be easily adapted to changes in feedstock composition; 2) the technology is relatively simple and can be made compact and lightweight and thus is amenable to spacecraft operations; 3) it can be conducted as a batch, low pressure process, with minimal requirements for feedstock preprocessing; 4) it can produce several usable products from solid waste streams (e.g.,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2$ ,  $\text{NH}_3$ ,  $\text{CH}_4$ , etc.); 5) the technology can be designed to produce minimal amounts of unusable byproducts; 6) it can produce potentially valuable chemicals and chemical feedstocks; (e.g., monomers, hydrocarbons, nitrogen rich compounds for fertilizers) 7) pyrolysis will significantly reduce the storage volume of the waste materials while important elements such as carbon and nitrogen can be efficiently stored in the form of pyrolysis char and later recovered by gasification or incineration when needed. In addition to being used as the primary waste treatment method, pyrolysis can also be used as a pretreatment for more conventional techniques, such as incineration or gasification. A summary of the pyrolysis processing concept is shown in Figure 1.

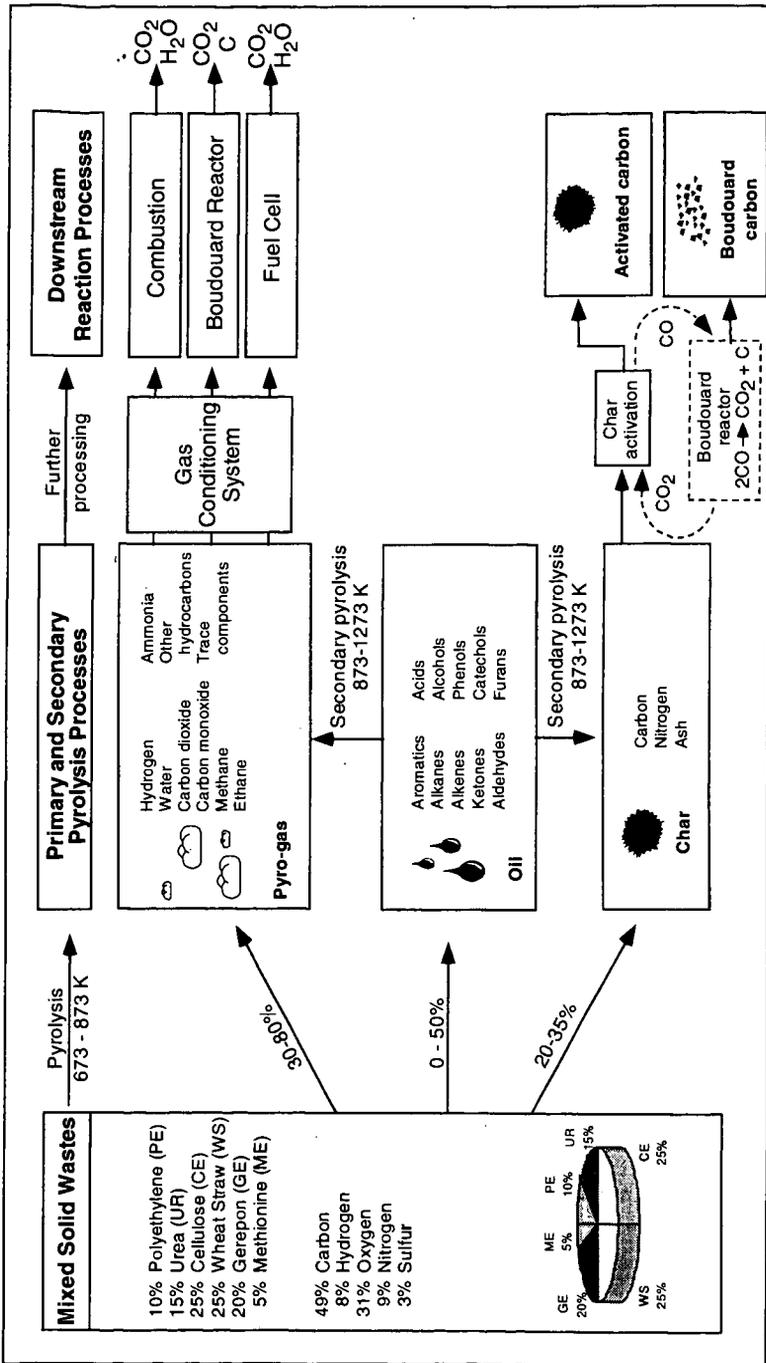


Figure 1. Summary of proposed pyrolysis-based solid waste processing scheme.

The primary disadvantages of pyrolysis processing are: 1) the product stream is more complex than for many of the alternative treatments; 2) the product gases cannot be vented directly in the cabin without further treatment because of the high CO concentrations. The former issue is a feature of pyrolysis processing (and also a potential benefit, as discussed above). The latter issue can be addressed by utilization of a water gas shift reactor or by introducing the product gases into an incinerator or high temperature fuel cell.

## EXPERIMENTAL METHODS

**Sample Selection** - It was decided to use a model waste feedstock similar to what was used in a previous study at Hamilton Standard [11], the so-called "Referee mix." That study used 10 wt. % polyethylene, 15% urea, 25% Avicel PH-200 cellulose, 25% wheat straw, 10% Gerepon TC-42 (space soap) and 5% methionine. The materials that were obtained and the elemental compositions of each (on a DAF basis) are given in Table 1. A different sample of Avicel cellulose was used (PH-102), as a supply was already on hand and significant amounts of data had been