

BIOMASS CONVERSION OF MUNICIPAL SOLID WASTE

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ABSTRACT

The amount of municipal solid waste (MSW) produced annually is increasing at an alarming rate. The potential hazards, lack of available landfill sites, and the increasingly strict regulations placed upon existing sites present serious problems in the disposal of solid wastes. Environmentalists and government regulations are forcing city and county governments to actively seek alternatives to landfilling. Unfortunately, direct incineration of MSW has not proved to be an adequate alternative due to the financial unfeasibility of this process and the additional contribution to our environment of unwanted by-products, i.e., polyaromatic hydrocarbons.

We are developing a cost-effective and profitable process for the bioconversion of MSW by selecting and evaluating various existing technologies. Our selected process involves in part the efficient separation of the inorganic fraction of MSW (ferrous, non-ferrous, etc.) from the organic fraction. In addition, both fractions are sterilized, which greatly reduces the health hazards associated with MSW handling and landfilling. The inorganic fraction is then separated further for recycling. The organic fraction, which is 50 wt % cellulose, is readily converted to glucose by hydrolysis and subsequently to ethanol by fermentation. At present, we are achieving approximately 80 gallons of ethanol per dry ton of organics.

1. INTRODUCTION

Municipal solid waste (MSW) is the material discarded daily in the form of paper waste, newsprint, corrugated cardboard, yard waste, food waste, glass containers, plastics, ferrous and aluminum containers, and so forth. The amount of MSW produced annually is increasing at an alarming rate. MSW discarded by Americans ranges from 2-5 pounds/person/day [1-3]. Based on 1980 census figures, this amounts to an estimated annual production of 144 million dry tons. In most municipalities, MSW is collected and landfilled by contract. The potential hazards, lack of available landfill sites, and the increasingly strict regulations placed upon existing sites present serious problems in the disposal of solid wastes.

For many years it has been the general opinion of the scientific community that MSW contains far more than enough extractable energy to cover the cost of treatment to obtain this energy. It is expected that, in addition to covering the cost of collection, the products from treatment of this material could result in substantial profits in terms of commercially valuable substances. Principal among these profits is the energy gained from the degradation of the organic part of the solid waste. In the past, two considerations have limited the incorporation of this technology into solid-waste management: the large capital commitment required to build plants capable of performing the conversion, and the absence of acceptable plant designs maximizing the efficiency of the conversion and yielding the projected profits.

Two alternative, fundamentally different approaches are now commonly considered for the management and disposal of MSW. The first approach is the thermal decomposition of this material with the concomitant generation of steam for operating municipal and industrial facilities and for generating electricity. One of the drawbacks to this system has been the environmental impact of applying this technology and controlling the pollution arising from this method. Difficulties also arise in providing electrical power to an existing monopoly at a fair price in a declining market for electrical consumption. The second approach to obtaining energy from municipal solid waste has been the biodegradation and fermentation of this material to obtain ethanol as an energy-containing product and, further, to separate and reuse the proteinaceous by-products for animal feed. Several pilot-scale facilities for performing this operation are now in operation. A major difficulty in the use of this process is in the initial separation and sterilization of the various components found in solid waste. Significant capital and energy are required to separate and sterilize the waste material to obtain a product useful for fermentation. Economic analysis of this approach, however, suggests that an acceptable return on investment can be achieved by application of this technology. Any process offering the potential to improve the efficiency and capital investment required for this operation could significantly influence the economics of producing ethanol and animal feed from solid waste. The process conceived and patented by Urban Waste Resources and evaluated by us is known as the Pressure Vessel Separation/Sterilization (PVSS) Process. It offers the requisite potential for achieving an improved conversion of MSW to sterile, fermentable products.

## 2. MATERIALS AND METHODS

An SCO composite was prepared by manually mixing 50-lb samples from five consecutive runs of the PVSS processor under identical parameters. Each run was performed on 600 lb (90 ft<sup>3</sup>) of MSW collected in the Hoover/Vestavia, Alabama area and 200 lb of water at 60 psig for 60 min. Samples of this composite were analyzed by the following: Analytical Labs and Services, Inc. (Huntsville, AL), Deep South Laboratories (Montgomery, AL), and Southern Research Institute (Birmingham, AL). Samples were submitted to the following investigators for saccharification and fermentation studies: Dr. Y. Y. Lee, Auburn University; Dr. J. S. Goldstein, North Carolina State University; Dr. M. Wayman, University of Toronto; Dr. J. L. Gaddy, University of Arkansas; Dr. A. O. Converse, Dartmouth College; and Dr. G. H. Emert, University of Arkansas. The following is a summary of each method, including methods used by us.

