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**CONVERSION OF MUNICIPAL
AND INDUSTRIAL REFUSE INTO USEFUL
MATERIALS BY PYROLYSIS**



UNITED STATES DEPARTMENT OF THE INTERIOR

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By W. S. Sanner, C. Ortuglio, J. G. Walters,
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CONVERSION OF MUNICIPAL AND INDUSTRIAL REFUSE INTO USEFUL MATERIALS BY PYROLYSIS

by

W. S. Sanner,¹ C. Ortuglio,² J. G. Walters,² and D. E. Wolfson³

ABSTRACT

Pyrolysis (destructive distillation) techniques developed at the Bureau of Mines to determine the yield and quality of the products from coal were used to convert municipal (household) and industrial refuse into potentially useful solids, liquids, and gases without adding to environmental pollution. The tests demonstrated that a ton of municipal refuse can be converted into 154 to 424 pounds of solid residue, 0.5 to 6 gallons of tar, 1 to 4 gallons of light oil, 97 to 133 gallons of liquor, 16 to 32 pounds of ammonium sulfate, and 7,380 to 18,058 cubic feet of gas. A ton of industrial refuse, consisting of paper, rags, and cardboard, can be converted to 618 to 838 pounds of residue, 1.5 to 3 gallons of light oil, 68 to 75 gallons of liquor, 12 to 23 pounds of ammonium sulfate, and 9,270 to 14,065 cubic feet of gas. The energy from the gas is more than sufficient to provide the heat for the pyrolysis.

INTRODUCTION

The increasing generation of solid wastes in the United States has created disposal problems that require urgent but technically sound solutions. It is estimated that 350 million tons of solid waste is generated from residential, commercial, and industrial sources in the United States each year. Residential waste accounts for about 160 million tons, and commercial and industrial wastes account for the remaining 190 million tons. By 1976 residential waste has been predicted to be 215 million tons.⁴ Sites for sanitary landfill are harder to obtain, and this method of waste disposal is becoming increasingly suspect as a polluter of ground water.⁵ Increased incineration,

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⁴U.S. Public Health Service. The Role of Packaging in Solid Waste Management, 1966-1976. Publication 1855, 1969, pp. 110-113.

⁵Qasim, Syed R., and Jerry C. Burchinal. Leaching From Simulated Landfills. J. Water Pollution Control Federation, v. 42, No. 3, March 1970, pp. 371-379.

as presently practiced, adds to air pollution, and conversion of residential refuse to compost by aerobic digestion has presently not been accepted in the United States.

For many years the Bureau has operated a unique pilot plant, the BM-AGA (Bureau of Mines-American Gas Association) apparatus, to determine the carbonizing properties of coal by means of destructive distillation (pyrolysis). The plant is equipped with a complete byproduct recovery train, and it produces enough solid, liquid, and gaseous products for analysis and processing. Virtually any carbonaceous material that can be volatilized can be pyrolyzed in the BM-AGA apparatus, and engineering data can be obtained for basic evaluation of the economics of the process.

These pyrolysis techniques were recently demonstrated to be feasible for disposal of scrap tires.⁶ This report describes the results of experiments begun in July 1969 to dispose of municipal (household) and industrial wastes by similar methods. By pyrolysis at elevated temperatures, the wastes are converted into usable or more manageable solid, liquid, and gaseous forms without contributing to land, air, or water pollution. Some possible uses of the solid residue are landfill, soil conditioner, briquetted fuel, and filter medium. The liquid fractions may be a source of usable chemicals; the gas could be used as the source of heat for the pyrolytic reaction.

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The authors wish to thank Daniel Detwiler, manager of the Altoona, Pa., Fairfield Aerobic Mulch (FAM) Plant, operated by Fairfield Engineering Company of Marion, Ohio, for his cooperation in allowing the Bureau to collect the samples of shredded municipal refuse used in these experiments. Special appreciation is also expressed to Paul M. Sullivan of the Bureau of Mines, College Park, Md., Metallurgy Research Center, for supplying the industrial refuse samples.

ANALYSIS OF MUNICIPAL AND INDUSTRIAL REFUSE

With an abundance of municipal refuse ever present and increasing in our society, it was not a problem to procure refuse samples, but rather one of getting a representative sample of the diversity of wastes that end up as municipal refuse. Of late, there has been considerable discussion of the merit of shredding (a grinding-mixing operation) refuse prior to disposal by landfill, incineration, etc., but the Bureau learned that none of the refuse disposal facilities in the industrialized Pittsburgh area, where the tests were conducted, was equipped to shred refuse. However, such equipment was available at the Fairfield Aerobic Mulch (FAM) Plant at Altoona, Pa., operated by Fairfield Engineering Company, Marion, Ohio, where a representative sample was obtained.

⁶Wolfson, D. E., J. A. Beckman, J. G. Walters, and D. J. Bennett. Destructive Distillation of Scrap Tires. BuMines Rept. of Inv. 7302, 1969, 19 pp.

