



**Battelle**

Columbus Laboratories

# Report

PROCEEDINGS FROM A  
TECHNICAL CONFERENCE ON  
WASTE-TO-ENERGY TECHNOLOGY UPDATE - 1980  
(April 15 and 16, 1980)

by

G. Ray Smithson, Jr.  
BATTELLE  
Columbus Laboratories  
505 King Avenue  
Columbus, Ohio 43201

PROCEEDINGS FROM A  
TECHNICAL CONFERENCE ON  
WASTE-TO-ENERGY TECHNOLOGY UPDATE - 1980  
(April 15 and 16, 1980)

by

G. Ray Smithson, Jr.  
BATTELLE  
Columbus Laboratories  
505 King Avenue  
Columbus, Ohio 43201

Grant No. R806653010

Harry Freeman  
Incineration Research Branch  
Industrial Pollution Control Division  
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY  
OFFICE OF RESEARCH AND DEVELOPMENT  
U.S. ENVIRONMENTAL PROTECTION AGENCY  
CINCINNATI, OHIO 45268

## DISCLAIMER

This report has been reviewed by the Industrial Environmental Research Laboratory-Cincinnati, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

## FOREWORD

This report contains the proceedings of a technical conference held in April of 1980 to review the status of U.S. EPA's waste-to-energy research programs. The information contained herein will be of interest to those in the private and public sectors working to develop and utilize waste-to-energy technology.

Requests for information on the topics discussed in the report should be directed to the Incineration Research Branch, IERL-Ci or to the individual authors.

David G. Stephan, Director  
Industrial Environmental Research Laboratory  
Cincinnati, Ohio



## CONTENTS

	<u>Page</u>
FORWARD . . . . .	iii
INTRODUCTION . . . . .	1
CONFERENCE PROCEEDINGS . . . . .	4
Session 1 - Conversion Processes	
Pilot Scale Pyrolytic Conversion of Mixed Wastes to Fuel . . . . .	4
Chemical Reclamation of Scrap Tires . . . . .	14
The California Mobile Pyrolysis System . . . . .	32
Thermochemical Conversion of Biomass to Gasoline . . . . .	42
Emerging Technology for Maximum Conversion of Waste Cellulose to Ethanol Fuel . . . . .	50
Atmospheric Fluidized Bed Combustion of Municipal Solid Waste: Test Program Results . . . . .	52
Session 2 - Combustion	
Evaluation of the Ames Solid Waste Recovery System . . . . .	80
Test Firing Refuse Derived Fuel in an Industrial Boiler . . . . .	88
Co-Firing Refuse Derived Fuel (Dross) in A Stokered Boiler . . . . .	100
Corrosion Inhibition in Refuse-to-Energy Systems . . . . .	106
Co-Firing Densified Refuse-Derived Fuel in A Spreader Stoker-Fired Boiler . . . . .	112
Co-Firing Fluff RDF and Coal in A Cement Kiln . . . . .	118
Steam Pyrolysis of Organic Wastes As A Source of Chemicals and Industrial Feedstocks . . . . .	138
Session 3 - Environmental Assessments and Pollution Control Technology	
Environmental Assessment of Waste-to-Energy Conversion Systems . . . . .	148
Emissions Assessment for Refuse-Derived Fuel Combustion . . . . .	156
Combustion and Emission Assessment of Refuse-Derived Fuel Cofired with Pulverized Coal . . . . .	166
Pilot Scale Evaluation of Four Refuse-Derived Fuels . . . . .	176
Application of Slipstreamed Air Pollution Control Devices on Waste-as-Fuel Processes . . . . .	194
Treatment of Wastewaters from Refuse-to-Energy Systems . . . . .	200

PROCEEDINGS FROM A  
TECHNICAL CONFERENCE ON  
WASTE-TO-ENERGY TECHNOLOGY UPDATE - 1980  
(April 15 and 16, 1980)

to

U.S. ENVIRONMENTAL PROTECTION AGENCY  
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY  
CINCINNATI, OHIO

from

BATTELLE  
Columbus Laboratories

July 30, 1980

INTRODUCTION

The U.S. EPA is vitally interested in the dissemination of the results of its research and development activities to inform potential users and to encourage widespread utilization of the technology under development. The Agency also is interested in the assessment of its research and in acquiring extramural input to the planning of future research and development. One of the more effective means to accomplish these goals is to sponsor periodic technical conferences whose basic objective is to provide an update of the status of technological developments in areas of interest. One such area is the utilization of the energy contained in municipal and industrial wastes for useful purposes.

The concept of recovering energy from wastes is not new but this practice has not been adopted to any significant extent within the United States. However, for several years there has been growing impetus in the U.S.--both within the private sector and Federal, state, and local governments--to develop various techniques for recovering energy from the combustible

fractions of solid wastes and for separating recyclable materials from wastes generated by industries and large communities. Research efforts have been expended on many technological approaches and several have been developed to various stages of practice.

Acting upon the belief that a technical conference on the status of waste-to-energy research activities would be beneficial and timely, Battelle Columbus Laboratories proposed such a conference to U.S. EPA. The purposes of the technical conference were:

- To review the status of relevant research and development activities being supported by U.S. EPA's Industrial Environmental Research Laboratory (IERL-Ci) at Cincinnati, Ohio.
- To consider the most effective means for the commercial exploitation of the results of this research.
- To review areas for future research and to recommend strategies for the implementation of such research.

After Battelle's grant proposal was accepted by the U.S. EPA, the specific objectives and mechanisms for conducting the technical conference were developed jointly with a steering committee composed of representatives of these two organizations. Following the adoption of the specific objectives and mechanisms, this committee selected speakers and discussions leaders from various organizations conducting R&D in waste-to-energy systems for IERL-Ci. These individuals were invited to participate in the conference with the understanding that the findings and recommendations would be made available to persons and organizations interested in this area of technology. The final agenda for the conference was as follows:

Tuesday, April 15, 1980

Session 1 - Conversion Processes

Registration and Coffee - Foyer

Introduction

Welcome

Session Overview - Walter Liberick, U.S. EPA, IERL

Pyrolysis of Mixed Waste to Fuel - Herbert Kosstrin, Energy Resources Co., Inc.

Pyrolysis of Industrial Waste - George Frazier, University of Tennessee

Portable Unit for Pyrolysis of Agricultural & Forestry Wastes -

Herbert Kosstrin, Energy Resources Co., Inc.

Coffee Break

Bench Scale Pyrolysis to Polymer Gasoline - Jim Biebold, Solar Energy  
Research Institute

Bio-Conversion-Acid Hydrolysis - Charles Rogers, U.S. EPA, MERL

Fluidized Bed Combustion of Solid Waste - Lyn Preuit, Combustion Power Co.

Luncheon

Guest Speaker - Dr. Eugene Moulin, University of Dayton

"Stress is Contagious"

Session 2 - Combustion

Session Overview - Bob Olexsey, U.S. EPA, IERL

Evaluation of Ames Energy Recovery System - Al Joensen, Iowa State University

Firing of Solid Waste in an Industrial Boiler - Gary Boley, City of  
Madison, Wisconsin

Cofiring Refuse Derived Fuel (RDF) Dross in a Stoker Boiler -

Fred R. Rehm, Department of Public Works, Milwaukee, Wisconsin

Effects of Using Solid Waste as a Supplementary Fuel - H. H. Krause,  
Battelle Columbus Division

Coffee Break

Cofiring Densified Refuse Derived Fuel in A Spreader Stoker Fired Boiler -  
Ned Kleinhenz, Systems Technology Corp.

Cofiring of Solid Waste in a Cement Kiln - Cliff Willey, State of Maryland

Pyrolysis of Agricultural Wastes in a Steam Atmosphere - Michael Antel,  
Princeton University

Wednesday, April 16, 1980

Session 3 - Environmental Assessments and Pollution Control Technology

Session Overview - Harry Freeman, U.S. EPA, IERL

Environmental Assessment of Waste-to-Energy Processes - K. P. Ananth,  
Midwest Research Institute

Emission Assessment from RDF/Hazardous Waste Combustion - Fluidized Bed -  
Jim Chrostowski, Energy Resources Co., Inc.

Emission Assessment from RDF/Hazardous Waste Combustion - Stoker Fired -  
John Allen, Battelle Columbus Division

Coffee Break

Emission Assessment from RDF/Hazardous Waste Combustion - Suspension Firing -  
Robert Pease, KVB, Inc.

Cofiring of four RDF's in a Pilot Scale Facility - Richard Brown, Acurex, Inc.  
Air Pollution Control for Waste as Fuel Processes - Fred Hall, PEDCo  
Environmental, Inc.  
Water Pollution Control for Waste as Fuel Processes - Gordon Treweek,  
James M. Montgomery, Inc.  
Luncheon

The conference was held in Cincinnati, Ohio. The proceedings of the conference are included in this report.

# PILOT SCALE PYROLYTIC CONVERSION OF MIXED WASTES TO FUEL

by H.M. Kosstrin, Ph.D.

## Introduction

One of the more promising techniques for reclaiming energy from municipal solid waste is through pyrolysis, which is the destructive distillation of waste materials thereby converting them to clean fuels such as low-Btu gas, residual oil, and char.

EPA has been involved in the development and demonstration of several different pyrolysis technologies such as the Landguard system based upon a rotary kiln, the Tech-air concept based upon a fixed bed pyrolyzer, and "Flash Pyrolysis" based upon an entrained bed heated with recirculating hot char. While all of these technologies are based upon pyrolysis, all of them produce different energy by-products because of the different reactor characteristics and operating parameters inherent in each one.

The objectives of the work being carried out by Energy Resources Co. are to explore the kinetics of pyrolysis of municipal waste and agricultural wastes and to develop a data base on pyrolysis that will allow design engineers to select pyrolysis system operating conditions for commercially available systems that will provide the desired mix of product yields given the mixture of wastes available in a given geographical area. Because the results of the data-taking efforts will be extrapolated to full-scale systems, it is necessary for the experimental work to be carried out on a pilot plant scale.

The work performed included a literature survey of pyrolysis to determine the properties of various wastes and the reactor operating variables which would have a significant influence on the project. With these data in hand, a fluidized-bed pilot plant was constructed to carry out the collection of kinetic data. The data analysis included product characterization of the char, oil and gas along with the development of a prediction model for the oil. The various parameters that were varied are listed in Table 1.

The result of the data base compiled is to assist the design engineer to understand the important trends in pyrolyzed design.

TABLE 1

PARAMETERS VARIED

---

Reactor Temperature

Fluidization Velocity

Feed Rate of Waste

Bed Height

Feed Particle Size

---

## Pyrolyzation of Wastes

The data obtained concern the conversion of a wide range of wastes to fuels in a fluidized-bed pyrolysis system. The materials pyrolyzed in both Phase I and Phase II of the test program are shown in Table 2. The variables studied as to their effect on the final products of pyrolysis were temperature, fluidization velocity, feed rate of pyrolyzable material, bed height (static), and particle size.

Various experimental conditions other than pyrolysis were run as a means of determining the usefulness of the system. These included steam gasification (pyrolysis), partial oxidation, combustion, and steam partial oxidation runs.

The major conclusion that comes out of this work is the importance of secondary reactions in determining the final product mix of the various waste materials. Pyrolysis occurs in two steps as described in the modeling section of this report.

1. Primary decomposition--devolatilizes the feed into its light fractions, oil and gas, and leaves a residue generally considered a char. The quality of the char depends upon the temperature of pyrolysis of the char formation. The char contains the inerts from the feed, generally considered ash.
2. Secondary decomposition--these secondary reactions, which predominate above a critical temperature, devolatilize the oil produced via the primary reactions into a gas and a residue. This residue is additional char.

From work performed during Phase I of the project, an analytical expression for the yield of pyrolytic oil and gas, taking into consideration both primary and secondary reactions, is derived in the modeling section of this report. The data obtained confirm the analytical expression.

Figure 1, the yield of pyrolytic oil for sawdust, shows the general shape of the oil yield curve. The secondary reactions begin to dominate after 400° C. At temperatures above 400° C the yield of pyrolytic oil decreases and the corresponding yield of gas increases because of these secondary reactions. The development of an analytical expression for the formation of gas from both primary and secondary reactions has been accomplished. The analytical expressions are shown in Tables 3 and 4.



MATERIAL: SAWDUST (SAW)

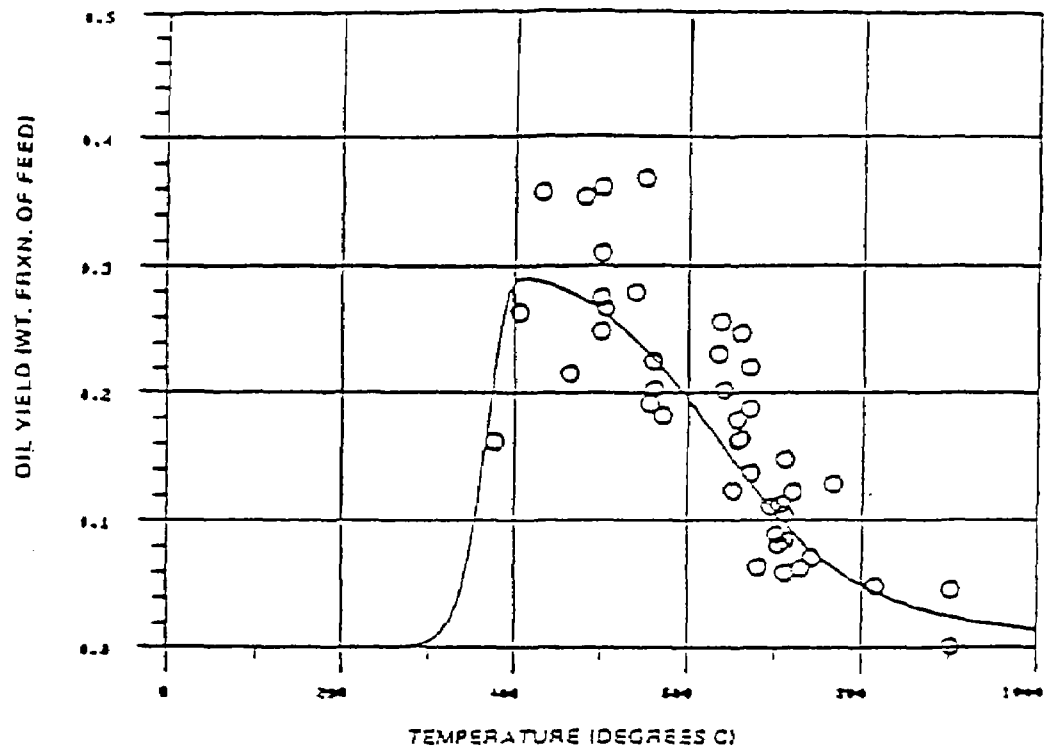


Figure 1. Model curve for pyrolysis oil yield data of sawdust.

TABLE 2  
MATERIALS PYROLYZED

---

INDIVIDUAL

Phase I

Paper  
Sawdust  
Corncobs  
Waste Oil  
Municipal Solid Waste  
Sludge  
Tires  
Plastics  
Wood Chips  
Pyrolytic Oil

Phase II

Wheat Straw  
Rice Straw  
Cotton Gin Waste  
Pine Bark  
Industrial Sewage Sludge  
Char (from pyrolysis of  
sawdust)  
Coal

MIXTURES

Paper + Sawdust  
Corncobs + Manure  
Paper + Plastics

Coal + Sawdust  
Coal + Sludge + Munic-  
ipal Solid Waste  
Coal + Municipal Solid  
Waste

---

TABLE 3

ANALYTICAL EXPRESSION FOR THEORETICAL GAS YIELD

$$V_{\text{gas}} = 1 - C - V_{\text{oil}}^* [1 - \phi_{\text{oil}} \phi' (1 - \alpha)] \phi_{\text{gas}} \\ + V_{\text{oil}}^* \phi_{\text{oil}} \cdot \phi' \cdot \alpha$$

where

$C$  = measured char yield, as provided by the data, mass fraction of refuse fed.

$V_{\text{oil}}^*$  = ultimate oil yield, from oil yield correlation, mass fraction of refuse fed.

$$\phi' = 1 - \frac{1 - e^{-k't'}}{k't'}$$

$$k' = k_o' e^{-E'/RT}$$

$$t' = a/vA$$

$$\phi_{\text{oil}} = 1 - \frac{1 - e^{-k_{\text{oil}} \tau_s}}{k_{\text{oil}} \tau_s} \times e^{-k_{\text{oil}} (t_s - t_f)}$$

$$k_{\text{oil}} = (k_o)_{\text{oil}} e^{-E_{\text{oil}}/RT}$$

$\tau_s$  = sampling time, provided from data

$t_s - t_f$  = lag time between start of feeding and start of sampling, provided from data

$\alpha$  = mass fraction of cracked oil which forms gas, must be  $0 \leq \alpha \leq 1$

$$\phi_{\text{gas}} = 1 - \frac{1 - e^{-k_{\text{gas}} \tau_s}}{k_{\text{gas}} \tau_s} \times e^{-k_{\text{gas}} (t_s - t_f)}$$

$$k_{\text{gas}} = (k_o)_{\text{gas}} e^{-E_{\text{gas}}/RT}$$

The terms  $\phi$ ,  $k'$ , and  $\tau'$  were obtained directly from the oil yield model, as was  $k_{\text{oil}}$ , except that the subscript "oil" was not used before. The other terms,  $\alpha$ ,  $\phi_{\text{gas}}$ , and  $k_{\text{gas}}$ , represent three new adjustable parameters, to be obtained by a computer analysis similar to that performed on the oil yield data but not done in this project.

TABLE 4  
ANALYTICAL EXPRESSION FOR THEORETICAL OIL YIELD

$$V_{oil} = V_{oil}^* \frac{1 - e^{-k'a/vA}}{k'a/vA} \left( 1 - \frac{1 - e^{-k\tau_s}}{k\tau_s} e^{-k(t_s - t_f)} \right)$$

Where

$V_{oil}$  = Mass of oil leaving the bed during the sampling period, per unit mass of the refuse fed (lb/lb).

$V_{oil}^*$  = Value of  $V_{oil}$  for an infinitely long residence time of the solids in the bed with no secondary reactions.

$t'$  =  $a/vA$ , sec

$$\phi' = 1 - \frac{1 - e^{-k't'}}{k't'}$$

$$\phi = 1 - \frac{1 - e^{-k\tau_s}}{k\tau_s} e^{-k(t_s - t_f)}$$

$$k = k_0 e^{-E/kT}$$

$$k' = k_0' e^{-E'/kT}$$

The data from the individual pyrolysis experiments give us the parameters  $V_{oil}$ ,  $\tau_s$ ,  $t'$ ,  $t_s - t_f$  and  $T$ .  $R$  is the universal gas constant defined as  $R = 1.987$  cal/°K-mole, with the temperature ( $T$ ) in degrees Kelvin.  $V_{oil}^*$  must be between 0 and 1.

The remaining parameters must be fitted to the data. These are  $k_0'$ ,  $k_0$ ,  $E'$ ,  $E$ ,  $V_{oil}^*$ . A complete computer fit of these five parameters was accomplished.

The ability to predict the yield of pyrolysis products by analytic expressions is important when trying to optimize a particular pyrolytic product, as is the case for several pyrolysis systems now in operation.

The products of pyrolysis are pyrolytic oil, char, a low-Btu gas, and water. Depending on the feed material the char product will contain various amounts of ash. Of the five variables studied, temperature had the greatest effect on the various product yields. Along with variation in the yields of the various products with temperature, the quality (heating value) of the different energy products changes, as is discussed in the section on product characterization.

The remaining four variables generally produced a perturbation about the change caused by the temperature variation. Bed height over the range studied had a negligible effect on the data. The remaining variables, feed rate, fluidization velocity, and particle size, had the effect of perturbing the general results caused by the temperature variation, but in the ranges studied these variables did not show an appreciable effect on the output. (Figure 2 shows the variation of the gas yield due to several parameters.)

Phase II testing allowed further investigation of the effects of particle size, fluidization velocity, and feed rate on the pyrolysis process, by providing a greater variation in magnitude of each of these variables. Results indicate the same minimal perturbations about the general temperature trends for variable feed rates. High and low fluidization velocities also seem to show a minimal effect, except in some cases where gas composition seems to be affected. Phase I tests on tires suggested that particle size could have a more profound effect than simply perturbing results about the general temperature trends. Phase II test results on pine bark of two particle sizes also indicate a more definite effect due to this variable.

## Conclusion

The modeling of the yields of pyrolytic oil from the various data runs shows a high degree of similarity between the several materials that were pyrolyzed in the fluidized-bed reactor. With some detailed work the ERCO model for the prediction of pyrolytic oil and gas yields from the fluidized-bed pyrolysis of waste products could be expanded to predict the behavior of both fixed-bed pyrolysis systems, and entrained-flow pyrolysis units.

OPERATING MODE: PYROLYSIS  
 MATERIAL: SAWDUST

KEY:

Symbol	Feed Rate	Fluidization Velocity	Bed Height (m)
○	Lo	Lo	0.8
×	Hi	Lo	0.8
□	Hi	Hi	0.8
△	Lo	Hi	0.8
◇	Lo	Lo	0.3
•	Hi	Hi	0.3
↑	Lo	Hi	0.3
↓	Hi	Lo	0.3
R	Replicates		

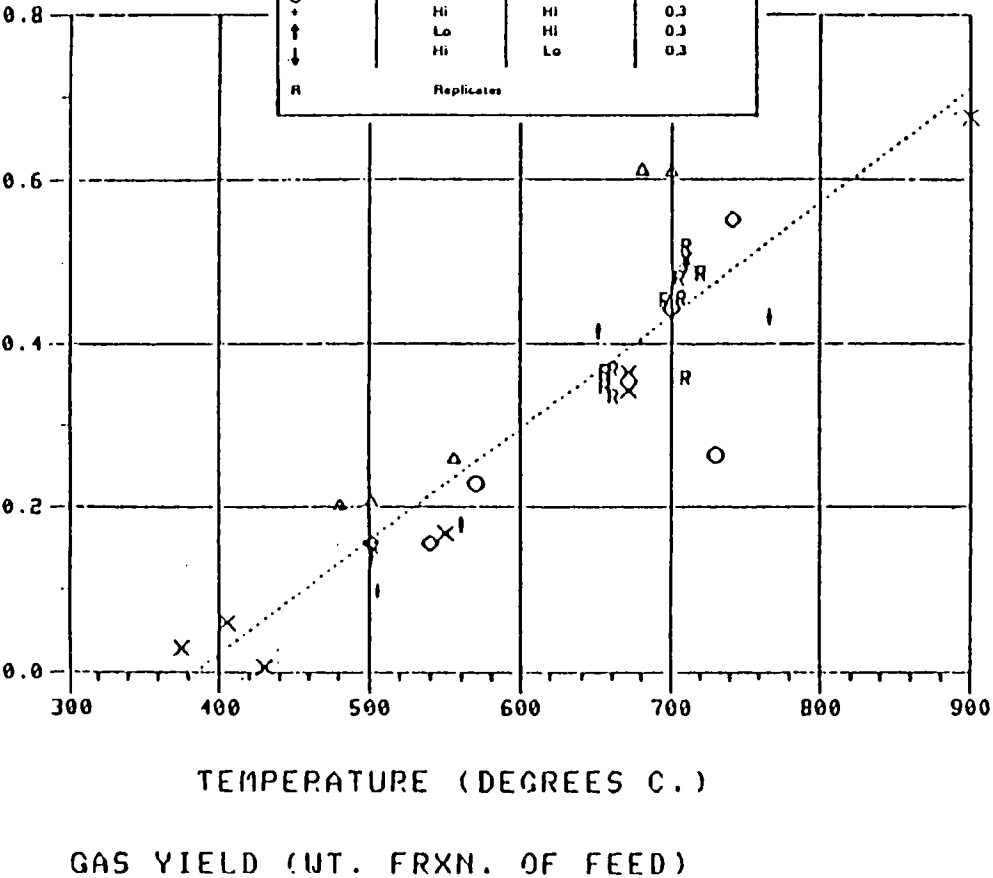


Figure 2.

## Chemical Reclamation of Scrap Tires

George C. Frazier, S.-M. Chan, O. L. Culberson, J. J. Perona and J. W. Larsen  
Departments of Chemistry and Chemical Engineering  
The University of Tennessee  
Knoxville, TN 37916

paper presented at the conference

"Waste-to-Energy Technology-Update 1980"

Sponsored by

U.S. Environmental Protection Agency  
Netherland Hilton Hotel  
Cincinnati, Ohio  
April 15-16, 1980

## Chemical Reclamation of Scrap Tires

George C. Frazier, S.-M. Chan, O. L. Culberson, J. J. Perona, and J. W. Larsen  
Departments of Chemistry and Chemical Engineering  
The University of Tennessee  
Knoxville, TN 37916

### Introduction

Interest in the utilization of scrap tires as a source of chemicals, fuel, and carbon black has been increasing in recent years, due not only to environmental regulations but also to the fact that chemicals and fuels based on petroleum and natural gas have been rising in price at rates much greater than the general inflationary trend. Numerous attempts are therefore being made around the industrialized world to recover chemical and fuel values from tires (See Berry, 1979, for a summary of these developments). Most of the current processes being developed for this purpose rely on pyrolysis of the rubber, by one method or another, requiring the heating of the rubber to temperatures in the range of 500-600°C, or above.

Our work, sponsored by the U.S. Environmental Protection Agency and supported in part by the Tennessee Valley Authority, utilizes a catalytic-pyrolytic process operating in the temperature range of about 360-400°C, to convert the scrap rubber to hydrocarbon gases, oil, and carbon black. The catalytic agent we have used the most is molten zinc chloride, although other halo salts are also effective (Larsen and Chang, 1976). The results we present in this paper are based exclusively on zinc chloride. Molten salts have been used previously to break down large organic molecules. For example, Zielke et al (1966) developed a process which became known as the Consol Synthetic Fuel (CSF) process for direct liquefaction of coal, using molten zinc chloride as a catalyst and heat transfer medium.

It is normal practice in the chemical process industries to develop a "conceptual process design" in the early stages of an actual project, in



order to identify crucial areas requiring further development, to evaluate various process options which may be available, to assess the overall technical feasibility of the project, and lastly but most importantly, to establish at the outset whether or not the process has the potential for economic profit. In this context, the objective of the work we report on here has been to obtain that bench scale experimental data required for the formulation and evaluation of a conceptual process design for the conversion of scrap tires to chemical and fuel products by molten salt pyrolysis, and to use this design as a basis for estimating the potential profitability of the process. Our experimental results and associated economic analysis indicate that such a processing plant converting 22,500 t/yr of tires has the potential for profit at current chemical prices, energy prices of \$3-\$4/MM Btu, assuming the carbon black, the major product, is marketable at prices in the range of at least 12¢/lb. Although there are a number of process steps requiring demonstration at the pilot plant scale, the biggest unknown at this point in our process is the marketability of the carbon black. A pilot plant is required to generate sufficient quantities of this material for testing its suitability in products such as rubber, ink, and plastics.

Although molten salt technology is not easy, advantages of this process lie in its relatively low operating temperature, in the range of 360-400°C, and the fact that there is no need to pulverize the tires. However, we do chop the tires for compaction purposes, in order to increase the reactor throughput. Further, the relatively large pieces of fiber glass and wire remaining after the chopping operation appear to be readily separated from the carbon residue downstream of the reactor. A test of this separability at the pilot plant scale is desirable.

#### Bench Scale Results.

A large scale reactor utilizing this technology will likely be a batch type, which is alternately charged with rubber, flooded with salt, and sub-

sequently discharged. We therefore simulated this procedure in our bench scale work in order that our processing conditions and product yields would correspond to what might be achievable in a large scale plant. Bench scale work is necessarily small scale so we were unable to work with large pieces of a tire. Our reactor was 2 inches i d and 12 inches long, and our most consistent, reasonably reproducible results were obtained when we charged the reactor with strips cut from a tire which were about 5/16 inch x 5/16 inch x 10 inches; for a total charge weight in the range of 160 grams. A layout of our bench scale apparatus, constructed of 316 stainless steel, is shown in Figure 1. The entire apparatus was heated electrically and insulated with a calcium silicate to minimize heat loss. The salt flowed by gravity from the reservoir, through the reactor, to the receiver. Contact times of the salt with the rubber ranged from 2 to 3 minutes to 30 to 40 minutes. However, the reaction was generally essentially over in less than 10-12 minutes, depending on temperature. Experimental runs were made with reaction temperatures in the range of 330 to 400°C. The carbon black residue was readily separated from the fiberglass tire cord after a run, due to its high friability, by crushing and screening. It is necessary to wash salt from the carbon black, but a small amount of chloride remains in both the carbon black and also in the product oil, the latter presumably in organic form. Small particles of carbonblack are entrained in the salt, but we have reused the salt as many as four times without apparent loss in its effectiveness in promoting this pyrolysis reaction.

After a series of exploratory and debugging experimental runs, a sequence of four runs in the temperature range 360-390°C gave the average percentage product yields and analyses shown in Tables 1-3. For each 100 lb of tire feed, 17.9 lb of hydrocarbon gases, chiefly methane, but with substantial amounts of ethylene, propylene and 1-butene, are produced, 30.7 lb of oil with an

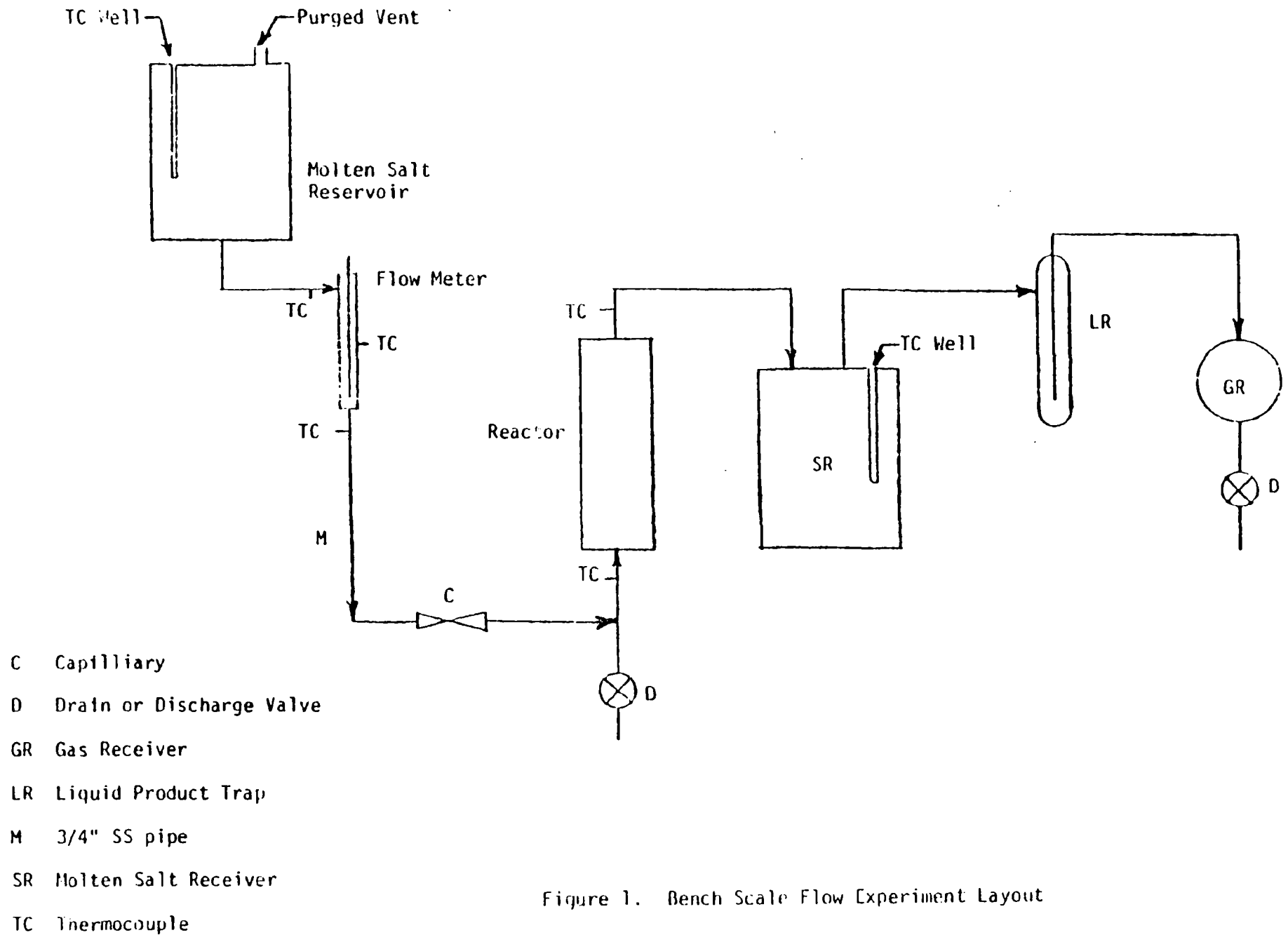


Figure 1. Bench Scale Flow Experiment Layout

Product	Yield Wt. % of Feed	Annual Yield* lb x 10 <sup>-7</sup>
Hydrocarbon Gases	17.9	0.305
Oil	30.7	1.38
Carbon Black	44.2	1.99
Refuse (Steelwire and Fiberglass)	5.0	0.225
Loss**	<u>2.2</u>	<u>0.099</u>
Total	100.0	4.5

\* For a plant processing 22,500 t/yr of tires

\*\* Estimated as 5% of the total carbon black.

Table 1. Estimated Products Yields for a Molten Salt Pyrolysis Plant, based on the average of four Bench Scale Experimental Runs.

Component	Annual Yield			Mole Percent of Total Gas*
	lbs x 10 <sup>-6</sup>	lb moles x 10 <sup>-4</sup>	SCF x 10 <sup>-7</sup>	
Methane	2.52	15.75	5.66	50.1
Ethylene	1.50	5.34	1.92	17.0
Ethane	1.68	5.57	2.00	17.7
Propylene	0.780	1.86	0.666	5.9
Propane	0.845	1.92	0.691	6.1
Isobutane	0.384	0.660	0.237	2.1
1-Butene	0.194	0.347	0.125	1.1
Total	7.90	31.4	11.3	100.0

\* Average of Bench Scale Runs 18-21.

Table 2. Gas Analysis and Yields for a Molten Salt Pyrolysis Plant Processing 22,500 t/yr of Scrap Tires

Component	Volume % of Total Oil	Annual Yield, gal
Aromatics (BTX)	27.05	516,000
Olefins	58.85	1,123,000
Paraffins	<u>14.10</u>	<u>269,000</u>
Total	100.0	1,908,000

Density of the oil = 0.87 g/ml = 7.25 lb/gal

Table 3. Major component classes in the oil and their yields, based on Bench Scale Runs 18-21. Annual Yields are based on a throughput of 22,500 t/yr of tires.

Product	Elemental Weight Percent					
	C	H	N	S	O	Cl
Oil	88.20	10.65	0.03	0.51	-	0.39
Carbon Black	87.14	2.28	-	2.10	4.84	0.94

Table 4. Elemental Analysis of the Oil and the Carbon Black from Bench Scale Run No. 18.

analysis of 27.1% aromatics (BTX) are produced, and 44.2 lb of carbon black are produced. This latter number takes into account an assumed, combined refuse (fiber glass tire cord and steel wire) and loss of 7.2%. Elemental analyses of the carbon black and oil are shown in Table 4. The chloride content of the oil is probably in organic form, but we have not factored the economic value of such products into the profitability analysis summarized here. However, makeup zinc chloride salt requirements were computed as if the chloride values in the products were lost.

Salts such as zinc chloride are corrosive, especially if moisture is present, and our laboratory apparatus of 316 stainless steel experienced corrosion in locations when moisture (from the air) entered the system during the frequent opening required of an experimental apparatus of this type. However, we have provided precautions, such as purges and dry storage for the feed tires in order to minimize corrosion problems in those parts of our conceptual design commercial plant which come into contact with the hot salt.

#### Conceptual Design Processing Plant

Our design basis is a plant which will process 22,500 t/yr of tires, with a 90% on-stream factor, and an assumed carbon black recovery factor of 95%. This throughput corresponds to 68.5 t/day, which may be on the lower end of the size scale for a plant of this type which can be economically feasible. A larger plant would be more attractive economically, but would also be limited to a fewer number of locations, due to the cost of transporting scrap tires over larger distances.

The conceptual layout for this plant is shown in Figure 2. Dry storage is provided for the scrap tires, where they are chopped into 12-13 inch pieces in order to increase their bulk density, thus allowing greater throughput for a given reactor size. The batch reactor is charged through a lock hopper

Figure 2. Conceptual Layout for a Molten Salt Pyrolysis Plant Designed for a Scrap tire throughput of 22,500 t/yr.

to prevent moist air from entering the system. The zinc chloride salt is heated by a direct-fired heater and forced into the reactor by compressed, dry flue gas, thereby eliminating the need for a salt pump and valves, which would be troublesome in a system of this type. The reactor loading, reaction, and discharging cycle time is estimated to be about 1 1/2 hours and at the end of the cycle, the gas pressure on the salt reservoir is released, and the salt drains by gravity from the reactor to the reservoir, until the next cycle. The reaction temperature is in the range of  $480 \pm 20^\circ\text{C}$  although we have not done a sufficient amount of work to determine whether or not this is optimum with respect to product yields and quality. For example, carbon black produced by this process at too low a temperature tends to be high in volatiles, whereas too high a reaction temperature tends to favor a high yield of methane in the product gas at the expense of the more valuable olefin gases.

Down stream of the reactor, the product vapor is processed by conventional technology to a gas stream and an oil stream both of which are, preferably, piped "over the fence" to existing refineries rather being stored and processed on site. Such an arrangement limits the location of tire processing plants to those locations in which gas (ethylene) and petroleum refineries already exist, as shown in Figures 3 and 4.

Returning to Figure 2, the solid refuse (carbon black, fiber glass, steel wire) is washed to remove salt, dewatered, dried, crushed, and the wire and fiber glass are separated first by a magnetic drum and then by a screen to retain the fiber glass "fluff". Top size of the carbon black at this point is about 3/8 inch, and requires grinding (not shown) to customers' specifications. Conventional technology is used throughout this process stream, although the process needs to be "piloted" in order to demonstrate the separability of these solids and to establish the degree of salt recovery in the two stage wash tank.



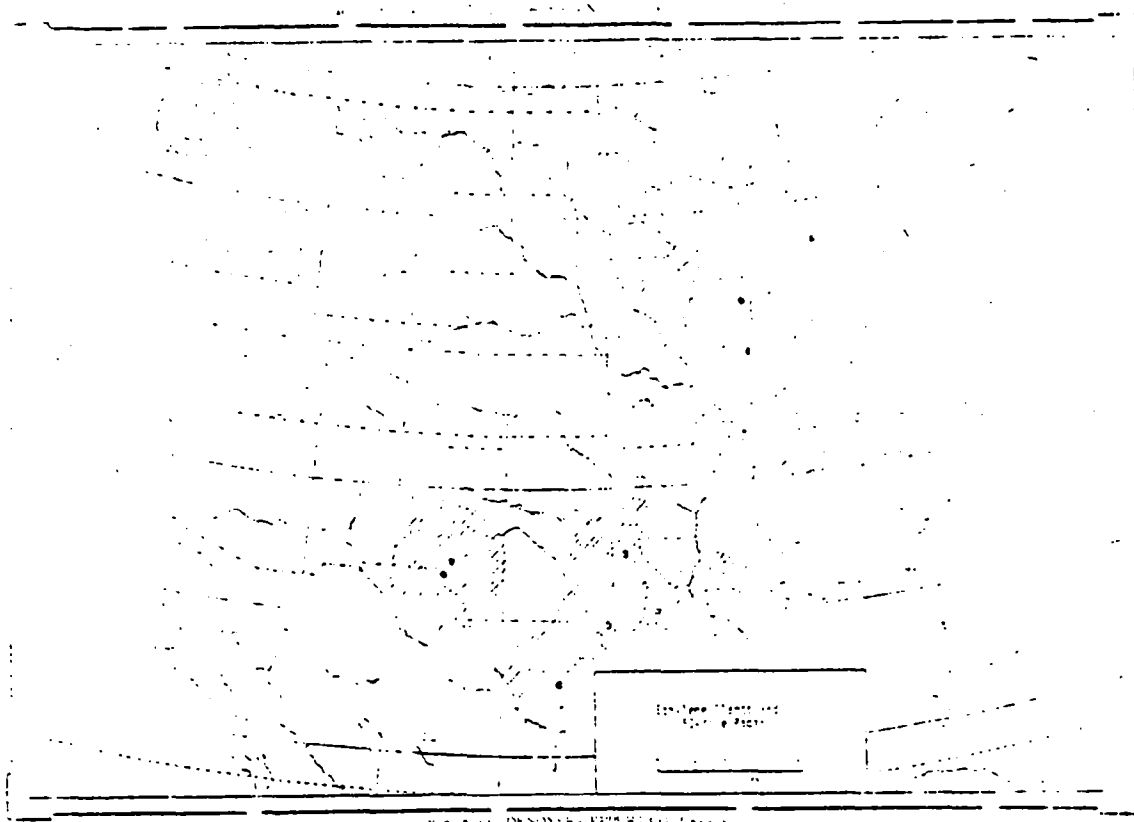


Figure 3. Location of Ethylene Plants in the Continental U. S.

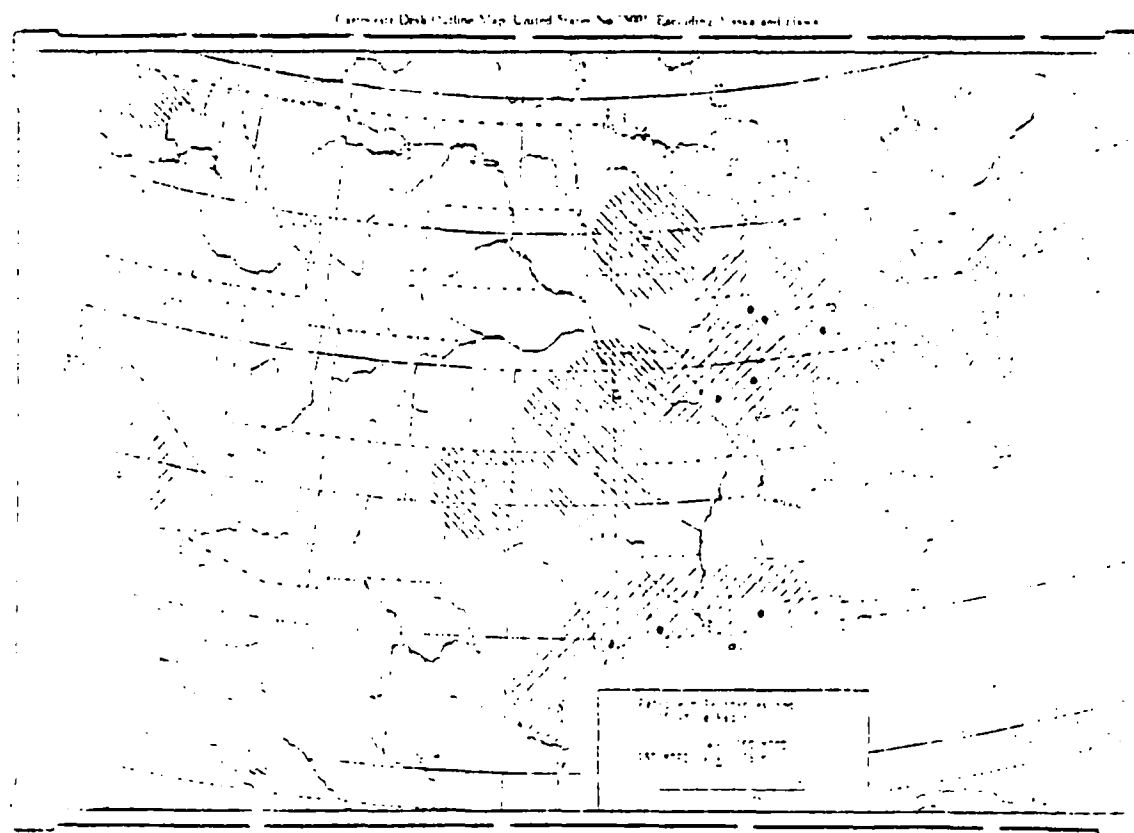


Figure 4. Location of Petroleum Refineries in the Continental U. S.

Salt is also recovered from the wash water by conventional technology: vacuum evaporation, crystallization, filtering, and drying, for recycle to the salt reservoir. The salt liquor is diluted and recycled to the wash tank, eliminating the need for disposal of salty, "black water". The only appreciable salt loss from the system is that carried by the oil and by the carbonblack, estimated to be about  $4.8 \times 10^5$  lb/yr, for this plant. The overall plant material balance is shown on Figure 2.

#### Economic Analysis and Profitability Estimates

The major components of the conceptual plant were sized for a throughput of 22,500 t/yr of tires and their costs (late 1979) were estimated in accordance with the data and procedures given by Peters and Timmerhaus (1968) and by Guthrie (1969), using a Marshall and Stevens cost index of 622.7 (fourth quarter, 1979). The Fixed Capital requirements of 4.81 MMS were then computed according to the summary shown in Table 5. Annual operating costs were also estimated in accordance with the ratios given by Peters and Timmerhaus and are summarized in Table 6. The cost of the feed tires is less certain and depends on numerous factors, an important one of which is hauling costs (Berry, 1979). We therefore considered this cost a parameter in our analysis, ranging from 20 to 40 \$/t.

Our initial analysis based on the sale of all products for fuel indicated there is little possibility (short of a "negative" tire feed cost) a plant of this type could be profitable with energy prices in the range of 3-4 \$/MM Btu. As our next case we considered recovery (and marketability at late 1979 prices) of the major components having value as chemical feed stocks, from the product streams: carbonblack, olefin gases, and the aromatic oils (BTX). The remaining gas and oil in the product stream was assigned fuel values. Prices for the chemical products were taken from Chemical Marketing Reporter (December 10, 1979), and those products were discounted up to 90% for refining and separation

<b>A. <u>Plant Physical Costs</u></b>	
Process Equipment, Delivered (E)	\$1,092,000.
Installation (.45E)	491,500.
Insulation (.08E)	87,400.
Instrumentation (.18E)	196,600.
Piping (.25E)	273,000.
Electrical (.125E)	136,500.
Buildings (.5E)	546,000.
Site with improvements (.14E)	152,000.
Auxiliaries (.4E)	<u>436,900.</u>
Plant Physical Cost (P)	\$3,412,000.
<b>B. <u>Indirect Costs</u></b>	
Engineering and Construction (.15P)	511,800.
Contractor's Fee (0.1P)	341,200.
Contingencies (.15P)	<u>511,800.</u>
Total Indirect Costs (I)	\$1,365,000.
C. Initial Charge of Zinc Chloride (C)	30,000.
D. Plant Capital Cost (P + I + C)	<u>\$4,810,000.</u>

Table 5. Fixed Capital Requirements for a Molten Salt Pyrolysis Plant Processing 22,500 t/yr of tires, in late 1979 dollars.

A. Labor and Supervision (Salaries and Wages)	\$295,000.
B. Plant Overhead (60% of Sal. and Wages)	177,000.
C. Utilities (17.5% of Total Product Cost)	513,600.
D. Chemicals, Makeup Zinc Chloride ( $4.71 \times 10^5$ lb/yr at 42¢/lb)	197,800.
E. Insurance (1% of Fixed Capital)	48,100.
F. Taxes (3% of Fixed Capital)	144,300.
G. Maintenance (5% of Fixed Capital)	240,500.
H. Operating Supplies (15% of Maintenance)	36,100.
I. Depreciation	
Machinery and Equipment @ 10%/yr	380,000.
Buildings @ 3%/yr	29,300.
J. Interest (8% of Fixed + Working Capital)	<u>461,800.</u>
Base Operating Costs	\$2,524,000.

Table 6. Annual Base Operating Costs for 22,500 t/yr MSP Plant.

In view of the fact that the grade of our carbon black has yet to be established, we also considered its value to be a parameter in this study. The lower end of the range used was established using the price of the lowest grade reported in CMR (Dec. 10, 1979) of 19.2 c/lb and then discounting this by .02 c/lb as a reasonable, lower estimate of the value of this product at the current time.

Working capital was assumed to be 20% of fixed capital, interest at 8% of total capital, and Sales, Corporate Administration and Research (SAR) fees of 10% of revenues were charged against the plant. A case analysis sheet is shown as Table 7, and the profitability (lose in some cases) is summarized in Figure 5, in terms of Return on Investment (ROI), as affected by scrap tire and purification costs, and carbon black and fuel prices. Additional detail of this work are provided in our final report (Frazier, et al 1980).

#### Acknowledgement

This work was supported by Grant No. USEPA R804321. Additional support was received from the Tennessee Valley Authority. Cost information was supplied by International Baler Corporation, Rawls Division of the National Standard Company and the W. S. Tyler Division of Combustion Engineering. Carbon Black Samples were characterized by the Cabot Corporation. Mr. Robert Wiesen provided timely assistance in the laboratory. Without the contribution of the above people and organizations, this project could not have been completed.

TIRES	<u>40</u>	\$/t
PURIFICATION	<u>30</u>	%
FUELS	<u>4</u>	\$/MMBTU
CARBON BLACK	<u>15</u>	c/LB

		<u>MMS/YR</u>
REVENUES		
C <sub>2</sub> H <sub>4</sub> , C <sub>3</sub> H <sub>6</sub> , C <sub>4</sub> H <sub>8</sub> , BTX		<u>1.12</u>
FUELS		<u>1.24</u>
CARBON BLACK		<u>2.99</u>
		<u>          </u>
	REVENUE TOTAL	<u>5.35</u>
LESS 10% SAR		<u>0.54</u>
NET REVENUE		<u>4.81</u>
OPERATING COSTS		
BASE (FROM TABLE 6)	<u>2.52</u>	MM\$/YR
PURIFICATION	<u>.34</u>	
TIRE RAW MATERIALS	<u>.90</u>	
		<u>          </u>
	OPERATING COST TOTAL	<u>3.76</u>
GROSS PROFIT		<u>1.05</u>
LESS 46% INCOME TAX		<u>0.48</u>
AFTER-TAX PROFIT		<u>0.57</u>
% RETURN ON \$5.77 MM INVESTMENT		<u>9.9</u>

Table 7. Case Analysis Sheet for a Molten Salt Pyrolysis Plant Sized for a Tire Throughput Rate of 22,500 t/yr.

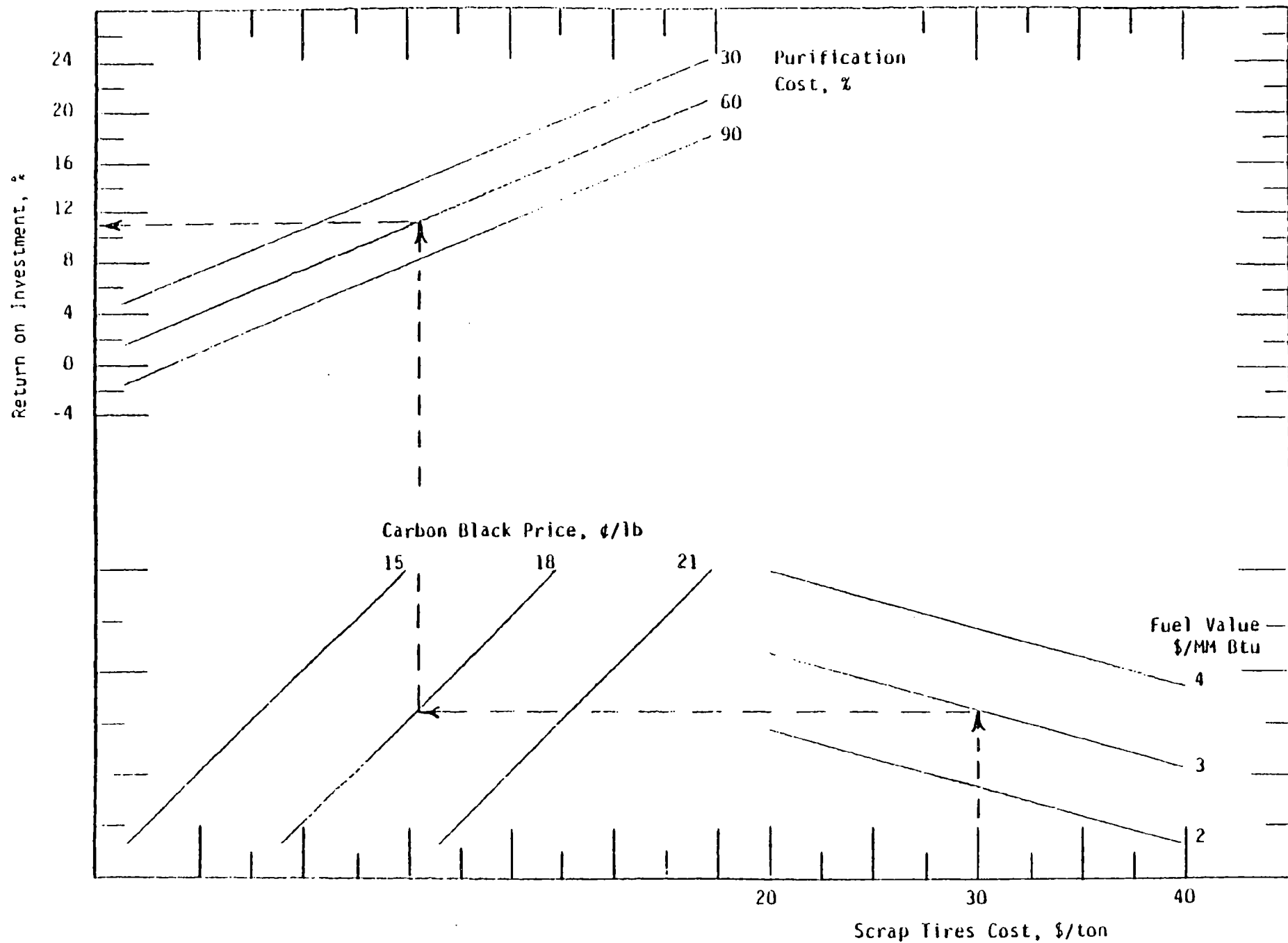


Figure 5. Estimated Profitability of a Molten Salt Pyrolysis Plant with a Scrap Tire throughput of 100,000 tons/yr. (Source: U.S. Environmental Protection Agency, 1979)

### References

Berry, Reginald I., Chem. Eng., p.30, Dec 31, 1979.

Frazier, George C., S.-M. Chan, O. L. Culberson, J. J. Perona, and J. W. Larsen, "Chemical Reclamation of Scrap Tires", Final Report on EPA Grant No. USEPA R804321, Spring 1980.

Guthrie, K. M., "Capital Cost Estimating", Chem. Eng. p. 114, March 24, 1969.

Larsen, J. W. and B. Chang, Rubber Chem. and Tech., 49, 1120 (1976).

Peters, Max S., and K. D. Timmerhaus, Plant Design and Economics for Chemical Engineers, McGraw-Hill Book Co. New York, Second Edition, 1968.

Zielke, C. W., R. T. Struck, J. M. Evans, C. P. Costanzy, and E. Gorin, Ind. Eng. Chem., Process Des. Dev. 5, 151, 158 (1966).

## THE CALIFORNIA MOBILE PYROLYSIS SYSTEM

Dr. Herbert M. Kosstrin,  
Principal Scientist  
Energy Resources Company, Inc.  
Cambridge, Mass.

### Introduction

A prototype mobile pyrolysis system to convert agricultural wastes to transportable fuel products is currently under construction. This demonstration project is being sponsored by the U.S. EPA and the State of California. The Solid Waste Management Board of the State of California is directing the California portion of the operation, and the Fuels Technology Branch of the Industrial Environmental Research Laboratory, Cincinnati, Ohio, the EPA share.

Energy Resources Company, Inc. of Cambridge, Mass. is the prime contractor for the project. Major subcontractors are Litwin Engineers of Houston, Texas, Valley Fabrication Engineers of Fowler, California, and Alpha National of El Segundo, California.

The mobile pyrolysis unit is a fluidized-bed pyrolysis system for the conversion of various agricultural wastes into a storable energy product. The waste products used by this system will be from the Central Valley of California. The waste conversion system is designed to be built on two low-boy trailers in order to improve the economics of converting widely dispersed agricultural wastes to useable fuel products. The pyrolysis system produces three fuels products, a low Btu gas, a pyrolytic oil, and a char.

The unique features of this system are the mobility of the unit and the total self-sufficiency from outside fuel sources after start-up. The system uses the pyrolytic gas generated during waste-to-fuel conversion process to operate a gas turbine cogeneration system. The cogeneration system produces the required electricity to operate the system and the heat necessary to dry the incoming feedstocks. Also, after the fluidized-bed



reactor is heated up to temperature with a startup fuel, a portion of the waste is combusted to supply the heat for the fluidized-bed reactor. In addition, No. 2 fuel oil is used as the initial scrubbing or cooling liquor in the oil separation system. As soon as sufficient pyrolytic oil is produced, it is utilized as the liquor. In this manner the mobile pyrolysis unit is independent of outside fuel sources.