Dr. Y. Y. Lee, carried out a hydrolysis under these conditions: 1 part oven-dried solid to 2.1 parts liquid; 12% H<sub>2</sub>SO<sub>4</sub>; 190 °C; 3.5 min. The hydrolyzate was analyzed for glucose by high-performance liquid chromatography

(HPLC). Dr. Lee also performed a fermentation test on this hydrolyzate. The pH of the hydrolyzate was raised to 10 by treatment with lime and left overnight. The pH was then readjusted to 4.5 by  $H_2SO_4$  and centrifuged to remove the precipitate. A Saccharomyces cerevisiae (ATCC 561) was grown on glucose medium and centrifuged to collect cells. Approximately 2 grams of the precipitated cells were transferred to a combination of 8 mL hydrolyzate and 10 mL medium containing 0.5% yeast extract, 0.5% peptone, and 0.5% malt extract to give a total of 18 mL. Fermentation was carried out in a 200-mL flask in a shaker bath at 200 rpm and 30°C.

Dr. J. S. Goldstein's process involved a hydrolysis of SCO with a 10:1 ratio of 15-16 N HCl (~45%) at 50 °C for 30 min with shaking at 120 oscillations per minute. Before being analyzed, the SCO was dried and high-density particles (e.g., glass) were removed. The hydrolyzate was analyzed by gas chromatography (which detected xylose, mannose, and glucose) and by the dinitrosalicylic acid procedure for total reducing sugars. Residue, soluble lignin, and hydroxy-methylfurfural were also determined.

Dr. M. Wayman used the following method. The hydrolysis procedure was carried out in 30-mL stainless steel pressure vessels. Prehydrolysis, to remove readily hydrolyzable material such as hemicellulose and starch, was performed at 150 °C (10 minutes to temperature, 20 minutes at temperature) with  $SO_2$  as the catalyst. The  $SO_2$  used was 4% of organic waste material (OWM), resulting in a 1% solution. The washed residue from prehydrolysis was then hydrolyzed at 190 °C (16 minutes to temperature, 4 minutes at temperature) with  $SO_2$  as catalyst.  $SO_2$  was 2% on OWM or a 0.5% solution. The washed residue from this stage was then recycled for similar treatment with  $SO_2$ . The resulting solutions were analyzed for glucose by a YSI glucose analyzer (glucose oxidase enzyme membrane) and for total reducing sugars by the DNSA method. Also, a sample of the sugar was posthydrolyzed with 6%  $H_2SO_4$  for 1 hour at 115 °C, and the analyses were repeated to determine oligomers.

Dr. J. L. Gaddy performed both a two-step and a single-step hydrolysis. The details of the method are proprietary. The two-step process consists of a prehydrolysis to convert hemicellulose to glucose and xylose and a main hydrolysis of the prehydrolysis residue to convert cellulose to glucose. The single-step process essentially combines prehydrolysis and hydrolysis into a single hydrolysis step. All experiments were carried out in batch reaction vessels maintained at constant temperature. All samples were air dried, and non-cellulose materials, such as metal and glass, were removed prior to the experiments. The ultraviolet spectrophotometric method developed by Scott (4) was used to determine glucose and xylose concentrations. The DNSA-reducing-sugar procedure and a glucose-analysis procedure were used as a back up. Dr. Gaddy also performed a fermentation by the following method. The sugar solutions were fermented in batch vessels, with agitation, by S. cerevisiae. As a control, synthetic glucose at the identical concentration was fermented simultaneously.

Dr. Alvin O. Converse performed both a straight  $H_2SO_4$  hydrolysis and an acid pretreatment followed by enzymatic hydrolysis. The SCO samples were oven dried and potentially damaging materials were removed by suspending the refuse in water with the aid of a Ross mixer. The supernatant slurry was then filtered and the filtrate was retained as a medium for resuspension. The solids were dried and then milled until the particles were small enough to pass through a 1-mm sieve.