At the Fairfield plant, all household refuse from the City of Altoona is converted into humus builder by aerobic digestion. By municipal ordinance, householders must keep metals, glass wastes, and plastic containers separate from other wastes so that the refuse processed consists mainly of food waste, paper, rags, and plastic film. In the processing plant, which is the only one of its kind in Pennsylvania, 40 to 50 tons of refuse per day is dumped from collection trucks into a receiving hopper, moved by chain conveyor to a hammermill, where it is shredded, and discharged to the belt feeding the aerobic digester. A magnetic separator removes small metallics such as bottle caps that slip through the refuse collection system. Representative samples of raw, shredded refuse were taken from the feed belt over a 2-hour period, placed in plastic bags, and returned to the Bureau's laboratory, where they were kept frozen until several days before they were pyrolyzed.

Plastic materials are removed from the finished mulch by air separation and screening, and since disposal of plastic waste is also a major problem, representative samples of this material were collected. This was the second type of material used in the investigation.

The third refuse material pyrolyzed was shredded industrial refuse, which originated in Madison, Wis. The refuse samples were shredded in two types of equipment, distinguished throughout this study by "Heil mill" and "Gondard mill," and were kept separate to maintain their identities in the pyrolysis tests. Metallics from the industrial refuse were removed prior to pyrolysis.

Each of the refuse materials was analyzed before pyrolysis. The average analyses of each material used in the investigation are shown in table 1. The samples were pyrolyzed as received. The moisture content in the municipal (household) refuse and the plastics was about 43 percent, and the ash content was 7 to 8 percent. In contrast, the industrial refuse contained about 20 to 30 percent moisture and 29 percent ash. The available heat per ton of refuse (as-received basis) was 9.6 to 10.6 million Btu for municipal refuse and 6.8 to 9.1 million Btu for industrial refuse.

TABLE 1. - Average analyses of refuse used in pyrolysis
(destructive distillation) tests

	Raw municipal refuse		Processed municipal refuse containing plastic film		Heil mill industrial refuse		Gondard mill industrial refuse	
	As received	Dry	As received	Dry	As received	Dry	As received	Dry
Proximate, percent:								
Moisture.....	43.3	-	42.3	-	20.5	-	33.2	-
Volatile matter....	43.0	76.3	44.3	76.8	40.3	49.7	33.5	50.6
Fixed carbon.....	6.7	11.7	5.6	9.7	9.9	12.3	4.6	7.0
Ash.....	7.0	12.0	7.8	13.5	29.3	38.0	28.7	42.4
Total.....	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ultimate, percent:								
Hydrogen.....	8.2	6.0	7.6	5.0	6.0	4.6	6.2	3.8
Carbon.....	27.2	47.6	27.2	47.3	27.5	33.9	20.6	31.2
Nitrogen.....	.7	1.2	.8	1.4	.5	.7	.5	.7
Oxygen.....	56.8	32.9	56.5	32.6	36.4	22.4	43.9	21.8
Sulfur.....	.1	.3	.1	.2	.3	.4	.1	.1
Ash.....	7.0	12.0	7.8	13.5	29.3	38.0	28.7	42.4
Total.....	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Btu per pound of refuse.....	4,827	8,546	5,310	9,180	4,570	5,645	3,415	5,155
Available Btu per ton of refuse, millions.	9.654	17.092	10.620	18.360	9.140	11.290	6.830	10.310

PYROLYSIS PILOT PLANT AND TEST PROCEDURES

The experiments were conducted in the pilot plant shown pictorially in figure 1 and schematically in figure 2. The plant consists essentially of an electric furnace, cylindrical steel retort, condensing and scrubbing train for product recovery, and gas-metering and sampling devices.

The electric furnace (2) is 26 inches inside diameter and 48 inches deep and is heated by nickel-chromium resistors spaced evenly in the furnace wall. The retort (3) is 18 inches in diameter and 26 inches deep and is made of 16-gage steel in the wall and 10-gage steel in top and bottom. Gases and vapors exit from the retort through a 2-inch-diameter offtake pipe and enter an air-cooled trap (4), where tar and heavy oils are collected. The gases and vapors are cooled to room temperature in two water-cooled condensers (5) connected in series, where additional heavy oil and liquor are collected. Final traces of heavy-oil mist are removed by one of the alternate electrostatic