The outputs of this mobile pyrolysis system are the storable and transportable fuel products, pyrolytic oil, and pyrolytic char. These two products have a greater energy density than the wastes from which they are generated, and therefore, can be economically transported. In addition, these products of pyrolysis are more uniform in composition than their respective feedstocks and can be utilized by existing fuel systems, whereas use of the individual wastes would require special boiler design.

### Background

The concept of a mobile pyrolysis waste conversion system resulted from programs sponsored by both the United States Environmental Protection Agency and the State of California Solid Waste Management Board. The initial EPA program, which proved that stationary pyrolysis of waste products was an acceptable means of converting waste products to fuels, was carried out under the auspices of the Fuel Technology Branch of IERL-CIN. In this program both fixed bed and fluidized bed pyrolysis processes were tested and evaluated for several years.

During this time period the State of California Solid Waste Management Board (SWMB) was concerned with disposal of various agricultural waste products. The waste products which need disposal are cotton gin trash, rice straw, orchard prunings, manure, and logging and lumber-mill wastes. These waste products are spread throughout the entire state. In addition, each of these waste products are generated during different seasons of the year. The geographic and seasonality dispersion led the SWMB to conduct a series of studies evaluating stationary vs. mobile disposal systems.

Two major findings convinced the SWMB that a mobile unit was preferred over a stationary system. One is the high cost of transporting low density, wet waste products. The second is that a fixed system might be located in a portion of the state that is not generating wastes year around and consequently, might not operate for a substantial part of the year. A State of California report, SB 1395 "Agricultural Economic Feasibility Analysis", gives the costs of transportation of the various waste products. The study which resulted in this report found that the cost of transporting these low-density wet wastes was prohibitively high. And that only a mobile type system was economically reasonable.

As a result of these independent studies the State of California and proposed a mobile pyrolysis waste disposal system that converts these wastes into useable forms of energy.

### The System

The major elements of the mobile pyrolysis system can be seen in the simplified flow sheet (Fig. 1). The major system components are feed preparation (sizing and drying), thermal decomposition (fluidized bed reactor), product separation (char and oil), and electrical cogeneration (gas turbines). The individual subsystems are integrated to as large an extent as possible in order to maximize the overall efficiency of the system.

The physical system is designed to operate on two low-boy trailers. Trailer #1 contains the fluidized bed reactor and product separation systems and auxiliaries. Trailer #2 incorporates the feed preparation and electrical cogeneration system. The trailers are forty-eight feet long and forty-seven feet long, respectively. The tractor and trailer combination weighs less than eighty thousand pounds each and meets all of the California transportation regulations for over-the-road operation.

The central element of the mobile pyrolysis unit is the fluidized-bed reactor. The reactor converts agricultural and forestry waste products to useable fuels. The unit uses a refractory sand as the inert fluidizing medium, and can handle feedstocks with moisture contents as high as 55 percent.

The feed preparation system reduces the moisture content of the feedstock entering the reactor to much less than this maximum amount. This sub-system is composed of a standard hammer-mill-type shredder and a pneumatic-type tower dryer. The drying system has been adapted from standard designs of the cotton ginning industry.

The product separation sub-system collects the storable and transportable fuel products. The dry mechanical collector (cyclone) captures the char (density 10-15 lbs/ft<sup>3</sup>), and the Venturi oil scrubber collects the pyrolytic oil (65-75 lbs/ft<sup>3</sup>). The Venturi oil scrubber is a modification of a standard wet scrubbing system. The principal change is in the flow rates of the scrubbing medium and the types of pumps employed. The pumps are capable of pumping a high viscosity fluid.

The final system component is the electrical cogeneration system. A gas turbine uses the low-Btu gas (150 Btu/scf) generated during the pyrolysis process to generate the required electricity for the several motors of the entire unit. The exhaust from the turbine is mixed with cooling air and then used as the heat source for the drying system. To integrate the system more completely, the gas turbine package supplies the required fluidization air for the reactor sub-system.

### The Products

The fluidized-bed pyrolysis system produces three fuel products-- a low-Btu gas, a pyrolytic oil, and a pyrolytic char. As can be seen in Figure 2, the quantity of the products can be varied by changing the operating temperature of the reactor. The operating temperature of the mobile pyrolysis system was selected in order to maximize the storable fuel products (char and oil) while producing a low-Btu gas that could be burned in the electrical generation sub-system.

The gas quality that can be burned in the gas turbine engines can be as low as 100 Btu/scf. The mobile pyrolysis unit is designed to produce a gas of 150 Btu/scf quality. During start-up the turbines will be tested

to determine the minimum gas quality that can be tolerated. As the turbines are shown to be able to burn a low-quality gas, the reactor conditions can be varied to produce a larger portion of storable oil product.

The char product resembles pulverized coal. The exact physical nature depends on the waste material from which the char is derived, and the temperature at which the char is produced. If waste wood is the feedstock, and the temperature of the reactor is approximately 1000 F, the char will have a heating value of approximately 13,000 Btu/lb, an ash value of less than 10 percent, and a particle size ranging from 1000 microns to 50 microns or less. The volatility of this material is approximately 20 percent. This char makes an excellent feedstock for charcoal briquets.

The oil product is similar to a heavy residual oil that is highly oxygenated. Its heating value ranges between 11,000 and 13,000 Btu/lb. The handling properties of the pyrolytic oil made from wood are different from a typical residual oil. The viscosity and corrosivity are higher and the material undergoes chemical changes when stored at elevated temperatures. However, the sulfur content of this oil is negligible which is of considerable importance today.

### System Efficiency

The principal objective of the mobile pyrolysis system is to dispose of waste products while producing a transportable fuel product. The energy flow diagram (Figure 3) shows the split in the energy product for the design case in which the quality of the low-Btu gas is 150 Btu/scf. This condition yields a storable energy fraction of 49 percent of the incoming feed. The additional recoverable energy in this case is used for drying of the feedstock or it is vented to the atmosphere.

The percentage of storable energy can be increased if the quality of the gas being burned in the gas turbine can be reduced.

The total system efficiency is increased when operating in a region where the low-grade heat being rejected by the oil scrubbing system and excess turbine exhaust heat can be utilized. This situation does occur

when operating at a cotton gin or sawmill. This low-grade heat can be used to supply the energy for preheat of a steam system or a hot water system.

#### Schedule

The mobile fluidized-bed pyrolysis system is scheduled to be completed by early May, 1980. The system will then undergo a three-month shakedown on sawmill waste at a site near the fabrication shop. After completion of the shakedown phase the unit will proceed on the remainder of the 9-month testing schedule on the remaining waste products, cotton gin trash, rice straw, and feedlot wastes.

During this testing period the entire system will undergo complete analysis as to environmental emissions, operating characteristics, fuel product quality, and overall system economics.

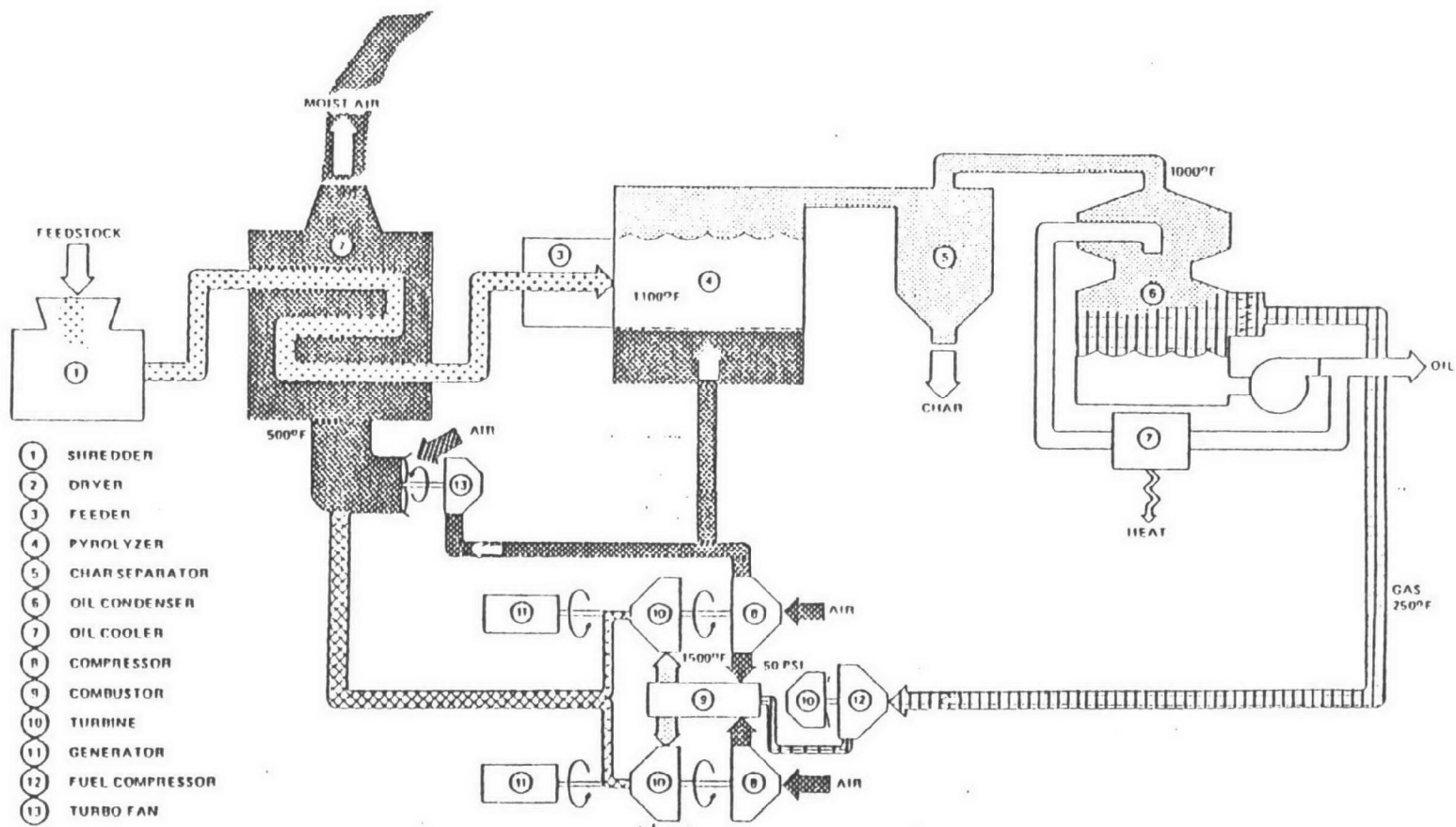


FIGURE 1 Mobile Pyrolysis Flow Sheet

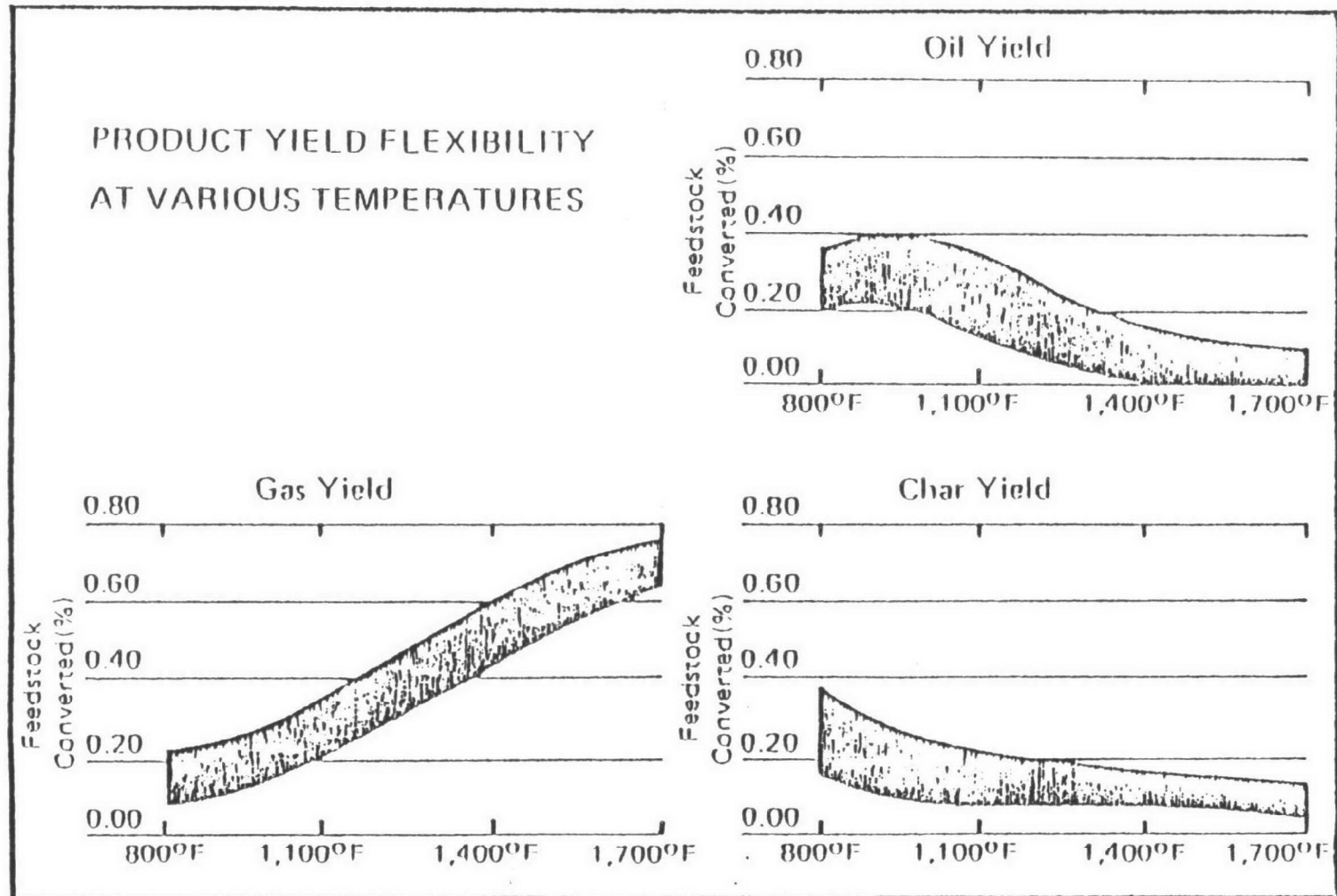


FIGURE 2 Mobile pyrolysis product yields

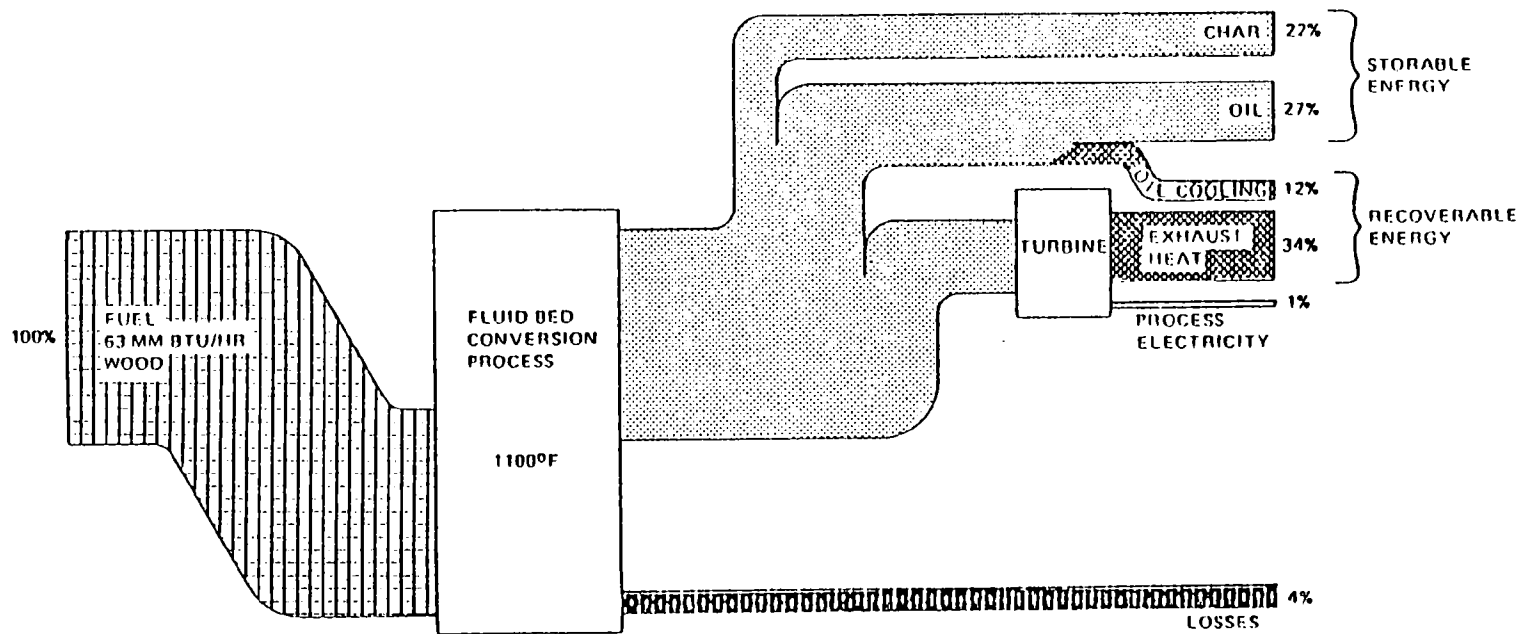


FIGURE 3 Mobile Pyrolysis Energy Flow Diagram



# THERMOCHEMICAL CONVERSION OF BIOMASS TO GASOLINE

J. P. Diebold and G. D. Smith  
Naval Weapons Center  
China Lake, CA 93555

## ABSTRACT

This noncatalytic process involves the low pressure, selective pyrolysis of organic wastes to gases containing relatively high amounts of ethylene and other olefins. After char, steam, and tars are removed at low pressure, the gases are compressed to 450 psia (3100 kPa) for purification. The concentrated olefins are then further compressed to 750 psi (5200 kPa) and fed to the polymerization reactor where they react with each other to form larger molecules, 90% of which boil in the "gasoline" range. Using organic feedstock derived from trash, gasoline was produced on a bench scale system which had the same appearance and distillation characteristics as gasoline made from pure ethylene which had an unleaded motor octane of 90. Preliminary economic analyses indicate that the process is currently competitive with petroleum derived gasoline. This program has been funded by the U.S. Environmental Protection Agency.

## INTRODUCTION

The petroleum resources of the free world are becoming increasingly scarce and expensive. As the search for new oil goes further out to sea and deeper in the ground, this new oil will be increasingly expensive to produce. Many of the existing oil fields in some countries apparently will not be pumped at their maximum rate in an effort to save that oil for future generations when the price will be presumably higher. Thus, it appears advantageous to develop sources of synthetic petroleum and in particular synthetic gasoline. Due to the high volumetric energy content of hydrocarbon liquids, they would have been invented for mobile transportation if they had not been naturally occurring. Usually the term "synthetic petroleum" brings to mind coal and/or oil shale liquefaction. However, these processes will involve a considerable amount of environmentally questionable strip mining and are normally considered to require a large amount of scarce water resources. The process to be discussed in this paper involves the use of organic wastes and/or biomass in a noncatalytic selective process to produce unleaded, high octane gasoline. Byproducts are fuel oil, lubricating oil, ash, water vapor, and carbon dioxide. Commercial sized plants would resemble small oil refineries in many aspects and could be widely deployed in order to be near the feedstock source.

The advantage of producing gasoline rather than other fuel forms becomes apparent by comparing common fuels

on a relative wholesale value basis. If a wholesale value of \$1.00 per unit of energy is assigned to natural gas for interruptible commercial usage, then in 1975 the value of noninterruptible domestic natural gas was \$1.42 per unit of energy. Number six fuel oil was \$3.08, while the value of gasoline was \$5.48 per unit of energy. Recent relative increases in the value of natural gas have reduced the ratio of gasoline to natural gas prices temporarily. However, the widely predicted continuation of today's petroleum shortage will cause the value of gasoline to escalate at a rate much greater than boiler fuels. This is because, although coal can again become the primary boiler fuel for the nation, coal fueled automobiles having today's performance are not being actively considered.

The conversion of organic waste to automotive fuel was consequently investigated for remote military installations in a Department of Defense Advanced Research Projects Agency sponsored program because of the high potential value of the product. The synthesis of methanol from organic wastes was evaluated in detail with mass and energy balances developed about two different flow diagrams. This approach would have pyrolyzed the organic fraction to form synthesis gases which would then have been compressed, purified, and catalytically reacted to form methanol. During the course of this study (1), several references were found which indicated the possibility of using pyrolysis to form a significant amount of low molecular weight hydrocarbons rather than just carbon oxides, methane, and hydrogen. These gaseous hydrocarbons of interest were predominantly ethylene, propylene, and other olefins.

In the 1930's the oil industry began to extensively pyrolyze ("crack") crude oil to increase the yield of gasoline. By-products of that process included large amounts of ethylene, propylene, and butylene. Extensive research was performed on the utilization of these by-product gases which led to the commercialization of their conversion to gasoline by both catalytic (2) and non-catalytic (3) processes. The gaseous hydrocarbons were compressed, purified, and then heated such that they reacted to link up with themselves to form the larger gasoline molecules by polymerization. This process produced a liquid which was over 75 percent gasoline. The proposed process substitutes solid organic wastes for the crude oil feedstock, but otherwise parallels the petroleum process used to make polymer gasoline. Due to the high ethylene content of the olefins formed during pyrolysis of cellulosic materials, the thermal or non-catalytic polymerization was chosen for

this process because the traditional catalytic method polymerized ethylene with difficulty.

The overall process for converting organic wastes to gasoline consists of: first, the pyrolysis of the wastes to gases containing large amounts of olefins, i.e. ethylene, propylene, etc.; second, the compression and purification of the olefins; and third, the polymerization of the smaller olefins to form larger gasoline molecules. Overall this amounts to a process which removes the oxygen from the cellulosic wastes to produce a gasoline consisting of hydrocarbons. Most of the rejected oxygen is in the form of carbon dioxide.

The critical technology that this program needed to demonstrate was the pyrolysis of cellulosic organic waste materials into gases containing large amounts of olefins and their subsequent processability. If the selective pyrolysis could be verified, and demonstrated, then the remainder of the process to make gasoline was thought to be relatively straightforward due to industrial experience with similar processes. In effect, the process parallels that of an oil refinery with the most significant difference being the use of today's cellulosic waste material rather than eons-old organic matter (crude oil) as a feedstock.

The potential impact this process could have on the gasoline consumed in the United States appears to be substantial. Assuming that this process will undergo a traditional developmental or scale-up period followed by a well financed program with high national priority, widespread deployment of conversion plants could be accomplished by 1998. A recent Market Oriented Program Planning Study by the Department of Energy (DOE) estimated the U.S. gasoline consumption in 1990 at 115 billion gallons (4). If 10% of the land currently in forest, pasture, or range usage having at least 25 inches of precipitation and less than 30% slopes were to be developed for silvicultural energy farms, approximately 28% of the gasoline consumed could be produced from the resultant biomass (5). Another 16% of the projected gasoline consumption could be produced from crop residues and spoiled forages (6). If the trash generated by 120 million people were to be converted to gasoline, 4% of the 1990 gasoline consumption would result. From these three biomass sources, slightly less than half of the

projected 1990 gasoline consumption could be produced by the conversion process described without impacting food production to any extent. To determine the net energy produced by the overall system including energy inputs to grow, harvest, transport, and process biomass into gasoline requires a very specific analysis for a given site and is outside the scope of this paper. However, the process would have the best economics where the biomass is a waste by-product and which now requires energy for its disposal.

Initial preliminary economic analyses looked very promising for fairly small cities to rid themselves of trash so the Environmental Protection Agency (IERL, Cinn.) was contacted to generate interest in this economical approach to trash disposal. As a result of their interest in this process, an interagency agreement (EPA-IAG-D5-0781) was written for NWC to pursue the technical and economic feasibility of converting organic wastes to gasoline by evaluation in a bench-scale unit (5 kg/hr). This EPA effort was begun in June 1975 and has been continuing.

## EXPERIMENTAL

### Pyrolysis

Figure 1 shows the currently evolved pyrolysis schematic. A finely ground organic fraction of municipal solid waste is continuously fed by a one-inch screw feeder. At the end of the screw feeder, the feed is fluidized and conveyed by a carrier gas stream (normally carbon dioxide) to the steam ejector. The mixture of solid waste, carrier gas, and steam then enter a long, red-hot 3/4 inch diameter tubular reactor. Reactor lengths of 2 and 6 meters resulted in pyrolysis times of about 50 to 150 milliseconds, respectively. The char is removed from the pyrolysis stream in a three inch diameter cyclone. The steam and tars are condensed out of the pyrolysis gas stream by the water quench system. The noncondensable gas stream volume is measured by an orifice flow meter and then either flared off or fed into a three stage compressor for storage at high pressure. This system pyrolyzes a nominal 5 kg of feed per hour.

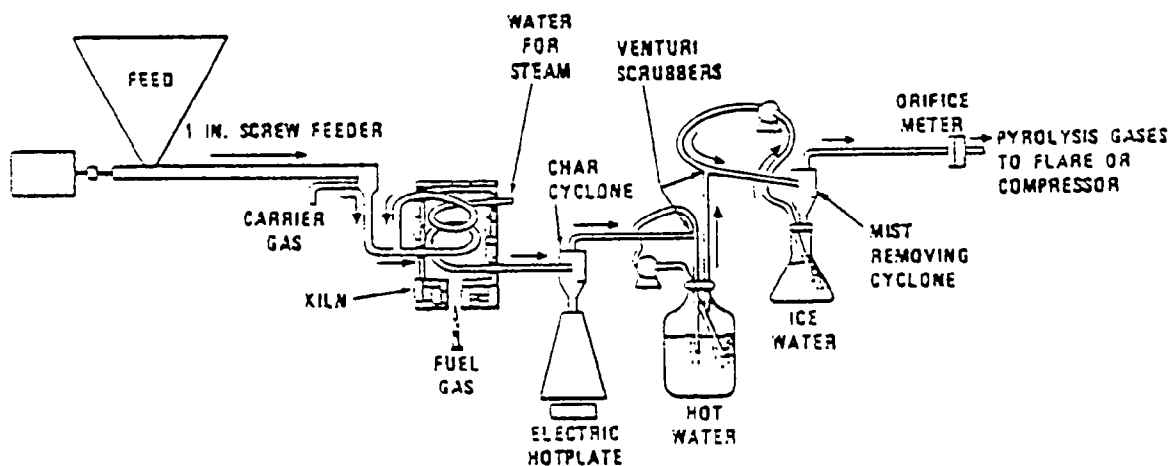


Fig. 1. Pyrolysis Schematic

The composition of the pyrolysis products has been found to be a function of the combination of temperature, residence time, and especially the dilution of the solid wastes by inert gases inside the reactor. As shown in Figure 2, the total hydrocarbon product (other than methane) can be varied by as much as 165% depending upon the relative dilution of the pyrolysis gases. Using the more favorable combination of these variables, a pyrolysis product distribution such as that represented in Figure 3 can be attained using organic material obtained from municipal solid wastes. Slightly more than half of the energy contained in the organic waste can be recovered in the gasoline precursors. About one third of the energy is recovered in the "medium Btu" by-product gas stream of carbon monoxide, methane, and hydrogen. About one-seventh of the energy is recovered in the char, which has a heating value similar to lignite coal.

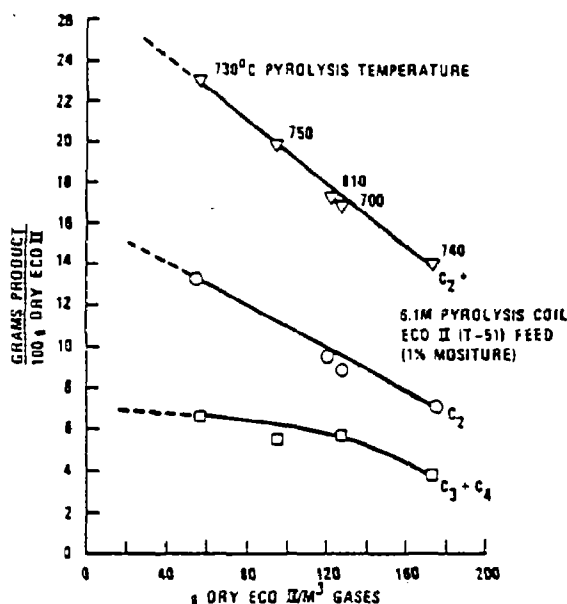


Fig. 2. Pyrolysis Products as a Function of Dilution

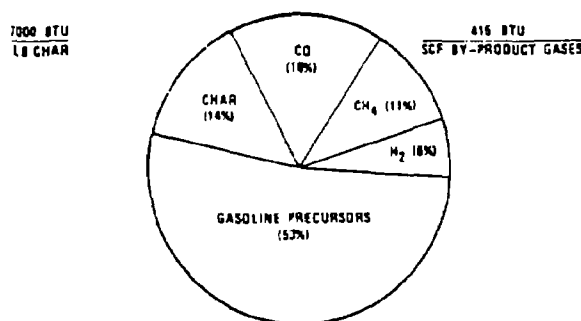


Fig. 3. Pyrolysis Product Energy Distribution

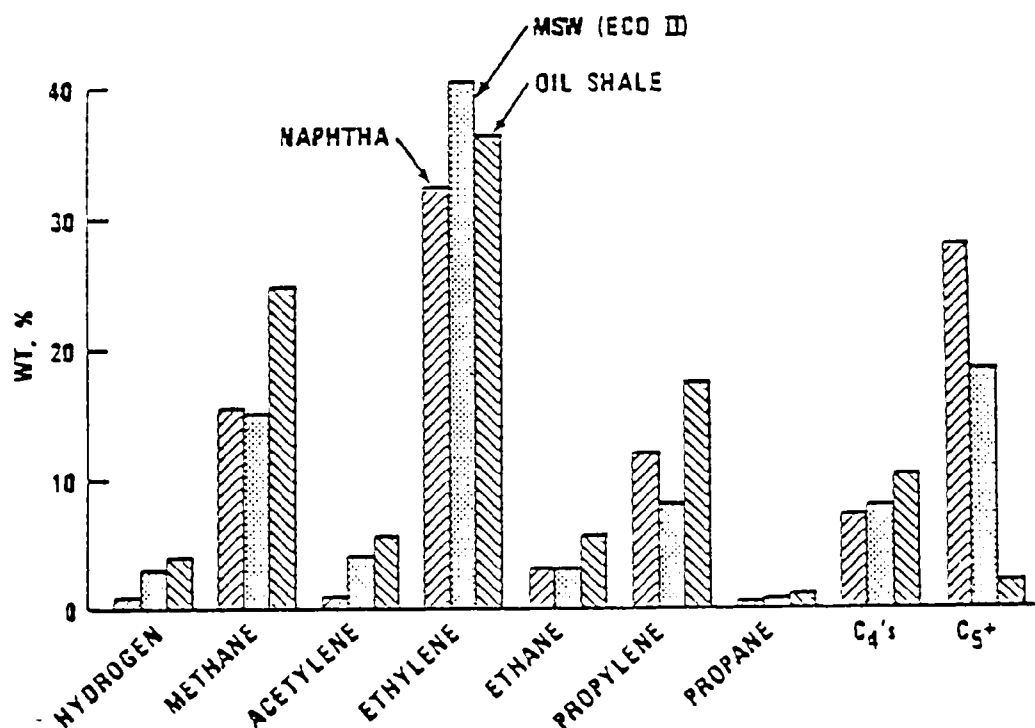
#### Pyrolysis Discussion

Pyrolysis of cellulosic materials has long been recognized as the result of several competing reactions taking place simultaneously. At low temperatures of 200 to 300°C,

the predominant reaction is of dehydration to form char and water vapor. At intermediate temperatures of 300 to 600°C the predominant reaction is a depolymerization or chain cleavage reaction to form levoglucosan tars. At elevated temperatures, gasification is the predominant reaction to form combustible volatiles. (7) This gasification reaction itself appears to have at least two major competing reactions: a) to form olefins, carbon monoxide, hydrogen, and methane; and b) to form thermally stable, water soluble, oxygenated compounds. The data suggest that the olefin forming reaction is favored when the partial pressure of the pyrolysis products is reduced by the addition of a relatively inert carrier gas, e.g. carbon dioxide, steam, methane, nitrogen, or carbon monoxide, or mixtures of these gases with hydrogen. It is interesting to note that although the quantity of gases produced can be varied by the relative dilution, the relative molar ratios of the gaseous species after water washing are relatively constant.

The by-product gases could be used to fuel stationary internal combustion engines to generate shaft power for the compressors and shredders, as well as to fuel the pyrolysis furnace along with the by-product char. As was mentioned, it was found that the use of steam to dilute the pyrolysis gases results in a higher conversion to gasoline precursors. It now appears that the process will be optimized by making as much steam as possible by energy recovery from hot gas streams as well as by utilizing all of the char and the by-product fuel gases for process energy. This will result in only gasoline, fuel oils, and lubricating oils as the products from the organic fraction. These products will be readily marketable compared to char, pyrolytic oils, or "medium Btu" gas. The generation of high pressure, superheated steam to cogenerate shaft energy and low pressure process steam may optimize the process.

It is interesting to note that the pyrolysis conditions found to be optimum for municipal solid wastes are coincidentally similar to those used by the petrochemical industry to pyrolyze naphtha or crude oil to form ethylene: e.g. about 750°C (~1400°F), steam dilution, pyrolysis times of less than a second, and long tubular reactors having inside diameters of less than five cm (8, 9, 10). It is even more interesting to note that if the carbon monoxide and carbon dioxide in the pyrolysis gas are ignored, and the remaining products are then normalized, that the relative weight percentages of the pyrolysis products from naphtha (8), solid wastes, and oil shale (11) are very similar, as shown in Figure 4. It appears that the molecular fragments from the pyrolysis of both cellulosic and large hydrocarbon molecules are very similar and that they achieve a similar short-lived "equilibrium" between the products. If not rapidly quenched, this pseudo "equilibrium" changes by the low-pressure, high temperature polymerization of ethylene, propylene, and butylene to form about half benzene and half aromatic tars with the evolution of hydrogen (12). If the pyrolysis system has a very long residence time, the benzene and tars further react to form char and hydrogen — the last mentioned being the traditional products from charcoal kilns, along with carbon monoxide.



(WEIGHT PERCENTAGES CALCULATED AFTER CO AND CO<sub>2</sub> DELETED)

Fig. 4. Pyrolysis Product Comparison

#### Polymerization with Pure Ethylene

To avoid the tar formation during polymerization, lower temperatures can be employed so that the gasoline fraction in the product is optimized. However, in order to maintain reasonable reaction rates, the pressure must be increased. Temperatures of 400 to 500°C (750 to 950°F) and pressures of 4800 to 6900 kPa (700 to 1000 psi) were often employed commercially (13, 14). To gain insights into the exothermic polymerization reaction, an experimental reactor was constructed as shown in Figure 5. This polymerization effort was conducted concurrently with the pyrolysis development, so no purified pyrolysis gases at elevated pressures were available for use. Since ethylene was the largest single

constituent in the gasoline precursors found in the pyrolysis gases, bottled ethylene was purchased and used for this study. The ethylene was regulated into a one-half inch diameter stainless steel tube which had been coiled and placed in a constant temperature, fluidized sand bath. The sand bath served to initially heat the coiled reactor until the exothermic reaction was initiated, after which the bath served to remove the heat generated. The ethylene slowly moved down the length of the reactor for a few minutes while polymerizing. The polymerized gases were then cooled to condense out the gasoline and oils. Noncondensable gases were measured and then flared off. Conversions per pass were as high as 30 percent. The liquids formed had very low viscosities and when distilled produced about 90 percent

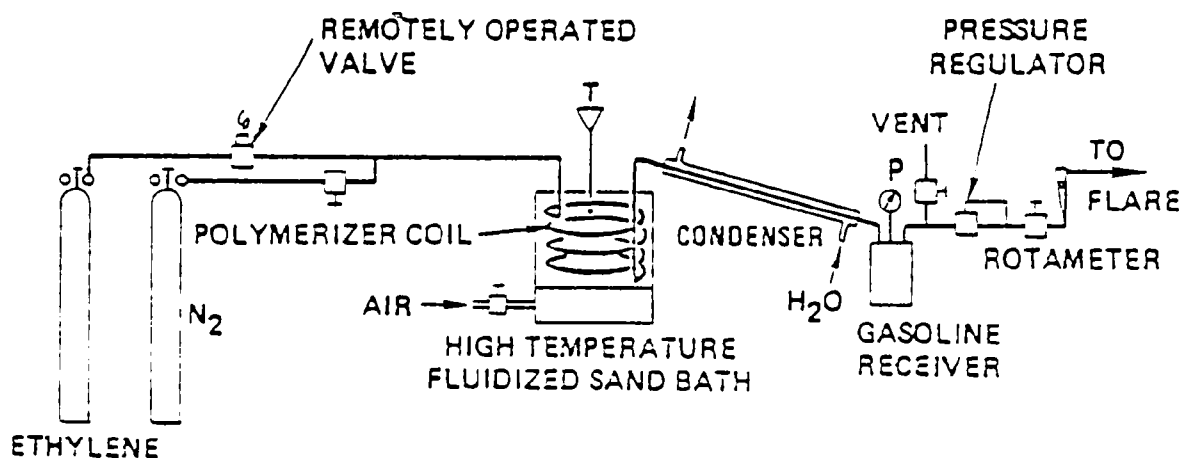


Fig. 5. Experimental Polymerization Reactor

gasoline. This distilled gasoline fraction was tested following the ASTM motor method and found to have a 90 octane rating in the unleaded condition (the research method would have resulted in a slightly higher octane number). The higher boiling liquids will yield a fuel oil and a lubricating oil fraction.

Based on the pyrolysis and ethylene polymerization experimentation it is estimated that 0.28 liter of gasoline and 0.03 liter of oils will be produced per kilogram of 90% by weight organic material (68 gal/ton gasoline, 8 gal/ton oils). The amount of lubricating oil in the oils is currently conjectured to be fairly small, but with a high potential total value due to its reported excellent viscosity characteristics (15).

#### Bench Scale Purification and Polymerization

The bench scale pyrolysis gas purification and polymerization flow diagram is shown in Figure 6. The pyrolysis gases are first compressed to 3100 kPa (~450 psi). The purification starts with the removal of carbon dioxide, hydrogen sulfide, and other water solubles with a hot, aqueous solution of potassium carbonate (16). Next the desirable olefins are absorbed in an organic solvent with the by-product fuel gases passing through unabsorbed. The olefin rich solvent is then heated to drive off the relatively volatile olefins (17). The purified olefins are then further compressed to 5200 kPa (~750 psi) and fed into the polymerizing reactor held at about 450°C (~850°F). The polymerizing reactor consists of a 3 meters long by 1.3 cm diameter 316 stainless steel tube (10 ft by 1/2 in dia) immersed in a boiling sulfur bath. The boiling sulfur bath has an extremely high heat transfer capability and serves to maintain a constant temperature as it removes the heat of polymerization. The polymerization reaction proceeds under these conditions of heat and pressure without catalysts to form a product consisting primarily of gasoline. After

polymerization, the hot gasoline vapors are cooled, condensed, and stored. Unpolymerized olefins can be recycled.

This bench-scale system is in the final stages of debugging. The hot carbonate system for carbon dioxide removal is very selective and has resulted in a carbon dioxide stream having a purity of greater than 99% by volume with the primary contaminant being acetylene. The potassium carbonate solution is easily regenerated, although it does require a considerable amount of energy to boil the solution at 120°C (250°F). The hydrocarbon absorption system needs additional tuning, but has resulted in a byproduct gas stream containing 20% hydrogen, 5% nitrogen, 11% methane, 61% carbon monoxide, and 2 to 3% gasoline precursors (mostly ethylene and propylene). The hydrocarbon stripper system also needs some additional tuning, but it has resulted in an enriched stream containing as high as 48% gasoline precursors with 4% hydrogen, 1% carbon dioxide, 1% nitrogen, 16% methane, and 29% carbon monoxide as the impurities.

The effect of these impurities in the polymerization was to lower the partial pressure of the reacting olefins to slow the bimolecular polymerization reaction. A longer residence time is indicated in the polymerizer reactor depending upon the relative purity attainable from the gas purification system. Using pyrolysis gases made from organics derived from trash, a small quantity of synthetic crude oil was produced from the partially purified gases available. This synthetic crude oil was distilled and 93% of it boiled in the gasoline range. The distillation curve for the polymer gasoline made from pure ethylene was virtually identical to that for the gasoline made from trash derived organics. The physical appearance of the two synthetic gasolines is an identical very pale yellow and with a gasoline odor. Although sufficient gasoline made from pyrolysis gases has not yet

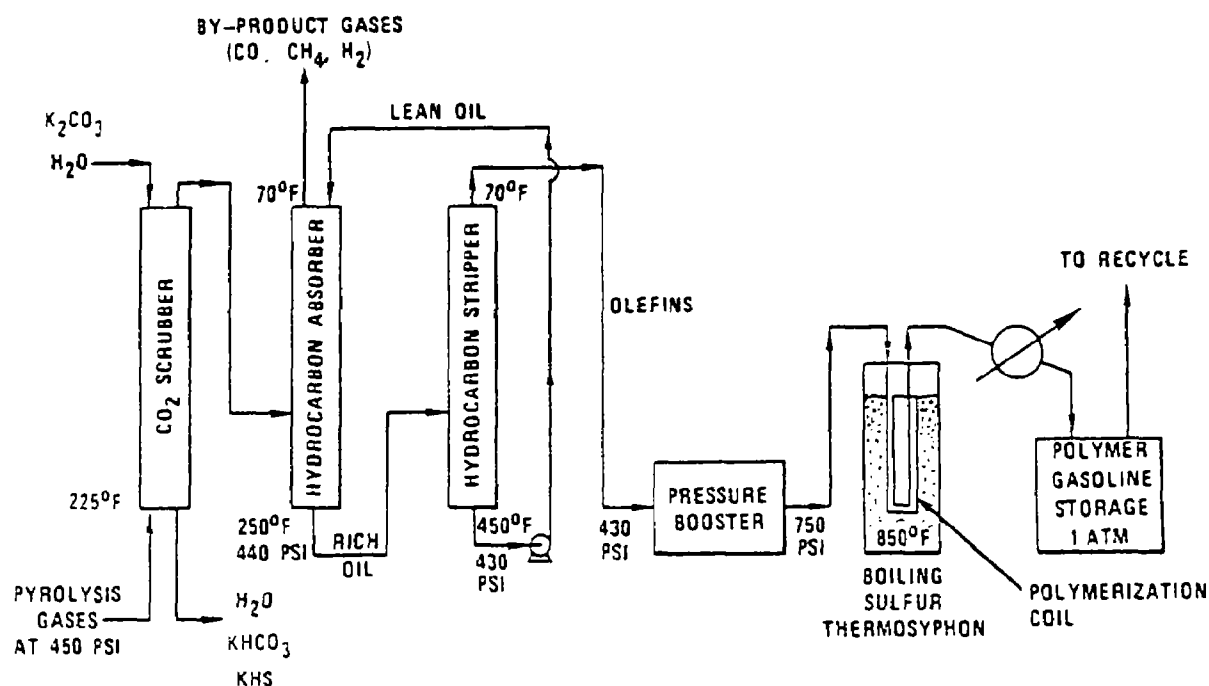


Fig. 6. Purification and Polymerization Schematic

been produced to allow an octane test to be run, it would appear reasonable to expect it to have an octane rating similar to that of the gasoline made from pure ethylene.

Additional effort needs to be expended in the bench scale system particularly in the areas of: low pressure pyrolysis gas scrubbing to more completely remove the tar mists; the hydrocarbon absorption and stripping system to verify that the reported high levels of gas purification can be attained with gases that contain carbon monoxide; the addition of a soaking chamber to the polymerizing reactor to increase the residence time to increase the conversion per pass; the addition of a recycle loop around the polymerizer to increase the overall yield; the full characterization of the synthetic gasoline and oil product; and the evaluation of feedstocks other than trash derived organics. A modest program to pyrolyze pure cellulose and pure lignin powders to be able to project biomass potential for this process has just been started with funding from the Solar Energy Research Institute.

## COMMERCIALIZATION POTENTIAL

It was noted previously that the pyrolysis conditions used in development for organic waste are very similar to those used to pyrolyze crude oil and naphtha to ethylene. It follows that once the solid wastes are fluidized by the carrier gas stream, that the technology exists in the petrochemical and petroleum industry to design and build commercially-sized organic waste pyrolysis units. Since similar compression, purification, and polymerization of the gaseous hydrocarbons have all been commercialized in the past, it would appear that the process could be contracted to any one of several petrochemical or petroleum construction firms with a fairly low technical risk. For pilot plant demonstration purposes, it may be economically advantageous to add this gasoline module to an existing trash processing plant already in operation or to locate it in an area having several types of agricultural wastes available.

## PRELIMINARY ECONOMICS

### Municipal Waste Feedstock

To determine the economic feasibility of the process to convert municipal trash into gasoline requires a long list of assumptions. For the use of municipal trash as feedstock it was assumed to contain 60% dry, ash free organic material, 13% inorganics (iron, aluminum, and glass), and the balance moisture. A credit of \$4.35 per tonne (\$4.40 per ton) of trash processed was assumed for the value of the reclaimed metals and glass. A yield of 0.19 liters of hydrocarbon liquids per kilogram (45 gal/ton) of trash processed was assumed. The relative economics of the process were taken to be a function of source of capital, plant size, gasoline (hydrocarbon) value, and the dump fee per tonne of trash credited to the process. The plant size can be converted to the population served by the process by assuming a daily per capita trash generation rate of 2.27 kg/day (2.5 tons/1000 daily people). The capital and operating cost figures are based on those generated by an outside petrochemical consultant under contract to EPA for a 100 ton per day plant during their evaluation of the

process. The consultant's cost estimate in early 1973 was \$7.6M capital costs and \$1.1M annual operating cost (exclusive of debt service). The capital costs were scaled using 0.65 as the exponential scaling factor, whereas 0.20 was used as the labor cost factor.

As will be illustrated, the method of financing the construction costs has a significant impact on the apparent economics of the process. Figure 7 shows the economics for a plant financed at an interest rate of 3% and a 25 year amortization. This would be fairly typical of a municipally financed plant which could be operated either by the municipality or by a contractor. It is seen that with a \$10/tonne dump fee credited to the plant that a 250 tonne/day plant would produce gasoline worth \$0.10/liter (\$0.38/gallon).

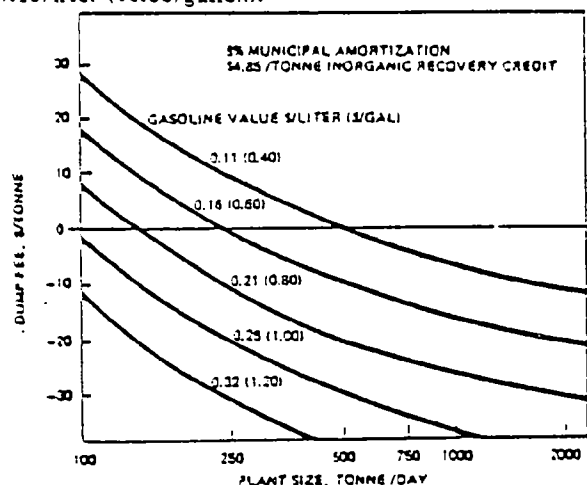


Fig. 7. Trash to Gasoline Economics with Municipal Financing

Figure 8 has the same assumptions as before, but with private enterprise involved at a 15% rate of return. At a 15% rate of return, the small 250 tonne per day plant with a \$10/tonne dump fee must charge about \$0.20/liter (\$0.75/gallon) to meet its financial obligations. For private enterprise, larger plant sizes are clearly indicated. For example, at a 15% rate of return and the same dump fee, a 500 tonne per day plant size is estimated to produce gasoline valued at about \$0.13/liter (\$0.50/gallon).

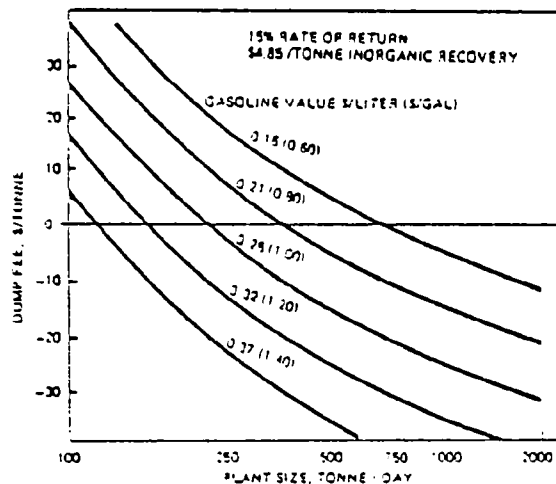


Fig. 8. Trash to Gasoline Economics with Private Financing

The 500 tonne per day plant therefore appears to be an economically interesting size. One of the problems in evaluating the economics of this system is to project the value of gasoline over the estimated 25 year life of the plant. Figure 9 shows the rate of return on the investment for a 500 tonne per day plant using the same bases as before. With a \$10 per tonne dump fee and a current \$0.685/gallon wholesale gasoline value, a 23% rate of return would be realized. If the wholesale value of gasoline were \$1.00 per gallon, the projected rate of return would be 34%.

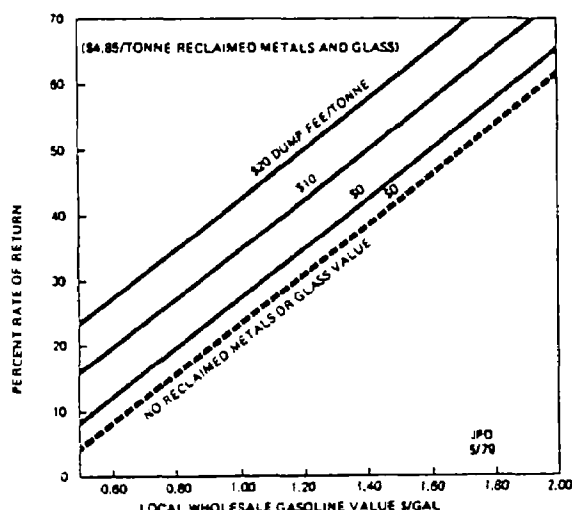


Fig. 9. Rate of Return for 500 Tonne/day Trash Plant

#### Biomass Feedstock

The process to convert trash to gasoline is thought to be applicable also to agricultural and silvicultural materials. These organics could be a mixture of wastes and/or material specifically grown for conversion to fuel. The assumptions were modified somewhat to reflect the lack of metal and glass recovery equipment and the lack of these salvage products. The feedstock was assumed to contain 90% dry, ash-free organic material. The yield of gasoline per unit weight of organic material was assumed to be the same as with municipal trash derived organics. Similar economic trends are observed with the biomass processing plants as with the trash plants, but the economical size of the biomass plants is larger than that of the trash plants due to the difference in feedstock cost.

To interest private capital at a 15% rate of return, a 1000 tonne per day plant could pay \$30 per tonne of organics and charge \$0.72 per gallon as can be seen in Figure 10. Examining a 1000 tonne per day plant in more detail, in Figure 11 it is seen that if the feedstock cost is \$30/tonne and the local wholesale gasoline value is \$1.00 per gallon, the projected rate of return would be 31%.

These economic predictions for the process point out that for the process to be able to buy the organic feedstock, fairly large plants will need to be constructed. However, by commercial standards these plants at the 1000 tonne/day size are in reality not very large and would have an output of a fairly small oil refinery (less than 2000 barrel per day). If the 1000 tonne/day

biomass-to-gasoline plant were to be located at the center of a biomass producing area having an assumed annual biomass production rate of 11.2 tonne/hectare (5 tons/acre), the necessary biomass could be raised within a 10.2 km radius. Long hauling distances would not seem to be involved with this process and the gasoline produced would be consumed relatively locally.

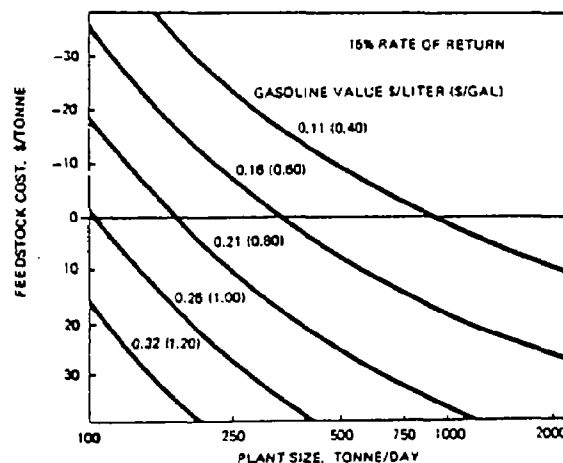


Fig. 10. Biomass-to-Gasoline Economics with Private Financing

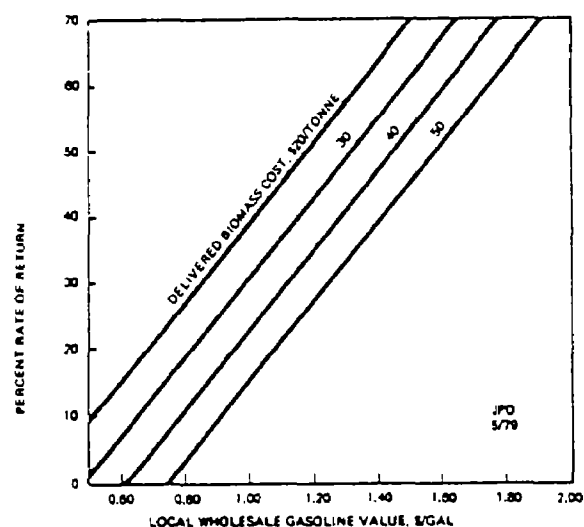


Fig. 11. Rate of Return for 1000 tonne/day Plant

#### SUMMARY

This process converts organic waste materials into the basic hydrocarbon building blocks, i.e. the olefins: ethylene, propylene, and butylene. Although these compounds could be used as highly valued petrochemicals, they can also be profitably converted to a high octane, unleaded gasoline with only a small amount of fuel and lubricating oils as the by-products. The process utilizes a high temperature, short residence time pyrolytic process with steam dilution to optimize the production of the desired gaseous olefins. This

process is virtually identical to that used by the petrochemical industry to make ethylene and propylene from crude oil. Once the gaseous olefins are produced, the technology required to convert them into gasoline is state-of-the-art. Experimentation on a 5 kg/hr bench scale system has demonstrated the selective pyrolysis to form unusually large amounts of the desired olefins as well as their purification and subsequent polymerization to gasoline. It is projected that about 1.3 U.S. petroleum barrels of gasoline can be produced per ton of dry ash free organic material or about a 50% efficiency in energy conversion. The economic projections indicate that this process will be viable in moderately sized plants which could be widely dispersed.

Although some additional bench-scale process development work is needed, it is timely to make long range plans to exploit this technology. The outlook of rising trash disposal costs and restrictions on agricultural burning of wastes, as well as increased petroleum costs combine to make the potential of this process very promising.

#### ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution to the effort made by Dr. Charles B. Benham (currently with the Solar Energy Research Institute), particularly in the polymerization demonstration with pure ethylene and the early development of the preliminary economics and their presentation format. Mr. Walter Liberick, Jr. and Mr. Charles Rogers of the Industrial Environmental Research Laboratory (EPA) have been the program officers responsible for the funding which made the hardware demonstrations possible. Portions of this paper also appear in the authors' paper "Noncatalytic Conversion of Biomass to Gasoline" presented to the ASME sponsored Solar Energy Conference held in March 1979 (ASME 79-Sol-29).