generated with this material for a private client in a previous study. It was thought that the difference between these two cellulose samples would be small and that there was an advantage to using a material whose individual pyrolysis behavior had already been characterized. The NIST wheat straw sample was previously studied under a USDA project [14]. The Gerepon TC-42 is the same as the Igepon TC-42, but the name was changed since the product line was sold to a new company (Rhône-Poulenc). It is a soap which is made from coconut oil, so its exact formula is unknown. The composition was estimated by assuming that most of the fatty acids were C<sub>12</sub>. The technical name for Gerepon TC-42 is sodium methyl cocoyl taurate.

**TG-FTIR System** - The samples in Table 1 were obtained and subjected to thermogravimetric analysis with FT-IR analysis of evolved gases (TG-FTIR) at 10 °C/min and 30 °C/min. Details of the TG-FTIR method can be found in references [15] and [16]. The apparatus consists of a sample suspended from a balance in a gas stream within a furnace. As the sample is heated, the evolving volatile products are carried out of the furnace directly into a 5 cm diameter gas cell (heated to 150 °C) for analysis by FT-IR. In the standard analysis procedure, a ~35 mg sample is taken on a 30 °C/min temperature excursion in helium, first to 150 °C to dry, then to 900 °C for pyrolysis. After cooling, a small flow of O<sub>2</sub> is added to the furnace and the temperature is ramped to 700 °C (or higher) for oxidation in order to measure the amount of inorganic residue. The TG-FTIR system can also be operated with a post pyrolysis attachment to examine secondary pyrolysis of the volatile species (see below).

During these excursions, infrared spectra are obtained approximately once every forty-one seconds. The spectra show absorption bands for infrared active gases, such as CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O, C<sub>2</sub>H<sub>4</sub>, HCl, NH<sub>3</sub>, and HCN. The spectra above 300 °C also show aliphatic, aromatic, hydroxyl, carbonyl and ether bands from tar (heavy liquid products). The evolution rates of gases derived from the IR absorbance spectra are obtained by a quantitative analysis program. The aliphatic region is used for the tar evolution peak. Quantitative analysis of tar is performed with the aid of the weight-loss data in the primary pyrolysis experiments.