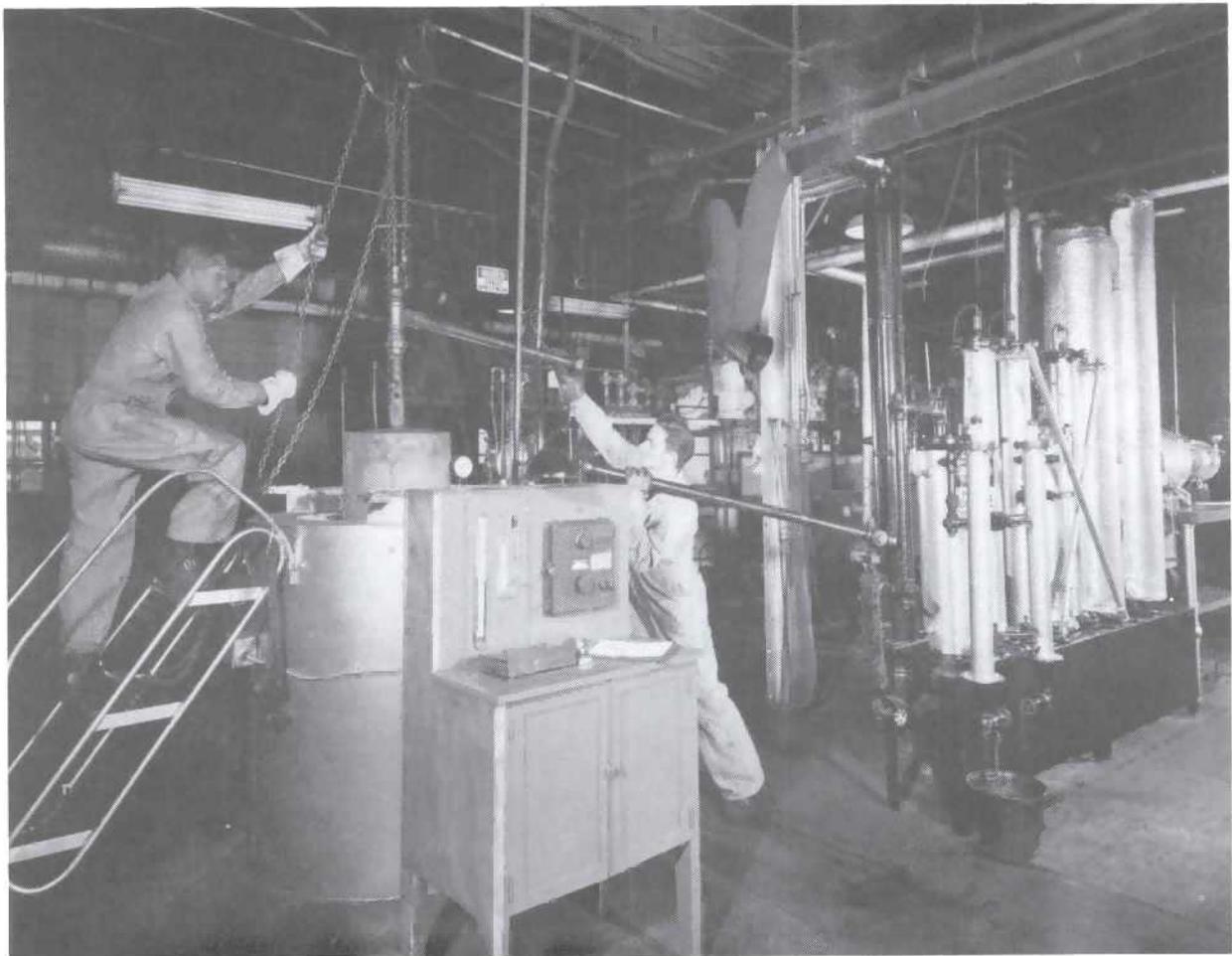


FIGURE 1. - Pilot Plant Used To Pyrolyze Refuse. Operator on left is lowering the retort into furnace as operator on right prepares to connect the gas offtake pipe to the distillation train.

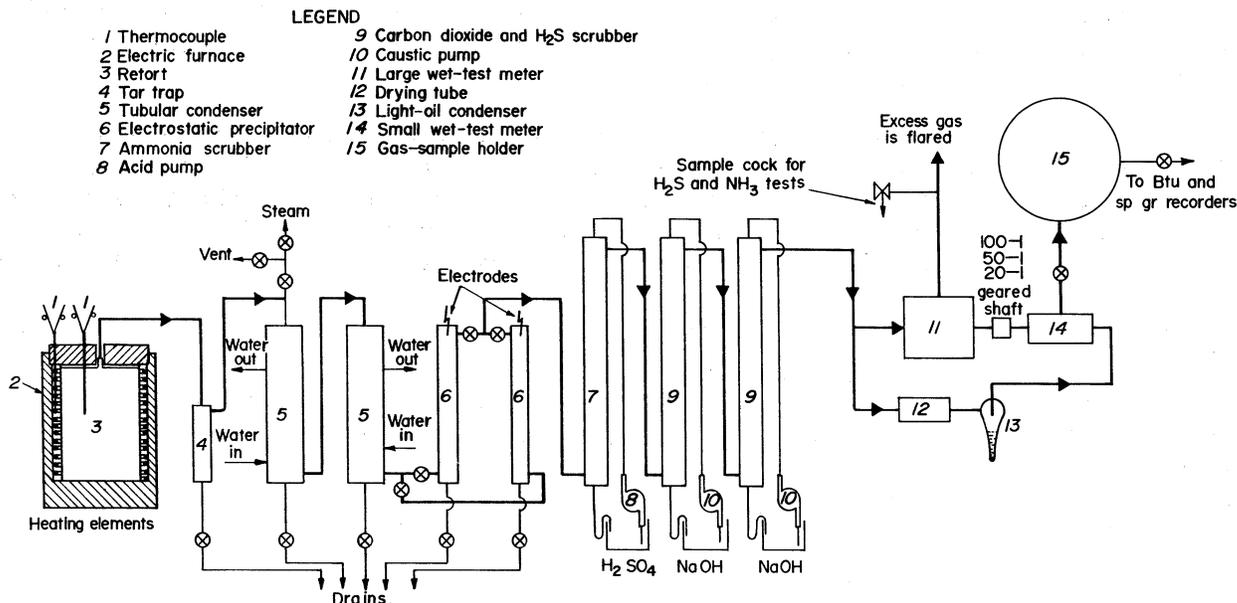


FIGURE 2. - Flow Diagram of Pilot Plant Used To Pyrolyze Municipal and Industrial Refuse.