A slurry of 1500 g of this clean, milled refuse in 17 L of water (15 L of filtrate from cleaning and 2 L of fresh, an 8.8% solution) was prepared for introduction into the reactor. This concentration was too high to be properly pumped, so the slurry was diluted to 5.2%. In the reactor this slurry was first injected with 0.93%  $H_2SO_4$  and followed with high-pressure steam. Samples were taken as the temperature inside the reactor was increased from 180 to 260 °C. These samples, plus a feed slurry sample, were separated into solid and liquid components. The liquid component was neutralized, and sugar analysis was performed by HPLC.

The following is the pretreatment/enzymatic procedure used by Dr. Converse. Pretreatment conditions were 220 °C and  $H_2SO_4$  concentrations of 1.03% by weight. Eight samples were prepared for the enzymatic hydrolysis: two each from the pretreatment runs performed at 180, 200, and 220 °C, and two from the original feed slurry. The samples prepared were 20 mg/mL in 100 mL. The samples were placed into eight 250-mL Erlenmeyer flasks, and 10 N NaOH was added to the pretreated samples so that a pH of 4.8 was attained in those six. Buffer (0.05 M citric acid containing 1.0%  $NaN_3$  to inhibit bacterial growth) was added to bring each final volume to 100 mL. Then the samples were placed in a shaker bath and allowed to equilibrate at 50 °C for 20 min. To initiate hydrolysis, 0.95 mg of NOVO C-30 cellulase and 0.10 mL of NOVO 250-L cellobiase were added to each of the pretreated samples and one of the feed samples. The other feed acts as a control. Samples (3 mL) were removed from each flask at 0, 0.25, 0.50, 1, 2, 4, 24, and 48 hours after initiation. Each 3-mL sample is stopped, after extraction, with 10  $\mu$ L of 72%  $H_2SO_4$  and refrigerated. After ~12 hours, each sample was neutralized with barium carbonate and centrifuged. The supernatant was analyzed by HPLC.

Dr. G. H. Emert used a proprietary enzymatic simultaneous saccharification fermentation (SSF) process (5,6) after a particle-size reduction (PSR) step. This process uses a crude enzyme extract produced from Trichoderma reesii and the simultaneous fermentation of glucose to ethanol to reduce the effects of end-product inhibition on the cellulose complex.

We performed acid hydrolyses using (98%)  $H_2SO_4$  and (37%) HCl. For the former, the moisture content of the SCO was determined to be 69.1% by drying overnight in a vacuum oven. A 250-g reaction mixture was then prepared by mixing 80.9 g of SCO (25 g by equivalent), 25 g of 98%  $H_2SO_4$ , and 144.1 g of distilled water. The reaction was immediately submerged in a 100 °C water bath for 2 hours. Then, the reaction mixture was filtered through a Büchner funnel. The filtrate was neutralized with  $CaCO_3$  and analyzed by HPLC.

The HCl hydrolysis was carried out under the following conditions. Dry SCO (10 g) was mixed with 90 g 37% of HCl and placed in a shaker for 2 hours. Cellulose was assayed by the method of Updegraff (7). Glucose was assayed by HPLC and the spectrophotometric method of Scott (4).

We performed an SSF using S. cerevisiae (ATCC 4132) alone and S. cerevisiae and C. wickerhamii together by the following method. Initially, all SCO samples were autoclaved at 121 °C for 15 minutes. Each fermentation flask contained, by weight, 50% SCO (determined to be 14% solids, 7.5% cellulose, 36% moisture), 0.2% yeast extract, 0.4% Miles Tv cellulase, tap water, and 10% yeast culture inoculum to yield a total medium weight of 75 g. Samples containing S. cerevisiae, S. cerevisiae, and C. wickerhamii and an uninoculated control were incubated at 35 and 49 °C. Samples were taken at 72, 96, 120, and 144 hours and analyzed for ethanol by HPLC.

### 3. RESULTS AND DISCUSSION

We have performed a technical and economic evaluation of the PVSS process for classifying and sterilizing MSW. This process efficiently separates the inorganic fraction (ferrous, nonferrous, etc.) from the organic fraction. Both fractions leave the processor sterilized, which greatly reduces the health hazards associated with MSW handling and landfilling. The technology exists for further separation and classification for recycling of the inorganic fraction, that is, as ferrous, aluminum, glass, and plastics. The steam-classified organic (SCO) fraction is readily converted to glucose by either acid or enzymatic hydrolysis and subsequently to ethanol by fermentation.