The TG-FTIR method provides a detailed characterization of the gas and liquid compositions and kinetic evolution rates from pyrolysis of materials under a standard condition. While the heating rates are slower (3-100 °C/min) than what is used in many practical processes, it is a useful way of benchmarking materials and was used in this study for characterizing both the primary and secondary pyrolysis behavior of the model waste samples and the individual components. In addition, Advanced Fuel Research, Inc. (AFR) has developed kinetic models based primarily on TG-FTIR data which can be extrapolated over a wide range of conditions.

**Differential Scanning Calorimetry (DSC)** - Measurements of the thermodynamics of the pyrolysis process, were made using differential scanning calorimetry (DSC) at Brown University. Samples of each of the materials in Table 1 were sent to Brown. The DSC experiments were done by heating at 10, 30 and 60 °C/min. These heating rates were the same or similar to the heating rates used in the TG-FTIR experiments, so a direct comparison could be made. A TA Instruments 2910 DSC system, with a maximum operating temperature of 600 °C, was employed in the DSC work. The sample cell was operated under a nitrogen flow rate of 100 cm<sup>3</sup>/min in order to keep the cell free of oxygen during the measurements. In preliminary work,

this was noted to be important. Small amounts of oxygen, participating in a combustion reaction, can significantly influence the thermal characteristics of the process.

**Table 1. Elemental Analysis of Individual and Composite Samples (DAF wt.%)**

Sample	C	H	O	S	N
Polyethylene <sup>a</sup> (Aldrich)	85.7	14.3	0.0	0.0	0.0
Cellulose <sup>b</sup> (Avicel PH-102)	44.0	6.2	49.8	-0.0	-0.0
Wheat Straw <sup>b</sup> (NIST)	48.0	6.2	44.9	0.2	0.7
Urea <sup>a</sup> (Aldrich)	20.0	6.7	26.6	0.0	46.7
Gerepon <sup>c</sup> TC-42 (Rhône -Poulenc)	60.5	11.5	11.5	11.5	5.0
Methionine <sup>a</sup> (Aldrich)	40.3	7.4	21.4	21.5	9.4
Composite	48.7	8.2	31.0	3.4	8.7

Notes: DAF = Dry, Ash Free

a = determined from chemical formula

b = determined by Huffman Laboratories (Golden, CO)

c = estimated from approximate chemical formula

Aluminum sample pans were used for the DSC experiments in a partially sealed mode. This was done by pushing down the top sample pan cover gently onto the bottom pan containing the sample. Following this, three small pinholes were poked into the sample pan to allow a limited amount of mass loss from the pan. This configuration has been used previously in work on cellulose samples [17], and gives results which are consistent with pyrolysis in a confined system with a slow rate of mass bleed out of the system. It was felt that this would be reasonably representative of a pyrolysis processing system. Typically, about 10 mg of sample was used in an experiment.

In many cases, particularly with charring samples, the initial DSC run was followed by a cooling of the sample back down to room temperature, followed by a retrace of the original heating profile. This procedure provided a background trace attributable to the heat capacity of the char residue. In cases involving formation of a char residue, the mass loss of the sample during the first heating was also established. These values were compared with the TG-FTIR results, to verify whether the pyrolysis was occurring in a consistent manner, or in a different manner due to the increased mass transport resistance in the DSC pans.

## RESULTS AND DISCUSSIONS

**TG-FTIR Results for Primary Pyrolysis** - An example of some representative data is shown in Table 2, which includes the average results of all the runs done at heating rates of 30°C/min. Similar results were obtained at 10°C/min [18,19]. For all of the samples, data from primary pyrolysis experiments for the same nominal pyrolysis conditions for each sample are generally in good agreement. For example, in the case of cellulose, there are differences in CO<sub>2</sub> yields that can probably be attributed to small air leaks in the system. For polyethylene, the material experiences a rapid and essentially complete depolymerization to tar which drives the balance pan below zero weight. Since the tar yields are ultimately determined by difference, this phenomenon results in integration errors which lead to tar yields above 100%. For the minor (trace) species for all of the samples, integration errors are also a concern and the results which are thought to be influenced mainly by noise are indicated by italics in Table 2.