precipitators (6). The gas then passes successively through packed scrubbers, where ammonia is removed with sulfuric acid (7), and carbon dioxide and hydrogen sulfide are removed with caustic soda solution (9). The scrubbed gases pass to the large (11) and small (14) meters, which are geared together so that 99 percent of the gas passes through the large meter and is flared. The suction side of the small meter is cross-connected to the inlet side of the large meter so that 1 percent of the gas passes through a drying tube (12) and a condenser (13) immersed in acetone and solid carbon dioxide, where light oil is removed. Light oil recovered from the gas that passes through the small meter is calculated to the total gas yield. The gas from the condenser passes through the small meter (14) to the gas holder (15), and representative samples are taken from the holder for analyses. Steam is used to purge the condensers and piping at the conclusion of the test.

In a test, the retort, with the bottom open, was inverted and a mesh screen was inserted below the retort exit pipe to prevent large refuse particles from being entrained in the gas stream, especially when the retort was placed in the furnace; then, expanding gases, steam, and volatile components are formed rapidly. The retort was then filled with a weighed charge and the bottom was welded in place. Altoona raw municipal refuse averaged 80 pounds per charge, or a bulk density of 24 pounds per cubic foot; Altoona processed refuse containing plastic film averaged 54 pounds per charge, or a bulk density of 16 pounds per cubic foot; and the industrial refuse averaged 64 pounds per charge, or 17 pounds per cubic foot bulk density.

The retort was lowered into the pyrolysis furnace, which had been preheated to 50° C above the desired temperature to allow for heat loss in charging. The retort wall was held at constant temperature ($\pm 5^\circ$ C) by automatic control of the power input. (The control is activated by a thermocouple (1) located on the retort wall midway between top and bottom.)

A test ended when gas evolution reached a rate that could no longer support combustion at the waste-gas burner. Depending on the test material and temperature, a test lasted 6 to 12 hours.

The refuse samples were pyrolyzed at various temperatures to determine the effect of temperature on the yield and quality of products. In the first series, the charge was inserted into the furnace at 500° C and the temperature was increased at 2° to 3° C per minute to 900° C; in the second series, each kind of refuse was pyrolyzed at two constant temperatures, 750° and 900° C.

YIELDS OF PRODUCTS FROM PYROLYSIS OF REFUSE

Tar, heavy oil, and liquor were collected from the air-cooled condenser, water-cooled condensers, and the electrostatic precipitator. Light oil was collected from the carbon dioxide-acetone condenser after the heavy oils had been removed and the gas had passed through the acid and caustic scrubbers. Residue remained in the retort after the test. Total gas, the sum of readings from both meters, was corrected to 60° F and 30 inches of mercury pressure.