#### 3.1. MSW Processing

During our investigation we have processed 30.5 tons of MSW and 1.5 tons of sewage, generated in Jefferson County, through a PVSS pilot plant. The MSW is separated into three fractions with an average of 43% in the organic fraction, 43% in the organic-inorganic mix, and 14% in the inorganic fraction. The organic fraction (Fraction 1) is similar to the paper pulp and passes through a 1/2-in. screen opening. The organic-inorganic mix (Fraction 2) is between 2 in. and 1/2 in. and can be reprocessed with 60% of the mix separated into an organic fraction and 35% of the mix separated into an inorganic fraction. Fraction 3 contains primarily recyclable glass and metal. The volume of the MSW was reduced 55% by PVSS processing. Utilization of all fermentable or recyclable components would yield an estimated 90% volume reduction. We have determined that the PVSS process requires  $\sim 2.3 \times 10^6$  Btu/ton of MSW processed, with most of this energy being recovered. Table 1 compares the lignocellulosic components of processed MSW to those of other biomass materials.

#### 3.2. MSW Assessment

Table 2 shows the composition of the average MSW based on consumer purchases. One column shows a comparison for a short-term assessment in 1980 of the MSW of southwest Jefferson County, Alabama. As seen by the differences in Jefferson County, it cannot be assumed that any two raw material sources are equivalent. The waste produced by a modern industrial city can vary greatly with the climate, the nature of its people's lifestyles, and the industrial and commercial facilities located in the region. Before any significant investment is made in the use of this or any process for municipal solid waste management, it must be demonstrated that the products of this process performed on locally produced waste is indeed useful in standard methods for hydrolysis and fermentation.

Moisture analysis (Table 3) of the Birmingham MSW revealed the water content of each component. From 100 tons of MSW, 19.91 tons of water was measured; thus, the moisture content of the MSW was about 20% by weight. However, it is evident from the data that the moisture contained in the MSW is found only in the components that are composed either wholly or partially of natural organic materials. Therefore, the inorganic components (glass, ceramic, and metal) can be readily quantitated on a dry-weight basis, even in the original MSW. Furthermore, the plastic component of the organic portion of the MSW which is composed of 100% synthetic material also does not contain significant moisture and, likewise, can be readily quantitated on a dry-weight basis in the original MSW. The textile and leather/rubber components are assumed for this treatise to be composed of 50% natural organic materials and 50% synthetic

TABLE 1. THE COMPOSITION OF PROCESSED MSW  
AND OTHER SELECTED BIOMASS MATERIALS<sup>a</sup>

Material	Approximate composition, % dry weight		
	Hemicellulose	Cellulose	Lignin
Coniferous wood	20-30	40-50	25-35
Deciduous wood	30-40	40-50	15-20
Corn stover	28.1	36.5	10.4
Wheat straw	50.0	30.0	15.0
Red clover hay	20.6	36.7	15.1
Bagasse	20.4	41.3	14.9
Cotton	2.0	94.0	0
Oat hulls	20.5	33.7	13.5
Nut shells	25-30	25-30	30-40
Newsprint	18.0	55.5	25.0
Processed MSW	5.0	45-55	14-18

<sup>a</sup>Adapted from various sources.

TABLE 2. COMPARISON OF JEFFERSON COUNTY MSW TO EPA  
PROJECTED NATIONAL AVERAGE, PERCENT BY WEIGHT

Component	EPA national average, 1973	EPA national average, 1975	EPA 1980 projected averages	Jefferson County MSW, 1980
Cardboard	39.6	34.9	37.75	38.08
Newspaper				
Misc. paper				
Plastics	4.1	3.8	4.44	6.62
Leather, rubber	2.7	2.6	2.6	0.88
Textiles (rags, etc.)	1.6	1.7	1.7	5.05
Lumber	3.6	3.8	3.8	1.08
Yard wastes	14.1	16.3	16.3	6.95
Ceramics, stones	1.5	1.6	1.6	0.93
Food wastes	13.3	14.9	12.15	18.58
Glass	10.3	10.5	10.18	14.63
Ferrous metal	9.9	9.8	9.48	7.19
Aluminum & other metals				