#### REFERENCES

- 1 Benham, C. B. and Diebold, J. P., "Conversion of Solid Waste to Fuels," NWC TP 5791, publication Unclassified, August 1975, Naval Weapons Center, China Lake, Calif.
- 2 Ipatieff, V. N., et al., "Polymerization, a New Source of Gasoline," Ind. Eng. Chem., 27, No. 9, 1935, pp. 1077-1081.
- 3 Frolich, K. and P. J. Wiezevich, "Cracking and Polymerization of Low Molecular Weight Hydrocarbons," Ind. Eng. Chem., 27, No. 9, 1935, pp. 1055-1062.
- 4 Park, W., Price, G., Salo, D., "Biomass-Based Alcohol Fuels: The Near-Term Potential for Use with Gasoline," (Mitre Corp.) DOE HCP/T4101-03 UC-61, Aug. 1973, p. 17.
- 5 Inman, R., Salo, D., "Silvicultural Energy Farms," (Mitre Corp) presented at Fuels from Biomass Symposium, April 18 - 19, 1977 at U. of Illinois, DOE C00/4225-1 UC-61.
- 6 Benson, W. "Biomass Potential from Agricultural Production," (MRI) presented at Fuels from Biomass Symposium, April 18 - 19, 1977, at U. of Illinois, DOE C00/4225-1 UC-61.
- 7 Shafizadeh, F. "Pyrolysis and Combustion of Cellulosic Materials," Advances in Carbohydrate Chemistry, 23, pp 419 - 475. (1968)
- 8 Nelson, W. L., Petroleum Refinery Engineering, 4th ed., McGraw-Hill, New York, 1958, pp. 525-593.
- 9 Prescott, J. H., "Pyrolysis Furnace Boosts Ethylene Yield by 10-20%," Chem. Eng., July 7, 1975, pp. 52-53.
- 10 Zdonik, S. B., et al., "Function of Dilution Steam in Cracking," Oil Gas J., May 27, 1968, pp. 103-108.
- 11 Sohns, H. W., et al., "Development and Operation of an Experimental Entrained-Solids Oil Shale Retort," BUMINES, R15522, 1959.
- 12 Cadman, W. H., "Semi Industrial Production of Aromatic Hydrocarbons from Natural Gas in Persia," Ind. Eng. Chem., 26, No. 3, 1934, pp. 313-320.
- 13 Wagner, C. R., "Production of Gasoline by Polymerization of Olefins," Ind. Eng. Chem., 27, No. 3, 1935, pp. 933-936.
- 14 Sullivan, F. W., Jr, Ruthruff, R. F., Kuentzel, W. E., "Pyrolysis and Polymerization of Gaseous Paraffins and Olefins," Ind. Eng. Chem., 27, No. 9, 1935, pp. 1072-1077.
- 15 Seger, F., Doherty, H., Sachanen, A., "Noncatalytic Polymerization of Olefins to Lubricating Oils," Ind. Eng. Chem., 42, No. 12, 1950, pp. 2446-2452.
- 16 Riesenfeld, F., and Kohl, A., Gas Purification, 2nd ed., Gulf Publishing Co, Houston, 1974, pp. 176-205.
- 17 Kniel, L., and Slager, W., "Ethylene Purification by Absorption Process," Chem Eng. Prog., 43, No. 7, 1947, pp. 335-342.



EMERGING TECHNOLOGY FOR MAXIMUM CONVERSION  
OF WASTE CELLULOSE TO ETHANOL FUEL

BY

Charles J. Rogers  
Industrial Environmental Research Laboratory  
U.S. Environmental Protection Agency  
Cincinnati, Ohio 45268

ABSTRACT

The U.S. Environmental Protection Agency-New York University scientists have been working over the past five years on continuous processing technology for industrial-scale conversion of waste cellulose to glucose. A continuous waste-cellulose to glucose pilot plant with a capacity of one ton per day has been in operation for approximately two years. The reactor device is a twin-screw extruder, selected because of its capacity for conveying, mixing, and hydrolyzing up to 60 percent of the cellulose values to glucose. In the past, acid hydrolysis reactor development studies have focused primarily on the conversion of hexosan to glucose. Agricultural residues and wood also contain a pentosan fraction that can be hydrolyzed and fermented to ethyl alcohol. This article reports results of a continuous acid hydrolysis development and a discussion of a two-stage reactor development to maximize ethanol production from carbohydrate-bearing waste.

AFB COMBUSTION OF MUNICIPAL SOLID WASTE:  
TEST PROGRAM RESULTS

by

L.C. Preuit, Project Scientist, Combustion Power Co.  
K.B. Wilson, Project Engineer, Combustion Power Co.

ABSTRACT

Air classified Municipal Solid Waste (MSW) was fired in an Atmospheric Fluidized Bed Combustor at low excess air to simulate boiler conditions. The 7 sq. ft. combustor at Combustion Power Company's energy laboratory in Menlo Park, CA, incorporates water tubes for heat extraction and recycles elutriated particles to the bed. System operation was stable while firing processed MSW for the duration of a 300-hour test. Low excess air, low exhaust gas emissions, and constant bed temperature demonstrated feasibility of steam generation from fluidized bed combustion of MSW.

During the 300-hour test combustion efficiency averaged 99%. Excess air was typically 44% while an average bed temperature of 1400 °F and an average superficial gas velocity of 4.6 ft/sec were maintained. Typical exhaust emission levels were 30 ppm SO<sub>2</sub>, 160 ppm NO<sub>x</sub>, 200 ppm CO, and 25 ppm hydrocarbons. No agglomeration of bed material or detrimental change in fluidization properties was experienced.

A conceptual design study of a full scale plant to be located at Stanford University was based on process conditions from the 300-hour test. The plant would produce 250,000 lb/hr steam at the maximum firing rate of 1000 tons per day (TPD) processed MSW. The average 800 TPD firing rate would utilize approximately 1200 TPD raw MSW from surrounding communities. The Stanford Solid Waste energy Program was aimed at development of a MSW fired fluidized bed boiler and cogeneration plant to supply most of the energy needs of Stanford University.

## INTRODUCTION

Disposal of solid waste has historically been an economic cost to municipalities and industry. The least expensive means of disposal in this country has traditionally been landfill for which the capital investment required is minimal. Rapidly decreasing availability of space for landfill and rapidly increasing need for recovery of the energy value of solid waste have generated considerable interest in the development of solid waste combustion technology. Mass burning incinerators, both with and without water walls for energy recovery, have seen the greatest use in combustion of municipal solid waste, particularly in Europe where incineration of solid waste is much more common. Drawbacks of mass burning include low process efficiency and high emissions levels. Alternative processes include atmospheric fluidized bed (AFB) boilers, semi-suspension fired boilers, and pyrolysis processes.

AFB boilers offer the advantage of low  $\text{NO}_x$  emissions and high combustion efficiency in relatively compact equipment for the firing of municipal solid waste (MSW). Prior to the present testing, however, MSW combustion in an AFB boiler had not been demonstrated. An experimental program was designed to investigate the favorable operating regimes for a bed with steam-raising tubes, to determine the combustion efficiency, to measure the gaseous pollutants, to determine the erosion or corrosion of the tubes, and to investigate the fouling of the tubes or system internals caused by the combustion of municipal solid waste. Two 50-hour preliminary experiments were run in order to shake down the equipment and to conduct parametric studies to identify the most favorable operating regime for a subsequent 300-hour test. This paper will describe the results of the experimental program and relate those results to the economics of a full scale cogeneration facility being considered for Stanford University.

## EQUIPMENT DESCRIPTION

Testing was conducted in a 7 sq. ft. atmospheric fluidized bed combustor at Combustion Power Company's energy laboratory. The refractory-lined combustor is cylindrical with an inside diameter of 3 ft. and an inside height of 16 ft. A view port permits observation of the bed during operation. Figure 1 diagrams the combustor facility as arranged for combustion of processed municipal solid waste (MSW). Figures 2 and 3 show the combustor and controls.

The combustor permits several arrangements of in-bed heat exchanger tubes so that heat extraction can be adjusted to suit desired test conditions.

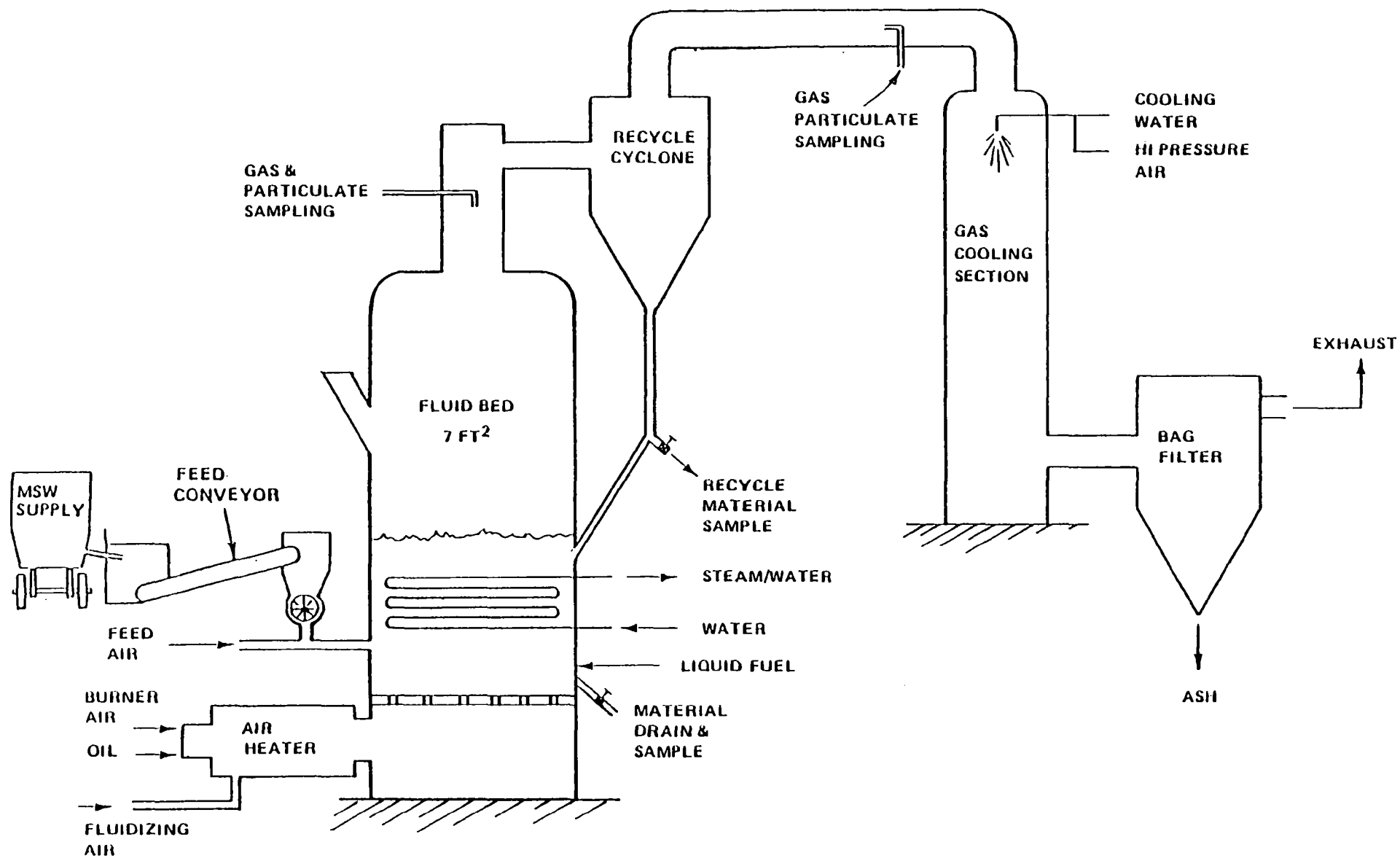


Figure 1 Fluid Bed Boiler Test Facility

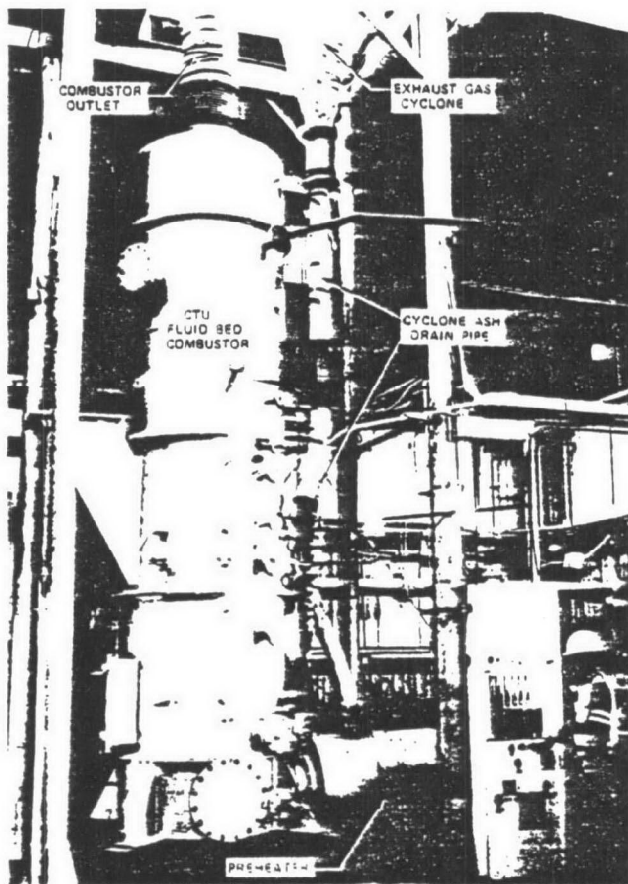


Figure 2  
CTU Fluidized Bed Combustor  
at Combustion Power Co., Inc.

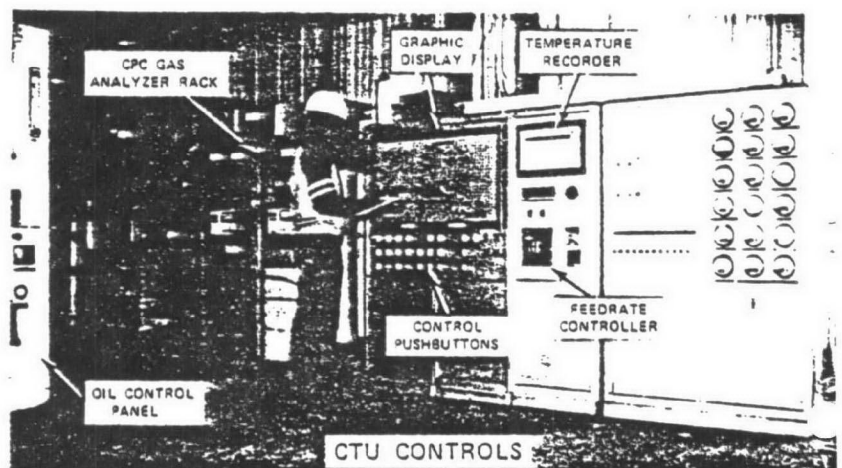


Figure 3  
CTU Controls

Primary heat extraction is through two, three, or four horizontal water tube bundles. These stainless steel tubes operate at low temperature to assure test reliability. Typically, 150 psig water is heated from 200 F to 300 F. This water is flashed to atmospheric pressure and make-up water reduces the feedwater temperature to 200 F. The water tube wall temperatures are lower than those of typical boiler tubes so that temperature-related corrosion does not occur. For the long duration test, air-cooled sample tubes were installed in the fluid bed and in the freeboard above the bed. These tubes were designed to duplicate boiler and superheater tube-wall temperatures for study of erosion and corrosion. Figure 4 shows the bed heat exchanger arrangement for the 300-hour test.

The combustor may be operated with or without recycle of elutriated bed material. During the first parametric test the exhaust cyclone at the combustor was arranged to discharge into a collection barrel rather than returning collected particles to the bed. During the second parametric test and the 300-hour test, elutriated particles were recycled back to the bed from the cyclone. Discharge piping from the stainless steel recycle cyclone permits sampling of recycle material during operation.

Exhaust gas from the recycle cyclone passes through a spray cooler before final particulate clean-up in a baghouse. Stack discharge from the baghouse meets all applicable emissions regulations. Sampling ports are provided before and after the recycle cyclone, and also in the discharge stack from the baghouse.

#### Solid Waste Processing and Feed

Municipal solid waste is received in conventional packer trucks, each containing 3 to 6 tons of refuse. The trucks dump their contents on a covered concrete pad from which the refuse is pushed onto shredder input conveyors as shown in Figure 5. The 100 hp Eidal mini-mill shredder has a nominal capacity of 5 tons per hour. Shredded solid waste is air-classified and the light fraction pneumatically transported to a storage shed to await transport to the combustor facility.

At the combustor a live bottom bin provides short term storage and variable outfeed capability. Processed MSW is carried from the bin by the feed conveyor which is designed to provide uniform volumetric flow of fuel. The combustor bed temperature control loop adjusts the speed of the feed conveyor, which discharges into a constant-speed rotary airlock. From the airlock fuel is fed pneumatically through a 3-inch feed pipe to the fluid bed combustor.

#### Instrumentation

During combustion of processed MSW, temperatures in the system are monitored at 37 points. Data is collected for pressure and flow of combustion air, exhaust gas, cooling air and water, and fuel oil. Exhaust gas composition is continuously monitored and concentrations of  $O_2$ , CO,  $NO_x$ , and hydrocarbons are recorded. Gas analysis is supplemented by Orsat testing

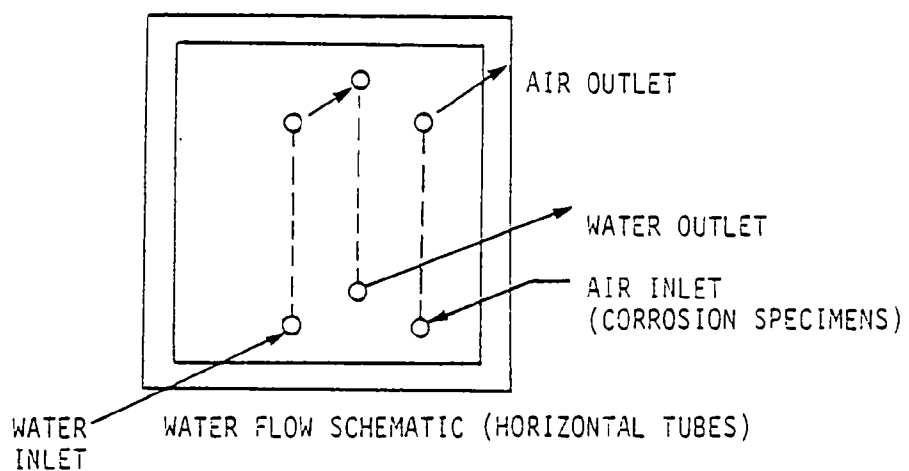
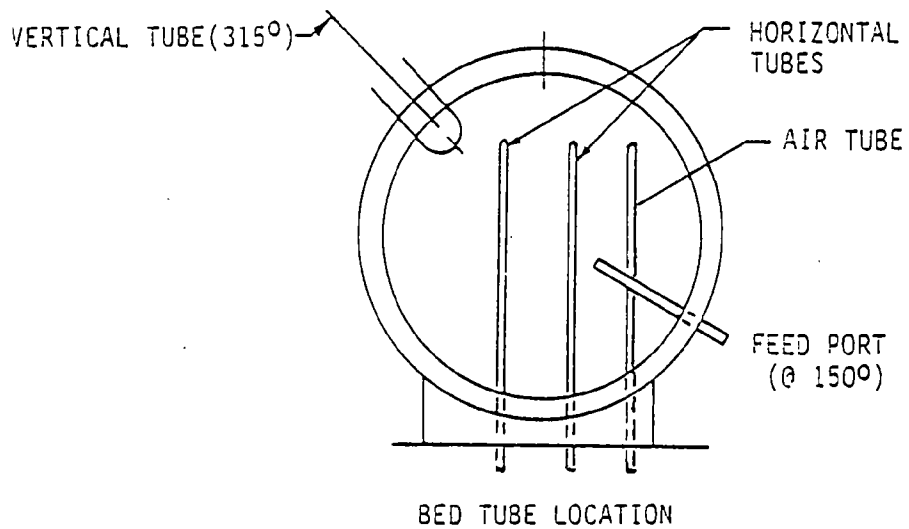


Figure  
SSWEP 300 HOUR TEST  
BED HEAT EXCHANGER ARRANGEMENT

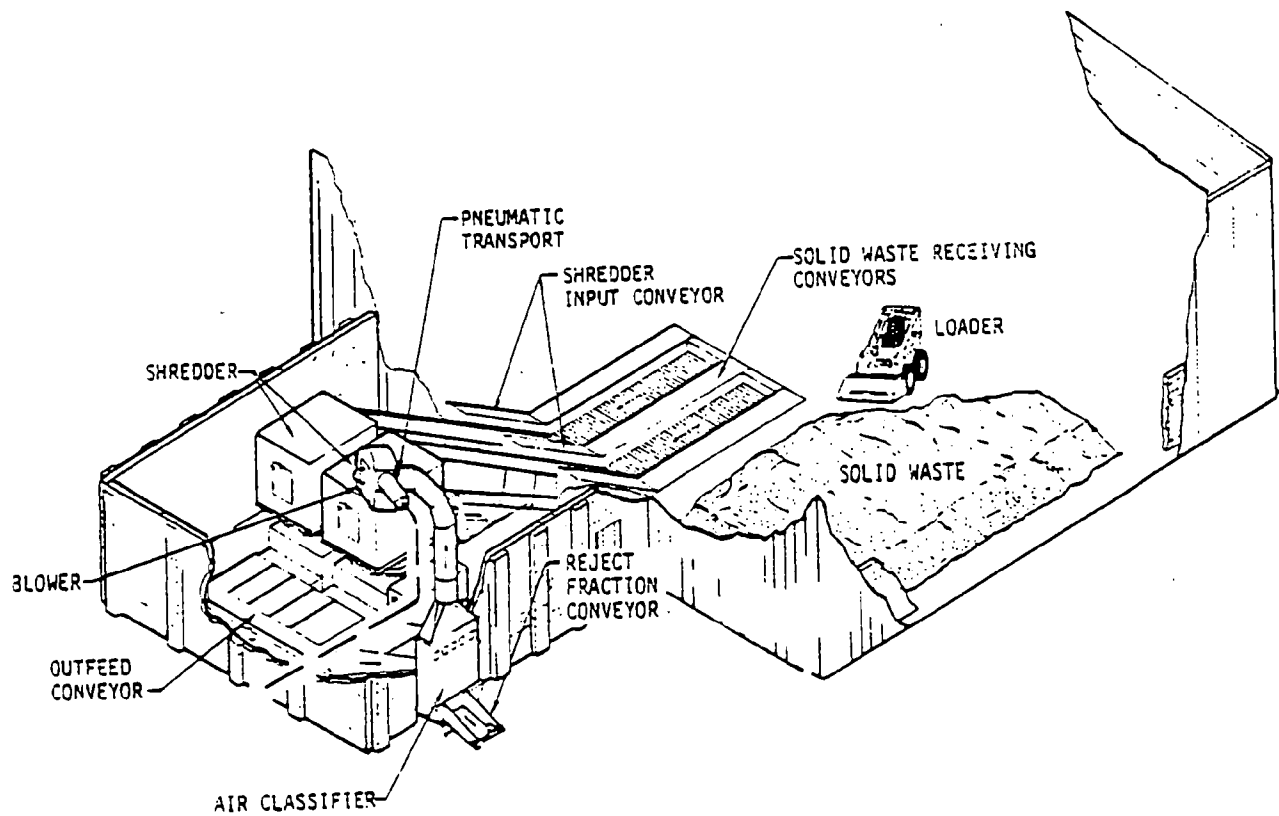


Figure 5 Solid Waste Processing Station



at frequent intervals. Samples are taken daily for determination of HCl concentration and particulate loading. Material samples for analysis are taken daily from the bed and from the baghouse.

## PARAMETRIC TESTS

Two 50-hour parametric tests were conducted to accomplish operational checkout of the system, explore the range of allowable process parameters, and identify the most desirable conditions for longer duration steady-state operation. Both parametric tests were planned to explore the same range of parameters. However, the first test was run without recycle while in the second parametric test elutriated material was recycled back to the bed. The first test ran 48 hours before being shut down by high pressures caused by slag build-up in the combustor freeboard and exhaust duct. The second parametric test was terminated after 73 hours of operation.

### Parametric Test Results

Parametric testing began with the bed depth maintained at 2.5 ft. (slumped), but freeboard combustion and temperatures were found to decrease considerably when bed depth was increased to 3 ft. (slumped). Deeper beds were used for all subsequent testing. Stable bed combustion was maintained within the ranges of:

Bed Temperature	1300 - 1410 OF
Superficial Velocity	4.1 - 6.8 ft/sec
Excess Air <sup>1</sup>	50 - 74%

Combustion efficiency<sup>2</sup> averaged 98.9%. Operation outside these ranges, particularly with excess air below 40% resulted in undesirable freeboard

---

<sup>1</sup>Excess air is calculated from:

$$EA = \frac{2.67C}{2.67C + 8H + S - O} \times \frac{O_2}{CO_2 + CO} \times 100\%$$

where: EA = Excess Air  
C, H, S, O = Respective Elemental dry weight %  
O<sub>2</sub>, CO<sub>2</sub>, CO = Respective gaseous dry volume %

<sup>2</sup>Combustion efficiency is based on unburned carbon in the flue gas and ash:

$$\eta = \frac{\frac{12}{44} a (\Delta H_{CO_2}) + \frac{12}{28} b (\Delta H_{CO}) + \frac{24}{30} c (\Delta H_{HC})}{\frac{12}{44} a + \frac{12}{28} b + \frac{24}{30} c + d H_{CO_2}}$$

where: a, b, c = respective weight concentration of CO<sub>2</sub>, CO, HC in flue gas  
and d = weight ratio of C to flue gas

afterburning and slag deposits in the combustor freeboard and exhaust ducting. The 3-inch diameter fuel feed line was found to be very susceptible to plugging problems caused by round plastic lids of approximately 4-inch diameter. These lids were resilient enough to pass through the shredder, light enough to pass through the air classifier, but just stiff enough to cause blockage of the pneumatic feed line. Adjustment of the air classifier eliminated most of the lids and the problem with feedline plugging, but also resulted in rejection of a larger proportion (near 50%) of the shredded MSW than had been desired. Larger diameter feedlines or improved shredding of the MSW would eliminate this problem in large scale equipment.

Slag deposits which formed during parametric tests were subjected to fusion-temperature analysis and found to have initial deformation temperatures of 1990 F and above. Differential thermal analysis confirmed the fusion test results. Since slag formation thus appeared to be related to high freeboard temperatures, one process condition set for the 300-hour test was a freeboard high temperature limit of 1600 F. The slag samples analyzed were, in general, calcium-rich alumina silicates.

### 300-HOUR TEST

Operating conditions for the 300-hour test were based on results of the two parametric tests. Test objectives were to:

- Demonstrate the feasibility of burning municipal solid waste in an atmospheric fluid bed combustor with energy extraction from the bed.
- Evaluate the fluid bed media and fluidization characteristics over a 300-hour time period.
- Characterize exhaust gas emissions
- Measure bed heat transfer coefficients
- Gather data on erosion and corrosion of typical boiler and superheater materials at representative tube wall temperatures.

The 310 hours of operation included 298 hours firing MSW at test conditions. The test was completed without any significant combustion-related problems, and operating conditions remained substantially constant. Upsets were caused by feedline plugs which occurred 35 times during the test. These blockages, caused by plastic lids which did not shred during fuel processing, were cleared within 2 to 5 minutes while combustor operation was maintained on oil. No material deposition or agglomeration was observed; at test conclusion the combustor and freeboard were virtually free of slag.

### Fuel Analysis

Samples of the processed MSW were analyzed daily. Fuel properties were reasonably consistent throughout the test. Results of proximate and ultimate analysis on the fuel are:

#### PROXIMATE ANALYSIS (As Received)

	<u>Average</u>	<u>Range</u>
Moisture Fraction (%)	23.6	17 - 26
Ash Fraction (%)	10.6	9 - 13
Volatiles (%)	57.6	54 - 64
Fixed Carbon (%)	8.2	8 - 9.7
Higher Heating Value (Btu/lb)	5572	5250 - 6050

#### ULTIMATE ANALYSIS (Dry Weight %)

	<u>Average</u>	<u>Range</u>
Carbon	44.46	43.9 - 45.2
Hydrogen	5.96	5.8 - 6.1
Oxygen	34.32	32.2 - 35.6
Nitrogen	0.67	.63 - .80
Chlorine	0.49	.40 - .67
Sulfur	0.13	.09 - .17
Ash	13.97	12.0 - 16.0
Higher Heating Value (Btu/lb)	7352	6900 - 7700

### Operating Conditions

Operating conditions remained substantially constant throughout the 300 hours of test operation although some parameters changed due to a gradual decrease in bed particle size that occurred during the first half of the test. As typical steady state operating conditions, data from the last 144 hours of the test were averaged:

Bed temperature	1392	°F
Freeboard temperature	1487	°F
Superficial velocity	4.6	ft/sec
Excess air	44	%
Bed depth (slumped, nominal)	3.5	feet
Fluidizing air flow	43.0	lb/min
Fuel feed rate	8.2	lb/min
Combustion efficiency	99.0	%
Exhaust material recycle rate	16	lb/min
Baghouse ash collection rate	0.9	lb/min
Bed material letdown rate	4.9	lb/hour

Figure 6 shows the temperature recorder chart for a portion of the twelfth day of operation (259 through 266 hours into the test) as representative of general test conditions. Bed temperature remains constant, despite fluctuations in freeboard and exhaust temperatures caused by variations in heating value of the processed MSW fuel. Note that sample time periods for emissions and gas analysis are identified and that, during two hours of the recorded period, gas analysis data were being recorded by the California Air Resources Board (CARB) using their mobile equipment. Satisfactory agreement was found between CARB and CPC data for gaseous emissions.

### Flue Gas Emissions

Emissions levels in the flue gas were considered very important to the basic program objective of demonstrating the feasibility of steam generation by firing MSW in an AFB boiler. Actual emission levels verified the potential for low flue gas emissions levels. Average emissions levels for the last 144 hours of test operation were:

#### Flue Gas Emissions

O <sub>2</sub>	6.7 %
CO <sub>2</sub>	13.5 %
CO	200 ppm
SO <sub>2</sub>	29 ppm
NO <sub>x</sub>	160 ppm
Hydrocarbons (as CH <sub>4</sub> )	40 ppm

Generally, each of the gaseous constituents monitored tended to exhibit constant variation. Occasional very high spikes of SO<sub>2</sub>, CO, and hydrocarbons occurred independently of each other or any other parameter recorded. These spikes were probably due to particular constituents of the MSW fuel. Emissions of SO<sub>2</sub> and NO<sub>x</sub> are of particular concern in light of the tight regulations regarding these pollutants. Actual emissions levels were well under 1979 EPA promulgated New Source Performance Standards (NSPS) for boilers but would require emissions offset consideration to be approved by California and local authorities. The indicated exhaust concentrations translate to approximately 0.06 lb/MMBtu fuel input for SO<sub>2</sub> and 0.25 lb/MMBtu for NO<sub>x</sub> average for the last 144 hours of operation.

### Bed Material

The original bed material was Monterey 16-mesh sand with an average particle size<sup>3</sup> between 1.0 and 1.1 mm. Daily samples were taken of bed material and of material returning to the bed from the recycle cyclone. Figure 7 shows the rapid drop in bed particle size at the beginning of the

---

<sup>3</sup>Particle size is calculated by the "Mean Specific Surface" method (1)

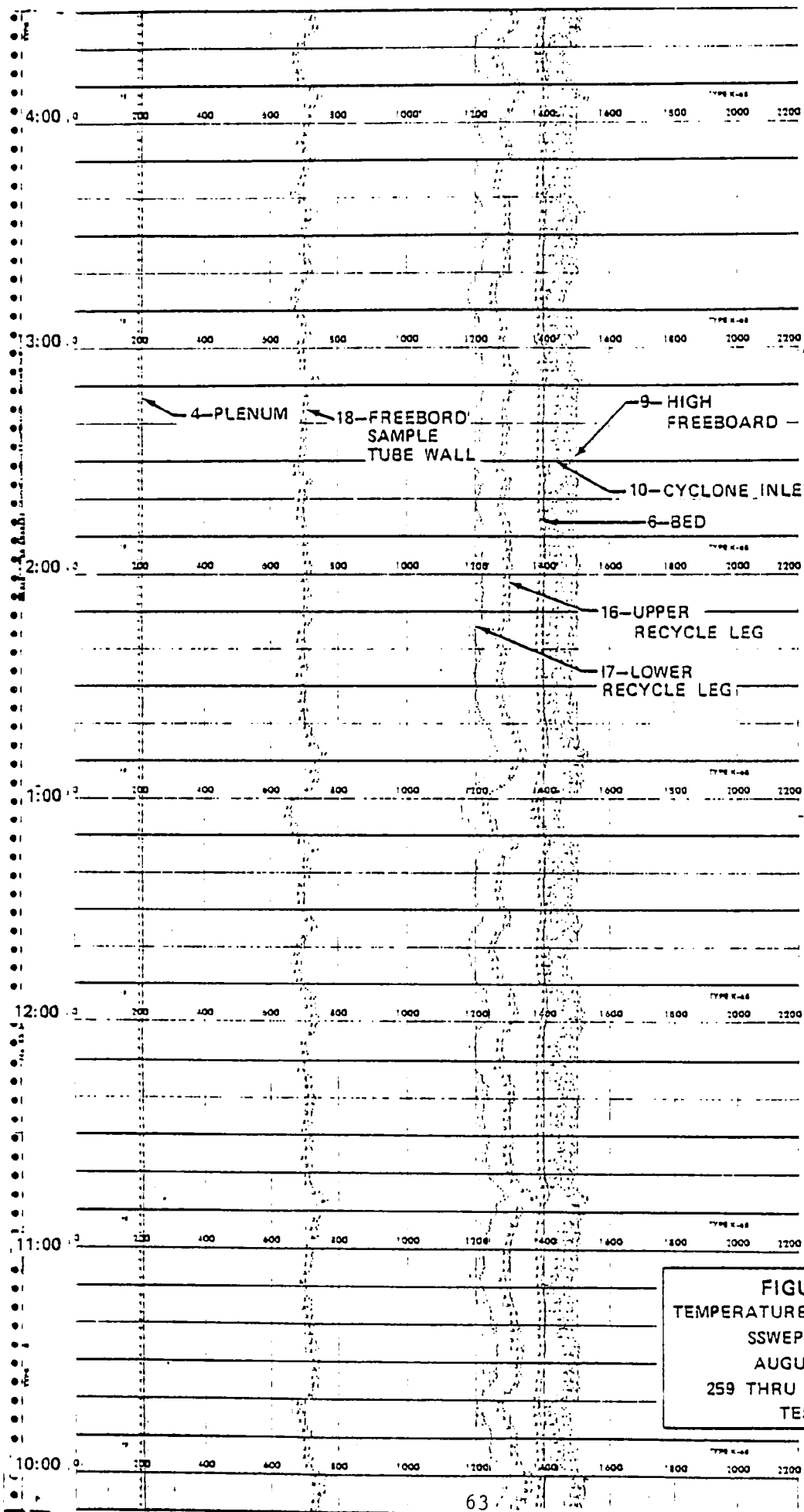


FIGURE 6  
TEMPERATURE RECORDER CHART  
SSWEP NO. 3 TEST  
AUGUST 29, 1979  
259 THRU 266 HOURS FROM  
TEST START

CARB MONITORING WITH  
PORTABLE EQUIPMENT

STACK PARTICULATE  
SAMPLE

HCl SAMPLES

INLET  
OUTLET

CYCLONE PARTICULATE  
SAMPLES

79-1680

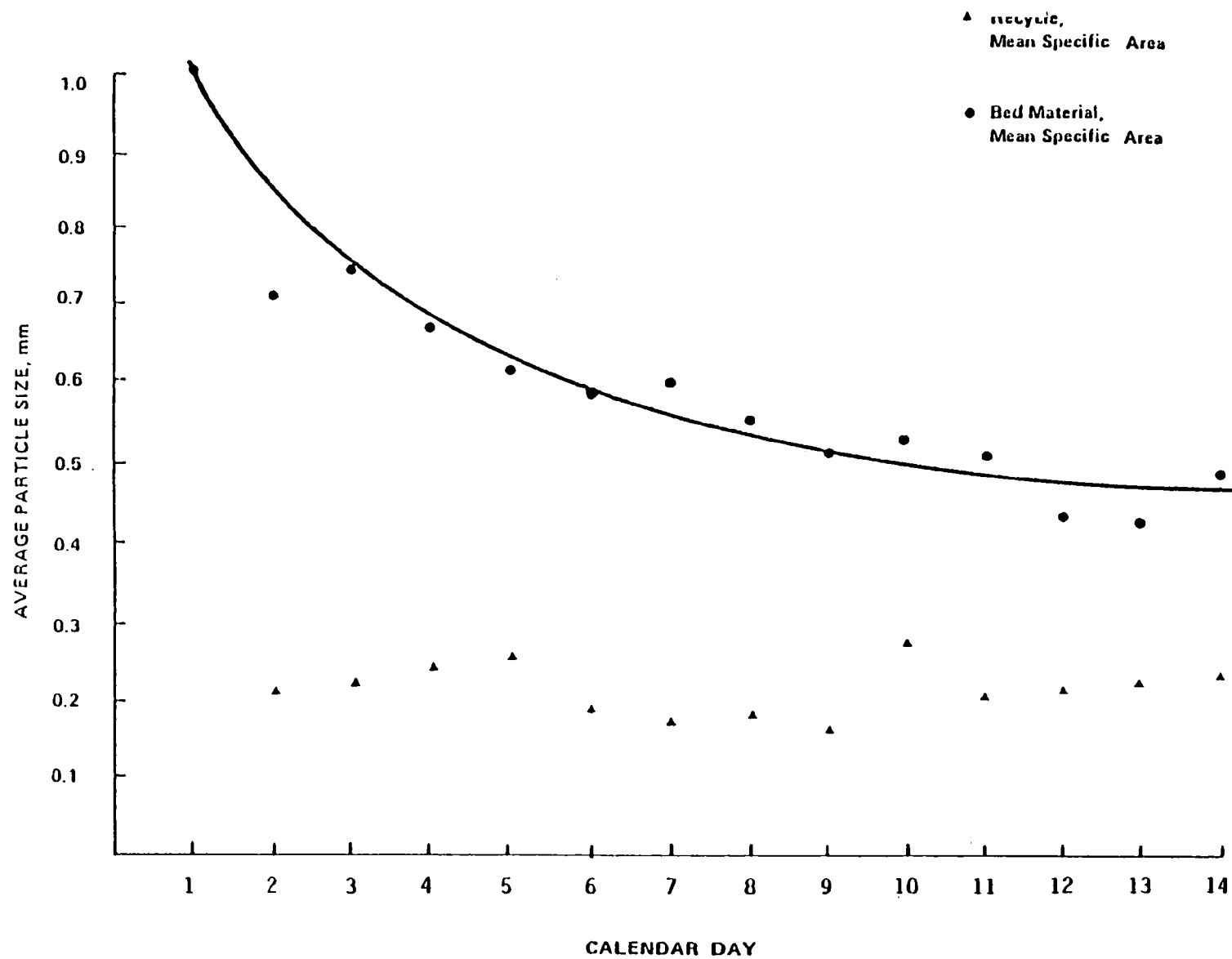


Figure 7

test, followed by a more gradual decline to nearly constant particle size at the end of the test. Also shown is the recycled material size which appeared unaffected by the changing bed material size. Some pieces of glass could be observed in the material samples and a few (less than 1%) pieces of agglomerated particles up to  $\frac{1}{2}$ " size.

Daily bed material samples were analyzed for cations and metals content by means of the emission spectroscopy scan method. The concentrations of the major constituents of the bed material were found to remain essentially constant. A number of elemental concentrations, however, increased throughout the test and accumulation of these materials appeared to be continuing up to the time the test was terminated. This accumulation of elements was the only observed phenomena which had not reached a steady state equilibrium before the end of the test. Longer test duration will be necessary to observe the effects of this accumulation. Elements which accumulated were Ca, Fe, Mg, Ti, Na, Cu, Mn, P, Zn, and possibly Pb. Concentrations of these elements are shown for samples taken early in the test and at the end of the test (Trace elements are not shown):

<u>Element</u>	<u>Concentration Weight %</u>	
	<u>Third Day</u>	<u>Twelfth Day</u>
Si	37.0	33.8
Al	4.0	3.8
Ca	1.8	5.5
K	2.8	2.7
Na	1.9	4.0
Fe	0.48	1.2
Mg	0.17	0.69
Ti	0.068	0.28
Ba	0.11	0.10

### Heat Transfer

Water inlet and outlet temperatures as well as flow through the main heat exchanger were monitored throughout the test. That heat exchanger consisted of two four-pass, horizontal tubes arranged in the bed as shown in Figure 4. Early in the test, the overall heat transfer coefficient averaged 46 Btu/hr-ft<sup>2</sup>-F. By the end of the test, the heat transfer coefficient had increased to 58 Btu/hr-ft<sup>2</sup>-F. The increase in heat transfer coefficient is attributed to the decrease in bed material particle size. The influence of particle size on outside wall heat transfer coefficient is predicted by Bashakov (2) or Locke (3).

### Corrosion and Erosion

In addition to the stainless steel (TP316H) water cooled tubes in the bed which were the primary means of heat extraction, air cooled sample tubes were installed in the bed and in the freeboard to duplicate wall

temperatures of superheater tubes. No significant corrosion or erosion was observed on the water cooled tubes in the bed. Mechanical failure of the air cooled tube in the bed invalidate its exposure as a tube sample.

The freeboard air cooled sample tube was installed to transverse gas flow in the exhaust ductwork from the combustor. The tube was fabricated from sample sections of six different tube materials. The samples were exposed to 1500 F - 1600 F flue gases heavily laden with particulate (40-50 gr/acf) at a gas velocity of about 35 fps. The sample tube wall temperature was about 720 F. Combined corrosion and erosion resulted in substantial metal wastage of carbon steel specimens, with less wastage apparent as the alloy content increased.

As shown in Figure 8 and Table I, metal wastage was greatest for carbon steel coupons, approximately 50-60% of the wall facing the gas side, while wastage of the sides and tops was less than 5%. Wastage was considerably less for the low alloy steels in the same orientation. On the side facing the gas flow, the wastage was 13-17% while elsewhere it was less than 3%. The metal wastage of the austenitic specimens (SS304, SS316, and Incoloy 825) was the lowest, being less than 6% on the side facing the gas flow and less than 1% elsewhere. Scaling and deposits were also orientation dependent, with bottoms of the coupons relatively free of scale and deposits compared to the sides and top. As expected, scale formation was thickest on the carbon steels, and the chrome-containing austenitic steels were resistant to scaling.

Residual corrosion penetration was very low on the bottoms of the carbon steel and low alloy specimens. Apparently, corroded areas and scale were removed by erosion as they formed, i.e., corrosion-erosion was a major factor in the metal wastage. Corrosion penetration on the low alloy specimens was comparatively low on the tops and sides at 5 - 10 microns. With respect to corrosion under the exposure conditions, the low alloy specimens compared well with the type SS316 that showed only 5 - 10 microns of corrosion penetration, while the metal wastage of the low alloy specimens was greater. The SS304 and Incoloy 825 showed corrosion penetrations ranging from 10-50 microns. Apparently, corrosion was by oxidation and sulfidation as sulfur was found in most corroded regions of all coupons.

## CONCEPTUAL DESIGN STUDY

An economic study was undertaken to determine the promise of the AFB boiler system as defined by the results of the experiments. The complete cogeneration system was envisaged for application to the Stanford University campus with the sizing and performance of the MSW fired AFB boiler based on test results. While the application at Stanford University might not have been the most favorable one, it was regarded as a typical situation and that there would be considerable benefit in having a study made to meet realistic requirements.



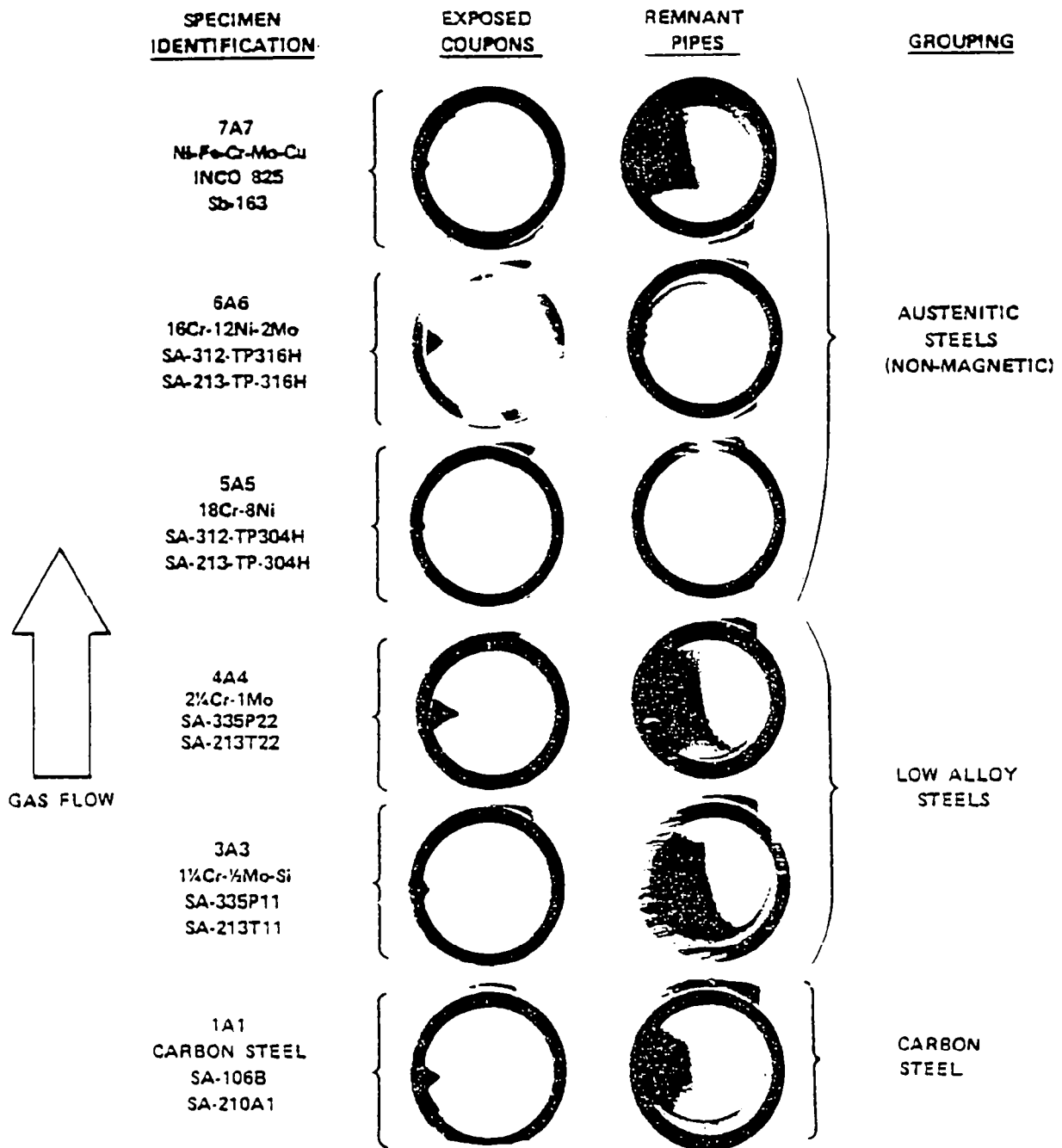
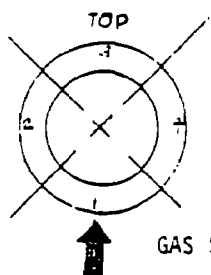


Figure 8 Photographic Comparison of the Seven Exposed Coupons and the Corresponding Unexposed Remnant Pipes



SSWEP: 300 HR TEST COUPONS

LOCATION: CTU FREEBOARD

TABLE I PIPE THICKNESS AND MICROGRAPH MEASUREMENTS

Specimen Identification	Pipe Orientation	Pipe Thickness (Inch)		% Wastage	(Residual Maximum) Micrograph Measurements		Comments
		* Unexposed	Exposed		Scale	Penetration M	
1A1 (Carbon Steel) (SA-106B) (SA-210A1)	1. Bottom	.115	.060	47.8	None(a)	6	(a) Corrosion-erosion
	2. Left Side	.112	.113	-.9	15	10	
	3. Top	.110	.116	-5.5	16	60	
	4. Right Side	.113	.110	2.7	(b)	14	(b) Spalled
3A3 (1½Cr-½Mo-Sf) (SA-335P11) (SA-213T11)	1.	.116	.100	13.8	3	<2	
	2.	.115	.116	-.9	60	10	
	3.	.118	.124	-5.1	15	10	
	4.	.120	.117	2.5	250(a)	10	(a) Scale and ash deposit
4A4 (2½Cr-1 Mo) (SA-335P22) (SA-213T22)	1.	.135	.113	16.3	80	<2	
	2.	.130	.129	.8	a.	5	a. Spalled
	3.	.129	.131	-1.6	b.	10	b. Spalled
	4.	.132	.132	0	c.	5	c. Spalled
5A5 (18Cr-8Ni)  (SA-312-TP304H) (SA-213-TP-304H)	1.	.105	.100	4.3	-	35	.005" wastage
	2.	.105	.105	0	100(a)	50	(a) Scale and ash deposit
	3.	.105	.106	-1.0	(b)	10	(b) Spalled
	4.	.104	.104	0	200(c)	10	(c) Scale and ash deposit
6A6 (16Cr-12Ni-2Mo) (SA-312-TP316H) (AS-213-TP-316H)	1	.107	.101	5.6	3	-	.006" wastage
	2	.118	.118	0	30	10	
	3	.107	.107	0	a.	-	a. Spalled
	4	.106	.106	0	b.	5	b. Spalled
7A7 (Ni-Fe-Cr-Mo-Cu) (INCO 825) (Sb-163)	1	.112	.109	2.7	20	30	.003" wastage
	2	.113	.113	0	a.	30	a. Spalled ?
	3	.117	.117	0	b.	4	b. Spalled ?
	4	.118	.119	-.8	c.	25	c. Ash deposit

\* Unexposed pipe remnant measurements.

### Proposed System

The AFB system for study was designed to meet an existing situation in which the local municipality is faced with unavailability of landfill disposal area while Stanford University is seeking to control energy costs. Municipal solid waste would be processed at a central collection location and the MSW fuel trucked to the campus boiler plant. Size of the system is specified by the 800 tons per day of processed MSW estimated to be available in 1983. The modular AFB boilers would produce 600 psia, 750 F steam for a turbine with extraction at a pressure of approximately 170 psia. The extraction steam would condense in a heat exchanger to provide heating and chilling steam for the campus. Steam not needed for campus services would flow through the condensing stage of the turbine. Thermodynamic and process studies provided estimates that the proposed system would supply all of the university steam demand and approximately 50% of the electricity needs.

A flow diagram of the proposed system is shown in Figure 9. No attempt was made to investigate the processing of the MSW; study was limited entirely to conversion of the processed MSW to thermal energy and to electricity. All ancilliary equipment necessary for energy production from MSW fuel was included.

### Plant Design and Cost Estimating

The plant design was broken down into 12 major components listed below:

1. Boiler system
2. Start-up system
3. Combustion air system
4. Flue gas system
5. Bed-maintenance system
6. Flyash-disposal system
7. Fuel-feed system
8. Fuel receiving and storage
9. Main steam system
10. Feed-water system
11. Electrical and control system
12. Buildings and site

For each of these systems, sufficient design work was done to define a concept and to specify the necessary size of the equipment. Wherever possible, standard components were used and cost estimates obtained from vendors. A plant plan, Figure 10, and layout drawings were made and necessary buildings included to enclose turbine, boiler, and fuel receiving areas so as to be compatible with the campus site. No cost was included for the value of the land. Table II lists the major cost components along with the principal items contributing to the cost. An artist's rendition of what the plant might look like is shown in Figure 11 and general performance figures for the plant are shown in Table III.