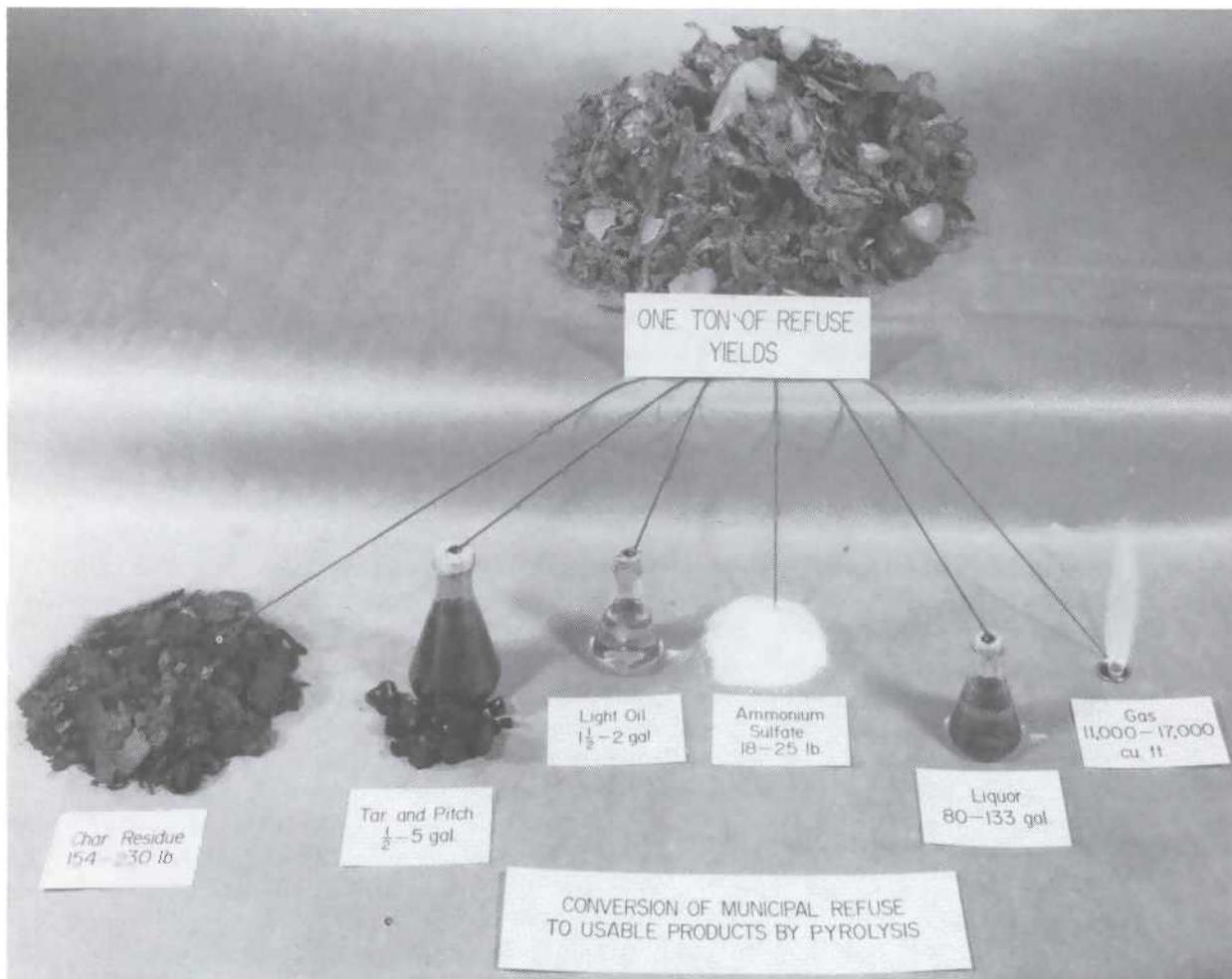


FIGURE 3. - Products From Pyrolysis of Refuse.

Figure 3 shows the products obtained from pyrolysis; the numerical yields are given in table 2. A ton of municipal refuse pyrolyzed at 900° C yielded 154 pounds (7.7 percent of refuse charge) of solid residue, 0.5 gallon of tar, 114 gallons of liquor, 25 pounds of ammonium sulfate, and 17,741 cubic feet of gas. Pyrolysis at 750° C increased tar production to 2.6 gallons per ton and light oil to 2.5 gallons per ton, but showed a marked decrease in gas production to 9,628 cubic feet per ton, which was slightly more than half that obtained at 900° C. Pyrolysis starting at 500° C and increasing to 900° C yielded the largest amount of tar (4.8 gallons per ton), but the gas yield was 11,509 cubic feet, which was intermediate to that obtained at the other two temperatures.

Pyrolysis at 900° C of a ton of municipal refuse containing mainly plastic film yielded 382 pounds (19.0 percent of refuse charge) of solid residue, 1.4 gallons of tar, 0.6 gallon of light oil, 97.4 gallons of liquor, 31.5 pounds of ammonium sulfate, and 18,058 cubic feet of gas. At 750° C, gas production decreased to 7,380 cubic feet, less than half that obtained at 900° C, and tar and light-oil production increased. Pyrolysis through a temperature range of 500° to 900° C yielded the largest quantity of tar, 5.6 gallons per ton, and 11,545 cubic feet of gas.

A ton of industrial refuse pyrolyzed at 900° C and containing mainly paper, rags, cardboard, and small amounts of metals yielded 618 pounds (30.9 percent of refuse charge) of solid residue, small amounts of tar, 1.4 gallons of light oil, 68.5 gallons of liquor, 22.9 pounds of ammonium sulfate, and 14,065 cubic feet of gas. Pyrolysis of industrial refuse at lower temperatures generally increased tar and light-oil yields but did not result in the marked decreases in gas production that were obtained when municipal refuse was pyrolyzed at the lower temperatures.

Solid Residue

The residue, as seen in figure 3, is a lightweight, flaky char, and all samples could be readily sieved to remove extraneous materials such as bottle caps, tin can lids, and aluminum. The municipal refuse contained less than 1.5 percent of such materials, the plastics about 7 percent, and the industrial refuse contained 2 to 3 percent extraneous materials.

The analyses of the residues are given in table 3. The processed municipal refuse containing mainly plastics yielded char with the highest fixed carbon (56.7 percent) and heating value (17.7 million Btu per ton). The industrial refuse from both shredding mills produced a char with the lowest fixed carbon and heating values; they ranged from 9.7 to 17.0 percent fixed carbon and from 3.3 to 5.8 million Btu per ton, respectively. The sulfur content of the residues did not exceed 0.2 percent with the exception of the one containing plastics, in which it ranged from 0.1 to 0.4 percent.