TABLE 3. COMPOSITION PER 100 TONS MSW (JEFFERSON COUNTY, ALABAMA),  
CORRECTED FOR MOISTURE

Component	Tons component (as received)	% moisture of component	Tons water of component	Dry weight, tons component
<u>Organic</u>				
Cardboard	8.11	5.0	0.41	7.70
Newspaper	12.57	6.0	0.75	11.82
Misc. paper	17.40	5.5	0.96	16.44
Lumber	1.08	10.0	0.11	0.97
Yard wastes	6.95	47.9	3.33	3.62
Food wastes	18.57	70.0	13.00	5.57
Textiles	5.05	25.0	1.26	3.79
Leather/rubber	0.88	10.0	0.09	0.79
Plastics	6.62	0.0	0.00	6.62
Total organics	77.23	25.8	19.91	57.32
<u>Inorganic</u>				
Glass	14.63	0.0	0.00	14.63
Ceramics	0.93	0.0	0.00	0.93
Ferrous metals	5.25	0.0	0.00	5.25
Nonferrous metals	1.94	0.0	0.00	1.94
Total inorganics	22.75	0.0	0.00	22.75
<u>Organic &amp; Inorganic</u>	99.98	19.9	19.91	80.07

organic materials. There is moisture associated with the textile and leather/rubber components, although the water may be considered to associate principally with the natural materials.

Another correction deemed necessary to establish the quality of MSW for the PVSS process was the determination of the inorganic ash content of each of the components. Table 4 shows the percent ash and weight of ash for each com-

TABLE 4. COMPOSITION PER 100 TONS MSW (80.07 TONS DRY WEIGHT),  
CORRECTED FOR INORGANIC ASH CONTENT

Component	Dry weight, tons	% ash, dry- weight basis	Tons ash of component	Tons combustible
<u>Organic</u>				
Cardboard	7.70	5.3	0.41	7.29
Newspaper	11.82	1.5	0.18	11.64
Misc. paper	16.44	6.3	1.04	15.40
Lumber	0.97	2.1	0.02	0.95
Yard wastes	3.62	8.3	0.30	3.32
Food wastes	5.57	16.7	0.93	4.64
Textiles	3.79	2.6	0.10	3.69
Leather/rubber	0.79	11.4	0.09	0.70
Plastics	6.62	10.0	0.66	5.96
Total organics	57.32	6.5	3.73	53.59
<u>Inorganic</u>				
Glass	14.63	100.0	14.63	--
Ceramic	0.93	100.0	0.93	--
Ferrous metal	5.25	100.0	5.25	--
Nonferrous metal	1.94	100.0	1.94	--
Total inorganic	22.75	100.0	22.75	--
<u>Organic &amp; Inorganic</u>	80.07	33.1	26.48	53.59

ponent. The last column, labeled tons of combustibles, thus represents the true organic content of each component. A combination of the data in Tables 2 and 3 indicates that Jefferson County MSW is composed of about 53.6% organic materials, 26.5% inorganic materials, and 19.9% water.

TABLE 5. COMPOSITION OF 100 TONS MSW (53.59% TOTAL COMBUSTIBLE ORGANIC MATERIALS), BASED ON DISTINGUISHING BETWEEN THE SYNTHETIC AND NATURAL ORGANIC COMPONENTS

Component	Tons combustible materials	Tons synthetic organics	Tons biomass
Cardboard	7.29	--	7.29
Newspaper	11.64	--	11.64
Misc. paper	15.40	--	15.40
Lumber	0.95	--	0.95
Yard wastes	3.32	--	3.32
Food wastes	4.64	--	4.64
Textiles	3.69 <sup>a</sup>	1.85	1.85
Leather/rubber	0.70 <sup>b</sup>	0.35	0.35
Plastics	5.96 <sup>c</sup>	5.96	--
Total combustibles	53.59	8.16	45.43

<sup>a</sup>Assumes 50% natural fibers (cotton, wool) and 50% synthetic fibers.

<sup>b</sup>Assumes 50% leather and 50% rubber.

<sup>c</sup>Assumes 100% synthetic materials.

One additional correction worth consideration in determining the potential yields of materials from the PVSS process is to distinguish between the synthetic organic and natural organic (biomass) materials. Although minor constituents of every organic component are most likely of synthetic origin, the major components under consideration in this section are textiles, leather/rubber, and plastics. The combustible fraction of the plastic component should be considered 100% synthetic organic materials. The combustible fraction of the textiles and leather/rubber components, on the other hand, is assumed to be composed of 50% synthetic materials and 50% natural materials. Table 5 summarizes this information. The biomass component of this sample of MSW is, therefore, 45.43%.