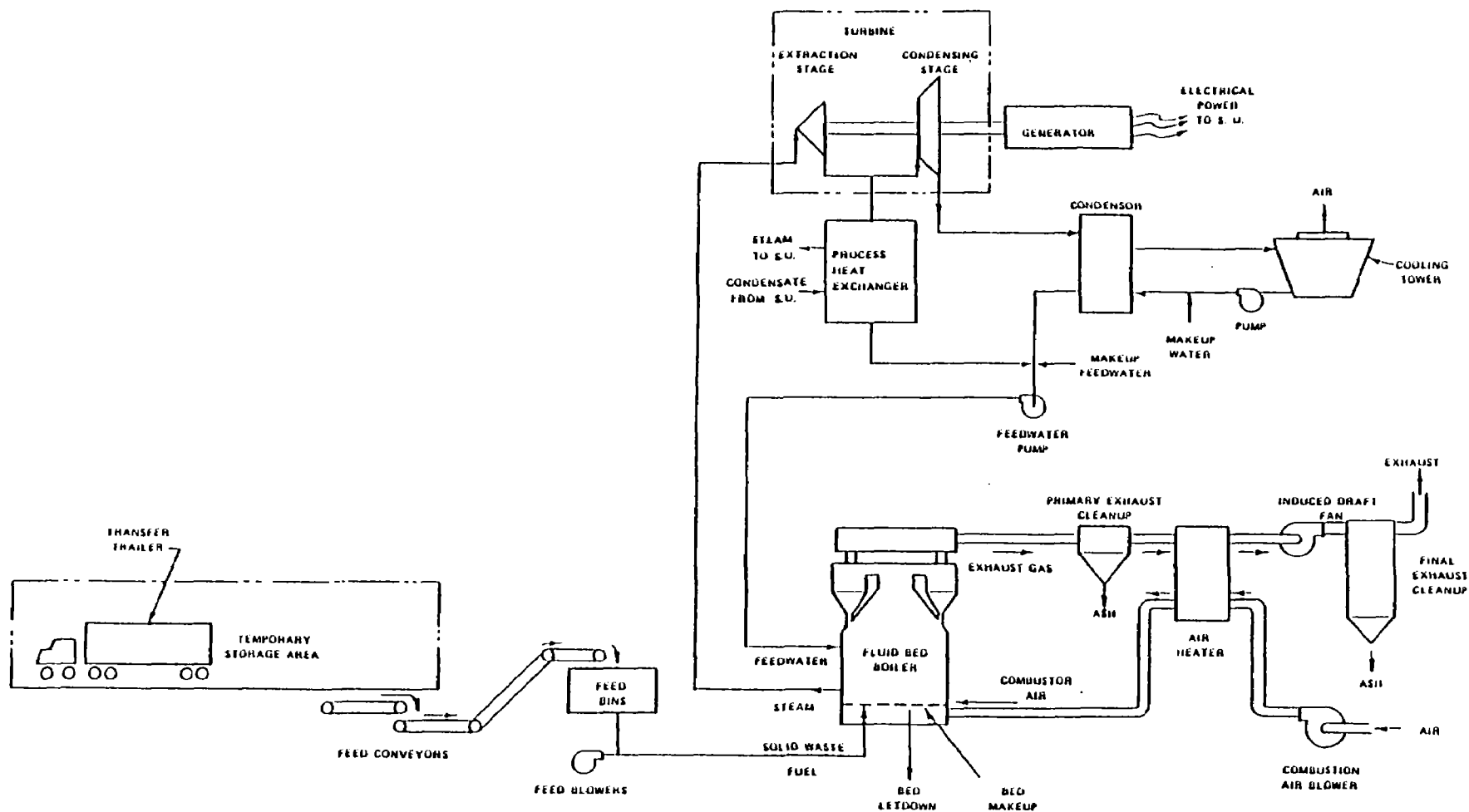


Figure 9 Stanford Solid Waste Energy Plant Flow Diagram

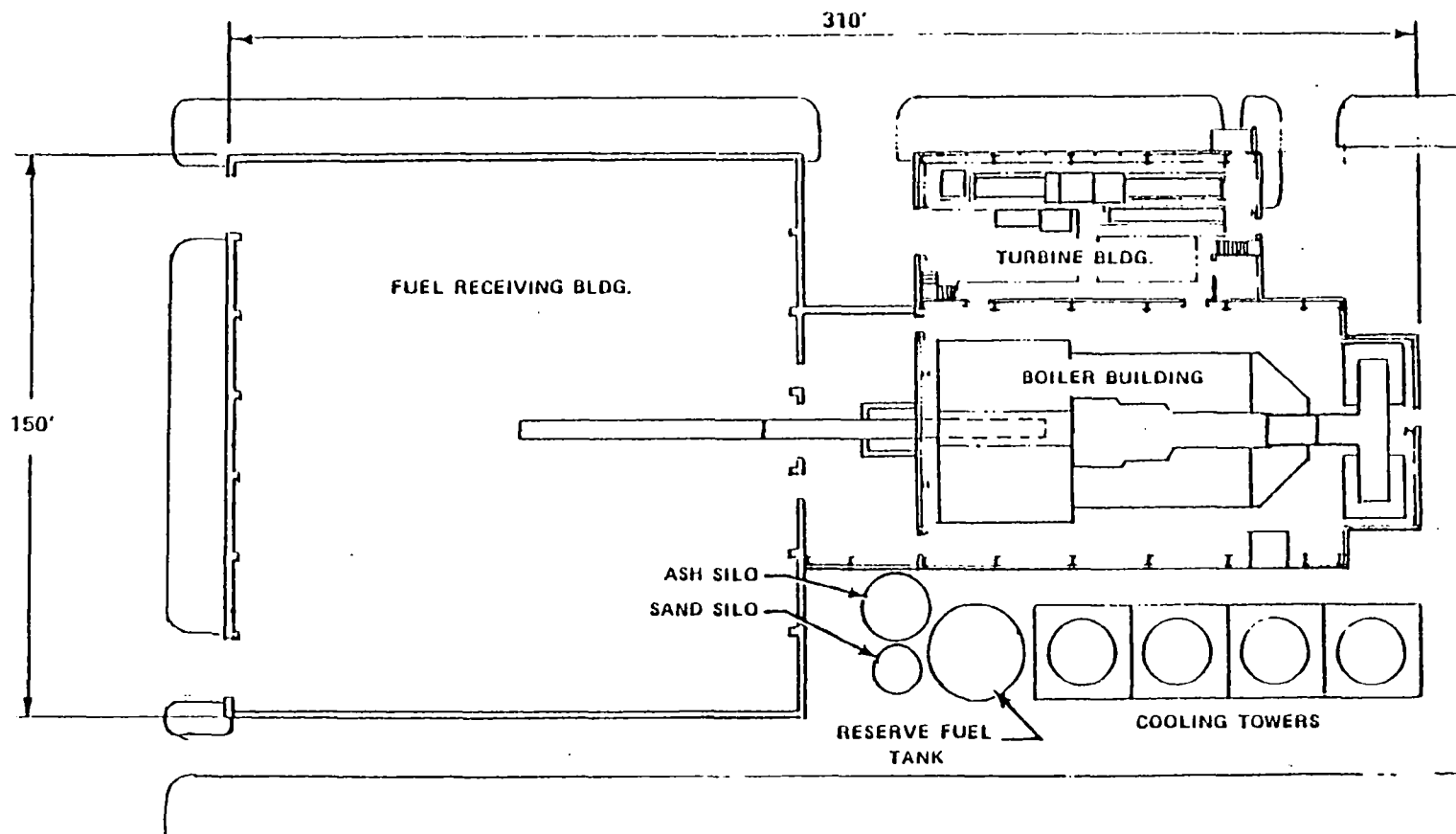


Figure 10  
SITE PLAN  
STANFORD SOLID WASTE ENERGY PLANT

Table II  
PLANT DESIGN - LIST OF MAJOR EQUIPMENT

1. Boiler System  
 Modules w/tubes & plenums (6)  
 Recycle cyclones (24)  
 Exhaust manifolds (2)  
 Evaporators (2)  
 Economizers (2)  
 Attenuators (2)  
 Supports & lagging  
 Soothblowers (6)

2. Start-up System  
 Duct-burner assembly  
 Booster fan  
 Fuel-oil pumps (dual)  
 Fuel-oil storage tank  
 Bed injectors (36)  
 Air manifold & dampers

3. Combustion Air System  
 F.D. fans & motors (2)  
 Intake silencers (2)  
 Tubular air preheaters (2)  
 Ductwork

4. Flue-Gas System  
 Multicyclones (2)  
 Electrostatic gran. filter  
 I. D. fan & motor  
 Ductwork

5. Bed-Maintenance Systems  
 Slide gates (6)  
 Water-cooled conveyors (2)  
 Blowers w/filter silencers (3)  
 Airlock feeders (3)

5. Bed Maintenance Systems (cont.)  
 Sand-storage bin  
 Bin discharger  
 Fabric filter  
 Transport piping  
 Discharge diverter valves (7)

6. Flyash Disposal System  
 Airlocks (6)  
 Screw conveyors (2)  
 Feeders (2)  
 Transport piping  
 Ash silo  
 Fabric filter  
 Blower w/filter/silencer (2)  
 Silo discharger  
 Discharge conveyor

7. Fuel-Feed System  
 Main conveyor  
 Distribution conveyor  
 Feed bins (6)  
 Metering conveyors (6)  
 Conditioners (6)  
 Airlocks (36)  
 Blowers w/filter silencers (2)  
 Transport piping

8. Fuel Receiving and Storage  
 Apron  
 Conditioners  
 Live storage bin  
 Fabric filter w/blower  
 Dust-collection ductwork  
 Front-end loader

9. Main Steam System  
 Turbine & assoc. equipment  
 Condensor  
 Condensate pumps  
 Condensor vacuum pumps  
 Condensate polishing  
 Cooling towers  
 Cooling-water pumps  
 Process heat exchangers

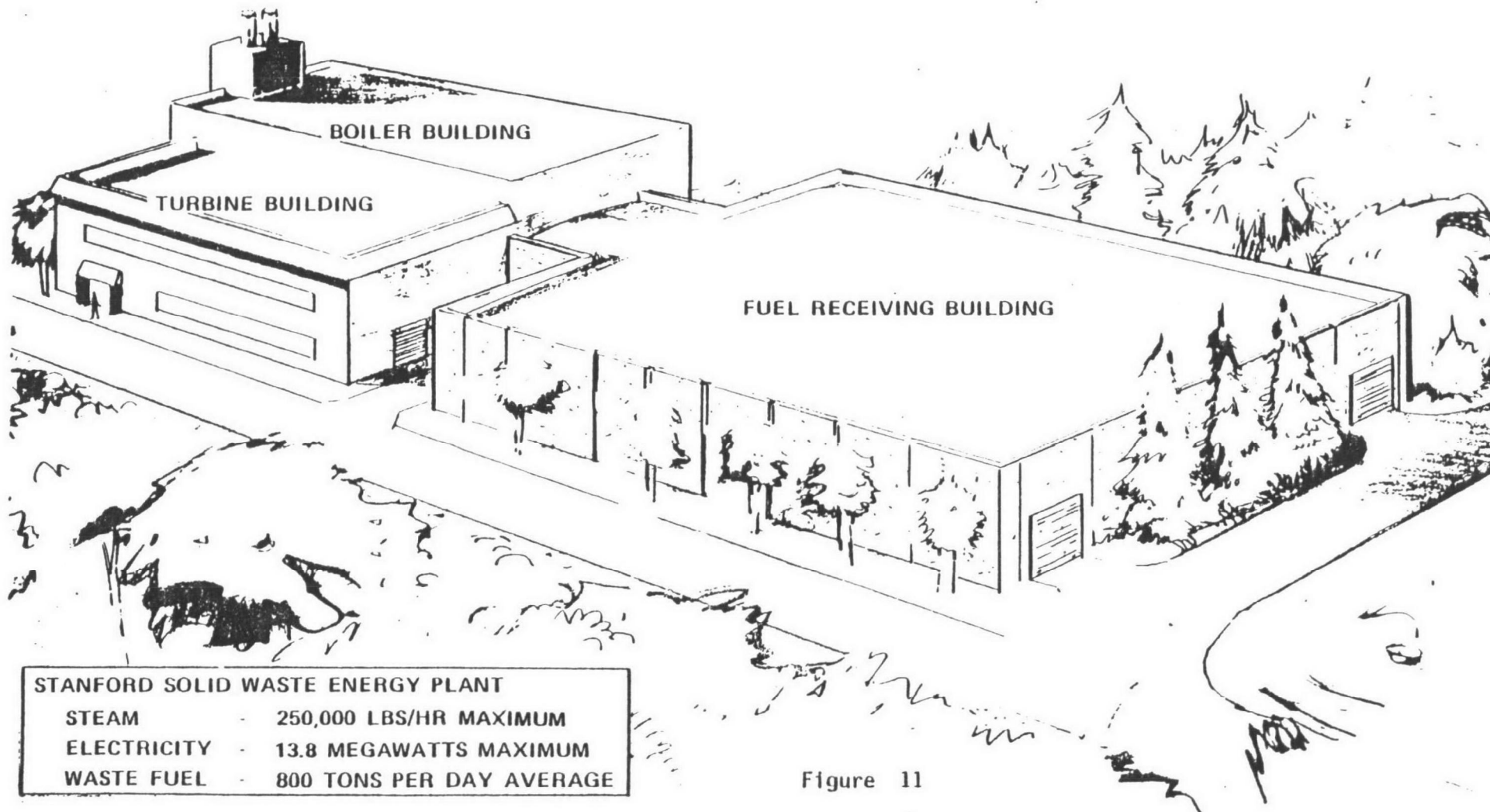
10. Feedwater System  
 Boiler feed pumps (motor) (2)  
 Feedwater heater  
 Deaerating feedwater heater  
 Boiler feedwater transfer pump  
 Deaerated feedwater storage tank  
 Boiler feed pumps (turb.) (2)  
 Feedwater piping valves

11. Electrical & Control Systems  
 Generator & controls  
 Switchgear  
 Transformers  
 Motor control center  
 Instrumentation & controls

12. Buildings & Site  
 Grading & roads, landscaping  
 Foundations  
 Structure  
 Enclosures  
 Maintenance & administration  
 Heating, ventilation, A.C.  
 Fire-safety equipment  
 Utilities

Table III  
PLANT PERFORMANCE

- Design Firing Rate for Processed MSW Fuel:
  - Average - 800 tons per day
  - Maximum - 1000 tons per day
- Yearly Average Plant Output
  - Steam at 125 psi, 110,800 lb/hr
  - Electricity - 6.7 MW
- Boiler Output:
  - Steam at 600 F, 750 psi
  - Average - 200,000 lb/hr
  - Maximum - 250,000 lb/hr
- Maximum Electrical Output (net) 13.8 MW
  - Concurrent 125 psi steam output 91,200 lb/hr
- Fuel Storage:
  - Normal: 200 tons (6 hrs average output)
  - Maximum: 500 tons (15 hrs average output)
- Reserve Fuel: Low-grade bunker oil - 35 GPM at maximum output
- Reserve Fuel Storage: 126,000 gal, 3 days





### Environmental Considerations

Emissions data collected during the 300-hour test were converted to a pounds per hour basis using the flow rate of combustion products for an 800 tons per day plant. Below are the data reported in this form, together with the "offset" that Stanford is permitted to take if it shuts down its present oil-fired heating plant.

<u>Emission</u>	<u>Projected 800-TPD Plant</u>	<u>Offset from Existing Plant</u>
SO <sub>2</sub>	2.9 lb/hr	24.1 lb/hr
NO <sub>x</sub>	7.7	23.1
CO	8.9	5.2
Hydrocarbons	0.7	1.1

Only CO would exceed the offset available from the existing boiler. The present boiler figures are based on steam generation at the rate of 80,000 lb/hr whereas the AFB plant figures are based on 800 tons per day fuel corresponding to 110,000 lb/hr of steam plus an average of 6.7 MW of electrical power. Thus the AFB boiler is nearly 40% larger than the present boiler and the emission levels are very similar. It appears that fluidized bed combustion of MSW is a sufficiently clean process that there would be little difficulty in meeting the stringent requirements of the San Francisco Bay Area Air Pollution Control District when the offset from the present boiler is considered.

### Economic Summary

Cost estimates for the proposed full scale system are summarized in Table IV. Each major subsystem is shown, along with the additional costs which are recommended for a construction project such as this by the standards of the Electrical Power Research Institute. The total direct cost as estimated is 16.7 million dollars, and the total plant investment, using various contingencies and sales tax, amounts to 23.1 million. This figure should be compared to plants which handle 1200 tons per day of raw municipal solid waste and produce both steam and electrical power. The costs presented do not include processing or transporting the processed MSW to the point of use.

### CONCLUSIONS

Successful completion of the 300-hour test demonstrated the feasibility of fluidized bed combustion of municipal solid waste to generate steam. Necessary conditions for steam generation were met:

1. Operation at reasonably low excess air (44%) for process efficiency.
2. Constant bed temperature ( $\pm 20$  F) for controllable system output.
3. Freedom from slag and its associated problems.
4. Low exhaust gas emissions for environmental acceptability.

Table IV  
STANFORD SOLID-WASTE ENERGY PLANT

Total plant investment	
1. Boiler system	\$ 2,239,700
2. Startup system	155,200
3. Combustion air system	798,900
4. Flue-gas system	2,382,000
5. Bed-maintenance system	84,100
6. Flyash-disposal system	79,200
7. Fuel-feed system	457,800
8. Fuel-receiving bldg., equipment	252,400
9. Main steam system	5,421,000
10. Feedwater system	1,942,600
11. Electrical/controls/misc.	1,204,100
12. Building, sitework, construction, A & E	<u>1,545,000</u>
Total Direct Costs	16,662,000
Undistributed Costs (6%)	<u>999,700</u>
Process Capital	17,661,700
Engineering & Home Office Fees	<u>1,566,700</u>
Subtotal	19,327,900
Project Contingency (Subtotal x 15%)	2,389,200
Process Contingency (Item 1 x 5%)	112,000
Sales Tax	<u>777,300</u>
Total Plant Investment	23,116,400

These conditions were met in a long-duration test designed to reveal any process problems likely to develop.

Bed material characteristics after long term operation will depend on the source and preparation of the solid waste fuel. Early in the 300-hour test the average bed particle size decreased significantly although it subsequently appeared to reach equilibrium. The elemental composition of the bed was still changing after 300 hours. Neither situation caused any detrimental change in bed fluidization properties nor were emissions affected. It was concluded that the overall heat transfer coefficient for the bed tubes increased due to the decrease in bed material size.

Sample tubes exposed to a high velocity flue gas stream with high particulate loading experienced substantial metal wastage. Alloy steels would be suitable for service if protected from abrasion but none of the samples tested would be suitable for long term service under test conditions.

Conveying air in the fuel feedline constitutes a significant (30%) portion of the total combustion and fluidizing air. This air enters the bed as a point source and is not easily distributed throughout the bed. While a larger feedline is desirable to avoid feedline plugging and permit firing of more coarse fuel, greater spacing between larger feedlines may create air distribution problems in the bed. Investigation of alternate fuel feed technology is warranted.

Based on data from 300 hours of testing, projected emissions from an AFB boiler firing municipal solid waste would be low compared to a existing conventional oil fired boiler. Total plant investment for a cogeneration plant burning 800 tons per day of processed MSW fuel would be \$23,116,000, corresponding to approximately \$1,150/kw if the entire steam output were converted to electricity.

#### ACKNOWLEDGEMENT

This work was accomplished at Combustion Power Company, Inc. under sub-contract to Stanford University with the program jointly sponsored by the United States Environmental Protection Agency and Department of Energy. The generous contribution of Professor R.H. Eustis of Stanford University is gratefully acknowledged.

## REFERENCES

1. Kunii, D., and Levenspiel, O., "Fluidization Engineering", John Wiley and Sons, 1979.
2. Bashakov et.al., (1973). Powder Technology, pp. 8, 273.
3. Locke, H.B. et al, "Fluidized Combustion in Great Britain", paper presented at Fourth International Conference on Fluidized Bed Combustion, Mitre Corporation, McLean, Virginia, December 1975.
4. Vander Molen, R.H., "Fluidized Bed Combustion of Solid Wastes", Presented at the Symposium on Thermal Conversion of Solid Waste and Biomass, American Chemical Society Meeting, September 1979, Washington, D.C.

EVALUATION OF THE AMES SOLID WASTE RECOVERY SYSTEM

Joensen, A.W.

Hall, J.L.

Even, J.

Van Meter, D.

Adams, S.K.

Gheresus, P.

Engineering Research Institute, Iowa State University, Ames, Iowa 50011

EPA CONFERENCE

WASTE TO ENERGY TECHNOLOGY UPDATE

Cincinnati, Ohio  
April 15-16, 1980

## INTRODUCTION

The City of Ames, Iowa has been commercially operating a Solid Waste Recovery System since November, 1975. This system processes municipal and commercial solid waste to recover refuse derived fuel (RDF) and ferrous metals. This solid waste recovery system consists of three major subsystems; a nominal 150 ton/day process plant, the 500 ton Atlas storage bin and the three coal fired steam generators at the existing municipal power plant.

Conceptual design for the system operation specified burning RDF with coal in a 35 MW tangentially fired pulverized coal fired boiler (unit No. 7) at firing rates up to 20% or 8 tons/hour. Initial operation in October 1975 resulted in a high dropout of unburned material into the bottom ash hopper. The power plant then began burning RDF with coal in the 7.5 MW or the 12.5 MW spreader stoker boilers. The problem of high unburned material dropout in the 35 MW unit was solved by the installation of a Combustion Engineering Company dump grate at the furnace bottom. This modification was completed by May 1, 1978, and RDF has been successfully burned in this unit since that time.

A three year evaluation of the Ames Solid Waste Recovery System was funded by the Environmental Protection Agency and the Department of Energy with additional support provided by Iowa State University and the American Public Power Association. Detailed results of the stoker performance and process plant operations have been reported previously [1,3,4,5,9]. Results of the unit No. 7 emissions evaluation is given in [8] while the total system study for year III is given in [7]. The inability of the process plant to initially remove ground glass and other fines resulted in extreme erosive wear at the process plant, Atlas bin and all of the pneumatic transport lines and in boiler slagging. This problem was solved by the installation of a double set of a disc screen fines removal system in October-December 1978. This modification and some process plant operational results are discussed in [2,7].

This paper presents some important results obtained from this three year system evaluation.

## PROCESS PLANT

A detailed description of the process plant is given in [1,2,5,7]. The material processed and materials recovered are listed in Table 1. The improvement in RDF quality due to the disc screen installation is shown in Table 2. Net costs per ton for 1976, 1977 and 1978 were \$14.27, \$11.44 and \$11.31 respectively.

RDF and metal sales for 1978 constituted 74.37% and 13.53% of total income. Electric energy consumption for 1978 is 63.17 kwh/ton.

## POWER PLANT

### Stoker Fired Boilers No. 5 and No. 6

Selected emissions from boilers No. 5 and 6 are listed in Tables 3 and 4. The coal contained a large number of fines which resulted in high particulate emissions. After the installation of new mechanical collectors in July 1979, along with cutting out of reinjection backpass fines and the increase of front overfire air, subsequent private tests indicated the reduction of stack particulate on coal only and coal plus RDF firing. This latter result was also due to the disc screen installation.

### Pulverized Coal Fired Unit No. 7

The installation of the dump grate resulted in the successful burning of RDF with coal. Selected emissions are listed in Table 5.

Combustion air to the furnace is supplied by secondary air from the air heater discharge, primary air from the pulverizer, cold undergrate air supplied from a separate fan, and cold overgrate air entering at each end through open observation doors, and the two diagonally opposed RDF transport lines which supply 1.67 m<sup>3</sup>/sec (3539 ft<sup>3</sup>/min) of cold air through the air-lock feeder at the Atlas bin. Undergrate air was 1.70 m<sup>3</sup>/sec (3603 ft<sup>3</sup>/min) and overgrate air flow was 0.94 m<sup>3</sup>/sec (2000 ft<sup>3</sup>/min).

Excess air at 80% steam load (based on fuel ultimate analysis) varied from 41.9% for coal only firing to 41.7% at 20% RDF nominal heat input. At 100% steam load the excess air varied from 42.5% for coal only to 34.6% at 20% RDF heat input firing.

At 80% steam load, the boiler efficiency decreased linearly from 84.4% (ASME Heat Loss Method) at 0% RDF to 81.1% at 20% RDF firing and these efficiencies include a manufacturer 1-1/2% unaccountable loss. The air heater outlet flue gas temperature increased from 181.1°C to 422°F.

At 100% steam load, the boiler efficiency decreased from 84.35% at 0% RDF to 83.02% at 20% RDF firing. The air heater outlet flue gas temperature increased from 191.7°C to 198.9°C.

At 80% steam load the bottom ash flow rate varied from 64 kg/hr at 0% RDF to 218 kg/hr at 20% RDF input. At 100% steam load, the bottom ash varied from 134 kg/hr at 0% RDF to 821 kg/hr at 20% RDF input. Likewise, the percent heat loss in bottom ash never exceeded 0.2%.

Thus, the installation of the bottom dump grates in the 35 MW pulverized coal boiler allowed for the successful burning of RDF with coal.

## ACKNOWLEDGMENTS

The summary data presented above were obtained from a research project performed by the Engineering Research Institute of Iowa State University through funds provided by IERL/EPA, Cincinnati, Ohio. Analysis of laboratory samples collected was performed by the Ames Laboratory/DOE through support by the DOE. Technical support and assistance was provided by the Midwest Research Institute. The generous support of the City of Ames is also greatly appreciated.



Table 1. Refuse Processed and Materials Recovery

Year	Raw Refuse Processed (Mg)	RDF <sup>a</sup> Produced (%)	Metals Recovery (%)	Rejects (%)	Other Material (%)
1976	37,252	84.2	7.00	7.5	1.30
1977	44,027	84.54	6.22	8.87	0.39
1978	34,216	84.26	6.31	9.39	0.04

<sup>a</sup>By mass difference

Table 2. RDF Characteristics Before and After Disc Screen Installation

	RDF <sup>a</sup>	
	Before	After
Higher Heating Value - BTU/lb (kJ/kg)	4904.9 (11,408.7)	6108.3 (14,209.1)
Proximate and Ultimate Analysis, %		
Ash	20.99	9.55
Moisture	22.06	13.42
Fixed Carbon	30.79	56.10
Volatile Matter	26.16	15.93
Carbon	28.45	36.67
Hydrogen	6.35	7.42
Nitrogen	0.39	0.34
Oxygen	42.75	43.62
Sulfur	0.34	0.19
Chloride	0.23	0.21

<sup>a</sup>Comparative Sampling Period Jan-Mar

Table 3. SELECTED EMISSIONS FROM BOILER UNIT 5

Parameter (units)		80% load 1976 Iowa coal with			80% load 1977 Iowa/Wyoming coal with		
		0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF
Particulates (controlled)	(g/MJ)	0.7 ± 0.5	0.4 ± 0.0	0.3 ± 0.1	0.8 ± 0.2	0.9 ± 0.1	1.0 ± 0.2
Particulates (uncontrolled)	(g/MJ)	3.6 ± 0.6	4.1 ± 0.2	3.4 ± 0.2	3.2 ± 0.5	3.8 ± 0.3	4.2 ± 0.9
Oxides of sulfur, SO <sub>x</sub>	(g/MJ)	2.3 ± 0.0	1.9 ± 0.2	1.5 ± 0.6	1.0 ± 0.3	0.7 ± 0.2	0.9 ± 0.4
Oxides of nitrogen, NO <sub>x</sub>	(mg/MJ)	80.0 ± 25.0	76.0 ± 10.0	64.0 ± 17.0	77.0 ± 6.0	67.0 ± 6.0	69.0 ± 13.0
Chlorides	(mg/MJ)	13.0 ± 3.0	68.0 ± 8.0	97.0 ± 43.0	6.5 ± 0.7	87.0 ± 21.0	139.0 ± 42.0
Formaldehyde	(mg/MJ)	0.2 ± 0.3	0.2 ± 0.1	4.3 ± 4.1	11.7 ± 18.2	3.7 ± 1.9	3.4 ± 3.1
Hydrocarbons	(mg/MJ)	0.22 ± 0.13	0.17 ± 0.07	0.19 ± 0.08	0.08 ± 0.06	0.09 ± 0.04	0.07 ± 0.03

84

Parameter (units)		60% load 1976 Iowa coal with			100% load 1976 Iowa coal with		
		0% RDF	20% RDF	50% RDF	0% RDF	20% RDF	50% RDF <sup>a/</sup>
Particulates (controlled)	(g/MJ)	0.9 ± 0.5	1.1 ± 0.6	1.3 ± 0.7	1.3 ± 0.9	0.4 ± 0.1	0.4 ± 0.1
Particulates (uncontrolled)	(g/MJ)	3.2 ± 0.5	4.4 ± 0.6	3.5 ± 1.4	4.1 ± 1.1	2.2 ± 0.8	3.1 ± 1.3
Oxides of sulfur, SO <sub>x</sub>	(g/MJ)	1.3 ± 1.0	2.3 ± 0.5	0.8 ± 0.4	2.4 ± 0.0	2.0 ± 0.3	1.7 ± 0.3
Oxides of nitrogen, NO <sub>x</sub>	(mg/MJ)	99.0 ± 12.0	104.0 ± 8.0	78.0 ± 20.0	81.0 ± 17.0	76.0 ± 17.0	50.0 ± 8.0
Chlorides	(mg/MJ)	22.0 ± 12.0	58.0 ± 17.0	100.0 ± 55.0	7.0 ± 0.0	62.0 ± 22.0	101.0 ± 21.0
Formaldehyde	(mg/MJ)	2.7 ± 2.7	3.1 ± 3.3	6.2 ± 8.1	3.3 ± 3.6	2.0 ± 2.8	0.2 ± 0.1
Hydrocarbons	(mg/MJ)	0.15 ± 0.08	0.19 ± 0.08	0.31 ± 0.12	0.09 ± 0.06	0.15 ± 0.06	0.17 ± 0.01

<sup>a/</sup>Only two runs at this load and % RDF were accomplished.

Table 4. SELECTED EMISSIONS FROM BOILER UNIT 6

Parameter (units)		80% load			80% load	
		1976 Iowa/Wyoming coal with 0% RDF	20% RDF	50% RDF	1977 Iowa/Wyoming coal with 0% RDF <sup>a/</sup>	50% RDF <sup>a/</sup>
Particulates (controlled)	(g/MJ)	0.5 ± 0.1	0.7 ± 0.2	0.9 ± 0.1	0.8 ± 0.1	1.9 ± 0.1
Particulates (uncontrolled)	(g/MJ)	2.5 ± 0.7	3.5 ± 0.3	4.4 ± 0.9	1.8 ± 0.3	3.9 ± 0.2
Oxides of sulfur, SO <sub>x</sub>	(g/MJ)	0.8 ± 0.5	0.3 ± 0.0	0.4 ± 0.4	0.9 ± 0.1	0.6 ± 0.1
Oxides of nitrogen, NO <sub>x</sub>	(mg/MJ)	133.0 ± 6.0	131.0 ± 5.0	106.0 ± 3.0	91.0 ± 6.0	88.0 ± 5.0
Chlorides	(mg/MJ)	6.3 ± 3.2	44.0 ± 5.0	88.0 ± 33.0	9.4 ± 1.5	110.0 ± 15.0
Formaldehyde	(mg/MJ)	5.8 ± 9.0	0.6 ± 0.1	1.6 ± 0.1	16.0 ± 5.0	20.0 ± 8.0
Hydrocarbons	(mg/MJ)	---	---	---	0.07 ± 0.00	0.13 ± 0.06

Parameter (units)		60% load		
		1977 Iowa/Wyoming coal with 0% RDF	20% RDF	50% RDF
Particulates (controlled)	(g/MJ)	0.7 ± 0.1	1.8 ± 0.4	1.7 ± 0.2
Particulates (uncontrolled)	(g/MJ)	2.0 ± 0.4	3.7 ± 0.4	4.3 ± 0.3
Oxides of sulfur, SO <sub>x</sub>	(g/MJ)	1.4 ± 0.2	0.8 ± 0.1	0.5 ± 0.0
Oxides of nitrogen, NO <sub>x</sub>	(mg/MJ)	106.0 ± 11.0	52.0 ± 10.0	96.0 ± 4.0
Chlorides	(mg/MJ)	4.2 ± 1.1	96.0 ± 12.0	127.0 ± 32.0
Formaldehyde	(mg/MJ)	22.0 ± 12.0	28.0 ± 7.0	23.0 ± 7.0
Hydrocarbons	(mg/MJ)	0.08 ± 0.04	0.07 ± 0.00	0.07 ± 0.01

<sup>a/</sup>Only two runs at this load and % RDF were accomplished.

Table 5. Selected Emissions from Boiler Unit 7

Prior to Installation of Dump Grates 1976, 1977									
Parameter	Units	60% Load		80% Load		100% Load			
		0% RDF		0% RDF		0% RDF		10% RDF	
Particulates (controlled)	1b/10 <sup>6</sup> BTU <sup>b</sup>	0.23	(0.07) <sup>a</sup>	0.35	(0.12)	0.60	(0.09)	0.53	(0.12)
Particulates (uncontrolled)	1b/10 <sup>6</sup> BTU	9.05	(1.02)	7.49	(1.72)	8.26	(0.05)	8.35	(0.30)
Oxides of Sulfur SO <sub>x</sub>	1b/10 <sup>6</sup> BTU	2.61	(0.40)	2.88	(0.70)	3.70	(0.16)	2.88	(1.14)
Oxides of Nitrogen NO <sub>x</sub>	1b/10 <sup>6</sup> BTU	0.32	(0.03)	0.26	(0.09)	0.35	(0.02)	0.27	(0.04)
Chlorides	1b/10 <sup>9</sup> BTU	5.14	(3.75)	13.6	(8.42)	28.14	(6.91)	7.65	(5.05)
Formaldehyde	1b/10 <sup>9</sup> BTU	4.56	(5.58)	20.9	(44.0)	5.49	(4.58)	60.0	(52.6)
Methane	1b/10 <sup>9</sup> BTU	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
After Installation of Dump Grates 1978									
Parameter	Units	80% Load			100% Load				
		0% RDF	10% RDF	20% RDF	0% RDF	10% RDF	20% RDF		
Particulates (controlled)	1b/10 <sup>6</sup> BTU	0.21 (0.05)	0.37 (0.09)	0.37 (0.07)	0.42 (0.21)	0.44 (0.07)	0.53 (0.09)		
Particulates (uncontrolled)	1b/10 <sup>6</sup> BTU	6.54 (1.33)	7.63 (0.63)	8.21 (1.21)	7.93 (3.58)	7.28 (0.53)	7.47 (0.53)		
Oxides of Sulfur SO <sub>x</sub>	1b/10 <sup>6</sup> BTU	3.42 (0.14)	2.84 (0.16)	2.33 (0.63)	3.30 (2.07)	2.33 (0.49)	1.93 (0.51)		
Oxides of Nitrogen NO <sub>x</sub>	1b/10 <sup>6</sup> BTU	0.39 (0.02)	0.33 (0.02)	0.33 (0.03)	0.31 (0.04)	0.26 (0.01)	0.26 (0.03)		
Chlorides	1b/10 <sup>9</sup> BTU	10.7 (1.77)	50.9 (35.8)	93.7 (8.96)	7.65 (1.88)	58.4 (31.9)	28.6 (9.35)		
Formaldehyde	1b/10 <sup>9</sup> BTU	8.37 (14.0)	12. (207.)	0.77 (0.42)	0.19 (0.33)	1.44 (0.72)	0.42 (0.19)		
Methane	1b/10 <sup>9</sup> BTU	5.30 (2.65)	6.07 (1.58)	3.77 (0.30)	3.35 (0.93)	4.58 (1.44)	2.47 (0.58)		

<sup>a</sup> values in parentheses are  $\pm$  one standard deviation

<sup>b</sup> to convert from 1b/10<sup>6</sup> BTU to micrograms/Joule, multiply values in the above table by 0.430

TEST FIRING REFUSE DERIVED FUEL  
IN AN INDUSTRIAL BOILER  
EPA GRANT NO. R806-328-010  
GARY L. BOLEY, P.E.  
PROJECT MANAGER  
CITY OF MADISON, WISCONSIN

In 1979 the City of Madison and the investor owned utility, Madison Gas & Electric Company, jointly implemented a prepared refuse derived fuel (RDF) energy recovery project. The City of Madison owns and operates a solid waste processing plant to process municipal solid wastes for the production of the RDF. The Madison Gas & Electric Company utilizes the RDF in two Babcock and Wilcox 50 megawatt pulverized coal boilers.

In the fall of 1978 the City of Madison in cooperation with Oscar Mayer & Company were recipients of an Environmental Protection Agency Research Grant to test fire RDF in an industrial boiler. The Oscar Mayer & Company could represent a second market to the City for the use of RDF.

The industrial sector is a potentially large user of prepared solid wastes as a supplemental fuel source. Industrial boiler installations are not able to take advantage of the highly favorable fuel price advantages that utilities can obtain, due to their high volume consumption. Therefore, industrial users may be willing to pay a higher price per unit of energy for RDF than utilities.

#### Research Purpose

The purpose of the research is to investigate the feasibility of cofiring municipal solid waste with fossil fuels to determine:

1. Industrial boiler operational performance when cofiring coal and RDF at various boiler loads and feed rates to determine optimum operating conditions.
2. Air emissions and performance of existing mechanical air cleaning system when cofiring coal and RDF.
3. Operational characteristics of the RDF feed system and the reliability and practicality of receiving, storing and firing RDF at an industrial operation.
4. Economic analysis of utilizing RDF at an industrial operation.

#### Project Participants

##### City of Madison

The City's grant responsibilities, in addition to providing the RDF, include overall project management, detail design of the RDF receiving facilities and overall project coordination.

## Oscar Mayer & Company

Oscar Mayer & Company operates a meat packing plant in Madison. As part of their plant operations, Oscar Mayer operates a power plant for the cogeneration of process steam and electricity. One of two Wicks 125,000 pound per hour boilers will be retrofitted for RDF firing. In addition to providing the boilers, Oscar Mayer will also operate the RDF receiving and firing facilities.

## M. L. Smith Environmental

M. L. Smith Environmental was retained by the City to provide special consultant services to provide technical direction and staff assistance in the Engineering evaluation of Boiler No. 5 to determine the method of RDF firing, assistance in the preparation of the necessary documents for the boiler retrofit work, develop the RDF receiving and feed process concept and system layout, provide assistance in the test program development, and assist in the preparation of the project's final report.

## University of Wisconsin-Madison

The University of Wisconsin-Madison, contracted by the City, will provide the facilities and personnel necessary for all sampling, data collection, analysis, and prepare all technical evaluations and reports.

## Existing Boiler Conditions and Modifications

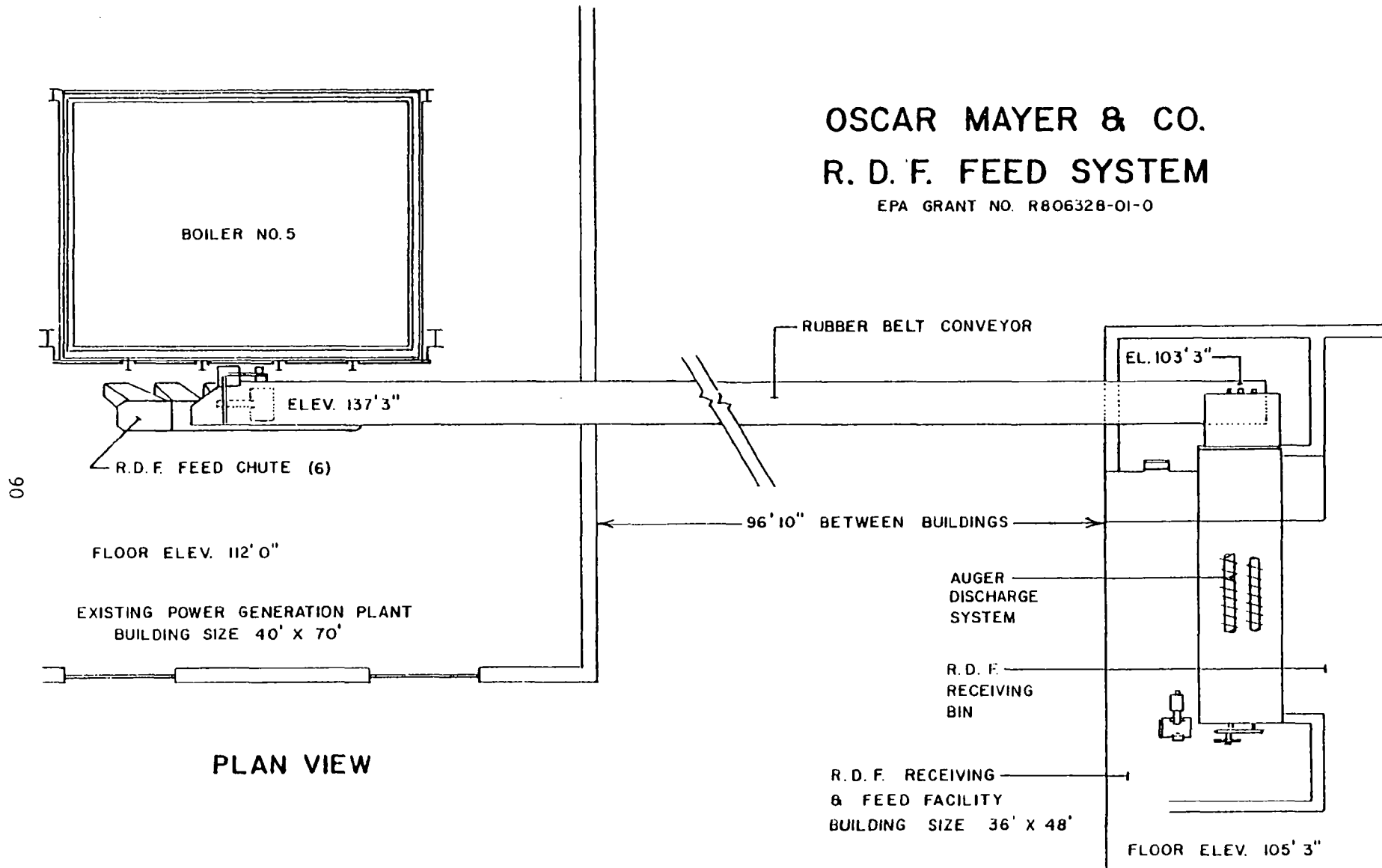
Oscar Mayer & Company's Boiler No. 5 is a Combustion Engineering, Inc. (Wicks) 4-drum water tube type with a rated steam load capacity of 125,000 pounds per hour. The 1 1/4" to 10-mesh coal is fed via a Detroit Stoker roto-grate spreader. The boiler is equipped with Zurn multiclone separators for particulate emission control.

After a detailed evaluation of the existing boiler coal feed and overfire air system, it was determined that it was desirable to fire the RDF as close to the traveling grate as possible. The selected system will fire the RDF immediately above the coal feeders. The RDF is to be air swept into the boiler by utilizing part of the overfire air. To insure an even distribution of the RDF across the boiler width all six existing coal feeder locations will be utilized. The existing coal feeders will be replaced with a combination coal-RDF feeder assembly. The combination feeders are of a standard design used to fire coal in combination with wood chips or hog fuel.

To insure adequate overfire air for RDF firing and combustion, the existing overfire air system was replaced to provide an increased capacity in overfire air volume. The induced draft fans have adequate excess capacity for the additional air volume.

## RDF Feed System

The RDF feed system was developed to provide flexibility in feeding the RDF at varying feed rates to meet the research objectives and to provide a very



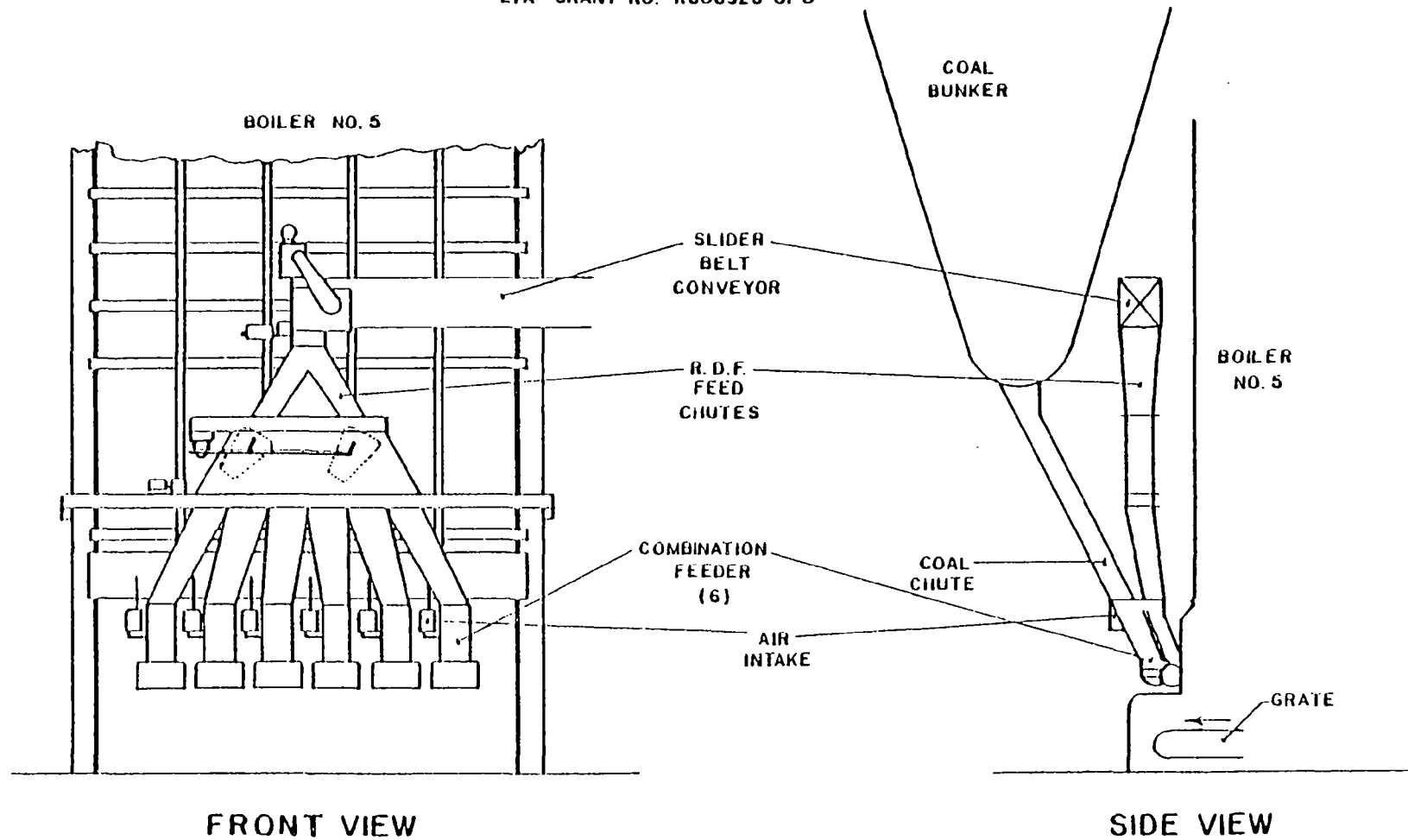
# OSCAR MAYER & CO. R. D. F. FEED SYSTEM

EPA GRANT NO. R806328-01-0

DIVISION OF ENGINEERING - CITY OF MADISON, WISCONSIN  
DRAWN BY T.L.J. 1-30-80

# OSCAR MAYER & CO. BOILER NO. 5 BOILER FEED

EPA GRANT NO. R806328-01-0



DIVISION OF ENGINEERING - CITY OF MADISON, WISCONSIN

DRAWN BY T.L.J. 1-30-80



clean system compatible with Oscar Mayer's high standards for plant cleanliness for food processing. To maintain that standard, all RDF handling activities will be housed in a building and all conveyors will be totally enclosed and tightly sealed.

The delivered RDF will be discharged from the delivery vehicle (75 C.Y. transfer trailers) onto a concrete floor. A small loader will load the RDF into a surge bin. The RDF will be discharged from the bin by two fourteen (14") inch diameter augers. The discharge augers are powered by a variable speed drive to provide the variable RDF feed rates (1.5 to 10 tons per hour). The augers will discharge the RDF onto a totally enclosed rubber slider belt conveyor to transport the RDF to the boiler front. The RDF will then be split to feed the six (6) combination feeders by use of a splitting roller and swinging chutes to provide the desired feed into the boiler.

### Test Program

The RDF-coal firing test program will consist of firing RDF at various energy replacement rates and at varying boiler steam loads. Tests to be conducted will include (see Table 1):

1. Characterization of all fuels used in the combustion tests.
2. Stack emission tests while firing RDF and coal at the various feed rates and boiler loads.
3. Boiler efficiency at the various RDF feed rates and boiler loads.
4. Operate the boilers for a sustained period at the optimum coal/RDF mix.

### RDF Quality

The RDF to be fired in the Oscar Mayer & Company boiler will be essentially the same as presently fired at the Madison Gas & Electric power plant. That RDF has a typical ash content of 10 to 12% and a moisture content of 20 to 30% as received.

### Project Schedule

As of February 1, 1980, all RDF feed equipment and boiler equipment have been ordered. Construction of all facilities is scheduled for completion by June 1, 1980. It is anticipated that all test runs will be conducted during the summer and early fall 1980.

TABLE I SUMMARY OF TEST PLAN

Test No.	1 RDF	2 Steam Load	Proximate Analysis	Ultimate Analysis	Mineral Analysis	Screen Size	Ash Fusion Temp.	1 Combustibles	Flyash Emissions	Flyash Particle Size	Flue Gas	Gaseous Emissions	Boiler Efficiency	Particulate Mass Balance	Chlorine Mass Balance	Trace Element Balance	Arsenic, Mercury In Flue Gas
1	0	60	Coal					Ash, FA	Yes		All	All	Yes				
2	0	80	Coal	Coal Ash, FA	Coal Ash, FA	Coal Ash	Coal	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
3	0	100	Coal					Ash, FA	Yes		All	All	Yes				
4	20	60	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
5	20	80	Coal RDF	RDF Coal	RDF	Coal RDF Ash	RDF Coal	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
6	20	100	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
7	50	60	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
8	50	80	Coal RDF	RDF Coal	RDF	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
9	50	100	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
10 Select	60		Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
11 Select	80		Coal RDF	RDF	RDF	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes				Yes
12 Select	100		Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
13 Optimum			Coal RDF	Coal RDF Ash, FA	Coal RDF Ash, FA	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes

NOTES:

- (I) All for Flue Gas means Flow rate,  $O_2$ ,  $CO_2$ , CO, Combustibles.
- (II) All for Gaseous Emissions means CO, NO,  $NOx$ , SOX, HCl.
- (III) RDF means Refuse Derived Fuel.
- (IV) Ash means bottom ash, economizer ash and cyclone ash.
- (V) FA means Flyash in the stack gas.
- (VI) Chlorine Mass Balance requires analysis of Coal, RDF, Ash, FA and HCl in flue gas.
- (VII) Trace Element Mass Balance requires analysis of Coal, RDF, Ash, and FA for As, Bg, Be, Cd, Cr, Cu and Asbestos.
- (VIII) Number of Samples: Proximate Analysis = 21, Ultimate Analysis = 16, Mineral Analysis = 14, Trace Element Analysis = 15, Arsenic and Mercury Analysis = 5, Chlorine Analysis = 19, Ash Fusion = 9, Solid combustibles = 52, Screen Size = 30.

TEST FIRING REFUSE DERIVED FUEL  
IN AN INDUSTRIAL BOILER  
EPA GRANT NO. R806-328-010  
GARY L. BOLEY, P.E.  
PROJECT MANAGER  
CITY OF MADISON, WISCONSIN

In 1979 the City of Madison and the investor owned utility, Madison Gas & Electric Company, jointly implemented a prepared refuse derived fuel (RDF) energy recovery project. The City of Madison owns and operates a solid waste processing plant to process municipal solid wastes for the production of the RDF. The Madison Gas & Electric Company utilizes the RDF in two Babcock and Wilcox 50 megawatt pulverized coal boilers.

In the fall of 1978 the City of Madison in cooperation with Oscar Mayer & Company were recipients of an Environmental Protection Agency Research Grant to test fire RDF in an industrial boiler. The Oscar Mayer & Company could represent a second market to the City for the use of RDF.

The industrial sector is a potentially large user of prepared solid wastes as a supplemental fuel source. Industrial boiler installations are not able to take advantage of the highly favorable fuel price advantages that utilities can obtain, due to their high volume consumption. Therefore, industrial users may be willing to pay a higher price per unit of energy for RDF than utilities.

#### Research Purpose

The purpose of the research is to investigate the feasibility of cofiring municipal solid waste with fossil fuels to determine:

1. Industrial boiler operational performance when cofiring coal and RDF at various boiler loads and feed rates to determine optimum operating conditions.
2. Air emissions and performance of existing mechanical air cleaning system when cofiring coal and RDF.
3. Operational characteristics of the RDF feed system and the reliability and practicality of receiving, storing and firing RDF at an industrial operation.
4. Economic analysis of utilizing RDF at an industrial operation.

#### Project Participants

##### City of Madison

The City's grant responsibilities, in addition to providing the RDF, include overall project management, detail design of the RDF receiving facilities and overall project coordination.

## Oscar Mayer & Company

Oscar Mayer & Company operates a meat packing plant in Madison. As part of their plant operations, Oscar Mayer operates a power plant for the cogeneration of process steam and electricity. One of two Wicks 125,000 pound per hour boilers will be retrofitted for RDF firing. In addition to providing the boilers, Oscar Mayer will also operate the RDF receiving and firing facilities.

## M. L. Smith Environmental

M. L. Smith Environmental was retained by the City to provide special consultant services to provide technical direction and staff assistance in the Engineering evaluation of Boiler No. 5 to determine the method of RDF firing, assistance in the preparation of the necessary documents for the boiler retrofit work, develop the RDF receiving and feed process concept and system layout, provide assistance in the test program development, and assist in the preparation of the project's final report.

## University of Wisconsin-Madison

The University of Wisconsin-Madison, contracted by the City, will provide the facilities and personnel necessary for all sampling, data collection, analysis, and prepare all technical evaluations and reports.

## Existing Boiler Conditions and Modifications

Oscar Mayer & Company's Boiler No. 5 is a Combustion Engineering, Inc. (Wicks) 4-drum water tube type with a rated steam load capacity of 125,000 pounds per hour. The 1 1/4" to 10-mesh coal is fed via a Detroit Stoker roto-grate spreader. The boiler is equipped with Zurn multiclone separators for particulate emission control.

After a detailed evaluation of the existing boiler coal feed and overfire air system, it was determined that it was desirable to fire the RDF as close to the traveling grate as possible. The selected system will fire the RDF immediately above the coal feeders. The RDF is to be air swept into the boiler by utilizing part of the overfire air. To insure an even distribution of the RDF across the boiler width all six existing coal feeder locations will be utilized. The existing coal feeders will be replaced with a combination coal-RDF feeder assembly. The combination feeders are of a standard design used to fire coal in combination with wood chips or hog fuel.

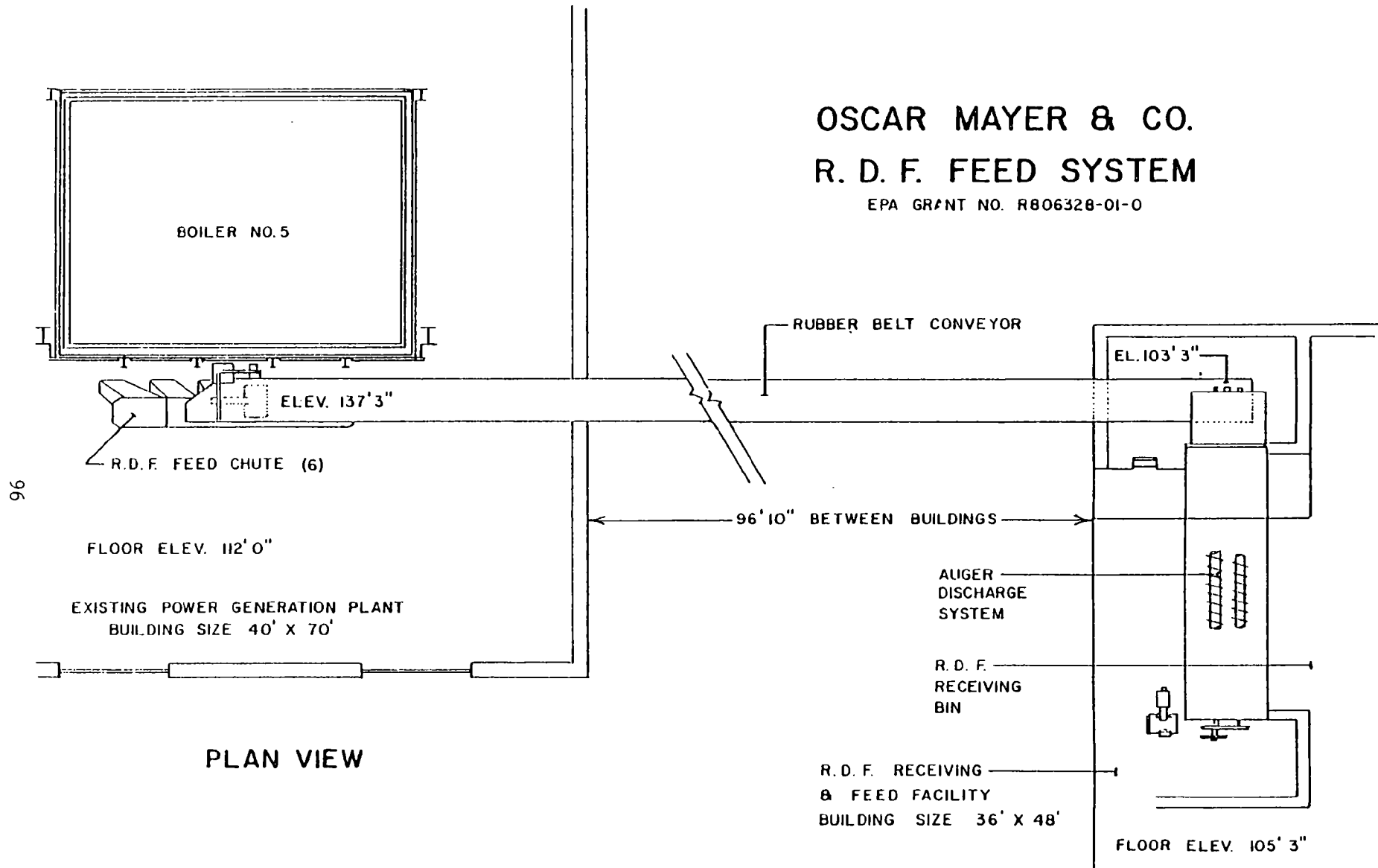
To insure adequate overfire air for RDF firing and combustion, the existing overfire air system was replaced to provide an increased capacity in overfire air volume. The induced draft fans have adequate excess capacity for the additional air volume.

## RDF Feed System

The RDF feed system was developed to provide flexibility in feeding the RDF at varying feed rates to meet the research objectives and to provide a very

# OSCAR MAYER & CO. R. D. F. FEED SYSTEM

EPA GRANT NO. R806328-01-0



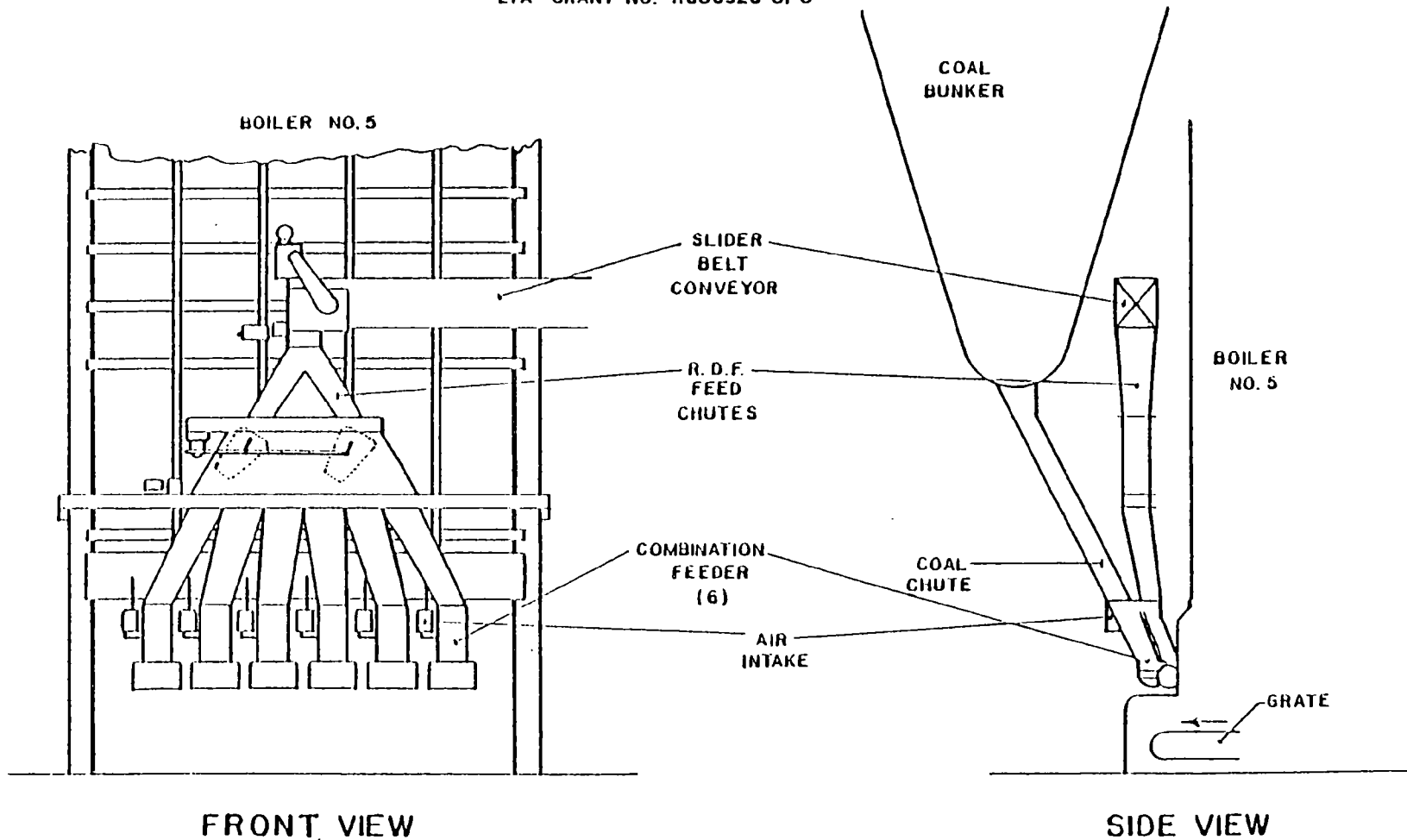
DIVISION OF ENGINEERING - CITY OF MADISON, WISCONSIN

DRAWN BY T.L.J. 1-30-80

# OSCAR MAYER & CO. BOILER NO. 5 BOILER FEED

EPA GRANT NO. R806328-01-0

97



DIVISION OF ENGINEERING - CITY OF MADISON, WISCONSIN

DRAWN BY T.L.J. 1-30-80

clean system compatible with Oscar Mayer's high standards for plant cleanliness for food processing. To maintain that standard, all RDF handling activities will be housed in a building and all conveyors will be totally enclosed and tightly sealed.