TABLE 2. - Yields of products from pyrolysis of municipal and industrial refuse

Refuse	Pyrolysis temp., ° C	Yields, weight-percent of refuse				Yields per ton of refuse					
		Residue	Gas	Tar	Light oil in gas	Total	Gas, cubic feet	Tar, gallons	Light oil in gas, gallons	Liquor, gallons	Ammonium sulfate, pounds
Raw municipal.....	500-900	9.3	26.7	2.2	0.5	94.6	11,509	4.8	1.5	133.4	17.9
	750	11.5	23.7	1.2	.9	92.3	9,628	2.6	2.5	131.6	23.7
	900	7.7	39.5	.2	.03	95.2	17,741	.5	-	113.9	25.1
Processed municipal containing plastic film.	500-900	21.2	27.7	2.3	1.3	93.2	11,545	5.6	3.7	96.7	16.2
	750	19.5	18.3	1.0	.9	91.2	7,380	2.2	2.6	122.6	28.4
	900	19.1	40.1	.6	.2	95.3	18,058	1.4	.6	97.4	31.5
Heil mill industrial.....	500-900	36.1	23.7	1.9	.5	93.9	9,563	4.1	1.4	75.2	12.5
	750	37.5	22.8	.7	.9	92.5	9,760	1.5	2.6	73.0	19.5
	900	38.8	29.4	.2	.6	90.8	12,318	.5	1.6	51.1	21.7
Gondard mill industrial.	500-900	41.9	21.8	.8	.6	94.6	9,270	1.7	1.6	70.2	20.4
	750	31.4	25.5	.8	.8	90.0	10,952	1.8	2.2	74.9	21.2
	900	30.9	31.5	.1	.5	92.0	14,065	.02	1.4	68.5	22.9

TABLE 3. - Chemical analyses¹ of solid residues from pyrolysis of municipal and industrial refuse

Refuse	Pyrolysis temp., ° C	Proximate, percent			Fixed carbon		Ash		Ultimate, percent			Heating value, million Btu/ton
		Moisture	Volatiles	Fixed carbon	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur	Heating value, Btu/lb		
Raw municipal.....	500-900	2.6	4.4	29.6	0.4	66.0	0.5	0.5	0.2	5,020	10.040	
	750	2.2	7.4	51.4	.8	41.2	1.1	1.8	.2	8,020	16.040	
	900	1.0	4.7	31.7	.3	63.6	.5	.0	.2	5,260	10.520	
Processed municipal containing plastic film.	500-900	1.7	4.8	56.7	.6	38.5	.8	2.1	.3	8,800	17.700	
	750	1.3	13.4	34.6	.8	52.0	.8	4.4	.1	6,080	12.160	
	900	1.2	3.3	53.5	.5	43.2	.7	1.8	.4	8,090	16.180	
Heil mill industrial.....	500-900	.9	2.6	15.2	.3	82.2	.1	.2	.2	2,520	5.040	
	750	1.2	5.1	17.0	.5	77.9	.2	1.8	.2	2,900	5.800	
	900	.1	2.5	12.9	.3	84.6	.2	.0	.2	2,180	4.360	
Gondard mill industrial.	500-900	.3	3.0	9.7	.2	87.3	.1	.4	.2	1,660	3.320	
	750	1.0	3.6	16.6	.3	79.8	.2	.0	.2	2,680	5.360	
	900	.2	6.4	16.2	.4	77.4	.3	2.4	.2	2,810	5.620	

¹Moisture on as-received basis; all other data on dry basis.

Aside from the indications that pyrolysis can convert obnoxious and harmful municipal and industrial refuse to a harmless char, the reduction in the amount of the initial waste material is noteworthy. Solid municipal refuse can be reduced in weight by 90 percent to a solid char, municipal plastic refuse by 80 percent, and industrial wastes by 65 percent. Tests have shown that the residue from municipal refuse can be readily briquetted with a starch binder. These briquets ignite easily and burn under normal atmospheric conditions. The residue is adequate for filtering sewage sludge and is also being examined as a filter medium for removing organic substances from the waste liquor produced during pyrolysis.

Gas

The analyses of the gases from the pyrolysis of the various types of refuse are given in table 4. The major constituents are hydrogen, carbon monoxide, methane, and ethylene, in that order. Pyrolysis at 750° C yielded gas with the highest heating values for both municipal and industrial refuse, but pyrolysis at 900° C yielded more available heat per ton of refuse because of the larger volume of gas produced at the higher temperature. For example, municipal refuse provided 7.93 million Btu per ton at 900° C as compared to 5.42 million Btu at a pyrolysis temperature of 750° C. Municipal refuse containing plastics yielded 9.23 million Btu per ton at 900° C, compared to 4.20 million Btu at 750° C, and industrial refuse yielded 6.13 million Btu per ton at 900° C, compared to 5.05 million Btu at 750° C.

The properties of the gas produced during pyrolysis relate significantly to the requirements of the pyrolytic process itself. The raw municipal refuse, for example, yielded gas containing as much as 25 percent carbon monoxide, 17.6 percent methane, and 10.4 percent ethylene. If all carbon dioxide had been removed by scrubbing, those values would have increased to 31.0, 21.6, and 13.0 percent, respectively. Preliminary calculations indicate that about 2 million Btu may be required to pyrolyze a ton of municipal refuse at 900° C. With approximately 8 million Btu available from the gas produced per ton of refuse, more than enough gas is available to sustain the gas requirements of the process.