For each of the samples, the data include moisture, total volatiles, fixed carbon, and ash. The yields of tar, CH<sub>4</sub>, water, CO<sub>2</sub>, and CO are reported as major pyrolysis products. In most cases, the minor pyrolysis products which are quantified include SO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, CS<sub>2</sub>, NH<sub>3</sub>, COS, and olefins and the amounts of these latter product are usually barely above the noise level. Hydrogen is not reported since the gas is not IR active. However only small amounts of

hydrogen are formed in primary pyrolysis experiments (<1 wt. %). It can be an important product from secondary pyrolysis experiments and for these experiments, the FT-IR measurements were supplemented by GC (see below).

The selection of the minor species to report is somewhat arbitrary and the current set of gases is historically based on our extensive work on coal pyrolysis. For some of the samples, (urea, methionine, composite), the selection of species was changed in order to reflect the important major and minor pyrolysis products. Obviously, any gas can be quantified that is IR active and for which a calibration exists. In the case of the cellulose, wheat straw and Gerepon TC-42, the results could be made quantitative without any new calibrations since the major products were in our existing reference library. However, for the urea, methionine, and composite mixture, some additional calibrations had to be done in order to describe the evolution of some of the important products.

Table 2 - Average Results from Primary Pyrolysis Experiments in TG-FTIR System at 30°C/min (wt. %, As-Received Basis)

Sample	Cellulose	Wheat Straw	Polyethylene	Urea	Gerepon TC-42	Methionine	Composite Mix
Moisture	3.5	5.2	0.6	1.8	67.1	0.0	0.6
Volatiles	94.4	69.4	99.2	98.2	27.2	99.2	87.0
Fixed Carbon	1.3	17.5	0.0	0.0	2.0	0.0	12.4
Ash	0.5	7.8	0.0	0.0	4.8	0.8	0.0
Tars	91.2	30.0	101.4*	0.00	20.8	46.55	30.9
CH <sub>4</sub>	0.23	0.88	0.11	0.00	0.13	0.00	0.56
C <sub>2</sub> H <sub>4</sub>	0.04	0.32	0.0	4.54	0.14	0.00	0.40
H <sub>2</sub> O	7.81	22.74	1.30	21.94	3.12	3.74	23.30
CO <sub>2</sub>	2.72	10.50	0.54	1.83	2.42	6.96	9.80
CO	1.04	6.56	0.00	1.66	0.85	0.00	5.58
NH <sub>3</sub>	0.05	0.07	0.00	13.89	0.26	0.58	0.86
COS	0.00	0.00	0.00	0.00	0.13	0.00	0.60
SO <sub>2</sub>	0.00	0.24	0.00	0.00	0.3	0.06	1.10
Cyanic acid (CHNO)				22.43			0.40
Cyanuric acid (C <sub>3</sub> H <sub>3</sub> N <sub>3</sub> O <sub>3</sub> )				0.56			
Biuret				32.70			
Methionine						27.77	
Methylthiopropyl amine						13.05	11.87

Notes: Yields are given on an as-received wt.% basis; numbers in italics are influenced by noise and may not be reliable; \* indicates numbers that are influenced by balance errors due to very rapid devolatilization; all runs done at standard carrier gas flow rate of ~400 cm<sup>3</sup>/min helium.

Both the cellulose and the polyethylene undergo nearly complete devolatilization to 100% tar plus gas. As expected, the cellulose and wheat straw produce oxygenated gases in addition to tar. However, the wheat straw produces about 20-25 wt.% char (fixed carbon plus ash) on an as-received basis. The formation of fixed carbon from whole biomass is known to result primarily from the aromatic lignin component of the plant, which typically comprises 20-25% by weight, with the remainder being primarily cellulose and hemicellulose [20]. Previous work at AFR and elsewhere has shown that the weight loss from pyrolysis for whole biomass samples can be understood as a linear superposition of these three main components to a first approximation [14]. However, one can not predict the yields of individual gas species using this approach, probably due to the catalytic effects of the trace minerals present in whole biomass.