The delivered RDF will be discharged from the delivery vehicle (75 C.Y. transfer trailers) onto a concrete floor. A small loader will load the RDF into a surge bin. The RDF will be discharged from the bin by two fourteen (14") inch diameter augers. The discharge augers are powered by a variable speed drive to provide the variable RDF feed rates (1.5 to 10 tons per hour). The augers will discharge the RDF onto a totally enclosed rubber slider belt conveyor to transport the RDF to the boiler front. The RDF will then be split to feed the six (6) combination feeders by use of a splitting roller and swinging chutes to provide the desired feed into the boiler.

#### Test Program

The RDF-coal firing test program will consist of firing RDF at various energy replacement rates and at varying boiler steam loads. Tests to be conducted will include (see Table 1):

1. Characterization of all fuels used in the combustion tests.
2. Stack emission tests while firing RDF and coal at the various feed rates and boiler loads.
3. Boiler efficiency at the various RDF feed rates and boiler loads.
4. Operate the boilers for a sustained period at the optimum coal/RDF mix.

#### RDF Quality

The RDF to be fired in the Oscar Mayer & Company boiler will be essentially the same as presently fired at the Madison Gas & Electric power plant. That RDF has a typical ash content of 10 to 12% and a moisture content of 20 to 30% as received.

#### Project Schedule

As of February 1, 1980, all RDF feed equipment and boiler equipment have been ordered. Construction of all facilities is scheduled for completion by June 1, 1980. It is anticipated that all test runs will be conducted during the summer and early fall 1980.

TABLE I SUMMARY OF TEST PLAN

Test No.	T RDF	1 Steam Load	Proximate Analysis	Ultimate Analysis	Mineral Analysis	Screen Size	Ash Fusion Temp.	2 Combustibles	Flyash Inhalations	Flyash Particle Size	Flue Gas	Gaseous Emissions	Butter Efficiency	Particulate Mass Balance	Chlorine Mass Balance	Trace Element Balance	Arsenic, Mercury in Flue Gas
1	0	60	Coal					Ash, FA	Yes		All	All	Yes				
2	0	80	Coal	Coal Ash, FA	Coal Ash, FA	Coal Ash	Coal	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
3	0	100	Coal					Ash, FA	Yes		All	All	Yes				
4	20	60	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
5	20	80	Coal RDF	RDF Coal	RDF	Coal RDF Ash	RDF Coal	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
6	20	100	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
7	50	60	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
8	50	80	Coal RDF	RDF Coal	RDF	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes
9	50	100	Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
10 Select	60		Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
11 Select	80		Coal RDF	RDF	RDF	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes				Yes
12 Select	100		Coal RDF			RDF		Ash, FA	Yes		All	All	Yes				
13 Optimum			Coal RDF	Coal RDF Ash, FA	Coal RDF Ash, FA	Coal RDF Ash	Coal RDF	Ash, FA	Yes	Yes	All	All	Yes	Yes	Yes	Yes	Yes

## NOTES:

- (I) All for Flue Gas means flow rate,  $O_2$ ,  $CO_2$ , CO, Combustibles.  
 (II) All for Gaseous Emissions means  $CO$ ,  $NO$ ,  $NO_2$ ,  $SO_2$ , HCl.  
 (III) RDF means Refuse Derived Fuel.  
 (IV) Ash means bottom ash, economizer ash and cyclone ash.  
 (V) FA means flyash in the stack gas.  
 (VI) Chlorine Mass Balance requires analysis of Coal, RDF, Ash, FA and HCl in flue gas.  
 (VII) Trace Element Mass Balance requires analysis of Coal, RDF, Ash, and FA for As, Hg, Be, Cd, Cr, Pb and Asbestos.  
 (VIII) Number of Samples: Proximate Analysis = 21, Ultimate Analysis = 16, Mineral Analysis = 16, Trace Element Analysis = 15, Arsenic and Mercury Analysis = 5, Chlorine Analysis = 19, Ash Fusion = 9, Solid Combustibles = 32, Screen Size = 30.



CO-FIRING REFUSE DERIVED FUEL (DROSS)  
IN A STOKERED BOILER  
BY  
FRED R. REHM, P.E.\*

BACKGROUND

Milwaukee County operates a co-generation power plant facility at its 900 acre Milwaukee County Institutions complex that encompasses a growing Regional Medical Center. This power plant is equipped with three (3)-110,000 #/Hour coal-fired Union Iron Works boilers and a single-125,000 #/Hour combination gas-oil fired Combustion Engineering boiler. The coal-fired boilers are each fired by a Hoffman "Firite" spreader stoker with a continuous front end ash discharge grate system. The coal-fired boilers were placed in operation in 1954 and each originally incorporated an economizer, an air preheater and a Western Precipitation "multiclone" mechanical centrifugal dust collector. In 1979, three new UOP-Air Correction Division electrostatic precipitators were installed and placed into operation at this power plant -- one precipitator on each coal-fired boiler. This plant customarily burns an Eastern (Kentucky) coal of less than 2% sulfur content but has operated for extended periods of time burning a Western (Montana) coal with a sulfur content of less than 1%.

With the startup of the American Can Company's "Americology" refuse processing plant, limited test trials were conducted at this plant while firing both the RDF "lights" and "heavies" (dross) fractions in conjunction with coal in the spring of 1977. This RDF firing was conducted using a temporary pneumatic firing system that utilized a farm silage blower setup similar in many respects to the improved pneumatic firing system that had been utilized in an EPA R&D project at the City of Columbus, Ohio municipal power plant. These preliminary firing tests showed sufficient promise that an EPA R&D grant for more extensive and definitive evaluation of co-firing of the dross or RDF "heavies" fraction along with coal was sought and received in late 1978. Dross, or the "heavies" fraction, is the material left after municipal solid waste is processed to produce a refined RDF "lights" fraction suitable for utility firing, a ferrous fraction, an aluminum fraction, and a glass fraction. The remaining material (dross) was demonstrated to have a high combustible content, but because of its unsuitability for firing in a suspension-fired utility boiler, it is normally destined for sanitary landfill. The Americology RDF "lights" fraction has been burned in the Wisconsin Electric Power Company's Oak Creek Station #7 and #8 Boilers for two years now. Those that have attempted to burn RDF in suspension in utility boilers have found that it must be substantially free of metals, glass and other abrasive materials in order to avoid excessive wear and pluggage problems in the pneumatic transport lines and to minimize slagging and other problems associated with boiler operation. Utilities have also learned that the denser combustible material in RDF tends to fall through the furnace without burning completely. Unless a grate is furnished in the utility furnace to retain this material in the high temperature zone, the heating value of the denser material is lost. Generally, speaking, the steps that have been taken to improve the quality of RDF "light" fractions for suspension firing tend to increase the quantity of dross or "heavies" that must be disposed in a landfill. The denseness of this dross,

\* Director of Environmental Services, Milwaukee County, Wis.  
Presented at U.S. EPA-IERL "Waste-To-Energy Technology Update 1980",  
April 15-16, 1980, Cincinnati, Ohio

which makes it unsuitable for suspension firing in a utility boiler, enhances its value as a fuel for a traveling-grate, spreader-stoker fired furnace. Thus, the dense material tends to fall on the grate to effect complete combustion rather than float up and out of the furnace as additional particulate. Our grate speeds are relatively slow and hence furnace retention time in our boilers at rated capacity operation is approximately 80 minutes. Consequently, the successful firing of the RDF "heavies" fraction in our spreader-stoker fired boilers is viewed as supplemental or complementary to the burning of the RDF "lights" fraction at the Wisconsin Electric Power Company pulverized coal-fired boilers.

#### PROJECT OVERVIEW

The RDF "heavies" for our project are to be supplied by the Americology plant. Approximately 3000 tons are expected to be utilized in the 3 month test and evaluation period. The following quality criteria have been established for the "heavies" fraction.

- Less than 12% glass by weight
- Less than 3% metals by weight
- Less than 25% total noncombustibles by weight
- Less than 33% moisture by weight
- A nominal top size of less than 4 inches
- Average heating value range 4000-4800 Btu's/#

The RDF "heavies" are to be transported to the plant by use of Waste Management, Inc. 15-ton self-unloading trailers. For the purposes of this project, on-site storage to provide for an uninterrupted supply of the RDF will be effected by use of Waste-Management trailers. The County's power plant is approximately 6 miles and 10 minutes away by direct freeway travel from the Americology plant.

The RDF fraction will be received in a screw conveyor bottom receiving bin capable of receiving a substantial portion of a full trailer load of RDF. The trailer will be positioned to continue to feed the receiving bin as the RDF is burned. We anticipate an RDF feed rate ranging up to 5.5 tons per hour for these tests. For purposes of these tests this arrangement will forestall the need for supplying a large RDF receiving and storage facility. The rate of operation of the screw conveyors in the receiving bin will be the mechanism for control of the RDF feed rate to the test boiler. One of the three existing boilers will be used in the project. The controlled RDF feed material will be fed to a pneumatic airlock feeder and will be transported pneumatically to the front of the test boiler. A single pneumatic injection RDF flared feed spout will be located in the front wall of the boiler approximately 10 feet above the top of the travelling grate. This location is approximately 7½ feet above the centerline of the coal-feeder reel which projects coal into the furnace. An extensive evaluation has been made by our consulting engineers on this project, Charles R. Velzy Associates, Inc., of the possible use of a mechanical RDF transport system at our plant in lieu of the pneumatic system. All parties involved in the project would have favored the use of a mechanical RDF conveying system to avoid some of the demonstrated problems found by others that have been associated with pneumatic RDF transport. Unfortunately, physical space limitations within the power plant make the use of a mechanical RDF conveying system impractical.

The first two months of plant operation will be used to establish the optimum RDF-coal combination firing rates at various boiler load rates of operation. During this trial period, consideration will be given to the following parameters in establishing and evaluating the optimum RDF substitution rates:

- 1.) RDF receiving, transport and firing system problems and limitations
- 2.) Impact on the steam generating capacity of the boiler
- 3.) Stability of steam generation
- 4.) Excess air requirements
- 5.) Boiler thermal efficiency impacts
- 6.) Carry-over of fuel into the boiler convection bank and boiler slagging
- 7.) Grate residue and fly ash production
- 8.) Residue combustible loss
- 9.) Adequacy or limitations of our pneumatic boiler ash conveying and ash storage facilities

We expect to explore RDF substitution rates ranging from 20% to 50% of the total boiler heat input at boiler steaming rates ranging from 60% to 100% of rated boiler capacity.

Once the two month trial period is completed, we plan to operate the test boiler continuously for approximately thirty (30) days at the optimum RDF input rate established in the trial period at or near 80% of the boilers rated steaming capacity -- the normal rate of boiler operation at this power plant. During this 30-day test period, we expect to conduct a comprehensive system and environmental performance analysis. The boiler and its related firing and ash handling systems will be evaluated and assessed for the aforesaid operating parameters previously outlined. RDF and coal analyses will be regularly conducted for heat content, moisture, ash, chloride and sulfur contents. A limited number of analyses of the RDF and coal will be conducted for their heavy metals content. Concurrent electrostatic precipitator inlet and outlet particulate testing will be performed both while burning coal alone and at the optimum RDF coal substitution rate. The sampled particulates will be analyzed for resistivity, combustible content and particle sizing. Gaseous emissions will be assessed for criteria pollutant loadings as well as for hydrogen chloride. Gas volume and temperature measurements will be made and Orsat analyses will be conducted. The grate ash residue will be quantified and will be analyzed for Btu content, combustible content, putrescibles and leachate potential. Much of the environmental sampling and analytical work for this project was to have been done by EPA contractors which were funded outside the grant project. Consequently, we will have to carefully prioritize the sampling and analytical program conducted to stay within our project's budgetary limitations should EPA funding for this aspect of this project be restricted, as now appears to be the present situation.

Our present timetable calls for our field testing program to be conducted in the Fall of 1980. We are restricted to the conduct of the field portions of this study to either the Fall or Spring of the year since the steam & electrical load demands in this power plant for our Medical Center would preclude the availability of the test boiler for this project during the heavy winter heating load and summer air conditioning load periods. The field test portion of this project was originally scheduled for the Fall of 1979. However, due to an explosion at the Americology plant and subsequent changes and modifications made at that plant, it was necessary to delay this R&D project by one year.

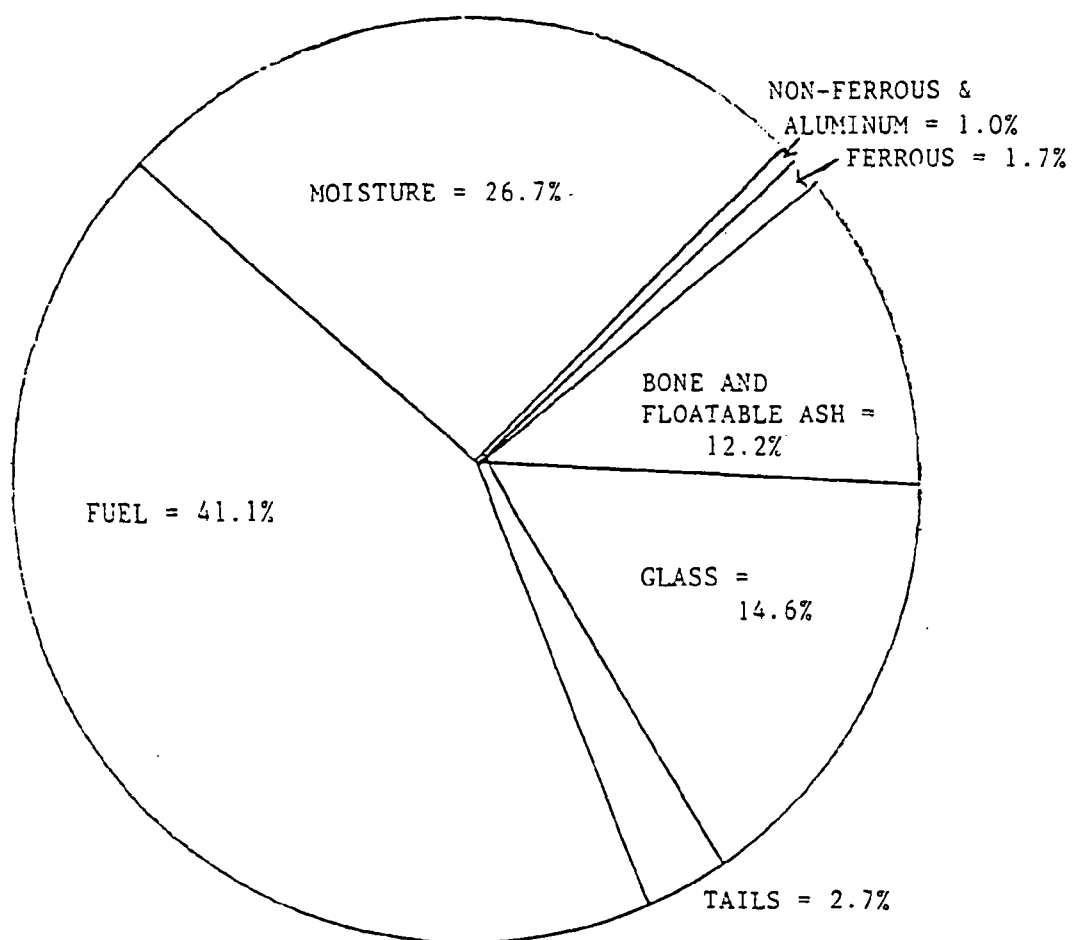
## PROJECT STATUS

We have conducted numerous operational tests at the Americology plant in the past few months directed toward upgrading the quality of the RDF "heavies" fraction. This has involved some plant revisions in the plant's RDF "heavies" processing operations. While the RDF "lights" fraction processing lines have now been modified and adjusted to produce a high quality RDF "lights" fraction for firing by Wisconsin Electric Power Company, there have been limited permanent revisions made to the RDF "heavies" processing system to date. Consequently, there has been need to make temporary changes in the mode of plant operations and in the upgrading of the metals and glass removal operations to improve the quality of the RDF "heavies" fraction to facilitate and enhance its handling and firing capabilities. Should the R&D test program ultimately prove successful and markets for the RDF "heavies" fraction become available, the Americology people would then consider incorporating the aforesaid temporary system changes into permanent modifications to their system that would provide a RDF "heavies" fraction of equal or superior qualities than those used in this research project. The analyses of the RDF "heavies" fraction from one of the series of recent operational tests is shown in the accompanying chart. It is felt by the Americology people that the quality of this material can be further improved by fine tuning the various operating systems in the plant during periods of more extensive running time than those provided in the  $\frac{1}{2}$  hour or 1 hour test periods that were used in the operational test runs to date and which would be required during the actual R&D project burning period. Additional operational test runs will be conducted under varying operating conditions at the Americology plant in the coming months to further reduce the quantity of material greater than 4" and to reduce the amount of glass and other incombustibles in the RDF "heavies" fraction.

Preliminary evaluations and designs for the RDF handling and firing system at the power plant are nearing completion and are expected to be completed soon and the installation of the RDF handling and firing system is expected to be bid in the near future.

Precipitator particulate emission tests have been conducted on all three coal fired boilers while operating at rated capacity while burning Eastern coal. These emission tests were conducted as part of the performance acceptance tests for the new electrostatic precipitators. These test results will be utilized in establishing the baseline for comparing the emission results of coal only burning versus co-firing of coal and the RDF fraction. A table showing the preliminary results of the particulate emission tests for the #3 boiler is attached.

HEAVY FRACTION FUEL ANALYSIS  
TEST ON 1/24/80



NOTE: PERCENTAGES SHOWN ON  
AS RECEIVED BASIS.

PARTICLE SIZE (AVERAGE OF 3 SEPARATE SCREENINGS)

% PASSING	4"	78%
	2"	71%
	1½"	65%
	1"	56%
	¾"	45%
	½"	31%

Table 1. Summary of the Results of the May 30, 1979 ESP Performance and Particulate Emission Test on the No. 3 Boiler ESP fired with Eastern Coal at the Milwaukee County Institutions Central Power Plant in Milwaukee, Wisconsin.

ITEM	RUN 1		RUN 2		RUN 3	
	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Time of Test (HRS)	1020-1130	1015-1130	1220-1350	1230-1347	1418-1535	1415-1530
Steam flow (10 <sup>3</sup> LB/HR)	109.1	109.1	110.9	110.9	109.8	109.8
Percent of rated capacity	99.2	99.2	100.8	100.8	99.8	99.8
Volumetric flow						
ACTUAL (ACFM)	66600	63200	67100	66200	66700	64600
STANDARD (DSCFM)	39400	37900	38700	39000	38800	38400
Gas Temperature (DEG-F)	356	344	363	345	362	345
Gas moisture (% v/v)	6.43	6.24	7.99	7.78	7.42	7.08
Gas composition (% v/v, dry)						
carbon dioxide	11.13	10.94	11.31	10.97	11.18	11.17
oxygen	8.32	8.63	8.14	8.65	8.27	8.35
nitrogen	80.55	80.43	80.55	80.38	80.55	80.48
Time-averaged velocity weighted oxygen (% v/v, dry)	7.74	8.66	7.76	8.43	7.97	8.42
Particulate concentration						
ACTUAL (GR/ACF)	.11	.024	.11	.021	.11	.024
STANDARD (GR/DSCF)	.18	.040	.19	.035	.19	.040
Isokinetic variation (%)	99.7	98.3	103.9	101.7	103.0	100.1
Particulate mass rate (LB/HR)	59.7	13.0	65.1	11.7	63.0	13.0
ESP collection efficiency (% w/w)		78.2		82.0		78.4
Pressure drop across ESP (in. wc)		.53		.53		.53
Particulate emission factors (LB/10 <sup>6</sup> BTU)						
Coal flow method	.45	.099	.50	.089	.48	.102
Steam flow method	.46	.101	.50	.089	.48	.100
F-Factor method (O <sub>2</sub> Analyzer)	.39	.097	.43	.082	.42	.093
F-Factor method (orsal)	.41	.096	.44	.083	.43	.092

## CORROSION INHIBITION IN REFUSE-TO-ENERGY SYSTEMS

H. H. Krause

Battelle  
Columbus Laboratories  
Columbus, Ohio

### ABSTRACT

The benefits of coking high-sulfur coal or sewage sludge with refuse to inhibit corrosion by chlorine were investigated by corrosion probe exposures in full-scale boilers. A spreader-stoker furnace at the Columbus, Ohio Municipal Electric Plant was used for the coal studies, to demonstrate that corrosion rates of carbon steel could be reduced by a factor of 5-10 below those occurring in bulk refuse burning. The sewage sludge program was conducted in the bulk-refuse incinerator at Harrisburg, Pennsylvania, where it was found that corrosion was reduced to half that from refuse alone.

### INTRODUCTION

A serious problem which has been encountered in energy recovery from refuse is the corrosion of boiler tubes, particularly when superheated steam is generated. Research conducted by Battelle in the early 1970's, sponsored by the Solid Waste Research Laboratory of the U.S. Environmental Protection Agency, Cincinnati, Ohio demonstrated that chlorine in the refuse was chiefly responsible for the corrosion.(1-5) This work was done at the Miami County Incinerator, Troy, Ohio, where bulk refuse was burned, and was supplemented by laboratory experiments.

In the course of this research program it was discovered that the corrosive effect of the chlorine could be made negligible by adding sufficient sulfur to the refuse to achieve a S/Cl ratio of 4.(6,7) The mechanism by which the sulfur inhibits corrosion is to promote the formation of HCl and chlorine in the flame zone rather than beneath deposits at the tube metal surface. It was then a logical step to proceed from the addition of sulfur to the use of high-sulfur coal as the source of SO<sub>2</sub> needed to suppress corrosion by chlorine.

At this point the Municipal and Industrial Environmental Research Laboratories were established, and the former took over the responsibility for a series of short-term corrosion probe experiments to demonstrate the feasibility of the coking approach. This work was done in a spreader-stoker boiler at the Columbus, Ohio, Municipal Electric Plant. The Fuels Technology Branch of the Industrial Environmental Research Laboratory then continued this program, to provide for large scale feeding of the shredded refuse and longer term corrosion probe exposures. Other operational variables of the system such as emissions, combustion quality, and ash properties also were studied.

On completion of the program at Columbus, Ohio, the effects of coking sewage sludge with refuse to achieve corrosion reduction were investigated, using the facilities of the Harrisburg, Pennsylvania, incinerator.

### COKING WITH HIGH SULFUR COAL

Although a program on burning of processed refuse was conducted at the Union Electric Company in St. Louis and is still underway at the Ames, Iowa Electric Utilities, the Battelle program differed from these in that the waste processing was limited to shredding and magnetic separation, thus providing a lower cost operation.

### Refuse Handling

During the first year on this program, a temporary system for handling, conveying, and furnace feeding of shredded waste was assembled utilizing commercially available agriculture equipment for handling forage and grain crops. This system was only useful for short term (eight to ten hr) runs to test the principles involved, because of high manpower requirements.(8,9) For continuous operation with refuse as a supplementary fuel a permanent installation was built.

The Columbus, Ohio municipal waste used in this program was processed through Jeffrey shredders that have a capacity of 60 tons (54.5 Mg) per hour with screens of 5 x 5 in. (13 x 15 cm) which produce 90 to 95 percent minus 4 in. (10 cm) product. The remaining five to ten percent of the product may vary in one dimension up to 18 to 20 in. (46 to 51 cm) even though the other dimensions may not exceed the nominal four in. (10 cm).

Shredded and magnetically separated refuse is generated at three shredder stations at a rate of 40 to 50 tons (36 to 45 Mg) per hour each, operating seven or eight days per week. Transfer trucks normally haul this refuse to landfill, but by request would deliver it in 15 to 20 ton (14 to 16 Mg) loads to the Municipal Electric Plant. The Sanitation Division transfer trucks had to be emptied in 20 to 30 minutes during the daytime to avoid delaying shredder operation, but could be used for storage and/or retained for longer periods at night.

Assuming an average steam flow of 100,000 lb/hr (45 Mg/hr) and 50 percent of the heat generated by refuse, the amount used per hour

would be about seven to eight tons (6 to 7 Mg). Thus, a truckload of refuse could be delivered to the power plant every two to three hours during the day and also through the night by storing refuse in the trucks from the daytime operation of the shredders. After consideration of the available space and possible equipment arrangement at the power plant, it was decided that the most suitable and cost-effective storage unit would consist of a bin similar to the transfer truck body with a hydraulic ram to feed the refuse as required.

The remainder of the external system comprised: (1) beater bars at the end of the bin to break up the refuse, (2) screw conveyors, (3) a 30 in. rubber belt conveyor, and (4) an inverted Y hopper to receive the refuse from the conveyor belt and direct it into two screw conveyors. The refuse storage and retrieval system is shown in Figure 1.

The refuse stream was divided at the Y hopper so that the larger portion was fed to the front of the boiler, near the spreaders. The two screw conveyors inside the building delivered the refuse to Riley air-swept spouts which were inserted in the side of the boiler, at a 90 degree angle to the grate. The modification of the boiler tubes to accommodate the spouts is shown in Figure 2. When this boiler was converted to a spreader stoker some years ago, the direction of the grate travel was not changed, so the grate moved away from the spreaders. For this reason about two-thirds of the refuse was introduced through the spout on the right, just in front of the spreaders. The boiler modification also included installation of overfire air jets beneath the refuse spouts and across the back of the furnace. During corrosion probe exposures the refuse feed rate was three to five tons/hr.

### Refuse Combustion

The boiler used in this program is rated at 150,000 lb (68 Mg) of steam per hour, but normally was operated over the range of 70,000 to 125,000 lb (32 to 57 Mg). In order to insure good distribution of refuse across the furnace, a rotating damper in the duct of each air-swept spout produced pulses to vary the input. The fuel trajectory was controlled by angling the distributor plate either up or down. However, to maintain suspension while the refuse was burning, two air nozzles were mounted beneath each refuse feeder. These air supplies provided part of the overfire air needed for combustion while the remaining air requirements were supplied by the blower through eighteen jets mounted in the rear wall of the boiler furnace. Butterfly dampers were located in each of the air ducts to provide manual adjustment of the air for each of the three functions. Control of the eighteen overfire air jets was based upon measured oxygen in the combustion chamber of the furnace, which normally operated at 8 to 10 percent oxygen.

The combustion of the refuse was complete for all amounts of refuse fed (up to 74 weight-percent of the fuel), with no unburned residue in the ash. However, for levels of refuse over 50 percent, to avoid pile up of refuse on the grates, careful attention was required to adjustment of:

1. The refuse injection air,
2. The distributor plates in the spouts,
3. Overfire air beneath the refuse spouts,
4. Underfire air.

The use of refuse which has been shredded and magnetically separated but not air classified demonstrated that the melting of aluminum cans and other low-melting alloys may become a problem. If the underfire air is not or cannot be adequately maintained, these materials will melt and either react with the oxide scale on the grate or run through and solidify on the underside, thus disrupting grate travel. The seriousness of this problem depends on the amount of low-melting material in the refuse, and it could require specially designed grates and underfire air supply to handle refuse that has not been air classified.

### Corrosion Probe Exposures

The corrosivity of the combustion products obtained from the burning of coal and the refuse-coal mixes was evaluated by inserting Battelle-designed air-cooled corrosion probes in the superheater section of the boiler. At this location the gas temperature varied from 1100°F (593°C) under low load conditions to 1400°F (760°C) for the higher loads. The internal air cooling of the probe specimens maintained metal temperatures of 500 to 950°F (260 to 510°C) as measured by thermocouples inserted in the wall of several specimens along the probe. The details of the probe design have been published previously.(9) The specimens were machined from one in. Schedule 40 pipe or equivalent tubing and were nested together end to end on the probe. Internal cooling of the specimens by high-velocity air that flowed over the tapered centerbody provided a temperature gradient along the probe. The alloys used in the corrosion probe exposures ranged from ordinary carbon steel to high-chromium steel and high-chromium-nickel alloys. In addition to ten probe runs of eight hour duration, two runs of 75-80 hours and one of 700 hours were conducted on this program.

## Corrosion Results

Corrosion rates were determined by weight loss measurements after removal of the reacted metal using initialed 10 percent  $\text{H}_2\text{SO}_4$  while the sample was made six volts cathodic to a carbon anode. The corrosion rate in mils per hour was calculated from the weight loss, assuming uniform attack around the specimen surface. The corrosion rates in the corfiring environment for A106 carbon steel as a function of time are shown in Figure 3. The corresponding rates for 100 percent refuse combustion were obtained from the previous exposures to mass burning of refuse at the Miami County incinerator and are shown in Figure 4. With high-sulfur coal and up to 46 weight-percent refuse, the initial rates were reduced by a factor of ten. As the exposure time increased, the rates for 100 percent refuse and coal plus refuse became closer, but the shapes of the curves indicate that for extended exposures the corrosivity of the 100 percent refuse combustion environment will be about 5 to 10 times that of the high-sulfur coal with refuse.

In general, the rates for the refuse-coal mixtures were about the same as for the coals alone. With carbon steel and 3 percent sulfur coal, corrosion rates were slightly greater at 700 and 900°F (371 and 482°C). For the 5 percent sulfur coal the relatively high rates were the result of sulfur attack on the steel. All of the corrosion rates measured at the Columbus site were smaller than those found for bulk refuse burning by at least a factor of ten, and in some cases, by a factor of fifty.

The initial corrosion rates (3-hour) for A106 steel as a function of the refuse percentage in the fuel are presented in Figure 5. The rates were essentially independent of the amount of refuse in the mixture, up to the 75 weight-percent used. The 100 percent values in the figure are from the bulk refuse incineration experiments, and it is quite possible that these values would be lower if shredded refuse were burned under comparable circumstances.

When the exposure time was lengthened to 30 hours, the corrosion rates for all of the steels were reduced as a result of the protective oxide layers which developed on the metal surfaces. As found in the eight hour exposures, the Type 310 stainless steel had the lowest corrosion rate, followed by the Types 316 and 347 stainless steels. The P9 alloy had a slightly higher rate, and the scatter in the data for the P9 specimens is attributed to the tendency of this alloy to undergo spalling of the oxide film. This effect would result in some inconsistencies of weight loss among the samples. Although the corrosion rate for A106 carbon steel was significantly lower than that for eight hour exposures, it was still about a factor of ten greater than that for the stainless steels.

The interpolated values for the long-term corrosion rates are given in Table 1, which includes data for the 708 hour corrosion probe exposure. As shown in the table, the corrosion rates generally decreased further with the longer time, to where they have probably leveled off and would not decrease significantly with additional exposure. Type 310 stainless steel, which already had a very low corrosion rate for the 79 hour exposure, incurred the same rate at 500 and 700°F in the 708 hour exposure, with a decrease at 900°F. At a metal temperature of 900°F the A106 steel also had the same rate for the two exposure times. It should be noted that when one percent sulfur coal was burned with only 16 weight-percent refuse (Probe 40), the corrosion rate of A106 steel was higher. This result indicates that the low-sulfur coal was not adequate to afford protection against even this small percentage of refuse.

## CORFIRING WITH SEWAGE SLUDGE

This part of the work was carried out at the Harrisburg, Pennsylvania, incinerator, where during initial operation, tube failures occurred every three to five months when only bulk solid waste was burned. For the past several years no tube failures have occurred, but during this period municipal sewage sludge has been burned along with the refuse. In addition, soot blowing was reduced in frequency and some of the carbon steel tubes were replaced with a low-chromium alloy. Consequently, the reason for the reduced metal wastage at the Harrisburg incinerator was uncertain and corrosion studies were needed to evaluate the effect of adding the sewage sludge to the refuse combustion environment. This facility has two identical boilers, each with a nominal capacity of 360 T/day (327 Mg per day) of refuse. At this rate of 15 tons (13.6 Mg) of refuse per hour, the normal steam production is 32,500 lb/hr (42.3 kg/hr). The steam pressure at the superheater outlet is 250 psig (18.5 kg/cm<sup>2</sup>) at a temperature of 456°F (236°C). These multistage boilers with welded water walls are fed from a single refuse pit and are exhausted through individual electrostatic precipitators before discharge into a single stack.

About 15 to 20 tons (13.6 to 18.3 Mg) of partially dried sewage sludge are delivered by truck to the incinerator every 24 hours, and the sludge is dumped into the refuse in the pit. This material contains 20 to 22 percent solids, so the incinerator handles the equivalent of about 5 to 6 tons (4.5-5.5 Mg) per day of dry solids. During the course of these corrosion studies, the partially dried sludge was delivered at an average rate of 18.5 tons (15 Mg) per working day. During the 3-hour and 30-hour probe exposures, the weight ratio of sludge to solid waste was about 1:10 on an as-received basis, but during the long-term run the ratio dropped to about 1:20.

As currently practiced, the dewatered sludge filter cake containing about 22 percent solids is mixed with the municipal refuse in the receiving pit. Considerable mixing occurs in the pit before the sludge and refuse are fed into the furnace charging chute. It seemed likely that sulfur and silica were present in the sludge in sufficient quantity and were burned effectively to reduce the corrosive effects of chlorine in the refuse.

Six corrosion probe exposures were made on this program, two with refuse alone and four during corfiring of refuse and sludge. Exposure times of 3, 30, and 316 hours were employed.

## Effect of Exposure Time

The corrosion rates for the carbon steel specimens are shown as a function of time in Figure 6. These results are compared with the corrosion data obtained previously at the Miami County incinerator at Troy, Ohio, where bulk refuse alone was burned. The data were interpolated from several specimen temperatures to a common temperature of 500°F (260°C). This temperature was selected to be similar to that of the Harrisburg incinerator superheater tubes which operate at a steam temperature of 450°F (232°C). The data point for the eight hour exposure time at Harrisburg when refuse alone was burned compared favorably with that from the Troy incinerator for which longer exposure times up to 328 hours also were obtained. The corrosion rate was slightly higher at Troy because the probe there was exposed to some flame radiation.

The addition of sewage sludge to the refuse reduced the initial corrosion rate of the carbon steel by about a factor of two. However, as the exposure time increased, the corrosion rates for operation with and without sludge converged. Thus at the 300 hour point, the rate experienced for the small amounts of sludge burned at Harrisburg was only slightly less than that for refuse alone at the Troy incinerator. Nevertheless, if the difference in the two curves at the 1000 hour point were to be maintained indefinitely, the result would be a 15 to 40 percent increase in boiler tube life for the system with the sludge added.

The corrosion rates for the other alloys used in the probe exposures at Harrisburg are given as a function of time in Table 2 for three temperatures covering the exposure range. The P22 alloy had metal wastage rates essentially the same as those for the carbon steel. Significantly lower rates were observed for the Type 310 and 347 stainless steels and the Incoloy 325.

## Effect of Metal Temperature

A plot of wastage rates for A106 carbon steel over the temperature range 300 to 900°F for the eight hours exposure to the burning refuse with and without sludge additions is shown in Figure 7. The line drawn on this figure from the studies conducted at the Troy, Ohio, incinerator is based upon ten or more A106 specimens exposed at a gas temperature of 1500°F (816°C) which is comparable to that of the Harrisburg probe in the superheater inlet. The increase in corrosion rate starting at 900°F (427°C) is typical of that found for carbon steel and low alloy steels in our past experience with the burning of bulk refuse at high gas temperatures. The three data points obtained for the carbon steel exposed to comparable conditions in the Harrisburg incinerator fall close to the curve established for the Troy incinerator. The corrosivity of the environment was significantly reduced when the sewage sludge was burned with the refuse. As shown in Figure 7, the eight hour corrosion rates with sludge present in the fuel are 2 to 2.5 times lower than those with refuse alone.

Similar conditions and results are shown in Figure 8 for the low chromium alloy, T22 now being used for the superheater tubes in the Harrisburg incinerator. The difference in corrosivity of the two fuels becomes more pronounced for both alloys as the metal temperature increases. Here again the line drawn in the figure was obtained at Troy for a similar low chromium alloy, T11. In comparing the performance of carbon steel and T22 when sewage sludge was burned with the refuse, little difference was observed in the corrosion rates, as noted in Figures 7 and 8. When refuse alone was burned the corrosion rate for T22 alloy was slightly lower than that of A106 at temperatures up to 900°F (427°C). However, at about 900°F (427°C) there was little difference in the corrosion rate of the two materials. These results indicate that the reduction in tube failures at the Harrisburg incinerator in recent years was not the result of replacing carbon steel tubes with the T22 alloy.

Both Type 310 and 347 stainless steel as well as Incoloy 325 showed very low wastage rates in the aggressive incinerator environment, as summarized in Figure 9. In comparable eight hour exposures the corrosion rates of these alloys at temperatures between 500°F (260°C) and 900°F (482°C) were only about one-fifth as great as those for the carbon steel and the low-alloy steel. These high chromium-nickel alloys afforded more protection as the temperature increased, probably due to more rapid diffusion of the chromium and nickel into the oxide layer with the formation of a thicker protective scale. The addition of sludge to the refuse had practically no effect on the corrosion rates of Type 310 and 347 stainless steel. The sludge did, however, slightly reduce the attack on Incoloy 325, particularly at lower temperatures.

## Effect of Gas Temperature

For this program two different locations for probe exposure were selected on the basis of their gas temperatures. The higher temperature location was in front of the first superheater bank and 5 feet below the location of the plant thermocouple for furnace temperature measurement. Gas temperatures in this zone are monitored and maintained near 1500°F (815°C).

Two of the eight hour probe runs were made in a relatively cool location which was about 15 ft downstream of the hotter location. At this point the tubes were practically black and the gas temperature as monitored



by the probe thermocouple was in the range 1100-1200°F (593-650°C). The corrosion rates of the carbon steel and the P22 alloy exposed at low gas temperature showed only a slight variation with metal temperature as compared to Figures 7 and 8 where the corrosion rates increased rapidly with metal temperature when exposed to high gas temperature. The corrosion data demonstrated that the same reduced temperature dependence existed at low gas temperature when the sludge was burned with the refuse. Under these low-temperature conditions, there was no apparent difference in the corrosion rates between the carbon steel and the P22 alloy.

It should be noted that a reduction in gas temperature is more effective in reducing the corrosivity of the environment over the entire metal temperature range than is the addition of sludge to the fuel. Thus, although additives to the refuse may improve the life of boiler tubes the design of the boiler to reduce the temperature in the steam generator section would also provide a significant improvement in boiler tube life.

#### CONCLUSIONS

The experimental program conducted at the Columbus, Ohio Municipal Electric Plant has demonstrated the technical feasibility of mechanical handling and furnace feeding of processed municipal solid waste at an existing stoker-fired boiler with limited space and accessibility. It also has been shown that the refuse combustibles can be burned completely on a grate in conjunction with coal, utilizing a spreader-stoker.

The following specific conclusions can be reached:

1. The corrosivity of combustion products from cofiring refuse and three percent sulfur coal up to a three to one weight ratio is only slightly greater than that of coal alone.
2. Boiler tube metals can be ranked in the following order of increasing resistance to corrosion: A106 carbon steel, P9 low alloy steel and Types 316, 347, and 310 stainless steel.
3. The corrosion rates of boiler tube metals decrease rapidly with exposure time. After 700 hr the rates for stainless steels level off.

Corrosion probe exposures conducted at the Harrisburg, Pennsylvania, incinerator demonstrated that the addition of low-chloride sewage sludge to municipal refuse reduced the corrosion of susceptible metals caused by chlorine in the refuse. Specific conclusions from this research program were:

1. The corrosiveness of the refuse combustion environment to carbon steel as indicated by 8-hour exposures was only 1/2 as great with sewage sludge present. Less reduction occurred at low temperatures with T22 steel, very little with Incoloy 825 and essentially none with Types 310 and 347 stainless steel.
2. For carbon and low alloy steels the corrosion rates increased with metal temperature in the range 500-900°F (260-482°C), while those for stainless steels decreased.
3. The short-term corrosion rates at gas temperatures of 1100-1200°F (593-649°C) were only 1/5 as great as at 1500°F (815°C) and showed less increase with metal temperature.

The cofiring of sewage sludge with municipal refuse is a practical means of reducing corrosion of heat recovery surfaces and at the same time providing sludge disposal. However, it should be pointed out that the sewage should not have been treated with ferric chloride, because chloride residue in the sludge would promote corrosion.

#### ACKNOWLEDGMENTS

This project has been financed in part with Federal funds from the Environmental Protection Agency under Grant No. R-804008-02 from the Industrial Environmental Research Laboratory, Cincinnati, Ohio. The contents do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

The cooperation of the Electric and Sanitation Divisions of the City of Columbus and the Bureau of Incineration of the City of Harrisburg is gratefully acknowledged.

The recommendations and assistance of the Project Officers: Mr. D. A. Oberacker of the Municipal Environmental Research Laboratory and Mr. R. A. Olexsey of the Industrial Environmental Research Laboratory also are acknowledged.

#### REFERENCES

1. Miller, P. D., et al., "Corrosion Studies in Municipal Incinerators", U. S. Environmental Protection Agency Report SW-72-3-3, 1972.
2. Miller, P. D., and Krause, H. H., "Corrosion of Carbon and Stainless Steels in Flue Gases from Municipal Incinerators", *Proceedings of the 1972 National Incinerator Conference*, American Society of Mechanical Engineers, June, 1972, pp. 300-309.

3. Miller, P. D., Krause, H. H., Vaughan, D. A., and Boyd, W. K., "The Mechanism in High Temperature Corrosion in Municipal Incinerators", *Corrosion*, Vol. 28, July, 1972, pp. 274-281.
4. Krause, H. H., Vaughan, D. A., and Miller, P. D., "Corrosion and Deposits from Combustion of Solid Waste", *Transactions of the ASME, Journal of Engineering for Power*, Series A, Vol. 95, 1973, pp. 45-52.
5. Krause, H. H., Vaughan, D. A., Miller, P. D., "Corrosion and Deposits from Combustion of Solid Waste. Part 2 - Chloride Effects on Boiler Tube and Scrubber Metals", *Transactions of the ASME, Journal of Engineering for Power*, Series A, Vol. 96, 1974, pp. 216-222.
6. Krause, H. H., Vaughan, D. A., Boyd, W. K., "Corrosion and Deposits from Combustion of Solid Waste. Part 3 - Effects of Sulfur on Boiler Tube Metals", *Transactions of the ASME, Journal of Engineering for Power*, Vol. 97, 1975, pp. 448-452.
7. Vaughan, D. A., Krause, H. H., Boyd, W. K., "Fireside Corrosion in Municipal Incinerators versus Refuse Composition", *Materials Performance*, Vol. 14, No. 5, 1975, pp. 16-24.
8. Krause, H. H., Vaughan, D. A., Boyd, W. K., "Corrosion and Deposits from Combustion of Solid Waste. Part 3 - Combined Firing of Refuse and Coal", *Transactions of the ASME, Journal of Engineering for Power*, Vol. 98, 1976, pp. 369-374.
9. Krause, H. H., Vaughan, D. A., Cover, P. W., Boyd, W. K., Oberacker, D. A., "Corrosion and Deposits from Combustion of Solid Waste. Part 5 - Firing of Refuse with High-Sulfur Coal", *Transactions of the ASME, Journal of Engineering for Power*, Vol. 99, 1977, pp. 449-459.

TABLE 1. LONG TERM CORROSION RATES FOR VARIOUS ALLOYS AS A FUNCTION OF METAL TEMPERATURE AND FUEL (MILS PER HOUR)

Alloy	Metal Temp. F	Probe 40	Probe 39	Probe 38
		75 Hours 1% S Coal 16 Wt % Refuse	79 Hours 3% S Coal 35 Wt % Refuse	708 Hours 3% S Coal 22 Wt % Refuse
A106	500	0.005	0.001	0.001
	700	0.012	0.005	0.003
	900	0.019	0.010	0.005
316	500	0.0001	0.0009	0.0002
	700	0.0002	0.001	0.0004
	900	0.0002	0.001	0.0008
310	500	Nil	Nil	Nil
	700	0.0001	0.0001	0.0001
	900	0.0002	0.0002	0.0001
P9	500	0.004	0.001	0.0008
	700	0.005	0.002	0.0010
	900	0.001	0.004	0.0012
347	500	Nil	0.0002	0.0001
	700	0.0002	0.0006	0.0003
	900	0.0004	0.0010	0.0008

TABLE 2. CORROSION RATES FOR 8, 80 AND 816 HOUR EXPOSURES TO BURNING REFUSE WITH SLUDGE

(Interpolated to fixed temperature values)

Alloy	Metal temperature		Waste rate, mils/hr. for time indicated		
	F	C	8 hours	80 hours	816 hours
A106	500	260	0.051	0.0093	0.0082
	700	371	0.100	0.0093	0.0086
	900	482	0.132	0.0105	0.0087
T/P 22	500	260	0.059	0.0098	0.0083
	700	371	0.080	0.0096	0.0085
	900	482	0.140	0.0102	0.0090
310SS	500	260	0.014	<0.0001	0.0011
	700	371	0.022	0.0002	0.0011
	900	482	0.007	0.0009	0.0017
347SS	500	260	0.038	0.0003	0.0025
	700	371	0.033	0.0011	0.0020
	900	482	0.009	0.0012	0.0020
Incoloy 825	500	260	<0.005	<0.0001	0.0011
	700	371	0.015	0.0005	0.0012
	900	482	0.014	0.0009	0.0020

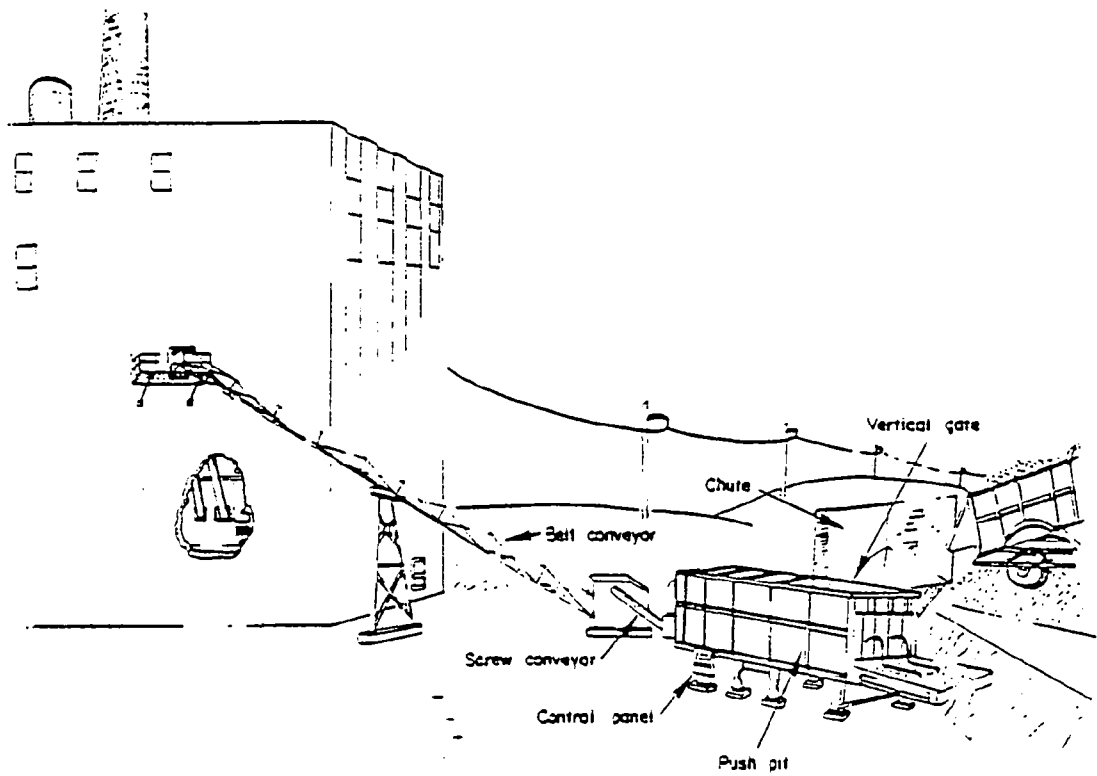


FIGURE 1. REFUSE HANDLING SYSTEM AT THE COLUMBUS, OHIO MUNICIPAL ELECTRIC PLANT

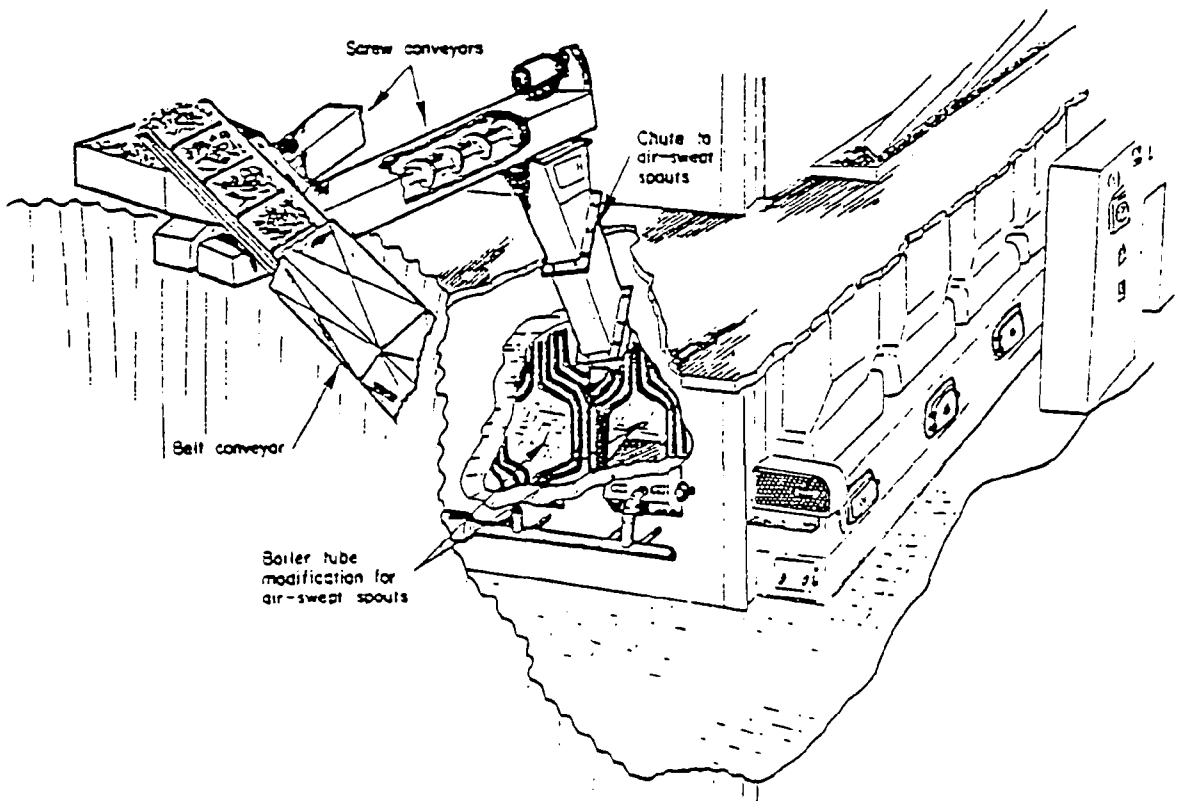


FIGURE 2. INTERFACE TRANSFER SYSTEM AND BOILER MODIFICATION

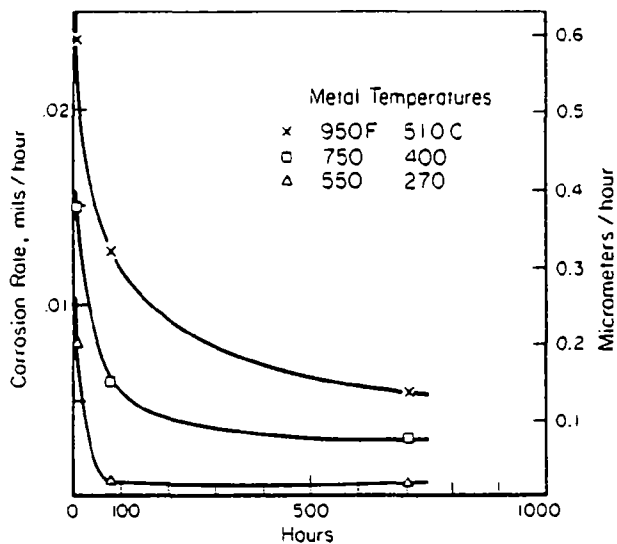


FIGURE 3. CORROSION RATES OF A106 CARBON STEEL AS A FUNCTION OF TIME FOR CO-FIRING OF REFUSE AND HIGH-SULFUR COAL

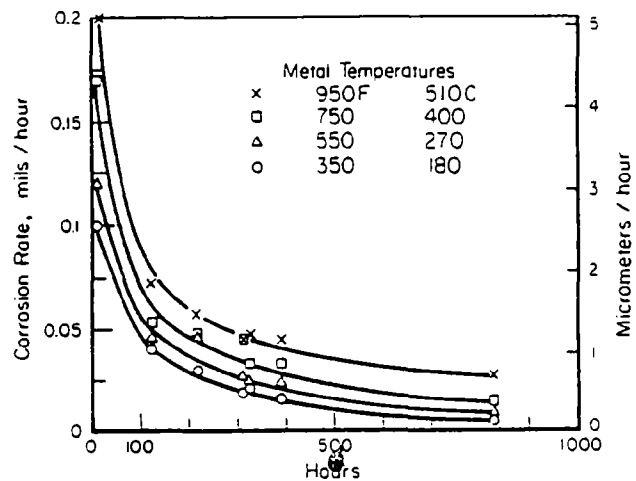


FIGURE 4. CORROSION RATES OF A106 CARBON STEEL AS A FUNCTION OF TIME FOR INCINERATION OF BULK REFUSE

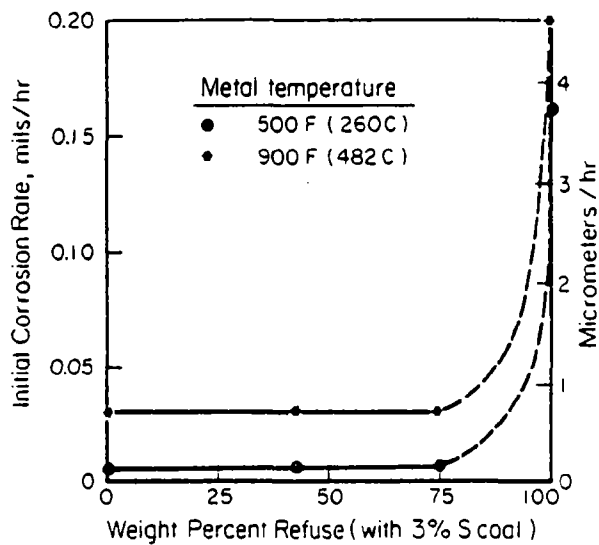


FIGURE 5. INITIAL CORROSION RATES (8 HR) FOR A106 CARBON STEEL AS A FUNCTION OF REFUSE PERCENTAGE IN THE FUEL (100 PERCENT VALUES FROM BULK REFUSE INCINERATION)

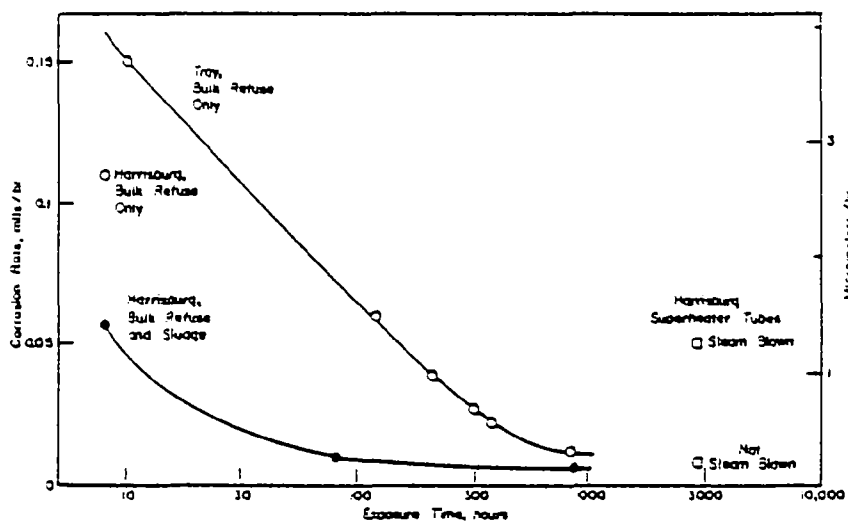


FIGURE 6. CORROSION RATES OF CARBON STEEL AT A METAL TEMPERATURE OF 260°C (500°F) VERSUS EXPOSURE TIME.