Tar

The tars were dehydrated and characterized according to the procedures of Reynolds and Holmes.⁷ The tests at 900° C did not yield sufficient tar for analysis. The data for the tars that were analyzed are given in table 5. The greater part of the tar distillate was neutral oil for the municipal as well as industrial refuse. Pyrolysis of municipal refuse at 500° to 900° C produced a tar distillate containing 31.9 percent neutral oil. However, at 750° C the tar distillate from the industrial refuse contained 38.3 percent neutral oil. The distillate oils from all refuse materials contained 16 to 25 percent olefins, 62 to 80 percent aromatics, and 3 to 14.5 percent paraffins and naphthenes. The yields of the tar components per ton of refuse are given in table 6.

⁷Reynolds, D. A., and C. R. Holmes. Procedure and Apparatus for Determining Carbonizing Properties of American Coals by the Bureau of Mines-American Gas Association Method. BuMines Tech. Paper 685, 1946, 35 pp.

TABLE 4. - Analyses of gases from pyrolysis of municipal and industrial refuse

	Raw municipal refuse		Processed municipal refuse containing plastic film		Heil mill industrial refuse		Gondard mill industrial refuse	
	500-900	750 900	500-900	750 900	500-900	750 900	500-900	750 900
Pyrolysis temp.....° C..								
Analysis, vol pct:								
Hydrogen.....	45.47	30.86	44.86	25.27	42.41	47.89	49.12	47.45
Carbon monoxide.....	21.54	15.57	19.62	25.09	20.16	13.04	19.39	20.70
Methane.....	13.15	22.57	18.73	17.57	13.92	20.27	15.94	12.59
Ethane.....	1.30	2.05	2.08	2.01	0.25	1.27	0.37	1.49
Ethylene.....	4.67	7.56	4.68	10.36	7.89	2.77	3.86	3.39
Carbon dioxide.....	11.41	18.44	11.42	8.02	13.91	11.99	10.25	10.24
Propane.....	<0.01	<0.01	<0.01	<0.01	1.17	<0.01	<0.01	<0.01
Propylene.....	1.32	1.53	0.32	0.76	0.10	1.38	0.34	2.35
Isobutane.....	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace
Butane.....	0.08	0.01	0.44	do.	0.11	0.05	<0.01	0.13
Butene-1.....	0.16	0.15	Trace	do.	Trace	0.15	0.04	0.16
Isobutylene.....	0.17	0.15	do.	do.	do.	0.23	0.07	0.25
trans-Butene-2.....	0.04	0.03	do.	do.	do.	0.12	0.02	0.02
cis-Butene-2.....	0.07	Trace	do.	do.	do.	<0.01	do.	<0.01
Pentane.....	Trace	do.	do.	do.	do.	Trace	do.	Trace
Pentenes.....	0.60	0.87	0.20	0.53	0.07	0.55	0.63	0.70
Unidentified.....	<0.01	0.21	0.06	0.15	0.01	0.04	0.08	<0.01
Btu/cubic foot of gas...	473	563	447	570	511	478	498	502
Million Btu/ton of refuse pyrolyzed.....	5.473	5.421	7.930	4.207	9.228	4.571	6.134	4.366

Note: <0.01 = 1 part in 10⁴. Trace = less than 1 part in 10⁵.

TABLE 5. - Analyses of tars from pyrolysis of municipal and industrial refuse by coal-tar method

Refuse	Specific gravity at 15.6° C	Weight-percent of dry tar	Boiling range, volume-percent				Distillate, volume-percent of dry tar		Neutral tar oil, volume-percent					
			0° to 170° C		235° to 270° C		Acids	Bases						
			Anthracene	Naphthalene	Residue	Neutral oil								
Raw municipal.....	1.077	0.0	0.0	4.4	12.4	7.2	20.0	56.0	7.4	4.7	31.9	17.5	68.1	14.4
Processed municipal containing plastic film	.974	.0	.0	1.7	9.1	7.0	19.3	62.9	5.2	3.7	28.0	25.0	62.6	12.4
Heil mill industrial....	1.111	.0	.0	3.3	11.1	5.4	10.2	70.0	5.9	3.7	20.4	23.0	68.5	8.5
Gondard mill industrial.	1.093	.0	.0	3.7	14.1	7.4	16.5	58.3	7.0	5.3	29.1	21.3	67.7	11.0
PYROLYSIS TEMPERATURE, 500°-900° C														
Raw municipal.....	1.115	0.59	3.17	1.9	11.1	4.1	8.1	74.8	4.0	2.1	17.5	16.3	79.9	3.8
Processed municipal containing plastic film	1.101	Trace	Trace	4.2	13.2	7.5	12.0	63.1	4.9	6.3	25.7	23.5	69.6	6.9
Gondard mill industrial.	1.099	.73	4.07	6.2	26.8	8.4	14.3	44.3	6.8	6.0	38.3	19.0	78.2	2.8
PYROLYSIS TEMPERATURE, 750° C														

TABLE 6. - Yields of tar components from pyrolysis of municipal and industrial refuse