Aside from NH<sub>3</sub> and small amounts of H<sub>2</sub>O, the pyrolysis products from urea (N<sub>2</sub>H<sub>4</sub>CO) include cyanic acid, CHNO, and another compound that is probably biuret, NH<sub>2</sub>CONHCONH<sub>2</sub>. The latter two products were initially identified by a target factor analysis program that separates real component spectra from FTIR data. The cyanic acid was verified by pyrolyzing cyanuric acid

(C<sub>3</sub>H<sub>3</sub>N<sub>3</sub>O<sub>3</sub>) a ring compound made essentially of three cyanic acid groups. Cyanuric acid produces cyanic acid and some cyanuric acid (either by evaporation or recombination of the cyanic acid) during pyrolysis. Biuret was tentatively identified by absorption peak positions, and comparison to solid phase spectra in the Aldrich Spectral Library book. The formation path for biuret is most likely from combination of cyanic acid with urea. All the products start evolving at fairly low temperatures, 125 to 145 °C but do not finish until around 420 °C.

Most of the mass loss from Gerepon TC-42 is from drying, due to the large moisture content. Additional water, along with CO<sub>2</sub>, tars and small amounts of CO are produced from pyrolysis of the organic part of the soap.

Methionine (C<sub>5</sub>H<sub>11</sub>O<sub>2</sub>N<sub>2</sub>S) pyrolysis proceeds in a much simpler fashion than in the case of urea. There is one basic weight loss event centered around 300 °C, producing mostly CO<sub>2</sub> and 3-(methylthio) propylamine. This is probably from decarboxylation of the methionine. To identify which other bonds in the methionine might be breaking, absorption spectra from the TG-FTIR runs were checked for some simple molecules that might result. For example, if the end C-S bond were to break, CH<sub>4</sub> would result. None was found, however. Similarly, there was no C<sub>2</sub>H<sub>4</sub>, NO, N<sub>2</sub>O, NO<sub>2</sub>, CH<sub>3</sub>SH, CH<sub>3</sub>SCH<sub>3</sub>, SO<sub>2</sub>, or CO and very little NH<sub>3</sub>, indicating that the C-S bonds remained intact as did the bonds between the alpha and beta C. The only other thing that happened was a little bit of deamination and some dehydrolysis (as evidenced by water loss) which may have led to a polymerized high molecular weight product (tar). A compound, not yet identified, evolves around 220 to 270°C and accounts for about 25% of the methionine's weight loss. The material does not coincide with any release of other small gases. This means the product is either from direct evaporation of the methionine or some rearrangement is taking place. The hydrogen bonding in the methionine keeps the melting point high (and therefore the vapor pressure low) at around 275°C. Rearrangement could alter the hydrogen bonding and lead to a more easily evaporated material. The remainder of the sulfur mass must be distributed between the tar and this early pyrolyzate.

For the composite mixture, most of these unknown products are inconsequential, because of the relatively small contribution of urea and methionine to the overall product distribution and the product transformations that occur in the mixture due to chemical interactions and catalytic effects. Consequently, it was decided to limit the amount of effort devoted to identification of the products of pyrolysis of pure urea and methionine.

The results for TG-FTIR runs with the composite ("referee") mixture are also shown in Table 2. It can be seen that, in terms of product distribution (char, tar, gas), the results are much more similar to the NIST Wheat Straw sample than the cellulose, polyethylene, Gerepon, methionine, or urea samples. This result makes sense in that the wheat straw is also a composite mixture which consists of cellulose, hemi-cellulose, and lignin, while the composite mixture is made up of 25% cellulose and 25% wheat straw as the largest components. The wheat straw sample also has an elemental composition which is relatively close to that of the composite mixture (see Table 1). Therefore, one might expect similar pyrolysis behavior.