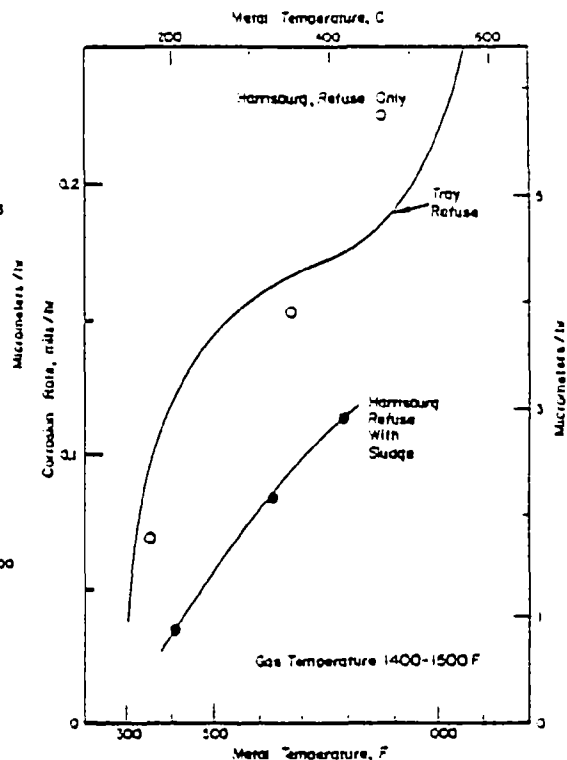


FIGURE 7. CORROSION RATES OF CARBON STEEL (A-108) SPECIMENS EXPOSED FOR 3 HOURS TO BURNING REFUSE ALONE AND WITH SLUDGE.

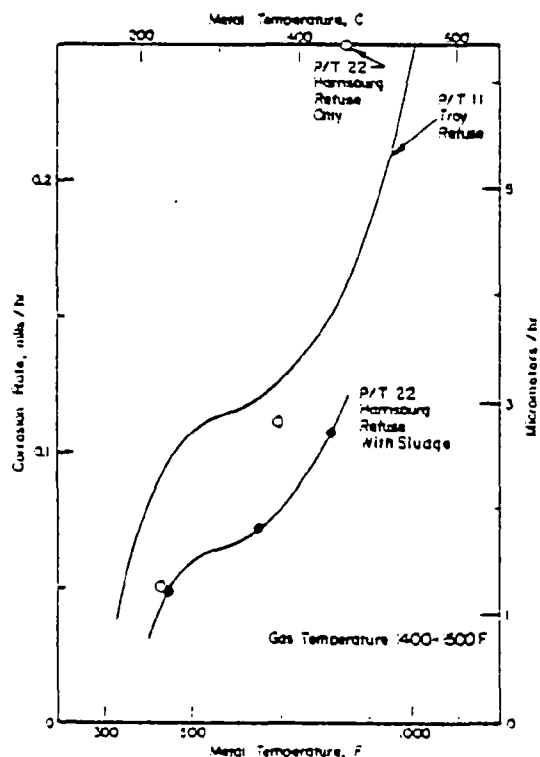


FIGURE 8. CORROSION RATES OF LOW CHROMIUM ALLOYS EXPOSED FOR 3 HOURS TO BURNING REFUSE ALONE AND WITH SLUDGE.

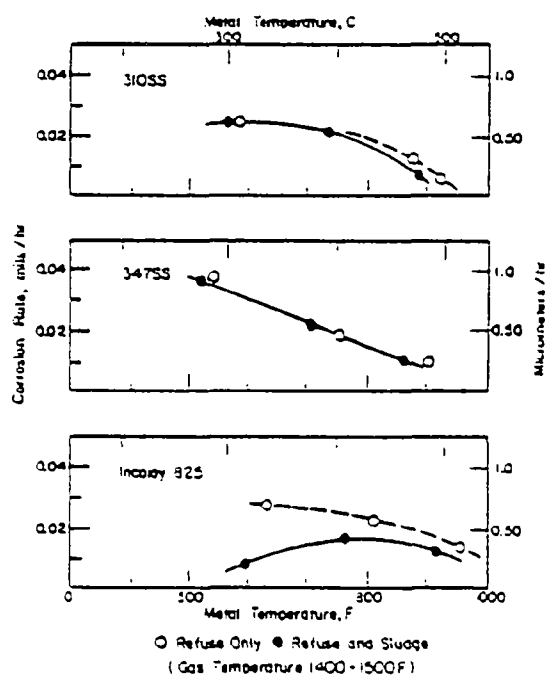


FIGURE 9. CORROSION RATES OF STAINLESS STEELS AND INCONEL 625 VERSUS METAL TEMPERATURE (3-HOUR EXPOSURE).

# CO-FIRING DENSIFIED REFUSE DERIVED FUEL IN A SPREADER STOKER FIRED BOILER

Gerald H. Degler  
Carlton C. Wiles

## ABSTRACT

As a resource recovery alternative, the use of refuse-derived fuel (dRDF) is being investigated as a substitute for coal in industrial spreader stoker boilers. Experiences are summarized from the combustion testing of 1/2-inch-diameter pellets using a modified animal pellet mill. Storage and handling experiences are also discussed.

Approximately 1800 MG of dRDF have been burned in a spreader stoker equipped boiler. The first phase of the combustion tests involved an evaluation of boiler performance and emission when firing at coal:dRDF blends of 1:0, 1:1, 1:2, and 0:1. A total 245 Mg of 1/2-inch-diameter by 3/4-inch-long pellets were consumed during these tests. The second phase of the combustion tests involved the combustion of 1555 Mg of pellets. Results are presented primarily from the Phase 1 test. Results from the Phase 2 test will be available in the near future.

## INTRODUCTION

Densified refuse-derived fuel (dRDF) is considered one of the more marketable products recovered from municipal solid waste. When densified in the form of pellets, cubettes, or briquettes, it can be easily handled, transported, and blended with coal and burned in existing stoker fired boilers without major equipment modification.

As a result of previous encouraging coal:dRDF tests, the U.S. Environmental Protection Agency sponsored a technical and environmental evaluation of co-firing tests conducted at the Maryland Correctional Institute (MCI) power plant in Hagerstown, Maryland, and at the General Electric Plant in Erie, Pennsylvania. The dRDF used in these tests were pellets prepared by the National Center for Resource Recovery (NCRR) and Teledyne under parallel contracts. The following discussion presents the results from the Phase 1 test.

## TEST OBJECTIVE

The objective of the study was to determine, characterize, and demonstrate the technical, economic, and environmental feasibility of combusting dRDF with coal in spreader stoker-fired boilers. The study was to specifically address the fuel handling, boiler performance, and environmental effects when dRDF pellets, cubettes, and briquettes were fired with coal in boilers rated at 11,300 to 90,400 kg/hr.

## SITE SELECTION

The Phase 1 testing was conducted at the State of Maryland Correctional Institute for Men, located near Hagerstown, Maryland. The boiler plant consists of a battery of three saturated steam 150-psig Erie City boilers.

The testing was carried out on two Erie City boilers rated at 27,200 and 35,600 kg/hr (60,000 and 78,500 lb/hr). The boilers were equipped with Hoffman Combustion Engineering "under throw" spreader stokers, vibrating grates with front ash discharge. The Erie City boilers are a tube-and-tile construction composed of wide-spaced nominal 3 1/4-inch-diameter tubes that were later partially embedded in refractory to approximately 8 ft above the grate. The gases are exhausted from the furnace through a two-drum boiler

bank, consisting of rows of 2 1/4-inch-diameter tubes, with two gas passes. The flue gases are cleaned in a two-stage multicyclone collector. The fly ash gathered in the first-stage collector is reinjected into the boiler to complete combustion of the fly char, and the fly ash in the second-stage collector is pneumatically transported to disposal. The cleaned gases are induced through a centrifugal fan and exhausted to a common breaching and stack.

#### TEST DESIGN

The test design called for the combustion of 258.5 Mg (285 tons) of dRDF during 236 hours of firing various blend ratios of coal:dRDF. These tests were conducted in a series of burns with volumetric coal:dRDF ratios of 1:1, 1:2, and 0:1 and with test durations ranging from 20 minutes to 132 hours. Each coal:dRDF test was preceded and followed by a coal-only test with duplicate conditions. The field tests involved a comprehensive study of (1) the material handling characteristics of dRDF, i.e., storage, conveying, feeding out of bunkers, etc.; (2) boiler performance, i.e., grate speeds, underfire and overfire air requirements, steam production, spreader limitations, boiler efficiency, flame impingement, slagging, fouling, clinkering, combustion gas analysis, etc.; and (3) environmental performance, i.e., particulates, gaseous emissions, and trace organic and inorganic emissions.

Since only pelletized dRDF was available, testing with cubettes and briquettes was not conducted. Also, because of insufficient plant steam demand, most of the testing had to be conducted at 30 to 55 percent boiler loads.

#### TEST RESULTS

Material Handling. Throughout the 6 months of field testing, 258.5 Mg (285 tons) of dRDF were received, stored, and conveyed to the boiler without major difficulty or malfunction. At successive periods, the pellets were stored in tarpaulin-covered 20-yd<sup>3</sup> drop boxes, in a warehouse, and on an outdoor concrete slab.

Drop Boxes--Since the pellets were received in covered drop boxes during the winter, they tended to steam and eventually freeze into a solid mass. Minimal rodding, however, broke the mass into blocks, and subsequent handling further reduced the blocks to individual pellets.

Warehouse and Open Slab--Approximately 125 Mg (140 tons) of pellets were stored in an unheated warehouse for 2 months. With the exception of mild offensive odors and some fungus growth, this storage proved to be the most effective in maintaining pellet integrity over extended periods of storage time. Since the depth of the piles was limited to 1.8 m (6 ft), increases in temperature due to composting effects were negligible, and the pile stabilized at 60°C (140°F). The pellets stored in the warehouse were subsequently moved to an outdoor storage area. The pellets were stored in 1.8-m (6-ft) piles on an outdoor slab and covered with a tarpaulin. Moisture accumulation under the tarpaulin caused pellets at the top of the piles to deteriorate and cake. Also, some pellets sustained minor damage, i.e., swelling and roughened edges, because of water infiltration due to poor drainage.

Pellet Feeding--The pellets were conveyed to the boiler feed hopper by a temporary fuel blending and handling system. The coal and dRDF were volumetrically blended in the various ratios by separately feeding coal and pellets from two hoppers to a common bucket elevator which subsequently conveyed both coal and pellets to a weigh lorry. The fuels were accurately blended by filling the feed conveyors to capacity (level with the conveyor

flights) and operating the feed conveyors at speeds commensurate with the desired blend ratio. Although this feeding system generally worked well, it had some difficulties with deteriorated pellets. As the amount of fines increased, the pellets would not flow from the feed hoppers without rodding. These fines also caused considerable dusting throughout the plant. This dusting was subsequently controlled by installing a steam jet at the conveyor transfer point.

**Pellet Properties**--The 1/2- x 3/4-inch pellets had an average bulk density of 425 kg/m<sup>3</sup> (26.5 lb/ft<sup>3</sup>) and ranged from 400 to 466 kg/m<sup>3</sup> (25 to 29 lb/ft<sup>3</sup>). The material density for intact pellets ranged from 1.22 to 1.34 g/cm<sup>3</sup> while that for deteriorated pellets averaged 0.98 g/cm<sup>3</sup>. The as-received properties were 12.10 to 15.12 MJ/kg (5200 to 6500 Btu/lb), 20 to 29 percent ash, 9 to 10 percent fixed carbon, 12 to 13 percent moisture, 50 to 57 percent volatiles, and 1142°C to 1152°C (2088° to 2105°F) hemispheric fusion temperatures.

**Boiler Performance.** **Feeder Performance**--The 1/2- x 3/4-inch pellets generally handled and fed well with the larger pellets traveling to the rear of the grate and the fines falling close to the spreader. During the initial combustion tests with 100 percent pellets, the spreader had to be adjusted to decrease the pellet trajectory by approximately 0.3 m (12 in.). In addition, due to volumetric feeding capacity limitations, the maximum load that the boiler could carry was 24,500 kg/hr (54,000 lb/hr) or 70 percent of rating.

**Combustion of dRDF**--The combustion of the various coal:dRDF blends was generally as good as the combustion of coal only. However, when the dRDF substitution was increased, the height, intensity, volume, and violence of the fireball increased correspondingly.

When test firing the 1:1 blend and 100 percent dRDF, the fireball was kept well away from the walls of the furnace by adjusting the overfire air. Once these jets were adjusted for minimum smoke and maximum efficiency for coal-only burning, they continued to meet the mixing and wall protection requirements when burning blends and 100 percent pellets. As viewed from the side of the furnace when firing both pellets and blends, the bed was well burned out by the time it approached the front ash pit. The flame pattern above the grate indicated that the fuel bed was maintaining proper porosity and that the combustion was good. With little attempt to optimize the system, a 10 to 12 percent carbon dioxide content in the flue gas at the boiler outlet was readily obtained.

**Fouling**--An increase in the flue gas temperature as the boiler test progressed indicated that the heat transfer sections had fouled somewhat. Inspection of the furnace interior after the tests revealed that a light coating of ash had accumulated on the tubes. Also, an interim boiler inspection revealed that one-third of the rear wall of the boiler was covered with slag. This slagging was subsequently eliminated when a spreader was adjusted to prevent pellet impingement on the rear wall. Subsequent inspections of the boiler after its being on-line for 8 days revealed that the slag had sloughed off.

**Clinkering**--During the initial tests, frequent clinkering occurred on the grate when firing a 1:1 blend. This clinkering was subsequently attributed to a low hemispheric fusion temperature, 1204°C (2200°F), of the coal. When the coal was changed to another coal having a higher fusion temperature,

1373°C (2500°F), the clinkering stopped. While coal with low fusion temperatures clinkered, the 100 percent pellets, which had a low fusion temperature of 1151°C (2103°F), did not clinker.

Corrosion--Eight clamp-on corrosion test specimens were installed on the down-comers of the rear screen wall 1.52 m (5 ft) above the fuel bed. After 478 hours of exposure to various blend and coal-only firings, normal wastage was evident on all specimens except the 1018 specimen. This test specimen, which had extremely high wastage, was mounted in the area where the heavy slagging occurred because of the maladjusted spreader.

Boiler Operation. Air Flow Controllers--During load shreds, the fuel bed was more susceptible to clinkering when coal:dRDF blends were fired. The clinkering was eliminated by biasing the underfire air control to supply approximately 70 percent excess air to the fuel bed. Reducing the ash content of the pellets to 10 to 12 percent should eliminate all clinkering problems and corresponding biasing of air controls.

Grate Dwell-Shake--Throughout the test, the duration and amplitude of the grate shake pulse was adjusted to advance the fire line at the rear of the boiler approximately 15.2 cm (6 in.) per excitation. In all advances, the pulse frequency was the principal controlling variable. At 40 percent load, the frequency of the pulse decreased from 11 minutes for 100 percent coal to 3 minutes for 100 percent pellets. When firing a blend, the pulse duration tended to increase because the bulk density of the blend ash was less than that of the coal ash.

Ash Handling--The sieve analysis of bottom ash samples taken during coal-only, blend, and pellet-only firings indicated that conventional pneumatic ash handling systems can handle the bottom ash from blend firings as well as they do the bottom ash from coal-only firings. On a few occasions fire occurred in the ash pit during blend firing. Rodding of the clinkers revealed that the ash had a soft, pliable consistency. Under similar conditions, when firing coal only, the bottom ash was much easier to break up by rodding. The bottom ash removal system malfunctioned only during 100 percent pellet firing. The bottom ash was so fine that it would not de-entrain properly in the cyclone. These particles, which had been wetted by the steam in the ejector, passed through the throat of the cyclone and eventually plugged the ejector.

As dRDF was substituted for coal, the ash distribution became finer. The size of the collector particles ranged from 200 micrometers for 100 percent coal firing to 90 micrometers (sizes at the 50th percentile) for 100 percent pellet firing. Also, the carbon content of the fly ash decreased significantly with increasing dRDF substitution.

Mass Balance--The mass balance indicated that an unusually large amount of the fuel ash had accumulated in the collectors. Subsequent analysis of the collector fly ash revealed that the high collector ash weights were due to the presence of 50 to 70 percent carbon in the ash and that 90 percent of the particles were greater than 50 micrometers in diameter. The carbon content of the bottom ash was 2 to 10 percent, and the carbon content of the fly ash was 30 to 40 percent. The analysis of the fly ash as a function of blend revealed that its carbon content decreased as the dRDF substitution increased.

Efficiencies--During the testing, the boiler efficiencies were extremely low, namely 52 to 60 percent. These low efficiencies were primarily due to the low boiler loads (less than 30 percent of rating) and extremely high



losses (up to 25 percent) of combustibles in the refuse. The analysis of the results indicated that the coal-only and blend firing efficiencies had no discernable differences. However, this fact is unique to the boiler installation at MCI since the large amount of unburned combustibles removed by the collectors is certainly an anomaly to expected boiler performance. Tables 1 and 2 present the results of the mass and energy balances.

TABLE 1. HEAT BALANCE SUMMARY

Blend PARAMETER	1:0	As Received		0:1
		1:1	1:2	
Fraction of Rating	.17	.33	.30	.19
Excess Air(%)	104	82	99	113
<u>LOSSES</u>				
Dry Gas	17.9	13.7	17.8	19.4
Fuel Moisture	.1	.9	1.2	4.0
H <sub>2</sub> O for H <sub>2</sub> Combustion	4.0	5.1	5.4	8.1
Combustibles in Refuse	18.3	25.3	16.6	3.0
Radiation	3.7	1.8	1.8	3.7
Unmeasured	1.5	1.5	1.5	1.5
TOTAL	45.5	48.3	44.1	39.7
EFFICIENCY	54.5	51.7	55.9	60.3

TABLE 2. ASH MASS BALANCE

Blend	Fuel Flow Kg/hr	% Ash in Fuel	Ash in Fuel Kg/hr	Bottom Ash Kg/hr		Fly Ash Kg/hr		Collector* Kg/hr	
				Carbon Free	With Carbon	Carbon Free	With Carbon	Carbon Free	With Carbon
Coal:dRDF									
1:0	872	21.9	191	82	89	5	7.7	104	219
1:1	1489	23.3	347	232	238	5	6.8	110	369
1:2	2035	23.4	476	324	341	7	10.2	145	300

\*Note: The collector weight was determined by difference.

Particulate Emissions. Mass Flux--The particulate mass flux in the 1:1 and 1:2 blend firings was slightly less than the flux in the coal-only firing. However, the reductions were not significant at the 90 percent confidence level. The mass flux at a 40 percent boiler load for 1:1 and 1:2 blend firings was 0.5 g/Nm<sup>3</sup>.

Particulate Size--As more dRDF was substituted for coal, the particulate diameter decreased. In the May tests the diameters for the coal-only firings were 3 micrometers and those for the dRDF-only firings were 0.8 micrometer (at the 50 percentile point).

Particulate Resistivity--Because of the unusually high carbon content in the fly ash during the coal-only firing, the resistivity was generally less than 10<sup>6</sup> ohm-cm. As dRDF was substituted for coal, the carbon burnout in the fly ash improved and the resistivity increased to 2 × 10<sup>10</sup> ohm-cm for the 1:1 blend firing.

Opacity--As dRDF was substituted for coal, the overall opacity of the plume reduced significantly. At 40 percent boiler load, the opacity for coal-only

firing was 16 percent (based on a 1.22 m (4 ft) diameter stack). At the same boiler load, the opacity dropped to 10 percent for dRDF-only firing.

Gaseous Emissions. SO<sub>2</sub>--Since the dRDF had a sulfur content of 0.6 percent, the SO<sub>2</sub> emissions reduced with increasing dRDF substitution. The decrease was particularly significant for the 1:2 and 0:1 (100 percent dRDF) blend firings. At 40 percent boiler load, the SO<sub>2</sub> dropped from 1300 ppm for coal-only firing to 250 ppm for dRDF-only firing.

NO<sub>x</sub>--There were no significant changes in NO<sub>x</sub> as dRDF was substituted for coal. At 40 percent boiler load, the NO<sub>x</sub> concentrations ranged from 200 to 350 ppm.

Chlorine--As dRDF was substituted for coal, the chlorine in the emissions increased from 60 ppm for coal-only firing to 650 ppm for dRDF-only firing. As the boiler loads changed, the chlorine concentrations differed negligibly.

Fluorine--Fluorine concentrations also increased with increasing dRDF substitution. However, the concentrations were very low, e.g., 8 ppm for coal-only firing and 12 ppm for dRDF-only firing at a 40 percent boiler load.

Hydrocarbons--There were no significant changes in hydrocarbon emissions when substituting dRDF for coal. At a 40 percent boiler load, the total hydrocarbons ranged from 10 to 25 ppm. As the boiler load increased, the hydrocarbon concentrations decreased significantly.

Organic Emissions--The overall emissions of polycyclic compounds for coal-only and blend firings were well below the threshold limits proposed by the National Academy of Science.

Inorganic Emissions--The analysis of the fly ash for trace metals revealed that relative to coal-only firing the blend firing enriched some metals but reduced others. For example, 34 times more lead was emitted when firing the 1:2 blend than when firing coal only. While dRDF was the main contributor of Br, Mn, Pb, and Sb, coal was the primary source of As, Ni, and V.

Several elements, particularly As, Ga, Na, and Sb, tended to concentrate in small particles. In addition, as the dRDF substitution increased, both the solubility of the fly and the amount of small-size particulates in the respiratory range increased. Consequently, the combined effects of the foregoing pose a potential hazard to respiration and landfills.

#### SUMMARY

The preliminary results from these field tests indicate that coal and dRDF can be co-fired at volumetric coal:dRDF ratios up to 1:2 with only minor adjustments to the boiler and fuel handling systems. The Phase 2 testing, which involved co-firing 1555 Mg of pellets at boiler loads of 40, 75, and 100 percent and coal:dRDF volumetric blends of 1:1, 1:2, and 1:4 have been completed. The tests were conducted in a Babcock and Wilcox spreader stoker fired boiler rated at 68,000 kg/hr (150,000 lb/hr), 4312 PA (625 psi), and 440°C (825°F). Emissions tests were carried out to determine the effects of blend firing on electrostatic precipitator performance with and without fly ash injection. Results from this evaluation will be available in the near future. The long-term effects of corrosion and erosion on boiler tubes when firing blends of coal:dRDF remains to be determined.

CO-FIRING FLUFF RDF AND COAL IN A CEMENT KILN

Cliff R. Willey  
Maryland Environmental Service  
Maryland Department of Natural Resources  
60 West Street  
Annapolis, MD 21401

Prepared for the Conference  
"Waste-to-Energy Update 1980"  
Cincinnati, OH  
April 15-16, 1980

## Co-Firing Fluff RDF and Coal in a Cement Kiln

Cliff R. Wiley

Fluff RDF from the Baltimore County, Maryland Resource Recovery Facility was successfully tested as a supplemental fuel with pulverized coal at the Lehigh Portland Cement Company, Union Bridge, Maryland. A total of 1400 tons of RDF was burned in a 700 ton-per-day (clinker capacity) rotary kiln, contributing 30 percent of the kiln heat. There were four days of preliminary RDF burns followed by a 27-day extended period of which 20 days involved burning RDF. Tests included air emissions, cement quality and chemistry, RDF characteristics, and checks on kiln operation.

Satisfactory Type I cement clinker was produced during most tests. Evidence of reducing conditions on the kiln bed due to incomplete burning of RDF in suspension was detected during initial tests; this problem, however, was quickly corrected by increasing RDF velocity into the kiln. Finely shredded RDF (roughly 95 percent less than one-inch size) was required to guarantee suspension burning. The average heat value of the RDF during the tests was approximately 6,500 BTU per pound. No adjustment in kiln raw materials feed was required when burning RDF.

In general, particulate and chloride emissions were higher during RDF burning, and  $\text{NO}_x$  lower. Equipment configuration was such that only stack emissions could be measured; therefore, the effect of burning RDF on kiln emissions, versus effect on electrostatic precipitator efficiency, could not be determined. After several days of burning RDF, some difficulty was experienced in removing ash and cement dust from collectors in the electrostatic precipitator; it was conjectured that this problem was caused by a decrease in the resistivity of airborne particles. The problem, however, was not considered serious as adjustments in the precipitator operation could be made to correct this situation.

## INTRODUCTION AND OVERVIEW OF TEST PROGRAM

In early 1975, during the construction phase of the Baltimore County Resource Recovery Facility (a joint venture of the Maryland Environmental Service<sup>1/</sup> and Baltimore County), Teledyne National, the project's prime contractor, held discussions with more than 30 industrial firms, institutions, and State organizations regarding their interest in burning RDF to be produced at the Facility. As a result of this survey, letters of interest were received from a number of potential users of RDF, three of whom were cement companies. Of the three cement companies, attention was directed to the Lehigh Portland Cement Company<sup>2/</sup> Union Bridge, Maryland, because of its large coal use (500 tons per day), interest in a test program, and shortest distance (45 miles) from the Baltimore County Resource Recovery Facility.

In ensuing discussions with Lehigh it became apparent that, even though there was interest in burning RDF, there were also a number of justified areas of concern. These included:

- a. ability to supply and feed RDF continuously
- b. firing characteristics and ability to burn RDF in suspension
- c. effect of RDF chemical composition and variations in composition on cement quality and chemistry.
- d. long-term effects of RDF on kiln operation and cement production
- e. effect on air emissions

A test program was therefore developed to tackle these concerns step by step, as follows:

- (1) It was agreed that RDF would first be tested at a coal-fired, Lehigh-owned, lightweight shale kiln at Woodsboro, Maryland. The advantage of this test would be that experience could be gained with the

---

<sup>1/</sup> A non-profit, waste management utility - an agency of the State of Maryland

<sup>2/</sup> Now a division of Heidelberg Cement Inc.

burning characteristics of RDF and the reliability of RDF feed equipment without facing concerns about cement quality and production. As part of the test, it was also agreed that the feed equipment would provide seven days of continuous operation before permission would be given to begin tests at the cement plant.

- (2) Provided there was satisfaction with the light-weight aggregate test, RDF feed equipment would be set up at the Union Bridge cement plant to produce test quantities of cement for analysis (a 2 to 3 day test).
- (3) Again based on satisfaction with the previous step, an extended burn test involving air emission measurements would be run.

Step (1) was carried out in 1977 and 1978 and Steps (2) and (3) in March and November-December of 1979, respectively. This paper summarizes results of these tests.

The test program was carried out by Teledyne National under contract to the Maryland Environmental Service. Support for the program was received from grants to the Maryland Environmental Service by the U.S. Environmental Protection Agency and other sources, as recognized in the Acknowledgment of this paper.

#### THE CEMENT INDUSTRY

Cement manufacturing presents an attractive opportunity for energy recovery from solid waste via the RDF approach. It is energy intensive, consuming 457 trillion BTU per year<sup>(1)3/</sup> and it involves a process in which ash as well as other products of combustion become part of the final product, thus minimizing residues requiring disposal and need for costly additional air emission control equipment.

Duckett and Weiss<sup>(2)</sup> have reviewed the potential of this RDF market, reporting that of 157 U.S. plants, 65 would have a capacity for 210 to 380 tons of RDF per day, 29 a capacity for 380 to 540 tons per day and

---

<sup>3/</sup> Numbers in parentheses denote references.

20 plants, over 540 tons per day when burning RDF as 30 percent of their fuel supply, assuming 5500 BTU/lb. RDF and 300 operating days per year. In addition, they point out that 26 plants are located within 25 miles of major metropolitan areas. In spite of this attractiveness, progress towards the use of RDF in the cement industry has been tempered by industry caution on one side and a lack of test information on the other.

Cement manufacturing typically consists of the following steps:

- (1) grinding and mixing raw materials in wet or dry form (limestone, shale and/or clay, silicone oxide and iron bearing materials)
- (2) drying (primarily for the wet process)
- (3) calcining (to burn off carbon dioxide from limestone)
- (4) clinkering (or burning), a process that takes place at 2,400 to 2,800°F (1,300 to 1,500° C)
- (5) cooling, clinker grinding and addition of gypsum to retard setting time

Although most new cement plants use a more energy efficient preheated, dry-process system in which only step 4, clinkering, is carried out in the rotary kiln, 80 percent of existing plants still perform steps 2 through 4 in the rotary kiln(1). In this process, Steps 2, 3 and 4 occur in succession as raw materials from Step 1 are placed in one end of the kiln and travel counter to the flow of heat and gases from fuel burned at the opposite end. The process requires careful control of both temperature and composition, which is adjusted to account for the ash of fuels used to fire the kiln.

At the end of 1978, 63 percent of cement was produced with coal or coke-fired plants, 20 percent with natural gas, and the remainder with other energy sources. The trend in cement production is towards coal-fired plants (1).

## TEST KILN

The Lehigh Portland Cement Company Union Bridge plant operates four parallel 400-ft. (121-m), 11-1/2-ft. (3.5-m) diameter, dry-process kilns, each rated at 700 tons per day capacity clinker production. The No. 4 kiln was selected as the test kiln. Characteristics of the kiln are as follows:

- a) kiln inclination - 5/8-inch (1.6-cm) per linear feet;
- b) rotation - 65 to 85 rph;
- c) fuel - bituminous Pennsylvania-type coal (12,000 BTU/lb. and 2-1/2 - 3 percent sulfur);
- d) fuel input - 6 tons per hour at 28 - 30 tons/hr. product throughput;
- e) reaction (burning) zone temperature - about 2,700°F (1,480°C).

Air pollution control equipment on the test kiln (No. 4) consists of two parallel Buell electrostatic precipitators (ESP). Total flow rate through the dual unit is 120,000 ACFM at 650°F (340°C). Approximately 95 percent of the ESP collected particles (ash and raw material dust) is reinjected back into the kiln. The precipitators exhaust to a common stack.

Raw material feed to the kiln consists of approximately 90 percent limestone, 10 percent shale, and small amounts of sand and iron bearing materials.

To inject RDF into the test kiln, Lehigh placed a second nozzle extending 11 feet (3.4 m) into the kiln, parallel to and under the coal nozzle. Placement above the coal nozzle would have increased RDF suspension time, but kiln design prevented this arrangement. RDF was conveyed to the nozzle pneumatically with about 3,200 ASCFM air at 30 percent RDF kiln heat contribution.



## BALTIMORE COUNTY RESOURCE RECOVERY FACILITY AND RDF FEED STATION

Figure 1 shows the fluff RDF process line of the Baltimore County facility as it now exists. Additional details on the facility and other recovered materials are found in References 3, 4 and 5. Daily average input to the facility is 750 tons residential solid waste per day. The RDF production line has a capacity to produce about 300 tons per day RDF under normal operating hours (10 hour day).

The 800 hp Williams secondary shredder was installed in October of 1979; prior to that, secondary shredding was done with a 350 hp Grundler horizontal hammermill. Approximate particle size distribution of RDF for each of the shredders is given in Table 1. (This will change somewhat with hammer wear and solid waste characteristics.) The Grundler was fitted with a 1-inch round hole grate.

---

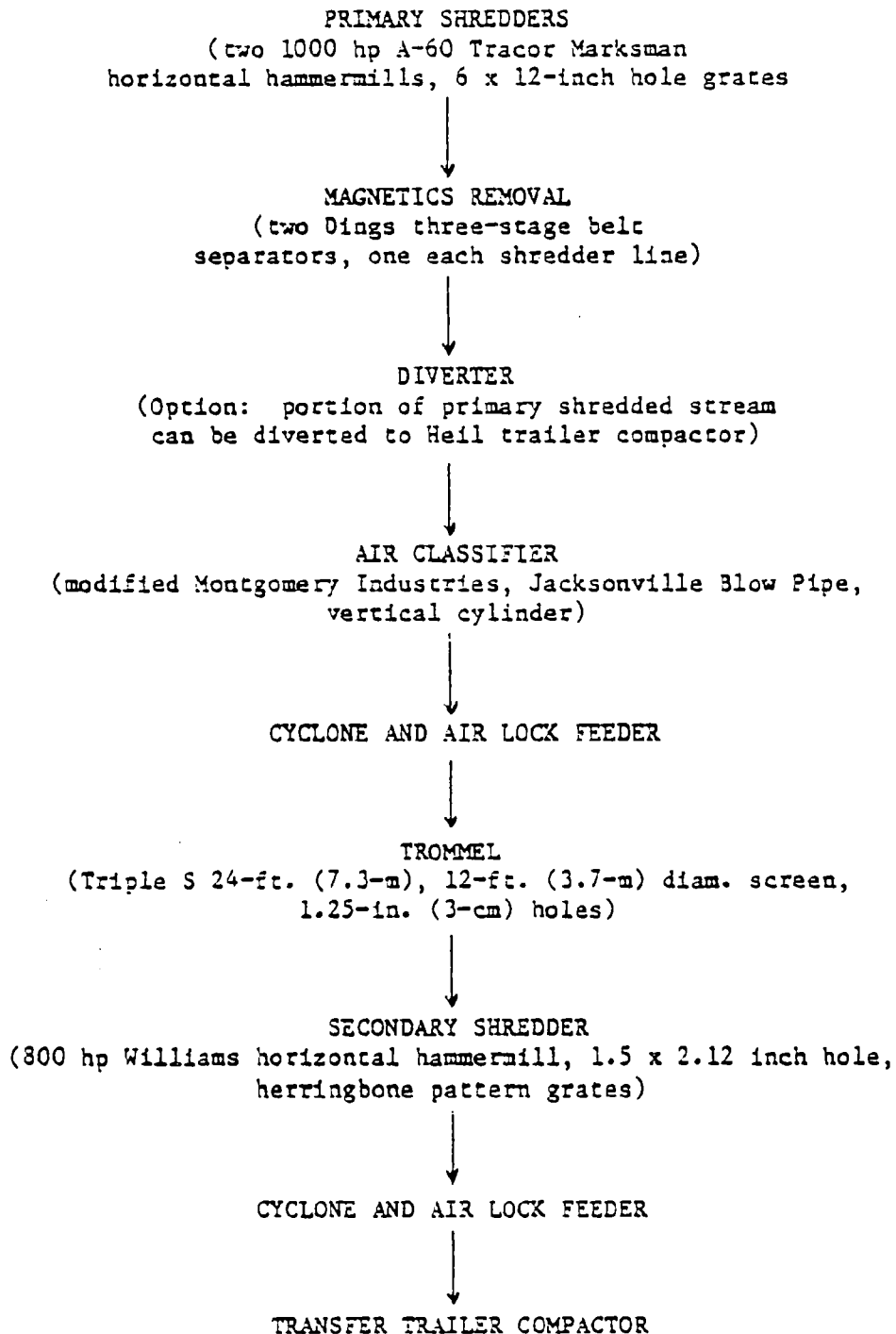
TABLE 1. RDF PARTICLE SIZE (NEW HAMMERS)

Screen Size		% Passing	
inch	centimeter	Grundler	Williams
3	7.6	100	99
2	5.0	100	98.5
1	2.5	95	94
1/2	1.3	51	84
3/8	1.0	17	57

---

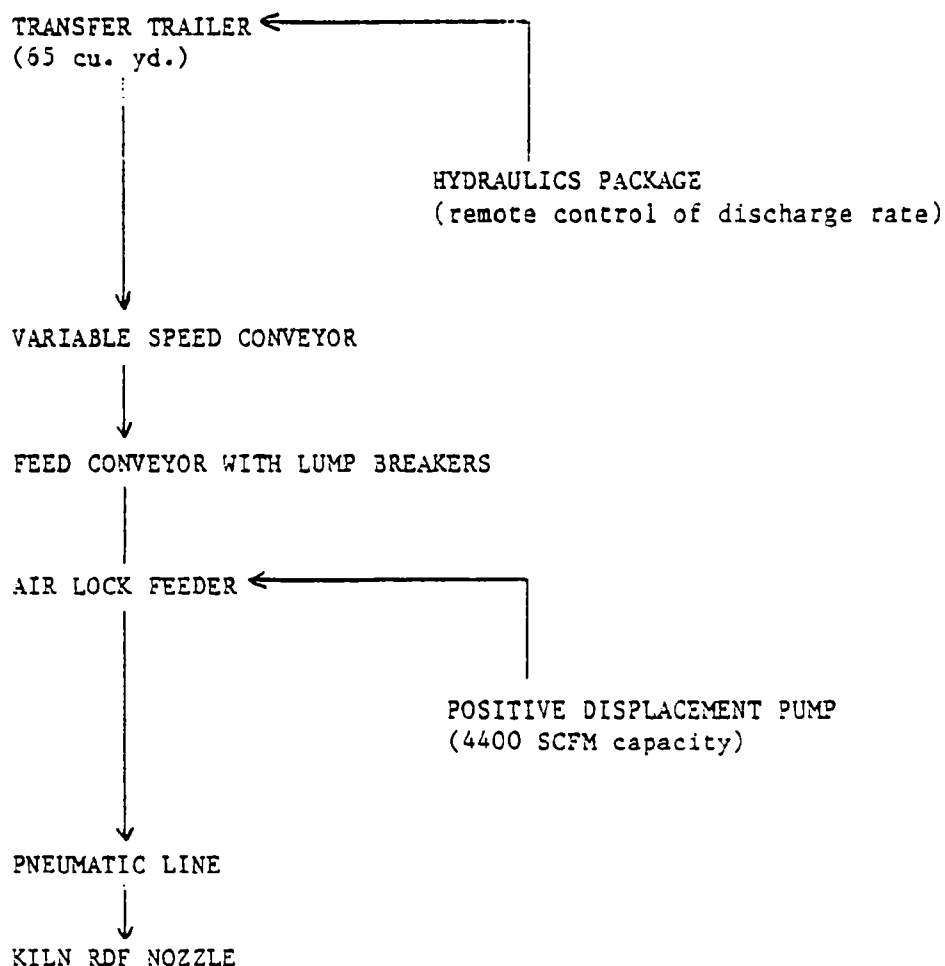
In connection with the cement kiln tests, an evaluation was done of secondary shredding to enhance RDF as a fuel for cement kilns; this work is discussed in Reference 6.

FIGURE 1. PROCESS FLOW FOR RDF PREPARATION - BALTIMORE COUNTY FACILITY



As part of a market development program associated with the Baltimore County project, a modular, transportable RDF feed system was constructed for receiving and pneumatically conveying RDF to various potential users. Figure 2 outlines components of this system as modified for the cement kiln tests. RDF is delivered in 65 cubic yard transfer trailers from the Baltimore recovery facility and hydraulically metered into the RDF feed system. Feed rates are controlled at the RDF feed module.

FIGURE 2. RDF FEED STATION



## LIGHT AGGREGATE KILN TESTS

Prior to conducting current kiln tests, the reliability of RDF feed equipment and burn characteristics of the RDF were demonstrated for Lehigh at a nearby plant producing a lightweight aggregate from shale. The advantage to this was that it was unlikely RDF would affect the quality of the aggregate.

At this plant, shale is heated and expanded in two 10-foot-diameter, pulverized coal-fired rotary kilns. A nozzle to inject RDF was added to one kiln, next to the coal nozzle, and was connected via pipe to the feed station set up outside, next to the kiln.

During February and March of 1977, 217 tons of RDF were burned intermittently. Although there were initial problems with temperature readings and shale buildup on the kiln wall, called "rings," these were overcome by adjustments in the RDF nozzle position and in the kiln controls. It was apparent in these tests that rather finely shredded RDF would probably be necessary to prevent the burning of RDF directly on the kiln bed (grate sizes 4 to 1/2-in. were tried).

The RDF feed system (which differed from that in Figure 2 in that secondary shredding was carried out at the kiln site, with RDF being aspirated from the shredder and blown into the kiln through a 12,000 CFM fan) did not prove reliable. Problems encountered were severe shredder hammer wear and maintenance, jamming, uneven feed rates, and excess air being blown into the kiln. Because of the inability to feed RDF satisfactorily with this system, modifications were made to the feed system, bringing it into the configuration shown in Figure 2.

In October of 1978, using the modified equipment, tests were run again at the kiln, sustaining an average RDF feed rate of 1.13 tons per hour, earning the permission of Lehigh to move the RDF feed station to the Union Bridge cement plant.

## PRELIMINARY CEMENT KILN TESTS

The object of this test was to produce initial quantities of cement clinker for analysis by Lehigh and by the Portland Cement Association and to make any necessary RDF feed equipment adjustments. Tests were run March 6 to March 9, 1979 and on April 26, 1979.

During the first test, 123 tons of RDF and 215 tons of coal were burned in 55 hours of operation. The average heat contribution of the RDF during this period was 24.7 percent. Cement clinker was sampled at 0, 10 and 30 percent RDF heat substitution.

During the tests, 13 transfer trailer loads of RDF were used. As each truck was unloaded, a composite sample was taken for analysis for heat value, percent moisture, and percent ash, according to ASTM procedures D2015-71, D3302-74, and D3174-73, respectively. Results of these tests are listed in Table 2.

---

TABLE 2. CHARACTERISTICS OF RDF - PRELIMINARY TEST

<u>Characteristic and Unit</u>	<u>Average Values<sup>a</sup>/</u>	<u>Low</u>	<u>High</u>
Heat Value, BTU/lb.	6897	5963	7832
Moisture, %	18.2	12.1	25.2
Ash, %	9.7	6.8	15.1
Metallic Aluminum, %	0.018	<0.01	0.04
Sulfur, %	0.19	--	--

<sup>a</sup>/Arithmetic average of 13 RDF samples except sulfur, which was run on a composite of all samples

---

Samples of clinker and cement were analyzed by PCA by x-ray fluorescence, x-ray diffraction, microscopic observation, and standard ASTM C-130 cement tests. Partial data are included as Table 3 for

reference by those familiar with cement chemistry and tests. From the analysis, PCA developed the following conclusions:

"The amounts of heavy metals found in the clinker were very low and it does not appear that these elements will cause problems in practice. No certain estimate of metallic aluminum could be made, but it seems likely that its concentration was negligible. The RDF clinkers were of poor quality, mainly because of poor control in the burning zone of the kiln. The burning zone should always be maintained in an oxidizing state (at least 1 percent excess oxygen) and none of the RDF should be allowed to fall into the clinker before being thoroughly burned. If the burning conditions are improved, it seems to us that good quality clinker will result."

---

TABLE 3. CEMENT CHARACTERISTICS FROM PRELIMINARY RDF TEST

<u>Characteristics</u>	<u>PERCENT RDF</u>		
	<u>0</u>	<u>10</u>	<u>30</u>
Compressive Strength			
3-day	3820	3620	4000
7-day	4650	4830	4870
28-day	5920	6200	5800
K <sub>2</sub> O	0.69	0.72	0.90
Na <sub>2</sub> O	0.06	0.11	0.14
Na <sub>2</sub> O Equiv.	0.51	0.58	0.73
Free CaO	2.14	1.13	0.95

---

Although kiln operators were pleased with the testing and overall control of RDF, there was concern about excess RDF burning on the kiln bed at the 30 percent rate, which caused reducing conditions, as noted in the PCA analysis. Because of this condition, nozzle size was reduced from 9 to 7 inches in diameter to increase RDF velocity and suspension time.

As a follow up to the previous test, a one-day run was made on April 26, in which 34.6 tons of RDF was burned. The smaller nozzle increased suspension time sufficiently to minimize RDF burning on the clinker bed. In addition to tests at 30 percent, short runs were made at 40 and 50 percent RDF heat contribution. At 40 percent, RDF also appeared to burn satisfactorily in suspension. However, at 50 percent there was dropout and flaming pieces on the bed and decreased visibility into the kiln. Since a few hours of operation is not enough to stabilize for clinker testing because of the slow redistribution of ash throughout the kiln and electrostatic precipitator system, no cement analysis was done.

Following these tests, permission was received from Lehigh to proceed with the extended cement kiln tests.

To allow time for installation of a larger shredder for secondary RDF shredding and for equipment repairs at Lehigh, not related to the tests but affecting them, further testing was deferred until the fall of 1979.

#### EXTENDED RDF CEMENT KILN TEST

This test was run November 27 to December 23, 1979, burning 1,272 tons of RDF for an average rate heat contribution of 30 percent (approximately 3.5 tons per hour). Average characteristics of RDF used in the tests are listed in Table 4. Table 5 summarizes coal usage and RDF heat input during this period. There were 20 days on which RDF was burned. During December 7 to 11 the kiln was on coal only for the emissions testing program.

TABLE 4. CHARACTERISTICS OF RDF - EXTENDED TEST

---

<u>Characteristics and Unit</u>	<u>Average Values <sup>a/</sup></u>	<u>Low</u>	<u>High</u>
Heat Value, BTU/lb.	6440	5067	8797
Moisture, %	20.4	6.7	39.0
Ash, %	11.8	6.4	27.7

---

a/ Arithmetic mean of 95 RDF samples

---

During December 5 through 14, the Environmental Engineering Division of the Energy System Group of TRW, Inc., conducted source emission tests to determine the amount of pollutants discharged from the electrostatic precipitator serving the test kiln. There were seven sample periods, four with RDF and three with coal only. Tests included flue gas flow rates and stack moisture determinations, particulate matter and sulfur oxides emissions, nitrogen oxides emissions, chlorides (as HCL) emissions, stationary gas analysis, and flue opacity readings. All sampling was conducted through four equally spaced openings located below the top of the stack. No sampling could be done prior to gases entering the electrostatic precipitator because of the design of the system.

Table 6 summarizes conditions during the emissions test, and Table 7 presents part of the test data. Because of electrostatic precipitator failure during the first test day, December 5, that day's data have been omitted.

During RDF burning, particulates were higher, chloride emissions increased, nitrous oxide emissions appeared lower, and, surprisingly, sulfur oxide emissions reached their highest levels, but remained well within Federal and State standards. Since the RDF, which is only 0.2% in sulfur, significantly lowered the overall sulfur content of the kiln



fuel, the increase must have been related to some other changing condition within the kiln or ESP. It was suggested that cleaning the ESP of dust, which adsorbs SO<sub>2</sub> and is recycled back into the kiln, prior to the tests, may have produced this effect.

As of the date of preparation of this paper, complete analysis of the cement is not available from PCA. However, we have been told by Lehigh that cement strength tests and other analysis so far show a satisfactory Type I cement was produced and indicate that the RDF fuel had no detrimental effects on the cement.

Although there was an initial concern by Lehigh that the raw material feed to the kiln would need adjustment to compensate for differences between the chemical composition of RDF/coal ash and the coal-only ash it replaced, this did not turn out to be the case. Therefore, to from coal-only to coal-plus-RDF firing required few operational changes.

---

TABLE 5. COAL AND RDF USAGE DURING NOVEMBER - DECEMBER TESTS

<u>Date</u>	<u>Coal Usage</u> Daily Totals (Tons)	<u>RDF Usage</u> Daily Totals (Tons)	Total Heat (Million BTU)	% Heat Contribution (RDF)
11-27	72.70	61.5	799.5	31.17
11-28	72.85	59.0	767.0	30.78
11-29	106.0	92.3	1199.9	32.35
11-30	42.55	31.8	413.4	29.10
12-1	105.95	74.2	964.6	27.78
12-2	99.10	68.5	890.5	27.51
12-4	87.35	63.0	819.0	28.37
12-5	106.00	82.2	1068.6	29.87
12-6	89.20	70.3	913.9	30.21
12-11*	30.80	20.5	266.5	25.96
12-12	32.60	26.7	347.1	30.14
12-13	105.30	91.5	1189.5	31.40
12-14	104.20	90.7	1179.1	31.43
12-15	105.95	90.7	1179.1	31.11
12-16	109.30	90.9	1181.7	30.46
12-17	103.85	74.1	963.3	27.32
12-18	84.55	63.2	821.6	28.25
12-19	43.85	41.7	542.1	33.37
12-20	26.15	25.5	331.5	33.93
12-23	44.50	53.7	698.1	38.6
<u>TOTAL</u>	<u>1721.4</u>	<u>1397.1</u>	<u>18,162.3</u>	<u>30.53</u>

\*Coal only for emissions testing 12-7 to 12-10

---

TABLE 6. OPERATING CONDITIONS AND FUEL FEED DURING EMISSIONS TEST RUNS

	TEST RUN NO.					
	2	3	4	5	6	7
Date	12/10	12/10	12/11	12/13	12/13	12/14
Test Time, start	0918	1211	0950	0840	1412	0801
end	1131	1426	1206	1049	1624	1026
Product Rate, ton/hr	29.2	29.4	28.9	25.1	27.1	29.2
Kiln, RPM	84	84	82	71	78	82
Coal Fuel Rate, #/hr	12,200	12,770	11,800	8,600	8,430	8,500
Coal Fuel Type*	R/H-V	H-V	H-V	H-V	H-V	H-V
RDF Fuel Rate, #/hr	0	0	0	7,209	9,366	7,963
% RDF by BTU Value	0	0	0	30.6	37.4	33.0
Kiln, Oxygen, %	3.2	2.8	2.6	3.0	2.3	3.0
Kiln End Water Spray (Gallons Per Minute)	26	26	23	31	34	30

\*R = Regular, H-V = High Volatile Coal

TABLE 7. CEMENT KILN EMISSIONS - CONDITIONS STATED IN TABLE 6

	TEST RUN					
	2	3	4	5	6	7
<u>Flue Gas</u>						
Temperature, °F	485	486	483	485	500	493
Flow rate, DSCFM	49,150	53,390	50,190	45,680	49,340	43,760
Water vapor, % by volume	15.05	14.60	13.47	19.32	19.33	20.95
Stack opacity, %	2.6	17.0	9.8	21.6	16.8	16.6
<u>Particulate Matter</u>						
Concentration, grain/DSCF	0.0128	0.0221	0.0331	0.0474	0.0801	0.0495
Emission rate, pounds per hour	5.38	10.12	14.26	18.56	33.83	18.56
<u>Chloride Emissions as HCl</u>						
HCl, ppm (dry)	7.47	191.	77.8	155.	223.	242.
, pounds per hour	2.09	58.0	22.2	40.3	62.6	60.2
<u>Sulfur Oxides Emissions</u>						
SO <sub>3</sub> , ppm (dry)	3.0	2.5	9.3	4.1	25.4	7.1
, pounds per hour	1.83	1.65	5.79	2.32	15.5	3.85
SO <sub>2</sub> , ppm (dry)	19.7	34.3	235	1,050.	353.	444.
, pounds per hour	9.65	18.3	118.	478.	174.	194.
<u>Nitrogen Oxides Emissions (as NO<sub>2</sub>)</u>						
NO <sub>x</sub> , ppm (dry)	135	295	112	72	130	160
, pounds per hour	47.6	113.	40.3	23.6	46.0	50.2
<u>Stationary Gas Analysis (dry)</u>						
CO <sub>2</sub> , %	10.7	10.1	14.2	11.4	11.6	12.6
O <sub>2</sub> , %	13.8	13.6	9.9	11.1	11.5	11.9
CO, %	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
N <sub>2</sub> , % by difference	75.5	76.3	75.9	77.5	76.9	75.5

## CONCLUSION

RDF proved to be an adequate fuel for firing with coal in a rotary cement kiln at rates of up to at least 30 percent heat contribution. No detrimental effects on the cement quality were noted once proper suspension burning of the RDF was accomplished. Compression test strengths were generally the same or higher when RDF was burned.

## ACKNOWLEDGMENT

This work was supported by the U.S. Environmental Protection Agency, Grant S-804786, "Marketing Refuse Derived Fuel," Office of Water and Hazardous Materials, Washington, DC, and Grant R-805613, "Refuse Derived Fuel as a Supplemental Fuel in Cement Kilns," Office of Research and Development, MERL and IERL, Cincinnati, OH, Mr. Robert Olexsey, Project Officer.

Significant contributions to the project also were made by the Lehigh Portland Cement Company, Teledyne National, and the Portland Cement Association.

The author wishes to thank Teledyne and Lehigh for their review and helpful comments in the preparation of this paper.

Air emission tests were performed by TRW, Environmental Engineering Division, Research Triangle Park, NC; RDF and coal analysis was performed by Penniman and Browne, Inc., Baltimore, MD.

## REFERENCES

- 1 Portland Cement Association, "1978 Energy Report U.S. Portland Cement Industry," Skokie, IL 60077.
- 2 Duckett, E.J., and Weiss, D., "The Use of RDF as a Kiln Fuel." In press for ASME National Solid Waste Processing Conference, Washington, DC, May 11-14, 1980.
- 3 Willey, C.R., and Bassin, M., "The Maryland Environmental Service/Baltimore County Resource Recovery Facility," Proceedings of the Sixth Mineral Waste Utilization Symposium, Chicago, IL, 1978, pp. 281-285.

- 4 Bendersky, D. and Simster, B., "Research and Evaluation of Solid Waste Processing Equipment," Municipal Solid Waste: Resource Recovery, Proceedings of the Fifth Annual Research Symposium, Orlando, FL, 1979, pp. 77-85.
- 5 Savage, G.M., et. al., "Evaluation and Performance of Hammermill Shredders Used in Refuse Processing," Municipal Solid Waste: Resource Recovery, Proceedings of the Fifth Annual Research Symposium, Orlando, FL, 1979, pp. 86-98.
- 6 Weinberger, C.S., "Evaluation of Secondary Shredding to Enhance RDF Production as Fuel for Cement Kilns - A Research Test," In press for ASME National Solid Waste Processing Conference, Washington, DC, May 11-14, 1980.

# STEAM PYROLYSIS OF ORGANIC WASTES AS A SOURCE OF CHEMICALS AND INDUSTRIAL FEEDSTOCKS

by

Michael J. Antal Jr.  
Department of Mechanical and Aerospace Engineering  
Princeton University  
Princeton, New Jersey 08540

## INTRODUCTION

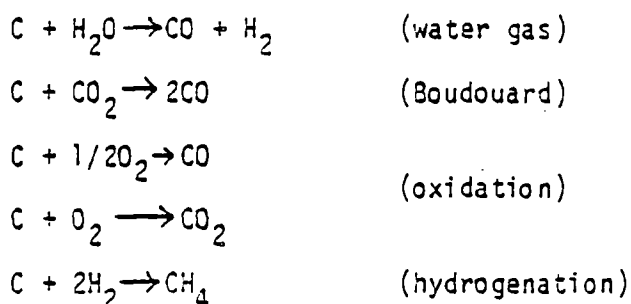
Recently completed research at Princeton University and elsewhere (1-4) has shown biomass gasification to be a three step process:

1. Solid Phase Pyrolysis. At modest heating rates ( $1^{\circ}\text{C}/\text{min}$  to  $100^{\circ}\text{C}/\text{min}$ ) biomass materials lose between 70% and 90% of their weight by pyrolysis, forming gaseous volatile matter and solid char. This weight loss occurs at temperatures below  $500^{\circ}\text{C}$ . As discussed later, very high heating rates enhance volatile matter production at the expense of char formation. Recent Princeton publications review mechanistic and kinetic research on cellulose (5), lignin(6), and wood (7) pyrolysis in more detail.

2. Gas Phase Cracking/Reforming of the Volatile Matter. At somewhat higher temperatures ( $600^{\circ}\text{C}$  or more) the volatile matter evolved by the pyrolysis reactions (step 1) reacts in the absence of oxygen to form a hydrocarbon rich synthesis gas. These gas phase reactions happen very

rapidly (seconds or less) and can be manipulated to favor the formation of various hydrocarbons (such as ethylene). Rates and products of the cracking reactions for volatile matter derived from cellulose, lignin, and wood are now becoming available in the literature (1, 3, 6, 7).

3. Char Gasification. At even higher temperatures char gasification occurs by the water gas and Boudouard reactions, and simple oxidation and hydrogenation:



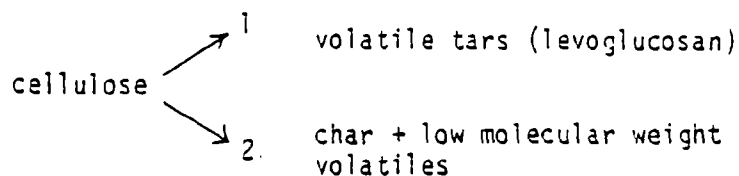
Because pyrolysis (step 1) produces less than 30% by weight char for most biomass materials, the char gasification reactions (step 3) play a less important role in biomass gasification than steps 1 and 2. This contrasts with coal gasification, where char gasification plays a much more important role because most coals contain less than 40% by weight volatile matter.

The following sections discuss steps 1 and 2 of the gasification process. This discussion assumes no free oxygen to be present in the gasification system, since oxidative processes seem likely to destroy the chemical products sought by this research.

#### SOLID PHASE PYROLYSIS OF PARTICULATE BIOMASS

The work of Broido (8), Shafizadeh (9), Lewellen (10) and others (11) has shown cellulose pyrolysis to be describable in terms of a competitive

mechanism:



Two pyrolysis reactions compete to consume the cellulose; however only one reaction produces char. The first reaction is favored by high temperatures and rapid heating, producing combustible volatile matter (levoglucosan) at the expense of char formation. The second reaction is favored by low temperatures and slow heating of the cellulose. Water, CO, CO<sub>2</sub> and char are the primary products of the second reaction.

Because char is an unlikely source of chemicals (having to compete directly with coal), conditions which optimize the production of levoglucosan (C<sub>6</sub> H<sub>10</sub> O<sub>5</sub>, or the "monomer" of cellulose) are of interest here. Levoglucosan (and related compounds) have been described as potentially important industrial intermediate chemicals (12). In addition it plays the role of a very reactive intermediate in the gas phase chemistry of biomass conversion (step 2).