Table 6 shows the composition of Birmingham SCO based on the previous analyses and the approximate carbohydrate expected for the various components.

TABLE 6. COMPOSITION OF BIRMINGHAM SCO (STEAM-CALSSIFIED ORGANICS)

Component	% dry weight of SCO	lb Component per ton SCO	Estimated % carbohydrate	Estimated lb carbohydrate
Cardboard	16.05	321.0	75.0	240.8
Newspaper	25.62	512.3	75.0	384.2
Misc. paper	33.90	678.0	75.0	508.5
Lumber	2.09	41.7	55.0	22.9
Yard wastes	7.30	146.2	55.0	80.4
Food wastes	10.20	204.2	40.0	81.7
Textiles	4.07	81.3	80.0	65.0
Leather	0.77	15.3	30.0	4.6
TOTALS	100.00	2000.0	69.4	1388.1

### 3.3. Analysis of SCO Material

After PVSS processing, several composite samples of SCO were sent to independent laboratories for feed analysis. The laboratories which participated were Analytical Labs and Services (Huntsville, AL); Deep South Laboratory (Montgomery, AL); and the University of Arkansas (Fayetteville, AR). The results for the composite Samples B445-124 and B445-126 series from runs 14-18 and 47-51 respectively are given in Table 7. The numbers presented are the results of individual analyses and their corresponding means and standard deviations. As indicated by the data presented in Table 7, the BOD analysis varied considerably among the different laboratories. The higher number is probably most accurate due to the high carbohydrate content and nutrient value of the samples. In addition, a comprehensive mineral analysis was completed for the SCO composite at the Institute and is presented in Table 8.

### 3.4. Acid Hydrolysis

We have conducted studies using various sulfuric and hydrochloric hydrolysis procedures. Also, samples have been sent to outside laboratories to examine several proprietary processes. Samples were sent to Auburn University, North Carolina State University, the University of Toronto, and the University

TABLE 7. SUMMARY OF FEED ANALYSIS FOR SCO COMPOSITE SAMPLES

Anal. Lab	Sample No.				
	B445-124-G	B445-124-H	B445-124-A	B445-126-E	B445-126-E
	a	b	c	a	b
Moisture	71.9	70.9	68.0	65.85	66.2
BOD	340.0	129,000.0	ND <sup>e</sup>	440.0	16950.0
Feed analysis (wt %) - dry basis					
fiber	70.28	76.4	66.3	64.91	72.2
cellulose	52.8	58.5	51.9	55.91	53.6
fat	5.2	4.50	5.3	2.77	5.3
protein	5.5	4.75	5.3	5.13	4.23
lignin	16.8	17.90	14.0	15.73	15.4
hemicellulose	0.42	ND <sup>e</sup>	0.4	8.14	3.20
ash	-- <sup>d</sup>	12.0	4.0	17.43	17.8
total carbohydrates	9.9	10.95	-- <sup>d</sup>	9.46	9.67
TOC	29.92	40.9	-- <sup>d</sup>	42.86	32.3
organic N	0.56	0.76	-- <sup>d</sup>	0.64	0.68
inorganic N	0.31	ND <sup>e</sup>	-- <sup>d</sup>	0.17	ND <sup>e</sup>
kjeldahl N	0.88	0.76	-- <sup>d</sup>	0.81	0.68
total solids	28.1	29.1	32.0	34.15	33.8

a Analytical Labs and Services, Incorporated.

b Deep South Laboratories.

c University of Arkansas.

d "--" = not determined.

e "ND" = not detectable.