## DSC EXPERIMENTS

The general conclusion which can be drawn from these measurements is that the composite mixture pyrolysis is only mildly endothermic (of order 100 J/g), under conditions in which a significant amount of mass loss is permitted to occur during pyrolysis. Confining pyrolysis more completely might be expected to drive the process in an even more exothermic direction, as it does in the case of pure cellulose [17]. In any event, it may be noted that, in comparison to this relatively modest enthalpy of pyrolysis, the sensible enthalpy for heating the sample is quite a bit larger. For example, using a "typical" average heat capacity for cellulose of 2 J/g-K to represent the composite mixture, it can be determined that heating from room temperature to 600°C will itself require 1150 J/g of sample. Additionally, the heat required to evaporate any residual moisture content could also far outweigh this small pyrolysis thermal demand. Thus it may be concluded that the heat of pyrolysis will not be of significant design concern unless conditions far removed from these are to be explored. Most of the heat input required will be to overcome heat losses from the reactor.

## RESULTS OF CHAR CHARACTERIZATION STUDIES

Much of the work on char characterization was also done at Brown University. The work at Brown included characterization of the gasification reactivity of the char using a TGA system and pore structure measurements using the Autosorb instrument made by Quantachrome. Char forming experiments were performed under conditions comparable to those at AFR. In addition, samples of char generated at AFR were supplied to Brown.

At both AFR and Brown, reactivity measurements were made using indices known as  $T_{critical}$  and  $T_{late}$ . These measure the temperature at which a char heated at  $30\text{ }^{\circ}\text{C}/\text{min}$  in air achieves a reaction rate of 6.5% per min in the early stage of reaction and where it returns to that value in the later stages. Low values of  $T_{critical}$  and  $T_{late}$  indicate a reactive material and vice versa. The results indicated that these chars are very reactive and would be easy to gasify or combust in order to recover additional carbon and nitrogen. The same conclusions were reached in the more extensive char characterization studies that were done at Brown, which also included characterization of pore structure [18].

## TG-FTIR EXPERIMENTS WITH THE POST PYROLYZER (TG-FTIR/PP)

The TG-FTIR system, was used as discussed above, to characterize the primary pyrolysis behavior of the individual components and the composite sample. Under this study, the system was also equipped with a post-pyrolysis system (isothermal secondary pyrolysis unit) in order to study the cracking of the heavy liquids (tars) and other volatiles that are formed during pyrolysis of these materials. This post pyrolysis unit can be operated from  $500\text{--}1000\text{ }^{\circ}\text{C}$  with an average volatile residence time of 0.4-2.6 seconds at atmospheric pressure. Under the right pyrolysis conditions, the liquids are cracked to produce primarily  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ , and small amounts of carbon.

In the current study, experiments were done with the TG-FTIR/PP system over the temperature range from  $600\text{--}1000\text{ }^{\circ}\text{C}$  in the post pyrolyzer. The helium gas flow rate through the  $14\text{ cm}^3$  volume post pyrolyzer for the "fast" runs was  $\sim 400\text{ cm}^3/\text{min}$  (at standard conditions). Additional runs were done at lower flow rates ( $\sim 100\text{ cm}^3/\text{min}$ ) in order to test the effect of this variable and also to provide gas concentration levels that would allow for simultaneous measurements by FT-IR and GC. Over a temperature range of  $600\text{--}1000\text{ }^{\circ}\text{C}$ , these gas flow rates correspond to a range of residence times for the fast flow conditions of 0.4 to 0.6 seconds and 1.8 to 2.6 seconds for the slower flow conditions, i.e., the flow rates were not adjusted to equalize the residence times at each temperature.