High yields of levoglucosan are obtained by rapid heating of the cellulose polymer (13, 14) and when condensation reactions (leading to the formation of char) are minimized. Dilute phase, transport reactors minimize condensation reactions by permitting the (gas phase) levoglucosan molecules to rapidly disperse themselves in a largely non-reactive carrier gas (such as H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub>, Ar, He, etc). Thus entrained flow, flash pyrolysis reactors appear to be best suited for the production of large yields of the



reactive intermediate "levoglucosan" from cellulose.

A recent paper by Krieger (15) summarizes much of what is known about lignin pyrolysis. Detailed studies of the mechanisms and kinetics are not available. Char yields approximating 50% by weight are obtained when lignin is heated at a moderate rate ( $100^{\circ}\text{C}/\text{min}$ ) to  $500^{\circ}\text{C}$  in steam. Rapid heating reduces char formation (4).

As discussed in the following section, the volatile matter evolved during lignin pyrolysis cracks rapidly in the gas phase to produce a hydrocarbon rich synthesis gas. This gas phase behavior of lignin volatile matter resembles that of the reactive intermediate levoglucosan, derived from cellulose pyrolysis. Since the monomeric phenylpropane units which compose lignin are joined by ether linkages (patterning to some extent the glucosidic linkages which tie cellulose monomer units together), rapid pyrolysis of lignin may result in the formation of monomeric phenylpropane units. These reactive gas phase intermediates could undergo higher temperature, gas phase pyrolysis to produce the permanent gases described in the following section of this paper. Although the results of some pyrolysis studies would seem to contradict this hypotheses (16), the effects of secondary gas phase reactions may have masked the formation of the primary intermediate molecule. Dilute phase, flash pyrolysis reactors minimize the effects of secondary reactions and promise to be a powerful tool for the study of lignin pyrolysis.

The pyrolysis chemistry of hemicelluloses has been reviewed by Soltes and Elder (16). Although furan derivatives might be expected to be a primary product of hemicellulose pyrolysis, low yields are usually observed relative to acetic acid. These results probably reflect the high reactivity

of furfural and related molecules, which decompose rapidly by gas phase pyrolysis. Consequently, reactive intermediates derived from hemicellulose pyrolysis have not been observed. Nevertheless, results discussed in the following section of this paper suggest the formation of a reactive intermediate product during hemicellulose pyrolysis which plays a role similar to that of levoglucosan.

#### GAS PHASE CRACKING/REFORMING OF VOLATILE MATTER DERIVED FROM PYROLYSIS OF BIOMASS

Biomass gasification chemistry is dominated by the role of the secondary gas phase cracking reactions, which are largely independent of the solid phase pyrolysis reactions. A tubular quartz, plug flow reactor has been used at Princeton (1-3, 6, 7) for two years to study the products and rates of these gas phase reactions as a function of gas phase conditions (temperature, residence time, steam dilution, etc.). Our results show that gas yields from cellulose can be increased by a factor of ten simply by increasing the gas phase temperature from 500°C to 700°C with a gas phase residence time of about 2 sec (1-3). Similarly, gas yields from Kraft lignin can be increased by a factor of three or more by the same variation in gas phase conditions (6). Table 1 lists typical product yields from cellulose, mannose, and kraft lignin for reactor conditions chosen to produce little or no condensible materials. Similar data for various woods will be available in the forthcoming thesis of Mr. T. Mattocks (7).

Apparent gas phase rates of production of the major permanent gas products of cellulose gasification are given as Arrhenius plots in Reference 1. Similar kinetic data for the gas phase conversion chemistry of lignin

is given in Reference 6. Due to insufficient funding, kinetic data for hemicellulose gasification has not been obtained. However, kinetic data for wood conversion will be presented in Reference 7.

TABLE 1. SELECTED GASIFICATION RESULTS FOR  
CELLULOSE, D MANNOSE AND KRAFT LIGNIN

	Cellulose	D Mannose	Kraft Lignin
Gas Phase Reactor Temperature	700	750	750°C
Gas Phase Reactor Residence Time	3.5	2.0	2.2 sec
Sample Weight	0.125	0.256	0.360 g
Char Residue Weight	0.012	0.053	0.176 g
Tar Residue Weight	0.003	0.011	0.052 g
Gas Volume Produced	84	81	73 ml
Gas Heating Value	490	455	579 Btu/scf
Calorific Value of Char	2.8	5.8	14.3 MM Btu/tonne
Calorific Value of Gases	13.7	5.7	4.9 MM Btu/tonne
Calorific Value of Tars	0.5	0.9	3.5 MM Btu/tonne
Carbon Balance	0.96	0.87	0.98
<u>Gas Analysis (Vol %)</u>			
CO	52	53	34
H <sub>2</sub>	18	10	15
CO <sub>2</sub>	8	16	13
CH <sub>4</sub>	14	14	32
C <sub>2</sub> H <sub>4</sub>	6	5	4
C <sub>2</sub> H <sub>6</sub>	1	1	1
C <sub>3</sub> H <sub>6</sub>	0.1	0.5	0.7
other	0.9	0.5	0.3

Because levoglucosan is known to be the major component of the volatile matter derived from rapidly heated cellulose pyrolyzate, the large increase in gas yields due to increasing gas phase temperatures may be presumed to be the result of the gas phase pyrolysis of the reactive intermediate levoglucosan. Similarly, the large increase in gas yields from lignin must be the

result of the gas phase pyrolysis of some condensable material derived from lignin. Although the identity of this intermediate compound is not presently known, it may be presumed to be related to the phenylpropane units which compose the lignin structure. Finally, the gas phase behavior of volatile matter derived from mannose, wood and corn cob materials also suggests the formation of an intermediate compound from the pyrolysis of hemicellulose, which cracks in the gas phase to yield a product slate relatively similar to that of levoglucosan derived from cellulose.

Somewhat surprisingly, strong similarities are evidenced between the product slates of cellulose, lignin and hemicellulose in Table 1. This ability of thermal processes to "normalize" the conversion chemistry of different biomass materials is an important advantage over the more feed-stock sensitive biological conversion routes.

#### DISCUSSION

Traditional feedstocks for the production of olefins (ethylene) and other valuable chemicals are becoming scarce and costly. For example, crude oil has recently been proposed as a feedstock for ethylene production by gas phase pyrolysis in an unusual reactor (17). An alternative source of ethylene is biomass: as described earlier six per cent yields of ethylene from cellulose and woody materials by gas phase cracking are regularly achieved at Princeton. With this yield, the yearly wood manufacturing ( $27 \times 10^6$  dry tons), cereal straw ( $161 \times 10^6$  dry tons), corn stalk ( $142 \times 10^6$  dry tons) and logging residues ( $75 \times 10^6$  dry tons) available in the U.S.A. (18) could be used to produce  $24 \times 10^6$  tons per year of ethylene without the use of imported hydrocarbons. The predicted 1980 demand for ethylene in the

U.S.A. is  $14 \times 10^6$  tons. Thus, presently obtainable yields of ethylene from organic wastes are sufficient to meet our annual ethylene demand by the gas phase cracking of agricultural and wood residues.

Olefin production also has a significant impact on process economics. Table 2 lists the values of various products obtained from Brazilian Eucalyptus Wood using a Princeton pyrolysis reactor. *Reactor conditions were not optimized for ethylene production.* Nevertheless, ethylene is the second most valuable product. Ongoing research at Princeton could more than quadruple the yield of ethylene from Eucalyptus wood over that indicated in Table 1.

## CONCLUSIONS

Flash pyrolysis of particulate biomass materials produces large yields of reactive intermediate compounds referred to as volatile matter. These intermediate compounds undergo further pyrolysis in the gas phase at somewhat higher temperatures, producing lighter weight oxygenates and hydrocarbons.

Research at Princeton has shown that yields of ethylene generally exceeding 6% by weight can be produced from cellulosic materials. The ethylene is produced entirely by the gas phase cracking reactions. Future research on the gas phase cracking chemistry of organic wastes could potentially quadruple the yields of ethylene. The production of ethylene and other valued chemicals from organic wastes has the potential of revolutionizing the petrochemicals industry within a decade.

TABLE 2. ESTIMATED VALUE OF THE PYROLYSIS PRODUCTS OF  
BRAZILIAN EUCALYPTUS WOOD

One metric ton Eucalyptus Wood	→	Gas :	9 Gj at \$2.00 per Gj	= \$18
		C <sub>2</sub> H <sub>4</sub> *:	32 kg at \$0.38 per kg	= \$12
		Char :	6 Gj at \$1.50 per Gj	= \$ 9
		Tar :	1 Gj at \$1.00 per Gj	= \$ 1
		total		

\*Yields of ethylene will be considerably improved in future reactor designs.

#### REFERENCES

1. Antal, M.J. "The Effects of Residence Time, Temperature and Pressure on the Steam Gasification of Biomass", American Chemical Society Division of Petroleum Chemistry, Honolulu, 1979.
2. Antal, M.J. "Synthesis Gas Production from Organic Wastes by Pyrolysis/Steam Reforming", IGT Conference on Energy from Biomass and Wastes, Washington, D.C., 1978.
3. Antal, M.J., Friedman, H.L., Rogers, F.E. "A Study of the Steam Gasification of Organic Wastes", (Final Progress Report, U.S.E.P.A.), Princeton University, Princeton, N.J. 1979.
4. Rensfelt, E., Blomkvist, G., Ekstrom, C., Engstrom, S., Espensas, B-G., Liinanki, L. "Basic Gasification Studies for Development of Biomass Medium Btu Gasification Process", IGT Conference on Energy from Biomass and Wastes, Washington, D.C., 1978.
5. Antal, M.J., Friedman, H.L., Rogers, F.E. "Kinetic Rates of Cellulose Pyrolysis in Nitrogen and Steam", to appear in Combustion Science and Technology, 1979.
6. Kothari, V.S., Antal, M.J., Reed, T.B. "A Comparison of the Gasification Properties of Cellulose and Lignin in Steam", to appear.
7. Mattocks, T. M.S.E. Thesis, Princeton University, Princeton, N.J., 1979.
8. Broido, A. "Kinetics of Solid Phase Cellulose Pyrolysis", in "Thermal Uses and Properties of Carbohydrates and Lignins", Shafizadeh, F. et al. (ed.), Academic Press, New York, 1976.
9. Shafizadeh, F., Groot, W.F. "Combustion Characteristics of Cellulosic Fuels" in "Thermal Uses and Properties of Carbohydrates and Lignins", Shafizadeh, F. et al. (ed.), Academic Press, New York, 1976.

10. Lewellen, P.C., Peters, W.A., Howard, J.B. "Cellulose Pyrolysis Kinetics and Char Formation Mechanisms", 16th International Symposium on Combustion, Cambridge, 1976.
11. Arseneau, D.F. Can. J. Chem., 1971, 49, 632.
12. Shafizadeh, F. "Thermal Conversion of Biomass" in RANNZ, Volume 2, NSF, 1976.
13. Berkowitz-Mattuck, J.B., Noguchi, J.B. Journal of Applied Polymer Science, 7, 709, 1963.
14. Martin, S. "Diffusion Controlled Ignition of Cellulosic Materials by Intense Radiation", 10th International Symposium on Combustion, Cambridge, Mass. 1964.
15. Graef, G., Allan, G.G., Krieger, B.B. "Rapid Pyrolysis of Biomass/Lignin for Production of Acetylene", American Chemical Society Division of Petroleum Chemistry, Honolulu, 1978.
16. Soltes, E.J., Elder, T.I. "Pyrolysis" in "Organic Chemicals from Biomass", CRC Press, to appear.
17. Yamaguchi, F., Sakai, A., Yoshitake, M. and H. Saegura "COSMOS Cracks Crude to Olefins", Hydrocarbon Processing, 9 (58), 167, 1979.
18. Burwell, C.C. "Solar Biomass Energy: An Overview of U.S. Potential", Science, 199, 1041, 1978.

ENVIRONMENTAL ASSESSMENT OF WASTE-TO-ENERGY  
CONVERSION SYSTEMS

by

K. P. Ananth  
M. A. Golembiewski

Midwest Research Institute  
425 Volker Boulevard  
Kansas City, Missouri 64110

EPA Contract No. 68-02-2166  
MRI Project No. 4290-G

EPA Project Officer: Harry M. Freeman

for

Presentation at the "Waste-to-Energy Technology--Update 1980" Conference

Cincinnati, Ohio  
April 15-16, 1980



## Introduction

The Fuels Technology Branch of EPA's Industrial Environmental Research Laboratory in Cincinnati is sponsoring a program at Midwest Research Institute (MRI) to conduct environmental assessments of waste-to-energy conversion facilities. The overall objective of this program is to evaluate the multi-media environmental impacts that result from using waste (municipal solid waste, industrial/sewage sludge, agricultural residue) as an energy source and to identify control technology needs. As part of this program, MRI has undertaken fairly extensive sampling and analysis efforts at the following waste conversion sites.

- \* A 200 ton/day refuse pyrolysis system
- \* A 120 ton/day municipal incinerator fired with municipal solid waste (MSW)
- \* 10MW power plant boiler fired with wood waste and No. 2 oil
- \* A 70,000 lb/hr steam boiler fired with coal and densified refuse-derived fuel (dRDF)
- \* A 20MW power boiler fired with refuse derived fuel

A brief description of the facility, the sampling and analysis methods used, and the results obtained are individually presented below for each of these facilities.

## Refuse Pyrolysis System

The Union Carbide refuse pyrolysis system (PUROX) at South Charleston, West Virginia, was designed to pyrolyze 200 tons/day of refuse. The refuse was obtained by shredding MSW to a 3 in. size and then removing the magnetic materials from the shredded waste. The PUROX system is a partial oxidation process that uses oxygen to convert solid wastes into a gas having a higher heating value (HHV) of about 370 Btu/scf.

The refuse is fed into the top of the reactor, the principal unit in the process. There are three general zones of reaction within the reactor (drying, pyrolysis, and combustion). The reactor is maintained essentially full of refuse which slowly descends by gravity from the drying zone through the pyrolysis zone into the combustion zone. A counterflow of hot gases, rising from the combustion zone at the bottom, dries the incoming moist refuse. As the material progresses downward, it is pyrolyzed to form fuel gas, char, and organic liquids.

Oxygen is injected into the bottom hearth section at a ratio of about 20% by weight of incoming refuse. The oxygen reacts with char formed from the refuse to generate temperatures of 2500 to 3000°F in the lower zone which converts the noncombustibles into a molten residue. This residue is discharged into a water quench tank where it forms a slag. The typical composition of the slag is reported to be 60% SiO<sub>2</sub>, 11% Al<sub>2</sub>O<sub>3</sub>, 11% CaO, 9% Na<sub>2</sub>O, 5% FeO, 2% MgO, and 2% other oxides.

The hot gases from the hearth section are cooled as they rise through the zones of the reactor. After leaving the reactor, the gases are passed through a recirculating water scrubber. Entrained solids are separated from the scrubber water in a solid-liquid separator, and recycled to the reactor for disposal. The water product discharged from the separator system is sent to a plant treatment system. The gas leaving the scrubber is further cleaned in an electrostatic precipitator and then cooled in a heat exchanger prior to combustion in a flare combustor. For purposes of this test program, however, the product gas was combusted in a package boiler and emissions resulting from its operation were characterized. As a baseline comparison, the source boiler was also tested when fired with natural gas.

Sampling and analysis of air emissions from the boiler included particulate loading determination by EPA Method 5 with a high volume sampling system (HVSS), gas analysis by continuous monitors for O<sub>2</sub>, CO, hydrocarbons and NO<sub>x</sub>. SO<sub>2</sub> was determined by EPA Method 6. Gas samples for total carbonyls were collected using grab sampling techniques and analyzed using prescribed procedures. In sampling for mercury and chlorides, fluorides, bromides and cyanides in the vapor form, a sampling train containing 5 midget impingers was used. In addition, the Source Assessment Sampling System (SASS) was used as prescribed by EPA for Level 1 environment assessment. Opacity of stack emissions was determined using EPA Method 9.

The PUROX gas fed into the boiler was also sampled for criteria pollutants using EPA methods.

Refuse fed into the reactor, slag from the quench tank, and wastewater before and after treatment were all sampled and analyzed for metals, anions, and PCB's. Wastewater analysis was also carried out for priority pollutants other than PCB's and for BOD, COD, turbidity, phenols, etc.

Results of the testing effort showed that, of the criteria pollutants, only NO<sub>x</sub> and particulate emissions increased when burning Purox gas as compared to natural gas. NO<sub>x</sub> and particulate levels were of the order of 350-400 ppm and 6-14 mg/dNm<sup>3</sup> respectively. SO<sub>2</sub> emissions averaged 70-100 ppm. Particulate and SO<sub>2</sub> emissions were below present standards, whereas NO<sub>x</sub> will require further reduction. Also, analysis for metals and other pollutants indicates that these

should not present any problems. The wastewater, however, without proper treatment would be a major area of concern.

The SAM-LA assessment methodology was utilized by applying it to the data obtained for each of the three primary effluent streams from the Purox process (slag, scrubber effluent, and boiler stack gas). Results of this application showed that the scrubber effluent had the highest degree of hazard, being considerably greater than the hazard value for the input river water. However, the slag stream had the highest toxic discharge rate (TUDR). The boiler flue gas effluent had the lowest hazard value and the lowest TUDR; both were close to the baseline values computed for boiler flue gas when burning natural gas.

#### Municipal Incinerator Fired With MSW

The Braintree municipal incinerator (Braintree, Massachusetts) is a mass-burn facility consisting of twin water-wall combustion units, each with a design capacity of 120 tons of MSW for 24-hr period. A portion of the steam produced (20-35%) is supplied to neighboring manufacturers and the remainder is condensed. Each furnace is equipped with an ESP and both ESP's exhaust to a common stack.

The Riley Stoker boilers are of the single pass design with each having a rated capacity of 30,000 lb of steam/hr at 400°F and 250/psig. The ESP units are single field, 12 passage precipitators with a specific collection area of 125 ft<sup>2</sup>/1000 acfm; each has a design collection efficiency of 93%.

Environmental assessment of the incinerator facility was conducted using EPA approved sampling and analysis procedures. Results and conclusions of the testing effort are summarized below.

Of the criteria pollutants, SO<sub>2</sub>, NO<sub>x</sub>, and hydrocarbon emissions were low. However, CO levels were high and could not be explained considering the large quantities of excess air that were used. The average particulate concentration was 0.24 gr/dscm, corrected to 12% CO<sub>2</sub>. This level exceeded the federal and state regulations. However, subsequent tests for compliance had an outlet particulate loading of 0.074 gr/dscf, which shows compliance.

Elemental analysis of the glass-and metal-free bottom ash revealed an overall increase in the elemental concentrations when compared to the refuse feed. The collected fly ash contained levels of chlorides, sulfates and some trace metals which may be of concern. PCB's were not detected in the collected fly ash; 4 PAH compounds were identified.

Levels of BOD, COD, oil and grease, TSS and TDS in the bottom ash quench water do not appear to be of concern. The phenolic content was found to be <0.1 mg/liter in all samples.

Levels of gaseous chlorides and other halides were low. Presence of PCB's was confirmed only in the SASS train XAD-2 resin at a concentration of  $3.6 \mu\text{g}/\text{m}^3$ .

Results of the SAM-1A environmental assessment procedure show the incinerator stack emissions to have the highest apparent degree of health hazard. Further analysis is needed to determine the exact composition of the organic components of the stack emissions to better ascertain the hazard potential. SAM-1A also showed that the bottom ash effluent had the largest toxic unit discharge rate due primarily to the abundance of phosphorus and metals in this stream.

#### Power Plant Boiler Fired With Woodwaste and Fuel Oil

The No. 1 unit at the Burlington Electric Plant (Burlington, Vermont) was originally a coal fired boiler which has since been modified to fire wood chips with supplementary No. 2 fuel oil. Because of the high moisture content of the chips, the boiler cannot provide the desired steam output on wood alone. Therefore, No. 2 fuel oil is used. Steam production is rated at 100,000 lb/hr, which powers a 10MW turbine generator. Residual ash from the boiler is discharged at the end of the grate into a hopper and is then pneumatically transported to an outdoor storage silo. The flue gases leaving the boiler are ducted to an emission control system consisting of two high efficiency mechanical collectors in series. For a flue gas flow rate of 60,000 acfm at 330°F, the collectors were designed for an overall pressure drop of 6.5 in. H<sub>2</sub>O and a collection efficiency of 97.75%.

Sampling and analysis was focused on the input fuels, bottom ash, primary and secondary collector ash, and air emissions at the collector inlet and outlet. The input fuels were analyzed for their heating value and trace metal content. The moisture content of wood was also determined. Bottom ash and collector ash were analyzed for their trace metal and PCB/PAH contents. Collector inlet gases were sampled using EPA Method 5 for particulate. Particle sizing and elemental analysis were also carried out. The stack gases were sampled and analyzed for criteria pollutants, trace metals, and PCB/PAH. EPA Method 5 and SASS trains were used for particulate measurement. Major results and conclusions of the sampling and analysis program are as follows:

On a heat input basis, wood accounted for 80% of the boiler fuel, and oil the remainder. The heat of combustion of wood was 5870 Btu/lb (as received) and for oil, the heat of combustion was 19,500 Btu/lb.

Bottom ash analysis indicated that most elements were more concentrated in the ash relative to the input fuels. No PCB's were detected in bottom ash but one PAH compound was present at a concentration of 0.89  $\mu\text{g}/\text{g}$ . Primary and secondary collector ash contained no PCB's but several PAH compounds were identified in the secondary ash with one sample containing 10  $\mu\text{g}/\text{g}$  of phenanthrene.

Particle sizing at the collector inlet and outlet could not be established due to constant plugging of the dilution system. Stack concentration of particulates averaged 0.08 gr/dscf and the collector had a particulate efficiency of 94.2%.  $\text{NO}_x$  and  $\text{SO}_2$  concentrations averaged 66 and 138 ppm respectively. CO averaged 213 ppm and hydrocarbons 9 ppm. Analysis of Method 5 particulate indicated concentrations approaching 100  $\mu\text{g}/\text{dscm}$  for Pb, Ba, Sr, Fe and Ti in the stack gases. PCB and PAH tests of the stack gases were negative.

EPA's SAM-LA analysis indicated that the secondary collector ash contained the highest degree of hazard although all 3 ash streams were similar in the magnitude of their hazard values. Stack emissions showed a low degree of hazard. The primary collector ash had the highest toxic unit discharge rate. However, because of the limitations of the methodology, these findings should not be viewed as conclusive.

#### Steam Boiler Fired With Coal and Densified Refuse Derived Fuel (dRDF)

MRI, in conjunction with the General Services Administration (GSA) and the National Center for Resource Recovery (NCRR), conducted emission tests on the No. 4 boiler at the GSA/Pentagon facility. The No. 4 unit was co-fired with different blends of coal and dRDF. Steam output of the underfed-ratort stoker boiler was rated at 70,000 lb/hr. The boiler was equipped with a multiclone unit for particulate removal.

Emission tests were conducted by MRI to determine particulate loadings, gaseous criteria pollutant and chloride concentrations in the stack gas. The particulate samples were also analyzed for lead. Testing was conducted first at baseline conditions (coal only as fuel) and then when firing blends of 20% dRDF:80% coal and 60% dRDF:40% coal. NCRR conducted other evaluations. The results of MRI's efforts are as follows:

- \* Particulate emissions were reduced from 22 to 36% when dRDF was blended with the original coal fuel. Filterable particulate emissions were lowest when using the 20% dRDF blend and rose again when the proportion of dRDF was raised to 60%. This finding may not be conclusive, however, since the boiler load was held steady during the 20% dRDF firing but not during the 60% mode.

- \* The amount of particulate lead emitted when burning dRDF with coal is substantially higher than that from combustion of coal alone (an average of 1000  $\mu\text{g}/\text{m}^3$  with 20% dRDF, and 2260  $\mu\text{g}/\text{m}^3$  with 60% dRDF, versus 330  $\mu\text{g}/\text{m}^3$  with coal only).

- \* Chloride emissions showed no definite trend which could be used to correlate chloride emissions with RDF modes, though slightly higher concentrations of HCl were observed in two of the samples collected during combustion of the 60% dRDF blend.

### Power Boiler Fired with RDF

The Hempstead Resource Recovery Plant (Long Island, New York) is a complete waste-to-energy facility in that it takes in municipal solid waste, produces an RDF and converts the fuel to electrical power. The facility consists of two distinct segments: a refuse processing operation, utilizing the Black Clawson Hydrasposal system; and a power house, which contains two steam boilers and two, 20 MW electrical turbine generators.

Tests were conducted by MRI on the No. 2 unit of the power house, which is an air-swept spreader stoker waterwall boiler with a nominal capacity of 200,000 lbs/hr of steam at 625 psig and 750°F. The boiler was fired with 100% refuse-derived fuel (RDF), although auxiliary oil burners are used for start-up and during fuel feed interruptions. Air pollution controls for the boiler consist of a bank of 12 mechanical cyclones followed by an electrostatic precipitator.

The purpose of the program was to primarily investigate organic constituents of the stack gases and to quantify odorous components.

Emission streams evaluated included the boiler bottom ash, cyclone ash, ESP ash and the stack effluent gases. Samples of the RDF were also collected for analysis. The three ash streams were analyzed for elemental composition, as well as for PCB and PAH materials. Stack emissions were continuously monitored for SO<sub>2</sub>, NO<sub>x</sub>, CO, O<sub>2</sub> and total hydrocarbon concentrations, and were also tested to determine levels of vaporous mercury and aldehydes. In addition, a test was conducted using the Source Assessment Sampling System (SASS) for analysis under EPA's Level 1 protocol. Samples of the RDF fed to the boiler were evaluated for moisture content, elemental composition and chemical parameters (proximate/ultimate analyses).

Laboratory analyses have only been partially completed. Therefore, the results will be reported at the time of presentation of this paper.

# EMISSIONS ASSESSMENT FOR REFUSE-DERIVED FUEL COMBUSTION

Prepared for:

Environmental Protection Agency  
Cincinnati, Ohio 45268

Under Contract No. 68-03-2771

Submitted by:

J.W. Chrostowski  
Energy Resources Co. Inc.  
185 Alewife Brook Parkway  
Cambridge, Massachusetts 02138  
(617) 661-3111

March 18, 1980

## 1. Introduction

Energy Resources Co. Inc. (ERCO) has been contracted by the Environmental Protection Agency (EPA) to investigate the emissions (gaseous and particulate) from co-firing of refuse-derived fuel (RDF) and coal in a pilot-plant scale atmospheric fluidized-bed combustor (AFBC). Gaseous emissions ( $\text{SO}_2$ ,  $\text{NO}_x$ , CO, and hydrocarbons) are continuously monitored with the appropriate instrumentation. Particulates samples are collected with a Source Assessment Sampling System (SASS train) and will be subsequently analyzed for trace metals and organic content using the EPA Level 1 procedure.

## 2. RDF/Coal Supplies

At the present time, two sources of RDF and a single source of coal have been obtained. The suppliers and properties of the fuels are summarized in Table 1.

## 3. Description of Work Plan

The major objectives of this investigation are as follow:

- Quantify the gaseous and particulate emissions from a co-fired RDF/coal feed in an atmospheric fluidized-bed combustor. The primary process variables include combustion temperature (1100 - 1400° F) and the weight fraction of RDF in the feed (0-75 percent). The upper temperature limit of 1400° F is set by the fusion temperature of glass which is present in the source RDF material.



TABLE 1

COAL/RDF SUPPLIERS AND FUEL PROPERTIES

	-----FEEDSTOCK-----		
	Crushed Coal	EcoFuel	Americology
Supplier	Battelle	Combustion Equipment Associates	American Can
Size	23%>1.7mm 59% mid-range 18%<300µm	28%<170 mesh 30% 170/230 mesh 42% 230/325 mesh	<1"
Heating Value (HHV, Btu/lb m.f.)	12953	7827	6430
Moisture (% wet basis)	9.38	3.2	25-35
Chemical Composition (wt %, m.f.)			
Sulfur	0.87	0.61	N.A.
Carbon	71.81	40.0	N.A.
Hydrogen	1.78	4.6	N.A.
Nitrogen	1.59	<.1	N.A.
Oxygen	15.5	45.5	N.A.
Chloride	--	.26	N.A.
Ash	8.53	9.0	N.A.
Fusion Temperature (°F)	--	~1800	~1300

- Obtain pilot plant performance data to assess the suitability of co-firing RDF/coal in an atmospheric fluidized-bed combustor. This includes the determination of associated heat and material balances to define the overall process.

#### 4. Description of Atmospheric Fluidized-Bed Combustor (AFBC) Pilot Plant

A schematic of the ERCO AFBC pilot plant is provided in Figure 1. The major equipment components include the following:

- Solids feed system (hopper, star valve and feed screw)
- Sutorbilt rotary vane air blower (600 SCFM at 6 psig discharge)
- 20" diameter fluidized bed ( $2.13 \text{ ft}^2$ ) with removable in-bed heat transfer tubes and convective heat transfer tubes in the freeboard
- Fisher-Klosterman cyclone for elutriated solids collection
- SASS train for particulate and organic collection

The fluidized bed has a Incalloy-800 perforated plate distributor which is mounted to permit thermal expansion. The fluidizing medium is refractory sand with a mean particle size of 400-500 microns diameter. The bed is heated to the desired ignition temperature of 800-1000° F (before the addition of the coal/RDF feed) by burning natural gas below the distributor plate.

The continuous monitoring equipment for gaseous emissions include the following:

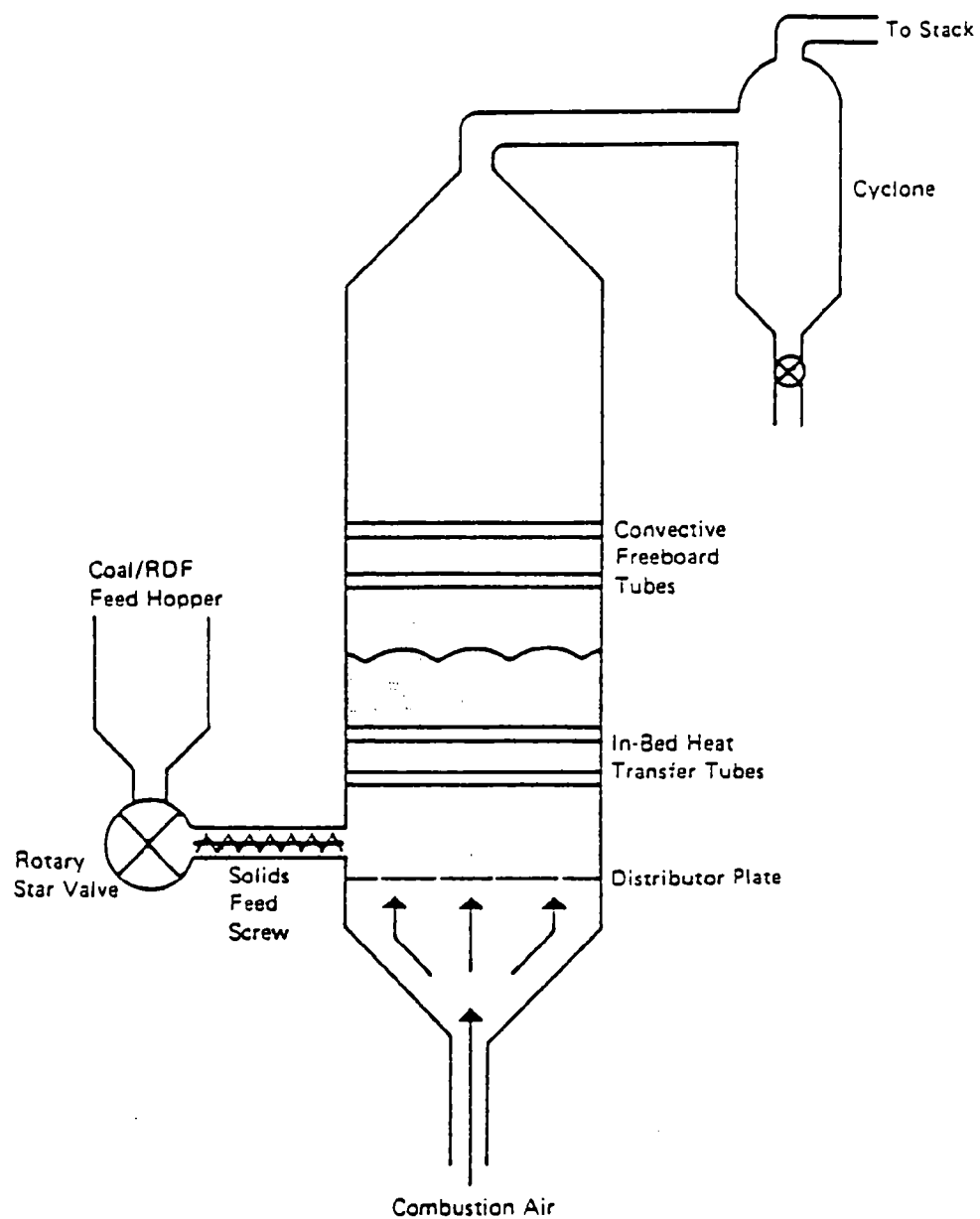


Figure 1: Schematic of ERCO Fluidized Bed Pilot Plant.

- Beckman Paramagnetic O<sub>2</sub> Analyzer
- Thermo-Electron Chemiluminescent NO-NO<sub>x</sub> Analyzer
- Thermo-Electron Pulsed Fluorescent SO<sub>2</sub> Analyzer
- Beckman NDIR Model 865 CO/CO<sub>2</sub> Analyzer
- Beckman FID Model 400 Total Hydrocarbon Analyzer

In addition to this on-line equipment, a Fischer Hamilton Model 1200 Gas Partitioner is used to periodically sample for C<sub>1</sub>-C<sub>5</sub>, O<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>, CO and CO<sub>2</sub>.

##### 5. Summary of Coal/RDF Runs

The pilot-plant AFBC has been run with crushed coal (no RDF) and with two RDF/coal mixtures (25 and 50 weight percent EcoFuel) with bed temperatures ranging from 1000 to 1320° F. The operating data and the heat and material balances for the individual runs are summarized in Table 2.

In these runs, the static bed height was maintained relatively constant at 16 to 18 inches and the fluidizing velocity ranged from 1.1 to 3.1 feet/sec at the actual operating conditions. The minimum fluidization velocity for the refractory sand with a mean particle diameter of 420 microns is nominally 0.28 feet/sec. Operation with a fluidizing velocity 3.9 to 11.1 times the minimum fluidization velocity ensures excellent solids mixing and uniform temperature distribution ( $\pm 25^\circ$  F) throughout the bed.

It should be noted that these preliminary runs were shake-down runs to ensure satisfactory operation of 1) the pilot-plant equipment (solids feed system and bed operation);

2) on-line instrumentation for  $\text{SO}_2$ ,  $\text{NO}_x$ , CO, and  $\text{O}_2$  measurement; and 3) evaluation of the SASS train for particulate and organic collection.

The data in Table 2 for runs #3-6 with crushed coal alone indicate satisfactory performance of the AFBC with combustion temperatures ranging from 1150-1318° F. The combustion temperature was varied by either changing the coal and air feedrates (maintain same excess air) or the number of in-bed tubes. Because of the fines in the crushed coal (18 wt percent less than 300 microns), 20 to 30 percent of the carbon was burned in the freeboard. The efficacy of the SASS train for particulate collection was initially evaluated in run #6. Because of the relatively high particulate loading from the cyclones, the SASS train filter clogged in approximately 30 minutes.

The two preliminary runs with EcoFuel/coal (run #7 with 50 percent RDF and run #8 with 25 percent RDF) at nominally 1300° F were successful from the standpoint of solids feeding and operation of the fluidized bed. The run (#7) with 50 percent RDF indicated a significant amount of freeboard burning associated with the fine particle size of the RDF (42 wt percent less than 230 mesh). The SASS train was again evaluated in run #8 with 25 percent RDF; as before, the filter clogged after about 30 minutes of sampling.

## 6. Future Work

The primary objectives of the future series of RDF/coal runs will be the following:

TABLE 2

SUMMARY OF RDF/COAL AFBC RUNS

RUN NUMBER	3	4	5	6	7	8
Feed Rates:						
Coal/RDF (lbs/hr)	71	42	30	30	24	34
Weight Fraction RDF	0.0	0.0	0.0	0.0	0.50	0.25
Air (SCFM)	115	71	56	64	39	59
Fluidizing Velocity (fps)	3.13	1.79	1.56	1.66	1.10	1.64
Temperatures (°F)						
Bed	1203	1150	1318	1210	1320	1309
Freeboard	866	1086	905	891	1060	868
Stack Gas Composition						
Oxygen (%)	1.7	3.1	2.9	3.7	2.5	3.2
CO (ppm)	1055	--	425	225	580	527
NO <sub>x</sub> (ppm)	124	--	--	--	80	96
SO <sub>x</sub> (ppm)	975	--	--	--	589	273
Energy Balance						
Heat Out/Heat In	1.02	1.18	1.20	1.09	1.01	0.78
Thermal Efficiency	0.43	0.73	0.85	0.76	0.70	0.50
Combustion Efficiency	0.64	0.76	0.87	0.90	0.93	0.91
Fraction C Burned in Freeboard	0.10	0.27	0.18	0.20	0.65	0.08

- Modify the SASS train to extend the sampling time from 30 minutes to permit collection of sufficient particulate and organic material for subsequent analysis.
- Run varying RDF/coal mixtures at temperatures of nominally 1100, 1200, and 1300° F to obtain gaseous emissions data. Run the SASS train with the optimum set of conditions to obtain particulate and organic emissions data. These runs will be performed with the two RDF fuels presently available, namely EcoFuel from CEA and the Americology fuel.
- Obtain a source of hazardous waste which can be co-fired with RDF to study emissions from an atmospheric fluidized-bed boiler.

KVB12-P-241

COMBUSTION AND EMISSION ASSESSMENT OF REFUSE-DERIVED  
FUEL COFIRED WITH PULVERIZED COAL

BY

L. J. MUZIO, PH.D.  
J. K. ARAND  
R. R. PEASE, II

KVB, INC.  
A RESEARCH-COTTRELL COMPANY

FOR

WASTE-TO-ENERGY TECHNOLOGY - UPDATE 1980  
CINCINNATI, OHIO

APRIL 15-16, 1980



## COMBUSTION AND EMISSION ASSESSMENT OF REFUSE-DERIVED FUEL COFIRED WITH PULVERIZED COAL

### INTRODUCTION

Solid waste burning is not a new concept. Incinerators for burning municipal waste were formerly common in most metropolitan areas. With the passage of stringent air pollution regulations and the advent of the sanitary landfill, burning of garbage has lost much of its widespread application. Recently, however, new incentives have surfaced which make the combustion of municipal waste an attractive disposal alternative. Today's proposed and prototype waste-burning installations are processing solid waste in a variety of methods that may shred, compact, or pelletize the refuse into valuable fuel. Resources in the waste stream are recovered, and conservation of energy is realized by the use of this alternate fuel.

A laboratory program is being conducted to measure emissions (aqueous, air, solid waste) from the combustion of refuse-derived fuel (RDF) and mixtures of RDF and coal in a suspension-fired system. Two sources of RDF will be evaluated, Combustion Equipment Associates' (CEA) Eco Fuel II and Americology RDF. Evaluation of transformer waste oil contaminated with polychlorinated biphenyls (PCB) is also planned. The criteria pollutants NO, SO<sub>2</sub>, CO, and hydrocarbons will be monitored continuously in the flue gas stream, and special tests will be performed to characterize the fuel, flue gas stream, and bottom ash in terms of trace elements and trace organics including POM and PCB, fluorine, chlorine, and bromine.

The combustion facility used for this program is capable of firing gaseous, liquid, and pulverized solid fuels. The basis of the combustion facility is the shell of an 80-horsepower firetube boiler which has been modified to fire various fuels and also includes capability of air preheat (~600 F), staged combustion, and flue gas recirculation. The facility and burner used in cofiring the coal and RDF are illustrated by Figure 1.

Testing is being conducted at a single load for all coal/RDF/waste oil mixtures. The burner settings which include primary/secondary air ratio and burner swirl are not being varied parametrically but rather have been optimized in terms of flame stability for each of the RDF/coal/waste oil mixtures. The combustion parameters that are being investigated during the program include:

- . RDF Type
- . RDF/Coal/Waste Oil Ratio
- . Excess Air
- . Air Preheat
- . Staged Combustion Configuration

KVB12-P-241

## TEST RESULTS

Included in this paper are the available gaseous and particulate results which have been performed to date. Samples are currently undergoing analysis for trace elements and organics and no results are presently available. The results which will be discussed were obtained burning the CEA material cofired with coal.

The gaseous data which were obtained are nitric oxides (NO), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), excess oxygen (O<sub>2</sub>), unburned hydrocarbons (UHC), sulfur dioxide (SO<sub>2</sub>), chlorine (Cl), fluorine (F), and bromine (Br). The Cl, F, and Br were obtained only on certain test points, with all other data obtained for each test point.

The gaseous emissions from the cofired coal and RDF are given in Figures 2, 3, and 4. The NO emissions for single-stage combustion are shown in Figure 2; the SO<sub>2</sub> emissions are shown in Figure 3. It can be seen from these data that the NO and SO<sub>2</sub> emissions increase as the percentage of RDF is increased to 20 percent; emissions then decrease as the RDF fraction is increased to 50 percent. Based upon the RDF fuel analysis supplied by the manufacturer and an independent testing lab analysis for the coal as given in Table 1, both the NO and SO<sub>2</sub> emissions should decrease as the RDF material is cofired with the coal due to the lower nitrogen and sulfur content of the RDF.

The unburned hydrocarbon emissions for the cofiring points were essentially 0 ppm. The carbon monoxide emissions were lower with increasing percentages of RDF than for coal alone, as illustrated by Figure 4. Typically, the emissions were about 50 ppm lower at a ratio of 50 percent RDF and 50 percent coal.

The chlorine, fluorine, and bromine concentrations are shown in Table 2 for all tests completed to date. Also included in this table are the particulate loadings and SO<sub>3</sub> concentration.

The loading results are consistent with what would be expected based on the percentage of ash contained in the coal and the RDF, since there is less than a percentage point difference in those ash values. The SO<sub>3</sub> values for the baseline coal are consistent with previous measurements that show a decrease in SO<sub>3</sub> concentration with staged combustion. However, this trend was reversed when 50 percent RDF was fired. Additional measurements are necessary before any conclusions can be made on the significance of this result.

The halogens show increased concentrations over the base coal when RDF is cofired. The multiple values for Test No. D reflect that two separate samples were taken at different times during the test and each analyzed. This probably reflects the compositionality of the RDF. Also, the data shows a trend of increasing halogen emissions as the percentage of RDF in the fuel is increased. Again, additional tests are required before firm conclusions can be drawn from these data.

#### ADDITIONAL TESTING

Further testing is planned to characterize the emissions from the cofiring of the Americology RDF and coal. Also planned for inclusion with these tests is the burning of transformer waste oil in combination with coal and RDF and with the coal only. Results are anticipated by November of this year.

KVB12-P-241

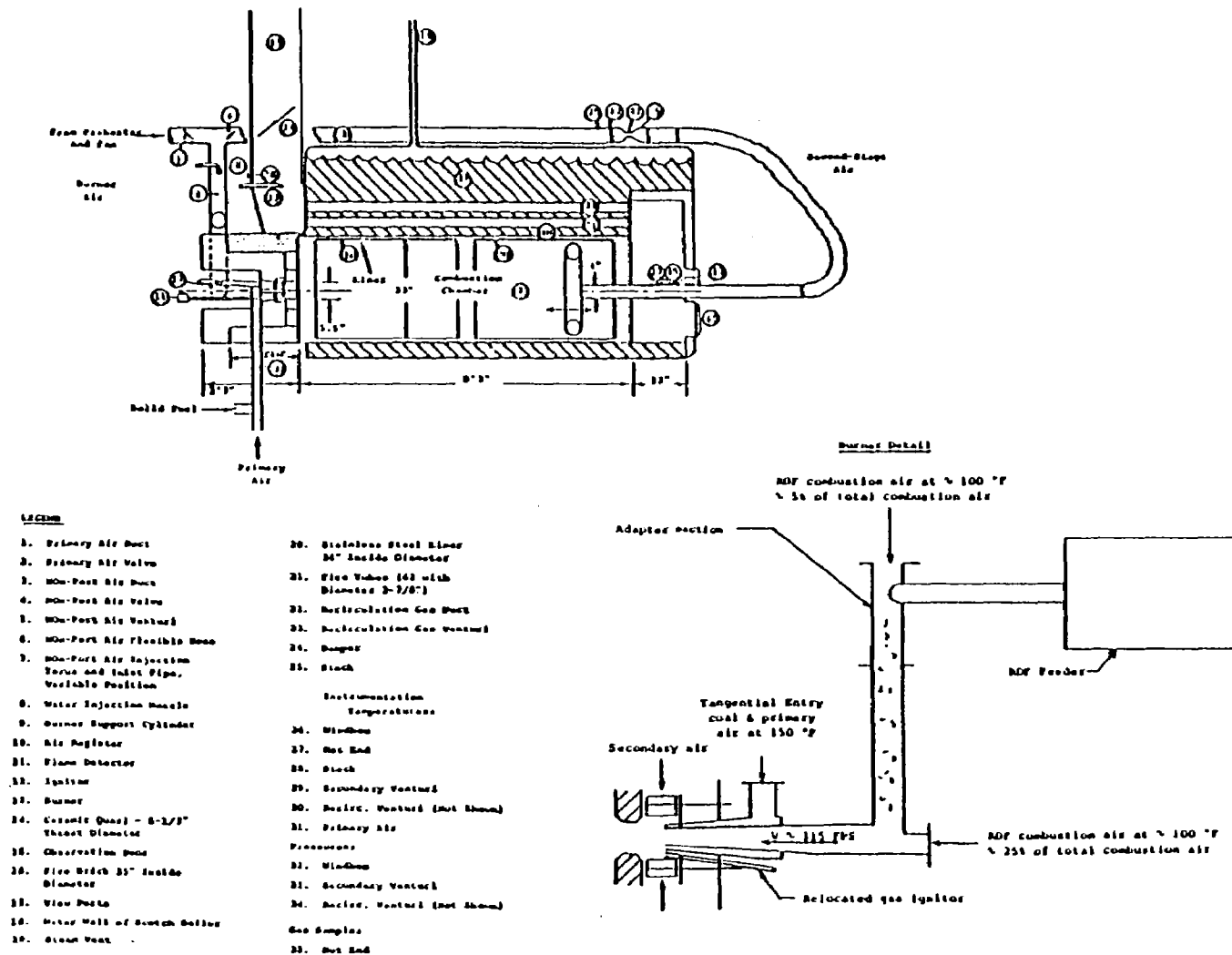


Figure 1. Schematic of 80 HP Combustion Facility.

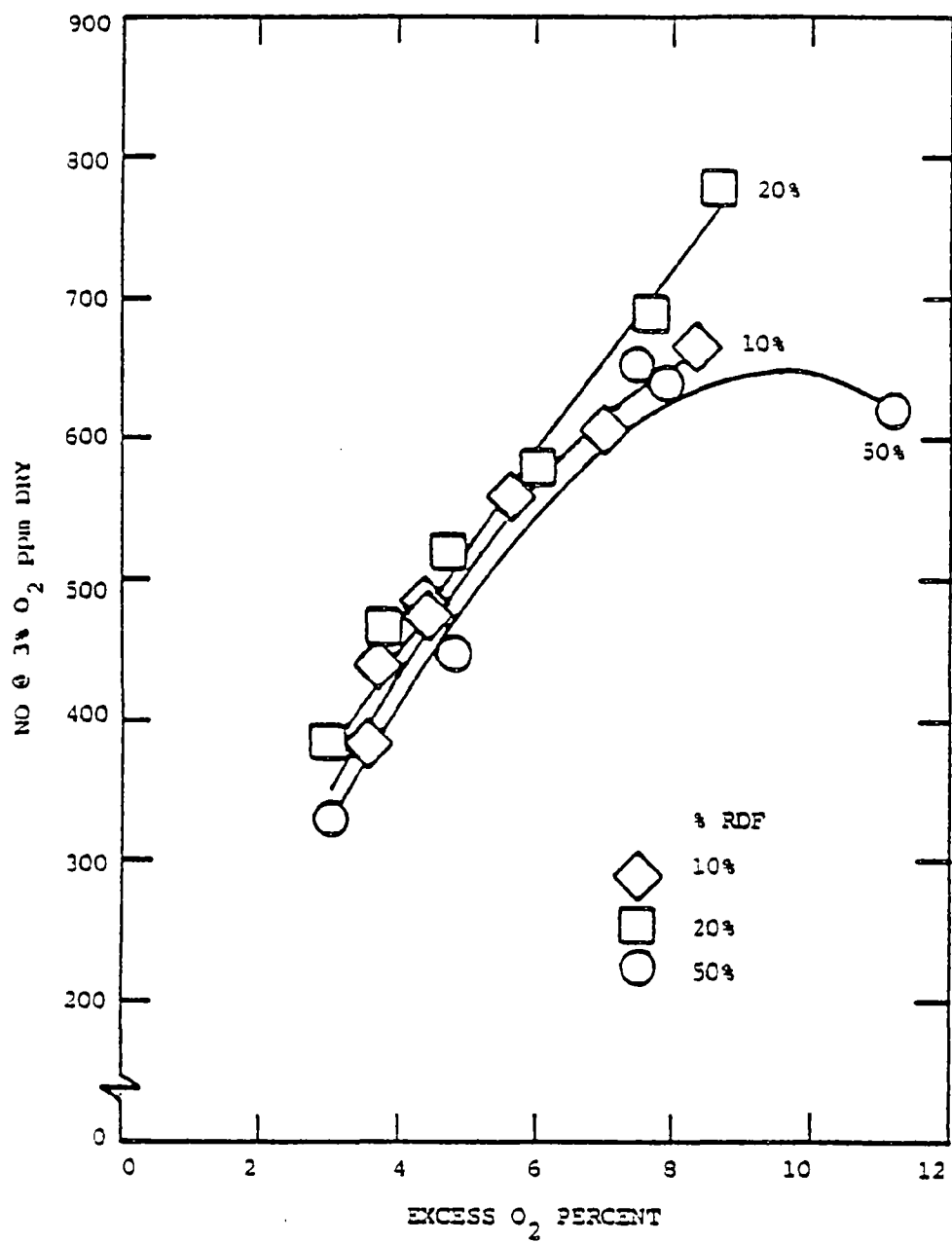


Figure 2. Nitric Oxide Emissions Cofired Coal and CEA RDF Single Stage Combustion.

TABLE 1  
ULTIMATE FUEL ANALYSIS

Chemical Analysis (Dry Basis)	CEA RDF	Coal
Carbon	39.82	74.17
Hydrogen	4.82	4.98
Nitrogen	>0.1	1.34
Chlorine	0.29	0.04
Sulfur	0.74	1.05
Ash	9.71	9.33
Oxygen (Diff)	<u>44.62</u>	<u>9.09</u>
	100.00	100.00
HHV, Btu/lb (dry basis)	7,754	13,206

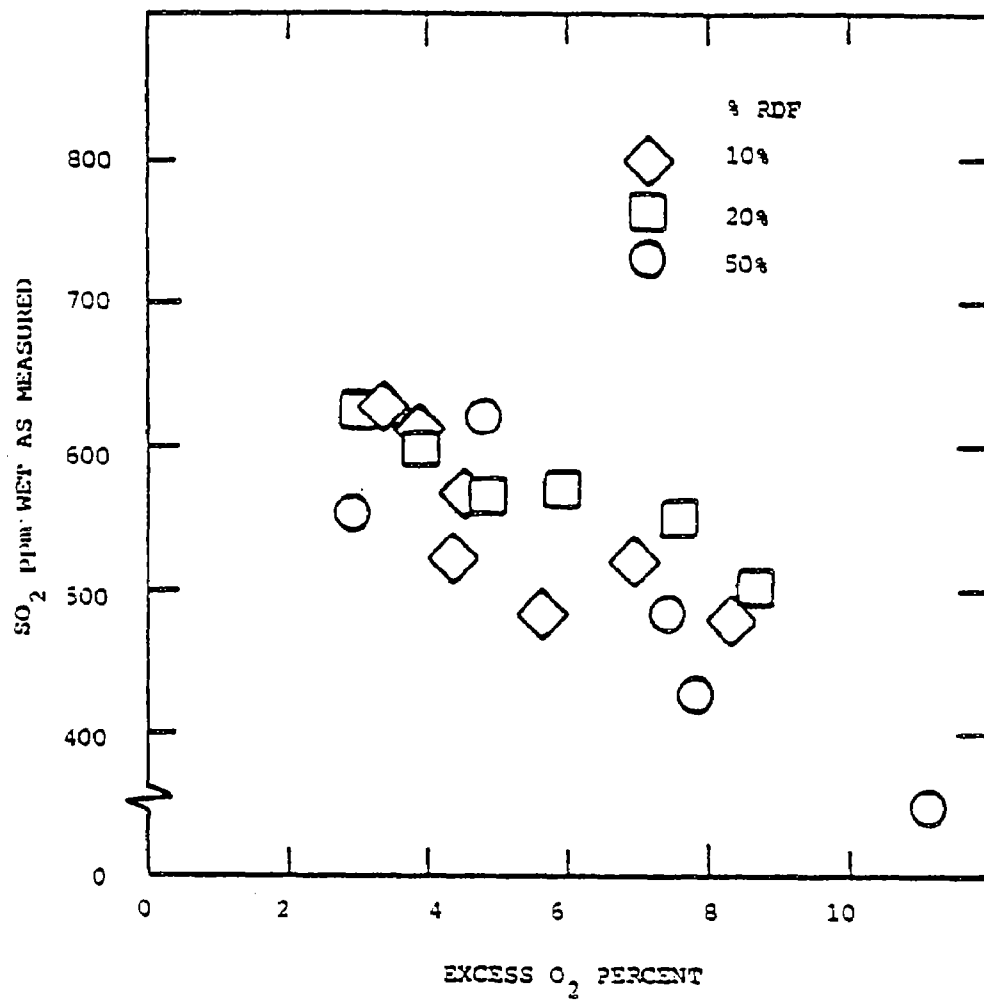


Figure 3. Sulfur Dioxide Emissions Cofired Coal and RDF.

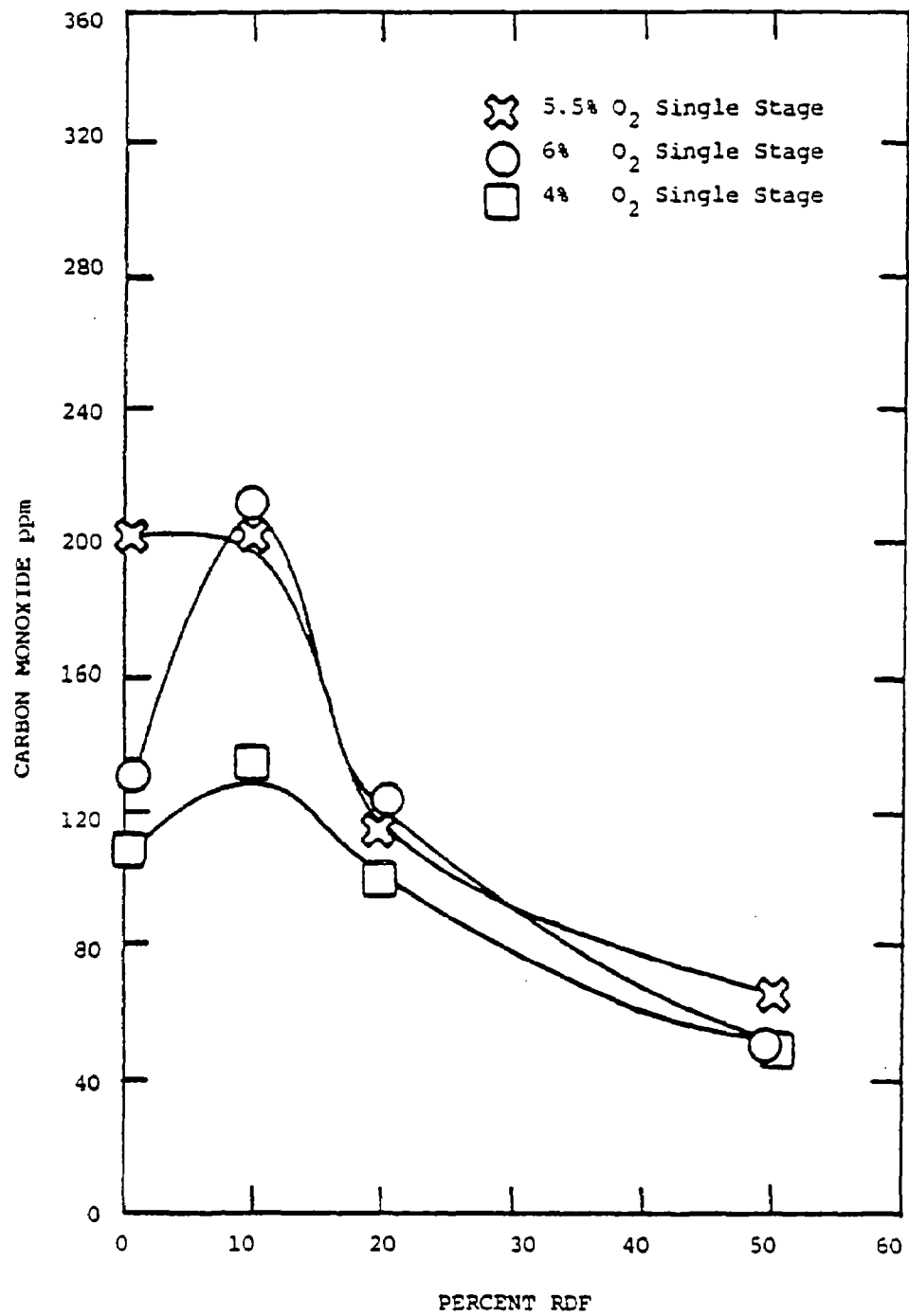


Figure 4. Carbon Monoxide Emissions Cofired CEA RDF and Coal.