Refuse	Gallons per ton of refuse								Pounds per ton of refuse	
	Tar	Acids	Bases	Neu- tral oil	Resi- due	Ole- fins	Aro- matics	Paraffins and naphthenes	Anthra- cenes	Naphtha- lenes
PYROLYSIS TEMPERATURE, 500°-900° C										
Raw municipal...	4.8	0.4	0.2	1.5	2.7	0.3	1.1	0.2	-	-
Processed munic- ipal containing plastic film...	5.6	.3	.2	1.6	3.5	.4	1.0	.2	-	-
Heil mill industrial.....	4.1	.2	.2	.8	2.9	.2	.6	.1	-	-
Gondard mill industrial.....	1.7	.1	.1	.5	1.0	.1	.3	.1	-	-
PYROLYSIS TEMPERATURE, 750° C										
Raw municipal...	2.6	0.1	0.1	0.5	2.0	0.1	0.4	0.02	0.14	0.76
Processed munic- ipal containing plastic film...	2.2	.1	.1	.6	1.4	.1	.4	.04	Trace	Trace
Gondard mill industrial.....	1.8	.12	.1	.7	.8	.1	.5	.02	.12	.67

Ultimate analyses of the tars for all pyrolysis temperatures are given in table 7. The compositions of the tars did not differ greatly for either municipal or industrial refuse, regardless of pyrolysis temperature, with the exception of oxygen in the industrial refuse.

Light Oils

Chromatographic analyses of the light oils (table 8) showed the major component to be benzene. Pyrolysis at 500° to 900° C yielded from as little as 37.5 percent benzene to as much as 73.4 percent at 900° C from the raw municipal refuse. Light oil from the processed municipal refuse containing plastics contained as much as 92.1 percent benzene when pyrolyzed at 900° C. Light oil from the industrial refuse ranged from 51.0 to 89.0 percent benzene, depending on pyrolysis temperature. The toluene content of the oils from all refuse types decreased substantially as pyrolysis temperatures increased. However, total light-oil production for all refuse types reached a maximum at 750° C.

Liquor

The bulk of the liquor was collected from the water condensers, but some was separated from the tar trap. Samples from each were analyzed for water content, and the data are given in table 9. The pyrolysis liquor from the municipal refuse in general was 94 to 100 percent water, and that from the industrial refuse was 90 to 96 percent water. The remainder of the liquor was organic compounds that have been identified as acids, ketones, and aldehydes containing one to eight carbon atoms. These compounds may be absorbed on the char for disposal by combustion or removed by other chemical treatment.

TABLE 9. - Water content of liquor produced in the pyrolysis of municipal and industrial refuse

Refuse	Pyrolysis temp., ° C	Percent water in--	
		Liquor from condensers	Liquor from tar trap
Raw municipal.....	500-900	96.1	96.2
	750	98.2	94.5
	900	98.9	94.6
Processed municipal containing plastic film.	500-900	97.4	99.7
	750	100.0	98.9
	900	99.3	91.5
Heil mill industrial....	500-900	91.4	94.5
	750	90.1	95.1
	900	96.8	92.0
Gondard mill industrial.	500-900	95.0	95.2
	750	94.2	95.4
	900	92.2	94.5

SUMMARY AND CONCLUSIONS

Pyrolysis techniques similar to those applied in destructive distillation of coal can be used to convert municipal (household) and industrial refuse into potentially useful solids, liquids, and gases without contributing to environmental pollution.

A ton of municipal refuse, pyrolyzed at 900° C, can be converted to 154 pounds of solid residue, 0.5 gallon of tar, 114 gallons of liquor, 25 pounds of ammonium sulfate, and 17,741 cubic feet of gas. A ton of municipal refuse containing mainly plastics can be converted to 382 pounds of solid residue, 1.5 gallons of tar, 0.5 gallon of light oil, 97.4 gallons of liquor, 31.5 pounds of ammonium sulfate, and 18,058 cubic feet of gas.

A ton of industrial refuse consisting mainly of paper, rags, and cardboard, pyrolyzed at 900° C, can be converted to 618 pounds of solid residue, small amounts of tar, 1.4 gallons of light oil, 68.5 gallons of liquor, 22.9 pounds of ammonium sulfate, and 14,065 cubic feet of gas.

The solid residue, a lightweight, flaky, carbonaceous material, represents a 90-percent weight reduction for the municipal refuse and a 65-percent reduction for industrial refuse. The residue from municipal refuse has the highest fuel value and can range from 10 to 17 million Btu per ton.

As much as 53 percent of the raw product gas is carbon monoxide, methane, and ethylene, and the volume of gas produced is ample to provide the energy for pyrolysis of the refuse. The high hydrogen content of the gas may also have promise as a source of hydrogen or methane.

The tar from the pyrolysis of refuse will provide an additional 736,000 Btu per ton of refuse, and the light oil produced is a potential source of benzene and toluene.

The results of these experiments strongly suggest that the pilot plant should be modified and expanded to provide for continuous operation so that reliable data can be obtained for projecting costs of large-scale pyrolysis plants. The effect that drying the raw refuse before pyrolysis would have on the yield and the quality of products should also be studied.