The TG-FTIR/PP experiments were done for both the composite mixture sample and the wheat straw sample. A set of results for the composite mixture, shown in Figure 2, demonstrate the

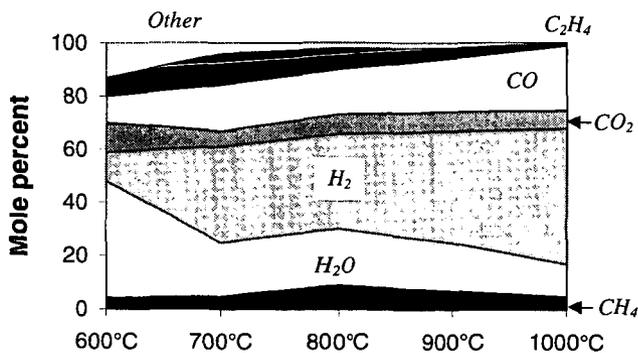


Figure 2. Estimated gas phase composition (mole %, excluding helium carrier) from TG-FT-IR pyrolysis experiments at  $30\text{ }^{\circ}\text{C}/\text{min}$  with the composite mixture followed by secondary pyrolysis over a range of isothermal temperatures.

very strong effect of the post pyrolysis temperature on the product composition. As the post pyrolysis temperature increases, the tar yields decline to zero and the CO yields increase dramatically. The CH<sub>4</sub>, H<sub>2</sub>O and CO<sub>2</sub> yields go through a maximum. Similar results are observed for post-pyrolysis runs done with the pure wheat straw sample [18]. In order to get yield data on H<sub>2</sub>, the GC system was used to take periodic samples.

The data shows that with increasing pyrolysis temperature, the gas composition becomes rich in H<sub>2</sub> and CO and that CH<sub>4</sub>, CO<sub>2</sub> and H<sub>2</sub>O are also key components. While tars and minor heterotomic species are present at low temperatures, these are largely eliminated as the temperature increases.

These results underscore the significant effect of primary and secondary pyrolysis conditions on the final product mix. There are many variables that can be manipulated for pyrolysis that can be used to compensate for changes in the feedstock composition and/or the desired product yields (e.g., time-temperature history, pressure). This provides a much greater degree of control over the solid waste processing step than is possible for either gasification or incineration. Changing the pyrolysis conditions allows one to effect significant changes in the pyrolysis product distribution (char, tar, gas) and the gas composition. Liquids can be produced if desired (under mild conditions) or cracked to form carbon oxides and fuel gases under severe conditions, depending on what is required for the life support system.

## SUMMARY AND CONCLUSIONS

This project demonstrated that it is possible to pyrolyze a representative composite mixture of mixed solid waste materials and produce usable gases as the main products (CH<sub>4</sub>, H<sub>2</sub>, CO<sub>2</sub>, CO, H<sub>2</sub>O, NH<sub>3</sub>) and a reactive carbon-rich char as the main byproduct. Significant amounts of liquid products were formed under less severe pyrolysis conditions, but these were cracked almost completely to gases as the secondary pyrolysis temperature was raised. A primary pyrolysis model was developed for the composite mixture based on an existing model for whole biomass materials, while an ANN model was used successfully to model the changes in gas composition with pyrolysis conditions [18].

This work has demonstrated that pyrolysis processing meets the requirements of solid waste resource recovery in space, i.e., it produces usable byproducts, with minimal side products, can be tailored to meet changes in the feedstock composition and the product requirements, significantly reduces storage volume, requires low maintenance can be conducted as a batch, low pressure process, and is compatible with the utilities that are present on board a spacecraft (electricity and small amounts of O<sub>2</sub> and H<sub>2</sub>O). It should be noted that the pyrolysis gases will require further treatment, such as water gas shift conversion to remove CO, before they can be vented into the cabin. However, these gases could also be introduced into an incinerator or a high temperature fuel cell system with minimal pretreatment.

In future work, a prototype waste pyrolysis system will be developed in collaboration with NASA, Hamilton Sunstrand Space Systems International and Brown University and delivered to NASA. This pyrolyzer will be useful to NASA in at least four respects: 1) it can be used as a pretreatment for an incineration process; 2) it can be used as a more efficient means of utilizing oxygen and recycling carbon and nitrogen; 3) it can be used to supply fuel gases to fuel cells for power generation; 4) it can be used as the basis for the production of chemicals and materials in space.

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