TABLE 8. SUMMARY OF MINERAL ANALYSIS OF  
SCO COMPOSITE SAMPLE B445-124

Element	Method	Amount, ppm (dry basis)
Zinc	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	420.0
Iron	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	1745.0
Copper	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	26.4
Manganese	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	63.1
Cadmium	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	2.85
Lead	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	92.7
Nickel	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	6.45
Magnesium	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	810.0
Silver	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	98.5
Cobalt	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	6.6
Antimony	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	36.7
Thallium	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	<6.0
Vanadium	Flame AA (Air/C <sub>2</sub> H <sub>2</sub> )	<100.0
Calcium	Flame AA (N <sub>2</sub> O/C <sub>2</sub> H <sub>2</sub> )	5950.0
Chromium	Flame AA (N <sub>2</sub> O/C <sub>2</sub> H <sub>2</sub> )	52.5
Boron	Flame AA (N <sub>2</sub> O/C <sub>2</sub> H <sub>2</sub> )	<1000.0
Beryllium	Flame AA (N <sub>2</sub> O/C <sub>2</sub> H <sub>2</sub> )	<0.2
Sodium	Flame AE	3800.0
Potassium	Flame AE	2235.0
Arsenic	Furnace AA	2.535
Sulfur (SO <sub>4</sub> <sup>=</sup> )	Ion Chrom.	1530.0
Fluorine	Ion Chrom.	230.0
Selenium	Furnace AA	4.0
Mercury	Furnace AA	<0.42

of Arkansas for acid hydrolysis studies with their respective proprietary process. A comparison of hydrolysis conditions and results is presented in Table 9.

Dr. Y. Y. Lee, Department of Chemical Engineering, Auburn University, using a 12% H<sub>2</sub>SO<sub>4</sub> process at 190 °C for 3.5 min, achieved a hydrolyzate containing approximately 12% glucose. By calculation the sugar yield was 25 g of glucose per 100 g of oven-dried SCO. These results indicate a conversion of

TABLE 9. COMPARISON OF HYDROLYSIS CONDITIONS AND YIELDS FROM SCO

Process	Glucose concentration, g/L	Glucose/SCO, g/g	Actual conversion, (% cellulose to glucose)	Theoretical EtOH/ton MSW, gal	Actual EtOH/ton MSW, gal	Overall conversion efficiency, %
12% H <sub>2</sub> SO <sub>4</sub> <sup>b</sup> 190 °C; 3.5 min	49	0.25	43.3	20	20	43.2
~45% HCl <sup>c</sup> 50 °C; 30 min	ND <sup>d</sup>	0.471	71	32.6	ND	ND
4% SO <sub>2</sub> gas <sup>e</sup> 150-190 °C; 50 min	ND	0.341	55.2	25.6	ND	ND
Proprietary (HCl)	83.8	0.58	100	46.3	43	93
Proprietary (HCl)	86.3	0.60	104	48.2	44.8	96.7
Proprietary (HCl)	59.1	0.50	86.2	39.9	37.1	80
0.93% H <sub>2</sub> SO <sub>4</sub> <sup>f</sup> 240 °C; 8.41 sec	8.45	0.221	38	17.6	ND	ND
1.03% H <sub>2</sub> SO <sub>4</sub> (pretreatment) <sup>g</sup> 220 °C; NOVO C-30 enzymatic hydrolysis	18.26	0.453	78.1	36.16	ND	ND
PSR <sup>g</sup> (pretreatment) <sup>h</sup> SSF 48 h	54.68	0.482	81.2	37.5	37.5	81
10% H <sub>2</sub> SO <sub>4</sub> <sup>i</sup> 100 °C; 2 h	4.5	0.10	17.1	7.91	ND	ND
37% HCl <sup>i</sup> 27 °C; 2 h	31.3	0.269	46.3	21.4	ND	ND
PSR (pretreatment) <sup>i</sup> SSF 72 h	24	0.35	61	28.2	28.2	61

<sup>a</sup>As received<sup>b</sup>Dr. Y. Y. Lee, Dept. of Chem. Eng., Auburn University<sup>c</sup>Dr. I. S. Goldstein, Dept. Wood & Paper Science, North Carolina State University<sup>d</sup>No data<sup>e</sup>Dr. M. Wayman, Dept. of Chem. Eng., University of Toronto<sup>f</sup>Dr. A. O. Converse, Thayer School of Eng., Dartmouth College<sup>g</sup>Particle size reduction<sup>h</sup>Dr. G. H. Emert, Biomass Research Center, University of Arkansas<sup>i</sup>Southern Research Institute, Biotechnology Division

approximately 43.3% of the total theoretical yield and would result in approximately 20 gal of ethanol being produced per ton of MSW, as received.

Dr. I. S. Goldstein, Department of Wood and Paper Science, North Carolina State University, using an ~45% HCl process at 50 °C for 30 min, achieved a conversion of approximately 75%, which would yield approximately 34 gal ethanol/ton MSW as received.

Dr. M. Wayman, Department of Chemical Engineering and Applied Chemistry, University of Toronto, using 4% SO<sub>2</sub> as the hydrolyzing agent at 150-190 °C for a total of 50 min, achieved approximately 55% hydrolysis, which converts to 25.6 gal ethanol/ton MSW as received.

Dr. J. L. Gaddy and Dr. E. C. Clausen, Department of Chemical Engineering, University of Arkansas, have carried out a series of hydrolysis experiments on the SCO fraction using a proprietary process. The results of these experiments indicate that approximately 0.5 g of glucose and 0.1 g of xylose may be obtained per gram of dried SCO material with a one-step process. By calculation this yield is approximately 86% with respect to theoretical and would yield approximately 40 gal ethanol/ton MSW as received.

In our laboratory, we have conducted studies to examine the effect of solids ratio and H<sub>2</sub>SO<sub>4</sub> concentration on hydrolysis. With a reaction time of 2 hours at 100 °C, acid hydrolysis was performed on 10 wt % slurries of SCO and α-cellulose. Concentrations of 1, 5, 10, 20, and 40% wt/wt H<sub>2</sub>SO<sub>4</sub> were used. From these data it was confirmed that 10 to 20 wt % is the optimal acid concentration for SCO hydrolysis under these conditions, although the yields are relatively low (Table 8). The maximum glucose yield is seen with 10 wt % H<sub>2</sub>SO<sub>4</sub>, and this yield is 0.1 g glucose/gram dried SCO. This represents approximately 17% hydrolysis and would convert to approximately 8 gal ethanol being produced per ton of MSW as received.

We have also examined the Uric-Rheinau HCl process using super-concentrated HCl (37-43%) at ambient temperature. Hydrolysis is carried out with 10 wt % slurries of SCO and 37 and 43% HCl. The results (Table 9) indicate that, by using 37% HCl, glucose yields are 0.27 g of glucose per gram of dried SCO material. By calculation this represent 46% hydrolysis of theoretical cellulose or 21 gal ethanol/ton MSW as received.

### 3.5. Enzymatic Hydrolysis

The enzymatic hydrolysis of the cellulose component of SCO has also been explored. Again, these studies were conducted both "in house" and at outside laboratories to examine proprietary processes. Composite samples of SCO were sent to Dartmouth College and the University of Arkansas for hydrolysis by their respective proprietary enzymatic processes. Again, a comparison of the conditions and results of these processes is presented in Table 9.

Dr. A. O. Converse, Thayer School of Engineering, Dartmouth College, using a 1.03% H<sub>2</sub>SO<sub>4</sub> pretreatment at 220 °C followed by treatment with NOVO C-30 cellulase, achieved a conversion of 0.453 gram glucose/gram dried SCO. This relates to approximately 78% conversion and would yield 36 gal ethanol being produced per ton MSW, as received.

Dr. G. H. Emert, Biomass Research Center, University of Arkansas, using only a PSR pretreatment followed by a simultaneous saccharification

fermentation process, achieved 0.48 g glucose/gram dried SCO. This converts to approximately 81% conversion of theoretical and results in almost 38 gal of ethanol being produced per ton of MSW, as received.

In our laboratory we too have conducted enzymatic hydrolysis studies using PSR pretreatment followed by an SSF process. Using this procedure, we obtained 0.35 g glucose/gram dried SCO which relates to a 61% conversion of theoretical. By calculation this would result in the production of over 28 gal of ethanol produced per ton of MSW, as received.

#### 4. CONCLUSIONS

- PVSS process efficiently separates the inorganics from the organic fraction of MSW, thus enhancing the recyclability of metals contained therein.
- PVSS process produces a cost-effective, high-value feed stock from a material having a negative environmental value.
- SCO produced can be hydrolyzed by either acid or enzymatic process to glucose and subsequently to ethyl alcohol.
- PVSS process reduces the material to be landfilled by as much as 90%.
- The recyclability of metals coupled with the production of chemicals from waste source and the advantage of landfilling substantially less material makes for a source of revenue to city and county governments which cannot be ignored.

As a final consideration, MSW is an environmental concern to which we in the U.S. must find a solution due to a rapidly dwindling availability of landfill areas. The cellulose-to-chemicals industry, coupled with MSW classification, represents one possible solution wherein metals may be recycled and cellulose may be converted to useful chemicals while landfill requirements are reduced by 90% or more.

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