KVB12-P-241



TABLE 2

Test No.	Excess Oxygen	Particulate Loading	SO <sub>2</sub>	Cl	BR	F	Fuel Type	Type Firing Condition
	Percent	lb/10 <sup>6</sup> Btu	ppm	ppm	ppm	ppm		
A	5.4	2.29	3.04	14.2	0.09	3.0	Coal	Single Stage Comb.
B	5.35	3.55	0	13.5	0.08	2.4	Coal	Two Stage Comb.
C	5.7	3.17	N/A	53.2	0.6	2.3	10% CEA RDF/ 90% Coal	Single Stage Comb.
D	6.5	3.48	N/A	79.4	0.6	2.8	20% CEA RDF/ 80% Coal	Single Stage Comb.
E	6	2.17	0	55.82	0.15	14.0	50% CEA RDF/ 50% Coal	Single Stage Comb.
F	5.0	2.28	4.48	79.4/ 148.1	0.21/ 0.07	5.71/ 11.6	50% CEA RDF/ 50% Coal	Two Stage Comb.

PILOT SCALE EVALUATION  
OF FOUR REFUSE-DERIVED FUELS

R. A. Brown  
Acurex Corporation  
485 Clyde Avenue  
Mountain View, California

## Abstract

### Pilot Scale Evaluation of Four Refuse-Derived Fuels

R. A. Brown

The EPA is continuing to explore control technology in the areas of alternate fuels, waste fuels and control of NO<sub>x</sub> emissions for boilers in the government-owned test facility located at Acurex Corporation.

Baseline tests on refuse derived fuels (RDF) fired either with pulverized coal or natural gas were determined. Emissions assessments made include NO<sub>x</sub>, CO, particulate loading and size distribution, twelve trace metals and a cursory search for PCB and POMs. NO<sub>x</sub> emissions decreased as the percent RDF increased even though the available fuel nitrogen increased. Particulate loadings from the RDF were concentrated in the less than 1μ size fraction.

This project was supported by EPA Contract 68-02-1885. Mr. H. M. Freeman was the project officer.

## PILOT SCALE EVALUATION OF FOUR REFUSE-DERIVED FUELS

### INTRODUCTION

There is considerable heating value (4000 to 7000 Btu/lbm) associated with municipal solid waste. If this resource could be used in steam boilers rather than lost by incineration, a significant energy resource would be tapped.

Research studies have included using heat recovery incinerators, spreader type stokers and suspension firing in large electric utility boilers. The EPA has supported experiments in cofiring the refuse-derived fuel (RDF) in full scale boilers in St. Louis, Missouri, Ames, Iowa, and Columbus, Ohio (References 1 through 4).

Although these full scale experiments are providing useful data, problems associated with the many varieties of RDF need to be studied. Because the refuse comes from local municipalities, there can be significant variations in the combustion and environmental characteristics of the fuel from season to season or from locale to locale.

There is little published data on the emissions from RDF when cofired with other fuels. Kilgroe (Reference 5) reported that the St. Louis demonstration site produced a moderate increase in chloride emissions but that the RDF did not significantly affect the SO<sub>2</sub> or NO<sub>x</sub> emissions. Little information is available on the amount of trace metals and organics or the nature of the particulates. The work performed here provides the initial data base to answer environmental questions on four RDF's.

## EXPERIMENTAL HARDWARE

The EPA experimental multiburner, furnace facility (Figure 1) was developed to study  $\text{NO}_x$  control technology problems associated with large-scale and utility and industrial boilers. Details on this facility design have been discussed in other papers (References 6 and 7).

The furnace fires from 293 kW-thermal to 880 kW-thermal (1 to  $3 \times 10^6$  Btu/hr) depending on the fuel and heat release per unit volume being simulated. The facility may either be front-wall fired using one to five variable swirl block burners, or it may be corner-fired using four to eight tangentially-fired burners patterned after Combustion Engineering's design.

The standard gaseous emissions ( $\text{NO}$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{SO}_2$ ) were continuously monitored throughout the test program. Particulates were obtained using a high volume EPA method 5 stack sampler; trace metals and organics sampling was obtained using the Source Assessment Sampling System (Reference 3).

The refuse-derived fuel tests were conducted in the main firebox in the tangentially-fired mode. First, a feed system (Figure 2) was designed to control and measure from 10 to 60 lbs/hr of varied refuse-derived materials. RDF is delivered to the upper part of two diagonally opposed corner-fired burners. Natural gas or coal is also delivered to these burners and to the other two burners. The RDF feed system consists of a rotating drum hopper which deposits the material on a conveyor belt. The conveyor delivers the material to a vertical downcomer, where it is pushed through by a blast of air. Additional air at the junction of the vertical downcomer and horizontal feed tube conveys the RDF into the furnace through a horizontal water-cooled feed tube. The RDF feedrate is controlled by a variable speed drive on the feed belt; the drum is maintained at constant optimum speed to keep the feed belt full.

The delivery tube is sized to prevent blockage while minimizing the transport air. This sizing is critical for a small-scale facility where the minimum pipe size is governed by the maximum particle size and the minimum conveyance air needed to keep the material suspended. The received RDF material was shredded from a nominal 2 to 4 inches down to 1 to 2 inches using a conventional garden shredder to reduce the feed tube diameter and transport air flow to an acceptable level.

#### EXPERIMENTAL RESULTS

The test program determined the gaseous, particulate trace metal and organic emissions of refuse-derived fuel from San Diego, California; Richmond, California; the Americology Facility in Milwaukee, Wisconsin; and Ames, Iowa.

All of these materials had gone through metals and glass separation and a primary shredding. Table I shows the composition and heating value for each fuel type.

Figure 3 shows the effect of NO versus excess air for the four fuels at 20 percent RDF and 80 percent natural gas. Although the NO levels are not particularly high, there was a definite difference between the fuels. The NO also increases with both excess air and increases in RDF. Also, when the percent RDF is increased and cofired with coal, the NO levels decrease (Figure 4) while total fuel nitrogen increases. This is possibly the result of enriched fuel jets at the coal-refuse injection guns. Except at very low excess air (5 percent) CO levels were always less than 100 ppm.

Results from the particulate, trace metal, and organics sampling also provide some interesting preliminary information on RDF emissions. Table II shows the results of particulate concentrations in the various size cuts for four RDF materials cofired with natural gas. Although the total particulate quantity was quite low in all cases, the majority of particles were smaller than

1 $\mu$  and collected only on the filter. Although the particulate may be rather friable and break up in the sampling equipment during collection, it may eventually end up in the respirable size range.

Table III shows particulate loading in the same size cuts for two levels of Richmond RDF cofired with coal and for coal alone. With the substitution of RDF, the total grain loadings decreased with increasing RDF. However, in both cases, adding RDF increased the percent of material in the 1 $\mu$  size cut over coal alone. Thus, it appears that adding RDF may increase the grain loading in size cuts less than 1 $\mu$ . This result could produce problems for flyash collection equipment. Percent combustibles in the particulate were generally less than 2 percent except when the excess air levels were 10 percent or less. This result also corresponds to generally low CO (<100 ppm) and unburned hydrocarbon levels.

Table IV lists the total trace metals in micrograms/Btu found in the particulates and the condensible vapor for: (1) coal only, (2) coal plus 10 percent RDF, and (3) gas plus 10 percent RDF. Increases in trace metal concentrations varied among the three tests. In the coal only test, the lead concentration was exceptionally high. In addition, no correlation was found as the percent of RDF was increased.

It is difficult to draw any conclusions from this trace metal data. Several factors may be contributing to the data variability:

- The RDF material is nonhomogeneous and will vary from minute to minute, hour to hour, and season to season
- Metals from the furnace and sampling system could contribute to the trace metal loadings
- Hold up in the convective section
- Analytical error

These factors indicate the need for a broader data base to draw meaningful conclusions on trace metal concentration when cofiring RDF with other fuels. This data will contribute to that base, but a larger sample of data is needed to statistically determine real trace metal effects.

In addition to trace metals, a limited search for organics in terms of (PNA or PCB's) was undertaken. A portion of the particulate and the XAD-2 organic section resin of the SASS train were analyzed by liquid chromatography according to EPA Level 1 procedures (Reference 9). Of the material divided into the standard seven cuts, only cuts two and three were expected to contain PNA and PCB. Therefore, these two fractions were combined for a single GC/MS analysis. Five out of nine tests where organic samples were taken contained no detectable compounds. Test conditions, and the PNA found in the remaining samples, are listed in Table V. No PCB was found in any of the test samples.

Little organic material, combustible CO, and unburned hydrocarbons were found in the particulate and gaseous streams. It has been reported (Reference 5) that significant quantities of unburned material have been found in full-scale tests. These pilot scale tests have higher combustion efficiency over full-scale tests possibly because of the additional shredding and/or hot refractory walls providing an improved ignition source.

In summary, up to 30 percent RDF may be cofired in a subscale test facility without experiencing a reduction in combustion efficiency. Additional studies are necessary to determine how this technology can be implemented in a full-scale facility using the same degree of efficiency but a higher RDF percentage. Furthermore, the flame's heat transfer characteristics must be clearly defined to determine the effect on the boiler steamside or to design a boiler specifically for cofiring RDF. Finally, more data is needed to statistically determine the trace metal and organic makeup of RDF cofired boilers emissions.



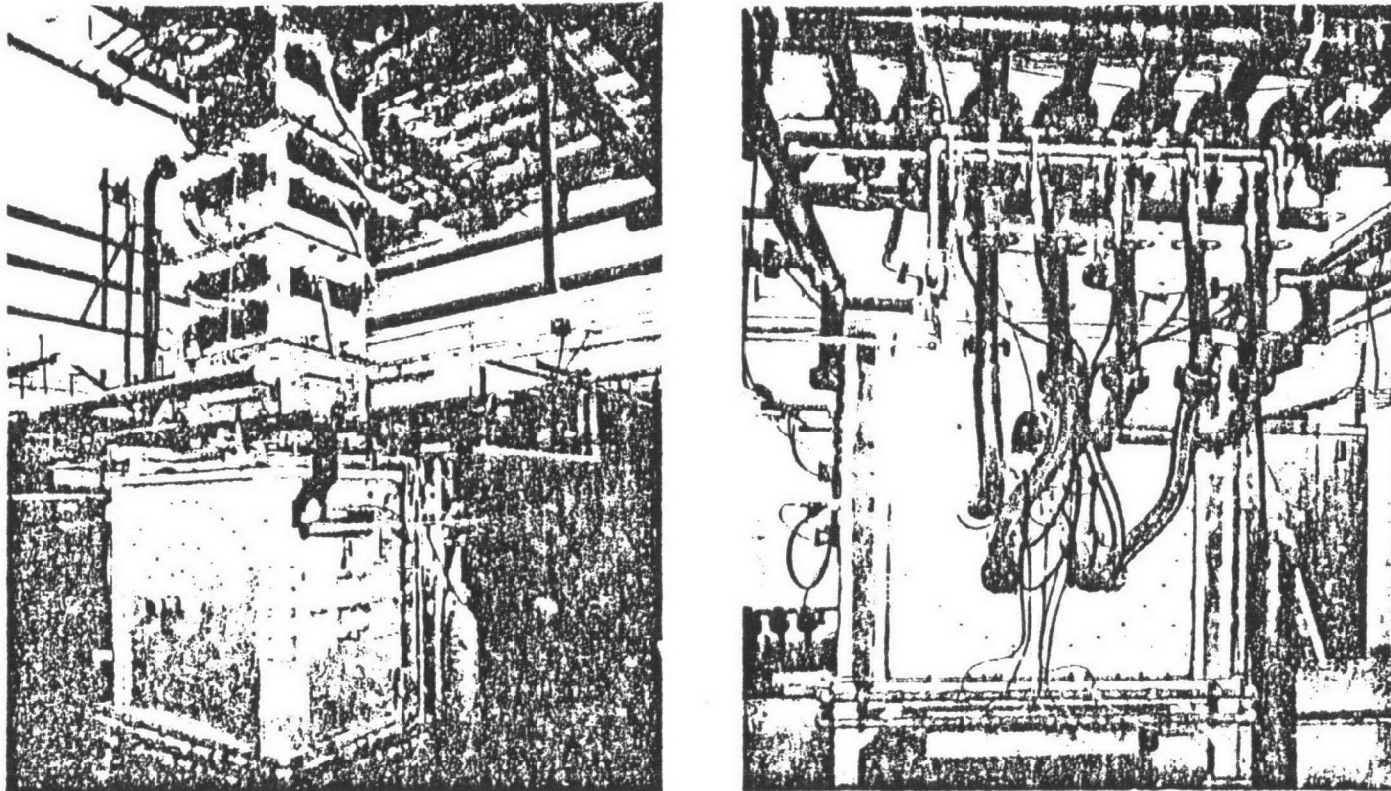


Figure 1. Photograph of experimental multiburner furnace.

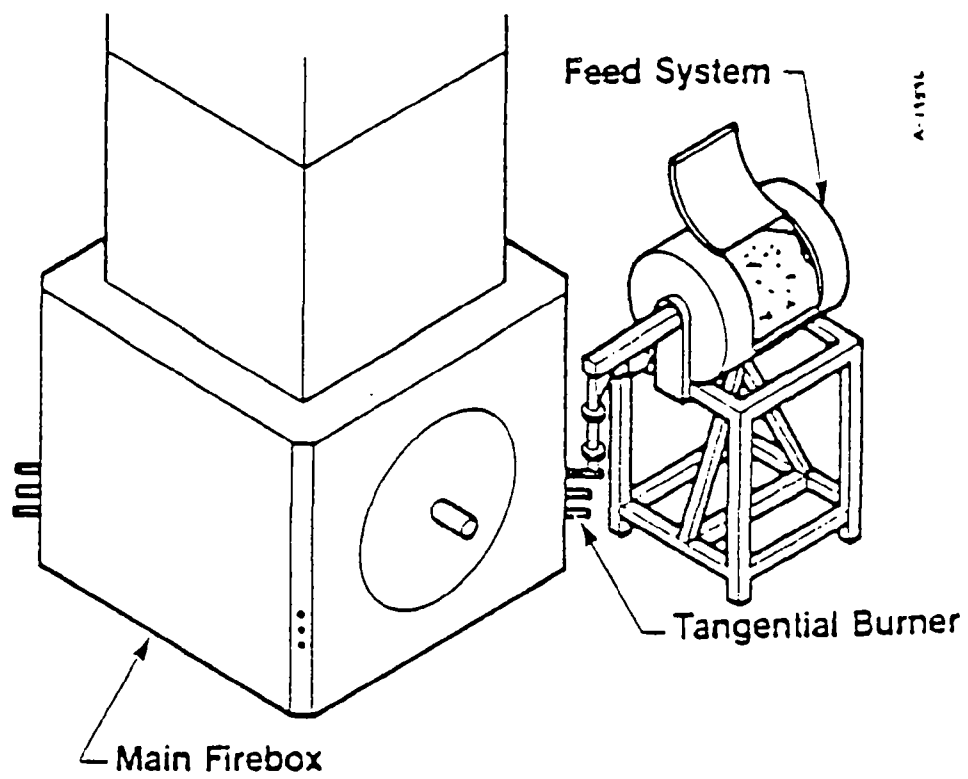


Figure 2. RDF feed system and firebox.

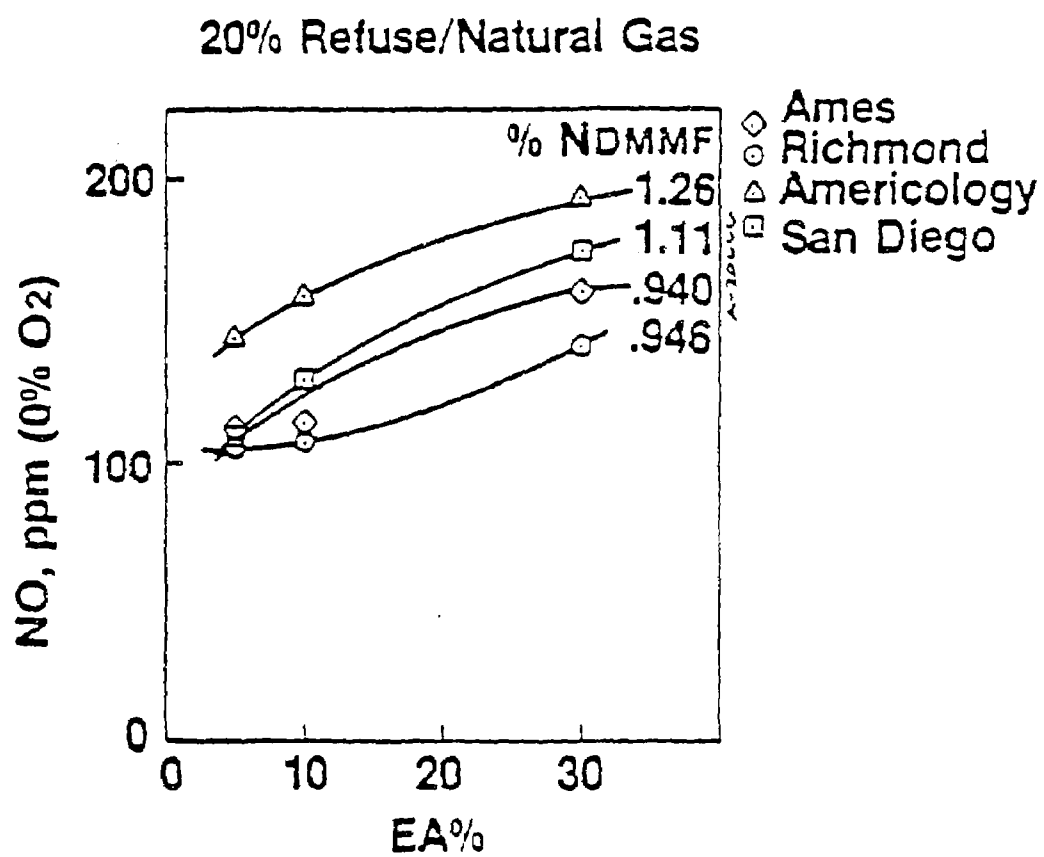


Figure 3. Baseline NO<sub>x</sub> - emissions - RDF and gas.

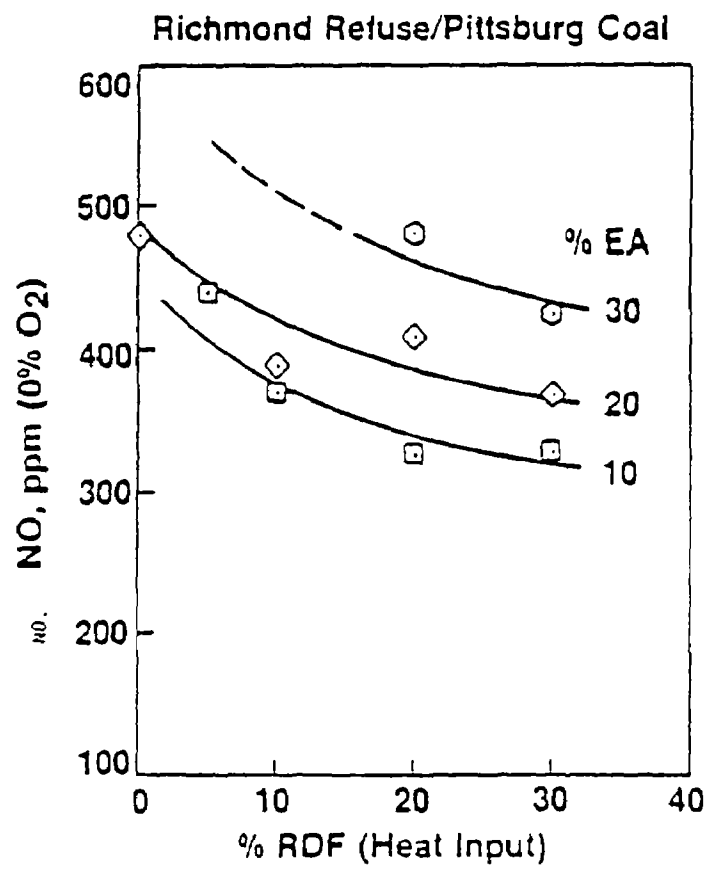


Figure 4. Effect of percent RDF coal and RDF.

TABLE I. RDF FUEL ANALYSES

Ultimate Analysis*	Fuel Type				
	Pittsburg No. 8 Coal	Richmond Refuse	Ames Refuse	Americology Refuse	San Diego Refuse
Carbon %	75.23	42.60	40.49	40.29	38.01
Hydrogen %	5.15	6.26	6.01	5.88	5.64
Oxygen %	8.12	37.90	30.04	25.20	17.40
Nitrogen %	1.49	0.83	0.73	0.91	0.69
Sulfur %	2.51	0.16	0.35	0.17	0.21
Ash %	7.50	12.25	22.38	27.55	38.05
Moisture % (as received)	0.93	23.8	15.2	24.4	26.3
Chlorine %	0.14	.46	.43	.72	.79
Heating Value Btu/lb	13,545	7696	7831	7164	7146

\* Dry Basis

TABLE II. EFFECT OF RDF TYPE ON PARTICULATE SIZE DISTRIBUTION

Fuel	Filter	>10 $\mu$	>3 $\mu$	>1 $\mu$
	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %
20% Ames + Nat Gas	0.039 (69)	0.011 (19)	0.003 (6)	0.004 (6)
20% Richmond + Nat Gas	0.032 (91)	0.0004 (1.)	0.0004 (1)	0.0024 (7)
20% Americo- logy + Nat Gas	0.041 (86)	0.002 (5)	0.002 (5)	0.002 (5)
20% San Diego + Nat Gas	0.062 (80)	0.007 (9)	0.002 (3)	0.006 (8)

TABLE III. EFFECT OF COAL AND RDF CONCENTRATIONS ON PARTICULATE SIZE DISTRIBUTION

Fuel	Filter	>10 $\mu$	>3 $\mu$	>1 $\mu$
	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %	Qty (gr/ft <sup>3</sup> ) %
20% Richmond + Coal RDF	.026 (9.1)	.134 (47.1)	.107 (38.0)	.016 (5.5)
10% Richmond + Coal RDF	.044 (7.6)	.269 (46.1)	.226 (38.8)	.044 (7.6)
Coal Only	.021 (2.1)	.539 (56.3)	.344 (35.9)	.055 (5.7)

TABLE IV. TRACE METAL CONCENTRATION FOR COAL VS 10% RDF + COAL VS 10% RDF + GAS ( $\mu\text{g/Btu}$ )

ELEMENT	Coal Only Test #40 <sup>a</sup>	10% RDF + Coal Test #38 <sup>a</sup>	10% RDF + Gas Test #11b <sup>a</sup>
Cu	1.9581	<0.3319	0.3402
Zn	0.5294	0.8227	0.4468
Mn	0.1526	<0.2693	0.0209
Pb	17.5319	0.3091	1.4996
Cd	0.0091	0.0048	0.0062
Be	<0.0176	0.0013	<0.0034
Tl	<1.7540	<0.0587	<0.0277
Sb	<0.0020	<0.0090	0.0333
Sn	0.1300	<0.0913	<3.5033
Hg	<0.0015	<0.0173	<0.0009
As	<0.0881	<0.0323	<0.0184

<sup>a</sup>20% excess air



TABLE V. ORGANICS FOUND

Test Condition	Organic	Amount (ug/10 <sup>6</sup> Btu)
Gas Cofire 10% RDF 20% EA Ames Fuel	Fluoranthene Pyrene	10 332
Gas Cofire 10% RDF 20% EA Richmond Fuel	Phenanthrene Fluoroanthene Pyrene Diphenyl Ether Biphenyl Phenylether	64 160 576 3395 1697
Gas Cofire 10% RDF 20% EA Americology Fuel	Phenanthrene Pyrene	59 104
Coal Cofire 10% RDF 20% EA	Phenanthrene	98

## REFERENCES

1. Vaughan, D. A. and Associates. Report of First Year Research on Environmental Effects of Utilizing Solid Waste as a Supplementary Powerplant Fuel, Battelle Columbus Ohio Laboratories, EPA Research Grant R-804008, June 1975.
2. Nydick, S. E. and Hurley, J. R. Study Program to Investigate Use of Solid Waste as a Supplementary Fuel in Industrial Boilers, Thermo-Electron Corporation. EPA Contract No. 68-03-3005, January 1976.
3. Riley, B. T. Reliminary Assessment of the Feasibility of Utilizing Densified Refuse Derived fuel (DRDF) as a Supplementary Fuel for Stoker Fired Boilers, published report to EPA, 1975.
4. Vaughan, D. A., Krause, H. H., Hunt, J. F., Cover, P. W., Dickson, J. D., and Boyd, W. K. Environmental Effects of Utilizing Solid Waste as a Supplementary Powerplant Fuel. Seventh Quarterly Progress Report, EPA Research Grant 804008-02-1, 1975.
5. Kilgroe, J. D., Shannon, L. J., Gorman, P. Environmental Studies on the St. Louis Union Electric Refuse Firing Demonstration.
6. Brown, R. A., et al. Pilot Scale Investigation of Combustion Modification Techniques for NO<sub>x</sub> Control in Industrial and Utility Boilers. EPA-600/2-76-152b. Proceedings of the Stationary Source Combustion Symposium, Volume II, June 1976.
7. Brown, R. A., et al. Investigation of Staging Parameters for NO<sub>x</sub> Control in Both Wall and Tangentially Coal-Fired Boilers. EPA-600/7-77-073C. Proceedings of the Secondary Stationary Source Combustion Symposium, Volume III, Stationary Engine, Industrial Process Combustion Systems, and Advanced Processes, July 1977.
8. Blake, D. Source Assessment System Design and Development, EPA-600/7-78-018, August 1977.
9. IERL/RTP Procedures Manual: Level 1, Environmental Assessment, Second Edition. June 1976.

APPLICATION OF SLIPSTREAMED AIR POLLUTION  
CONTROL DEVICES ON WASTE-AS-FUEL PROCESSES

Fred D. Hall, John M. Bruck, and Diane N. Albrinck  
PEDCo Environmental, Inc.

Robert A. Olexsey  
U.S. Environmental Protection Agency

INTRODUCTION

PEDCo is currently involved in an EPA contract for testing and evaluating prototype air pollution control devices on various waste-as-fuel processes for the control of potential harmful air emissions. As part of the contract, sampling and analysis programs were conducted at the RDF and coal cofiring facility in Ames, Iowa and the mass burn incineration facility in Braintree, Massachusetts. These programs involved evaluating the pollutant removal efficiency of a pilot fabric filter, a pilot scrubber, and a pilot ESP. The objective of the program was to determine pollutant removal efficiencies of each device for variable process and control device operating parameters. Operation and testing of the control devices took place in October and November 1978 and June through October, 1979.

This project focused on three primary thermal waste-as-fuel technologies: 1) Co-firing - The combined firing of a solid, largely cellulosic waste with coal, oil, or natural gas in a modified conventional boiler, 2) Mass burn incineration - The combustion of unprocessed or processed solid wastes in water-wall incinerators for the generation of steam, and 3) Pyrolysis - The thermochemical decomposition of solid wastes in an oxygen-starved environment that converts a heterogeneous waste material into a liquid, gaseous, or solid fuel product.

These technologies were studied with respect to atmospheric pollution and potential control techniques in various phases as follows: 1) Collection of data on known and potential air pollutants for waste-as-fuel processes, 2) Assessment of air pollution control devices applicable to waste-as-fuel processes, 3) Determination of the best air pollution control devices to be developed as pilot-scale air pollution control devices for the most

significant problems associated with waste-as-fuel processes, 4) Procurement of two to four pilot-scale air pollution control devices, and 5) Operation of the pilot-scale units to generate and analyze data.

Midwest Research Institute (MRI), concurrent with the PEDCo effort, conducted a comprehensive environmental assessment of various resource recovery operations for EPA. Data from this project provided valuable technical information for the PEDCo study with respect to test site and control device selection, and air pollution problems associated with waste-as-fuel processes.

#### PRELIMINARY PROGRAM

The nature and magnitude of atmospheric pollutant emissions from waste-as-fuel processes were investigated as were the requirements for emission control technology. The focal point of the study was the combustion process. Pyrolysis processes are still under development and no continuously operating systems were available for testing. Therefore, pyrolysis was not of primary interest in this project.

Waste preparation (preprocessing) as well as the combustion process were studied. Particulate was the most apparent problem associated with waste preprocessing but for the combustion process, trace elements in the particulate as well as gaseous chlorides and mercury vapor were also of interest. Previous studies had theorized that there logically should be an increase in particulate emissions when co-firing RDF and coal versus coal-firing alone because of the normally greater ash content of RDF versus coal and an expected decrease in control device efficiency. Although the MRI study did not show a definite increase in particulate emissions for co-fired boilers, gaseous chlorides as well as trace elements in the particulates such as lead, copper, and zinc were shown to increase when burning RDF plus coal versus coal alone while others, such as iron and calcium were shown to decrease.

From an air pollution control technology standpoint, PEDCo investigated state-of-the-art technologies (e.g., fabric filter, ESP, and scrubber) for control of waste-as-fuel processes as well as more novel devices (e.g., wet ESP's, jet ejector scrubbers, etc.). Fabric filters have been successfully applied to preprocessing operations and ESP's are the most common air pollution control equipment used on co-fired boilers and mass burn incinerators. Full scale fabric filters have not been applied to waste-as-fuel combustion processes and wet scrubbers have been

used on incinerators with less success. Since state-of-the-art devices effectively controlled pollutants of concern from waste-as-fuel processes, the other more novel devices were not considered for the PEDCo test program.

## TEST PROGRAM

Early in the project, several waste-as-fuel facilities were visited as a prelude to later, more extensive test site selection and to observe the effectiveness of the applied control technologies. Table 1 describes those sites visited.

TABLE 1. PEDCo RESOURCE RECOVERY SITE VISIT SUMMARY

Generic technology	Plant location	Preprocessing product	Preprocessing emissions control	ROF combustion equipment	Combustion emission control device
Co-firing	Ames, Iowa	Fluff	Baghouse system	Pulverized coal and stoker-boiler	ESP
	Chicago SW	Fluff	Baghouse system	Pulverized coal boiler	ESP
	Columbus, Ohio	Shredded waste	None	Stoker-boiler	Cyclone
	Hagerstown, MD. Milwaukee, Wis.	Pellets Fluff	None Baghouse system	Stoker-boiler Pulverized coal boiler	Cyclone ESP
Mass burn	Chicago, NW	Bulky items removed	Not applicable	Incinerator/boiler	ESP
	Harrisburg, Pa.	Bulky items removed	Not applicable	Incinerator/boiler	ESP
	Nashville, Tenn.	Bulky items removed	Not applicable	Incinerator/boiler	ESP
	Saugus, Mass.	As received refuse	Not applicable	Incinerator/boiler	ESP
	Hamilton, Ontario Braintree, Mass.	Pulverized refuse As received refuse	None Not applicable	Incinerator/boiler Incinerator/boiler	ESP ESP
Pyrolysis	South Charleston, W. Va.	Shredded waste	None	Open burner	None
Other	Fairmont, Minn.	Shredded waste	None	Incinerator/boiler	Wet scrubber
	Houston, Texas	Shredded waste	Baghouse	Cement kiln (co-fired with gas)	Wet scrubber
	Minneapolis, Minn.	Dewatered sludge	None	Multi-hearth sludge incinerator	None

From these sites, the Ames, Iowa cofiring facility and the Braintree, Massachusetts incinerator were selected as test sites because of the cooperation of the management, availability of data from the MRI source assessment project, high reliability of the preprocessing and utility operations, and limited facility modifications required.

The execution of a program of this type relies heavily on the cooperation of plant management. The administrative, operating, and maintenance staffs of the Ames Municipal Electric System and the Braintree Municipal Incinerator provided EPA and PEDCo with invaluable assistance throughout the program.

Concurrent to the site selection process, available pilot air pollution control devices were investigated. Suitable pilot ESP's and scrubbers were available from vendors and IERL/RTP. A transportable pilot fabric filter typical of a full scale unit was not available for the test program. Since the fabric filter testing was to be an integral part of the test program, a 1.4 m<sup>3</sup>/s (3000 acfm) pilot fabric filter was designed and assembled by PEDCo for IERL/Cincinnati.

The project objective for both test sites was to characterize the specific pollutant removal efficiencies of each control device for different boiler loads, RDF inputs, and operating parameters. It has been assumed that any full-scale application of these control devices to a coal- and RDF-fired boiler must operate with varying flue gas temperatures and compositions. A plan was developed to monitor and measure these two factors, but not to modify or control them.

The IERL/RTP mobile ESP and scrubber as well as the IERL/Cincinnati pilot fabric filter were slipstreamed on Ames' Boiler 7. The scrubber and ESP were tested in October and November 1978 while the fabric filter was tested in June and July 1979. Ames Boiler 7 is a tangential fired pulverized coal unit with a 33 MW capacity. During the test program, RDF supplied from 0 to 25 percent of the total boiler heat input. The scrubber was tested both upstream and downstream (primary and secondary) of the existing full scale ESP and the mobile ESP and fabric filter were tested only as primary devices.

At Ames, total uncontrolled particulate emissions did not appear significantly different when comparing coal only tests to coal plus RDF tests. Some uncontrolled trace elements and gaseous chlorides increased significantly when burning RDF plus coal. Lead and zinc emissions concentrations were about 3 times higher and gaseous chlorides emission concentrations were about ten times higher when burning 25 percent RDF plus coal than when burning coal alone.

The scrubber operated at pressure drops of 25.4 and 76.2 cm (10 and 30 in.) H<sub>2</sub>O. The particulate removal efficiency of the scrubber was consistently above 99 percent when used as a primary device but considerably less (72 to 97 percent) when used as a secondary device. The particulate removal efficiency of the ESP ranged from 94 to 98 percent and of the fabric filter above 99

percent. Neither scrubber, ESP, or fabric filter particulate removal efficiencies changed appreciably as the portion of heat input supplied by RDF increased. The efficiency of trace element removal was typically less with the scrubber than with the ESP or fabric filter. For example, lead removal efficiency was about 90 percent with the scrubber, but greater than 95 percent with the ESP and fabric filter. Alternatively, the gaseous chloride removal efficiency was greater than 95 percent for the scrubber but negligible for the ESP and about 20 percent for the fabric filter.

At Ames, the full scale fabric filter controlling the pre-processing system was tested to determine its particulate removal efficiency. The fabric filter controlling the 140 Mg (150 tons) per eight hour day plant operates at 22.4 m<sup>3</sup>/s (47,000 acfm) and collects the in-plant air via hoods located at critical dusting points, especially transfer points. The cleaned air from the fabric filter is discharged back into the resource recovery plant. The tests showed average inlet and outlet concentrations of 446 mg/m<sup>3</sup> and 9.73 mg/m<sup>3</sup> respectively for an average particulate removal efficiency of 97.8 percent.

The IERL/Cincinnati pilot fabric filter and a pilot venturi scrubber from Neptune/Airpol were slipstreamed as primary controls on the Braintree Municipal Incinerator. These control units were tested August through September 1979. The Braintree plant has two waterwall incinerators with a design capacity of 5 tons of unprocessed refuse per hour each. Incinerator No. 1 which operates continuously was used for testing, and it is controlled by a Wheelabrator-Frye ESP.

The pilot fabric filter that was tested at the Ames site was transported to Braintree and slipstreamed upstream of the full scale ESP. The fabric filter was automatically operated and functioned 24 hours a day. By varying operating conditions of the fabric filter and maintaining steady-state conditions at the furnace and boiler, the control performance of the fabric filter was evaluated with respect to: precoat, pressure drop, air-to-cloth ratio, and cleaning mechanism. A lime precoat was added to the flue gas stream during some of the tests upstream of the fabric filter but downstream of the inlet sampling location. The pressure drop across the fabric filter ranged from 8.9 to 15.8 cm (3.5 to 6.2 in.) of water. The cleaning mechanism was reverse air, shake, or both. Varying the air-to-cloth ratio from 1.1 to 2.0 did not significantly effect the pollutant removal efficiencies. The cleaning mechanism also did not appear to have a perceptible affect on performance, however the amount of time necessary for each mechanism varied. Shaking took the longest, reverse air next and both took the least amount of off-line cleaning time. The particulate removal efficiency averaged 95.2 percent for all tests. Most trace element removal efficiencies

were consistent with the particulate removal. Sulfur oxides were not effectively controlled by this device, however precoating the fabric with lime roughly doubled the SO<sub>x</sub> removal efficiency (20 to 40%), when compared to the "without precoating" tests. Gaseous chloride removal efficiency for "without precoating" tests averaged 28 percent, and increased to 38 percent with the lime precoat.

The scrubber used at this site was a pilot venturi scrubber rented from Neptune/Airpol. It was installed on Braintree's incinerator no. 1, using the same slipstream duct work as the pilot fabric filter. The pilot scrubber operated unfiltered, recirculating scrubber liquor. The pH was controlled through addition of soda ash. The liquid-to-gas ratio ranged from 5.5 to 18.4 gal/1000 ft<sup>3</sup> and the pressure drop ranged from 10 to 32 in. H<sub>2</sub>O. The particulate and trace metal removal efficiencies for the scrubber were much lower than the pilot fabric filter, however, gaseous chlorides were removed with 96.5 percent efficiency.

The scrubber tests showed some re-entrainment of particulate in a few of the runs due to poor demister removal of water droplets. The particulate removal efficiency averaged 72 percent during tests in which re-entrainment was minimized.

In summary, the fabric filter performed more effectively than the scrubber in removing particulate pollutants but not gaseous compounds.

Currently, all field and analytical work is completed on this project. One report entitled "Evaluation of Fabric Filter Performance at Ames Solid Waste Recovery System" is in preliminary draft stage and evaluates the particulate control achieved by the fabric filter at the Ames RDF plant. Two other reports are presently being prepared, one covering the evaluation of the mobile ESP, scrubber and fabric filter tests conducted at the Ames Power Plant, and the other report will discuss results of our tests of the mobile fabric filter and scrubber at the Braintree mass burn incinerator.



TREATMENT OF WASTEWATERS FROM  
REFUSE-TO-ENERGY SYSTEMS

BY

GORDON P. TREWEEK, Ph.D.  
MEMBER ASCE

ABSTRACT

This paper discusses the wastewater treatment technologies that can be effectively utilized at WAF facilities to treat waterborne pollutants. The principal water-borne emissions contain organic surrogates (BOD, COD, TSS) in concentrations up to 100,000 mg/l at pyrolysis units; organic priority pollutants in concentrations up to 100 mg/l at pyrolysis and digester units; and trace metals in concentrations up to 1,000 mg/l in incinerator scrubbers. The efficacy of aerobic, anaerobic, and physical chemical treatment steps on the wastestreams produced at incinerators, hydropulping facilities, pyrolysis units, and digesters is projected and potential treatment trains are recommended.

INTRODUCTION

During the past ten years, shortages of basic raw materials such as ferrous metals, scrap paper, and fuel oil have prompted private and governmental agencies to investigate the recovery of valuable materials from solid wastes.

James M. Montgomery, Consulting Engineers, Inc.  
555 East Walnut Street, Pasadena, California 91101

For example, the fuel shortage of late 1973 and the subsequent dramatic increase in fuel prices have resulted in a major effort to find alternative sources of energy. One possible source of energy is the solid waste generated from municipal, agricultural, and forestry operations. Although the composition of these wastes varies widely with the type of enterprise, consumer habits, geographical location, time of year, and numerous other factors, the waste streams invariably contain a high organic content which can be either directly combusted or converted to conventional fuels. Without some form of recovery of their material and energy properties, the increasing quantities of solid waste, along with projected depletion of economical waste disposal sites, constitute a growing waste disposal problem. Thus, the increased cost of fuel and raw materials coupled with the increased concern over the environmental impact of disposing large volumes of solid wastes, has prompted significant investigation into waste-as-fuel (WAF) processes. This paper discusses one aspect of WAF processes: the water pollutants produced and the technology available to treat these wastes.

#### WASTESTREAM IDENTIFICATION

A two-step procedure is followed in processing refuse into useable fuel: preprocessing and conversion. Preprocessing consists of a series of physical operations which size, classify, and segregate the raw refuse into useable fractions. Conversion consists of one of the following four unit operations: combustion (mass incineration or co-firing), pyrolysis, anaerobic digestion, or methanation. From a water pollution control standpoint, filtrate from hydropulping (preprocessing), incinerator scrubber

washwaters, pyrolysis condensate, centrate from anaerobic digesters, and leachate from landfills (methanation) constitute the major sources of wastewater.

The extent of water use and wastewater production are primarily dependent upon the type of process utilized for preparing the municipal solid waste (MSW) and the actual combustion process itself. Wastewater streams range from very small quantities of high organic demand wastewater, such as that associated with the condensate of pyrolysis units, to relatively large volumes of low organic demand wastewater, such as that utilized to sluice ash residue from mass burn combustors. Four major categories of pollutants were identified in the wastestreams at WAF facilities: the organic surrogates (BOD, COD, TSS), which measure the oxygen demand of the wastewater on the receiving water body; the mineral quantity, specifically corrosive agents such as chlorides and sulfates, and the hydrogen ion concentration; the organic priority pollutants including total organic carbon and total organic nitrogen; and the heavy metal priority pollutants. While in most cases, good data were available on the organic surrogates and the mineral quality of wastewater produced at refuse-derived-fuels (RDF) and WAF facilities, very little information was available on the organic and heavy metal priority pollutants.

#### PREPROCESSING

The extent of wastewater production in preprocessing operations depends almost exclusively on whether wet or dry preprocessing steps are utilized.

In dry preprocessing operations, wastewaters are produced in small quantities at only a few locations. Water is used rarely in the actual process since any moisture added to the RDF must be eventually evaporated in the conversion facility. The primary uses for water are dust control, fire fighting, and clean-up activities. Water is also used occasionally in some types of material separation units, such as those recovering aluminum and glass. Wastewaters primarily originate from washdown operations, drainage from storage pits, and the above-mentioned materials recovery processes. Trash confined in the storage pit may leach compounds such as pesticides and organic solvents which can have adverse effects on wastewater treatment, but these conditions must be evaluated on an individual basis and treated accordingly. In most cases the wastewater from dry preprocessing operations can be discharged safely to sanitary sewers.

In contrast to dry preprocessing, wet preprocessing or pulping of MSW involves placing the material into a large hydropulper, analogous in operation to a household garbage grinder. A thick slurry of MSW is formed with heavy particles of ferrous materials and other non-ferrous materials separated by centrifugal action. The slurry containing the organic fraction, glass, and small pieces of metal is segregated into light and heavy fractions via liquid cyclone. The light organic fraction is dewatered by screening and pressing, and the liquid waste stream is recirculated to the pulper. The dewatered pulp can be cleaned and dried for use in paper products or burned for energy production.

Depending on the combination of energy recovery and materials separation,

water is required for pulping, cleaning, equipment cooling, and resource recovery. In most cases the quality of water is not critical, which permits the use of non-potable supplies such as sewage treatment plant effluents and sludges. By far the largest quantity of water is required by the hydropulper. Water for the hydropulper can be obtained from the dewatering and material recovery units through recirculation.

Three sources of wastewater exist in the hydropulping system: the wastewater blowdown from the recycling hydropulping system, the sludge/slurry mixture which has been dewatered in the cone press, and the effluent from air pollution scrubbers. These wastewaters are characterized by their large volume and high organic content. (Table 1.)

#### CONVERSION

Following preprocessing, the MSW is converted either directly into energy or into fuels for combustion. Our study found wastewaters associated with the two principal combustion processes; the mass burn incinerator and the co-firing boiler; the anaerobic digestion process; and the pyrolysis process. The latter two processes produce fuels for subsequent combustion.

The wastewaters from combustion processes consist primarily of site drainage and washwaters; quench and sluice waters; boiler blowdown; and scrubber effluent. The first three categories of wastewater are generally small in quantity or of low strength and can be discharged directly into sanitary sewers. The largest quantity of water is used for scrubbing exhaust gases. Waterwall incinerator facilities help keep water use to a minimum by using

electrostatic precipitators and dry handling systems for ash. While electrostatic precipitators are preferred from a water pollution control viewpoint, nevertheless wet scrubbers may be required for the removal of gaseous chlorides and  $\text{SO}_2$  in order to meet air quality standards. The scrubber waters are generally acidic, with pH's in the range 2.5 to 5.0. The total solids concentration varies from 500 to 7000 mg/l with about 80-85 percent being dissolved solids. The chloride, hardness, sulfate, and phosphate concentrations of the incoming raw water are significantly increased after passing through the scrubber. Furthermore, the scrubber wastewaters often contain high concentrations of trace metal priority pollutants which must be removed prior to discharge to either the sanitary sewer or the ambient receiving water. (Table 2.)

Pyrolysis involves heating a preprocessed MSW to a sufficiently high temperature in a low-oxygen environment so that the organic components break down chemically. The heat for pyrolysis of MSW usually is obtained by totally oxidizing part of the refuse. The pyrolysis reaction produces three components: 1) a gas consisting primarily of hydrogen, methane, carbon monoxide, and carbon dioxide; 2) an oily or liquid fraction which contains organic chemicals such as acetic acid, acetone, and methanol plus water derived from hydrolysis or organic compounds, and 3) a solid char fraction consisting of unburned carbon plus inert materials such as glass.

Water is used in pyrolysis plants for cooling, gas scrubbing, char quenching, and miscellaneous housekeeping. Wastewater streams of major concern are those collected from scrubbers, condensers, and other gas cleaning devices.

These wastewaters usually are high strength and contain a variety of organic materials formed during the pyrolytic reaction or vaporized from the raw RDF. A BOD<sub>5</sub> in the range 50,000 to 100,000 ppm is caused by water-soluble organics such as alcohols, organic acids, and aldehydes. BOD's in this range are too high for conventional activated sludge and must be pretreated by other processes. In addition to the high organic strength, the pyrolysis condensate is characterized by high concentrations of organic priority pollutants such as phenol, benzene, and toluene; and the gas scrubber waters are characterized by high concentrations of trace metal priority pollutants. (Table 3.)

Anaerobic digestion of sewage sludge to produce methane gas has been a common practice in sewage treatment, however, anaerobic digestion of MSW is only in the developmental stage at this time. A system for digesting the organic part of municipal trash in a mixture with sewage sludge is currently under shake down testing in Pompano Beach, Florida. Two wastewater streams are anticipated: storage pit drainage and a liquid effluent generated from dewatering the digested sludge. No data are available on the composition of these waste streams when MSW is digested with the sewage sludge. We anticipate that the dewatered filtrate from the digestion of combined MSW/sewage sludge will be similar to that which exists at normal sewage sludge digesters. Thus, the wastewaters will be characterized by high BOD's, in the range 500-10,000 mg/l and high concentrations of organic priority pollutants, in the range of 650-3,800 mg/l. (Table 4.)

In summary, although many sources of wastewater exist at RDF and WAF

facilities, the quantities and strengths of the wastewater are often small. Consequently, these wastes can usually be discharged directly into the sanitary sewer or held for a brief period in an oxidation pond before discharge to ambient receiving waters. In addition to these small insignificant sources, we found several major waste streams generated in RDF/WAF facilities. The exact quantities and strengths of these wastes are highly dependent upon the operating characteristics of the particular facility. Important constraints on operating characteristics have been 1) the local air and water quality standards, and 2) the availability of sanitary sewers.

The major waste streams of concern, associated with current RDF/WAF facilities, are:

- 1) Pressate from the dewatered subsystem of the hydropulping wet preprocessing facility. This wastewater is characterized by moderate BOD/COD (less than 10,000 mg/l), moderate suspended solids (less than 10,000 mg/l), and acidic pH (pH less than 7.0).
- 2) Pyrolysis condensates and gas scrubber effluents. These wastewaters are characterized by very high (greater than 10,000 mg/l) BOD/COD, low (less than 1,000 mg/l) suspended solids, and high organic content, especially phenols and benzene compounds.
- 3) Filtrate and supernatant from anaerobic digesters. These wastewaters are characterized by high (greater than 10,000 mg/l) BOD/COD, high (greater than 10,000 mg/l) suspended solids, and neutral pH's.
- 4) Gas scrubber effluent from combustion facilities. These wastewaters



are characterized by low (less than 1,000 mg/l) BOD/COD, low (less than 1,000 mg/l) suspended solids, variable pH, and the presence of heavy metals.

#### PROJECTED TREATMENT EFFICIENCIES

The efficiencies of pollution control technologies applicable to the identified waste streams are discussed in the following paragraphs.

As presented earlier, the principal waterborne emissions are the organic surrogates (BOD, COD, TSS), the organic priority pollutants, and trace metals. The first two are efficiently treated with biological processes, either aerobic or anaerobic; whereas the latter are successfully removed via physical-chemical processes. Physical-chemical methods are also effective in removing organic surrogates but the total cost is higher than with usual biological processes. Similarly, some adsorption and removal of trace metals occurs in biological processes, but this removal is incidental to the real purpose: the conversion of soluble organic material into microorganisms and gas.

Waste streams identified as quench water, sluice water, and ash pond effluent associated with mass burn and co-firing incinerators are readily treated with existing control technology. Other waste streams such as the scrubber waters at mass burn and incinerator facilities and digester supernatants at the anaerobic digester facilities appear amenable to treatment via physical-chemical and aerobic biological processes, respectively. Which of the two control processes would be most successful in treating these wastes or whether the control processes may be required in tandem should be investigated in pilot studies. The remaining two

waste streams, the pyrolysis gas scrubber water and the thickner wastewater from the hydropulping process have far greater strength than normally associated with domestic wastewater. Pilot plant data (14-19) indicate that these wastewaters should be amenable to treatment by anaerobic processes; the pyrolysis gas scrubber water being especially adaptable to the anaerobic filter treatment process because of low suspended solids and elevated temperatures, the hydropulping wastewater being amenable to the anaerobic biological contact process because of its high suspended solids. Both of these treatment processes are in the developmental stage and will require verification testing to determine operating parameters and applicability to particular waste streams.

Aerobic biological processes can be applied effectively to any of the organic pollutants identified earlier. Under aerobic conditions, the soluble organic matter in a waste stream is converted into active biomass. Organic removal efficiencies of aerobic processes range between 80 and 90 percent. The removal efficiency of soluble organic material from the liquid phase is actually greater; however, enough solids escape the final clarification process to reduce the overall efficiency.

The efficiencies of the various treatment steps discussed above in removing significant pollutants from pertinent industrial discharges are presented in Table 5. The listed industries produce wastestreams similar to those encountered in RDF-WAF facilities.

#### RECOMMENDED PILOT PLANT STUDIES

Based on the strengths of wastewaters produced at RDF-WAF facilities, and the anticipated removal efficiencies of various treatment processes, pilot plant studies are recommended to verify removal efficiencies and to determine whether linkage of processes in series is required to meet discharge standards. The pilot plant studies would investigate the effectiveness of aerobic, anaerobic, and physical-chemical processes in obtaining the desired effluent quality.

Two main aerobic processes are available: filters and activated sludge. In the biological filter, waste is applied continuously or intermittently to the top surface of the filter. Natural rocks or ceramic or plastic fill material have been successfully used as filter media. Air is circulated through the filter either by natural convection or forced draft to maintain aerobic conditions throughout the depth of the media. A diverse population of microbes and microlutes live on the surface of the media and utilize the waste either directly or as high food chain consumers.

In the activated sludge process, the microbial population is dispersed in the liquid phase. The population is less diverse but more concentrated than in a biological filter. Air is introduced into the liquid phase to maintain aerobic conditions and to keep the microbial population in suspension. Organic removal in activated sludge can be improved by increasing the number of microorganisms in the mixed liquor or the period of contact of the waste with the microorganisms.

In order to provide flexibility in the operation of an aerobic pilot plant, both the biofilter and the activated sludge processes should be constructed. The biological filter can be selectively inserted into the treatment train in front of the aeration tank. In addition to overall increased efficiency, the diverse biota of the biological filter are resistant to shock loadings and toxic elements, thus affording a degree of protection against upset not available in an activated sludge process alone. The effective depth of the biological filter can be varied, as can the amount of flow path of recirculation within the filter. Waste streams with high COD will probably require the use of a biological filter as a first stage roughing filter prior to activated sludge treatment.

The activated sludge aeration stage should be designed as a completely mixed reactor; a configuration suitable for high organic loads and easy operation. The aeration tank should be divisible into four compartments to facilitate variation of aeration time. The aeration system can be converted from air to pure oxygen.

Anaerobic treatment is well adapted to target waste streams containing high concentrations of organic surrogates. An exception to the above statement is the digester supernatant, where the efficacy of treating the effluent from an anaerobic treatment system with another anaerobic treatment system is dubious.

The efficiency of anaerobic processes appears to increase with higher

concentrations of organic surrogates and high temperatures in the anaerobic reaction vessel. Thus, an anaerobic treatment process is ideally suited for a warm, concentrated waste stream. The pyrolysis waste is the primary candidate for anaerobic treatment because of its concentration and elevated temperature. Another likely candidate is the hydropulping waste stream.

Based on the available data for waste streams at WAF facilities, two anaerobic treatment processes are recommended for construction in the anaerobic pilot plant. These processes are the anaerobic filter and the anaerobic contact chamber. In the anaerobic contact process, the solids retention time is increased by recirculating sludge removed in the secondary sedimentation tank. The anaerobic filter, on the other hand, retains the sludge within the primary vessel; both on the media and between the voids of the media. In anaerobic processes the conversion of soluble organics to gases is high; eighty percent gas ( $\text{CH}_4 + \text{CO}_2$ ) to twenty percent sludge production is not uncommon. Because of this, anaerobic processes can treat large quantities of organic waste with only a moderate build up of sludge. Indeed, low sludge generation and methane production are the two major advantages of anaerobic treatment.

Operating experience with both types of anaerobic processes is scant. Our literature review showed only one full-scale operation of the anaerobic filter and no full scale operation of the anaerobic contact chamber. In spite of these limited operations, both processes have significant advantages over aerobic treatment. The anaerobic filter is simple to operate, does not require sludge recirculation, and requires construction of only one vessel.

The physical-chemical treatment process is directly applicable to the treatment of wastes found in incinerator scrubber waters. Furthermore, the process may be combined with either the aerobic or anaerobic treatment processes to produce an effluent acceptable for discharge to ambient receiving waters.

Since a physical-chemical pilot plant may be used in a tertiary role as well as by itself, the flow must be compatible with the other pilot plants, particularly with the aerobic unit. Extensive bypass capability must be provided so that in the tertiary treatment mode, individual unit processes can be inserted or removed as desired. The unit processes of flocculation, sedimentation, filtration, and carbon adsorption should be provided in the physical-chemical pilot plant.

Operational variables that can be controlled for experimental purposes are 1) the chemical dose--variation in amount and type of primary coagulant and filter aid; 2) flocculation--flocculation energy input, detention time, and sludge-solid content; 3) filtration--filter media design and filtration rate; 4) carbon adsorption--contact time in the adsorption column.

Unlike the biological units, the physical-chemical pilot plant does not require a period of cell growth and acclimation upon startup. Most modifications to the treatment process can be accomplished in a matter of minutes. Housing the physical-chemical processes in a separate trailer will provide additional flexibility in the sequential or concurrent operation of the different processes on the WAF waste streams.

Based on the waste streams generated in WAF facilities, and the available wastewater treatment processes and efficiencies, combinations of treatment

processes may be required to achieve the effluent limitations for discharge to ambient receiving waters. In most cases, the use of a single treatment process will produce an effluent acceptable for discharge to a publicly-owned treatment works. However, in virtually all cases, a physical-chemical process following either an anaerobic or aerobic process will be required to polish the effluent and thereby meet discharge standards for surface waters.

For hydropulping waste streams, either anaerobic or aerobic processes should be effective in producing a 90 percent reduction in the high BOD and COD of these wastewaters. For comparison purposes, two anaerobic processes, the anaerobic filter and the anaerobic contact chamber will be operated in parallel along with the aerobic pilot plant, consisting of a roughing filter and activated sludge aeration. Based on the efficiencies of these processes, the effluent should be acceptable for discharge to POTW. For discharge to surface waters, a physical-chemical pilot plant must be utilized to further reduce both organic and inorganic contaminants.

(Figure 1.)

For contaminants identified as occurring in incinerator or boiler scrubber waters, either aerobic or physical-chemical processes should be effective in treating the relatively low BOD waste streams. The physical-chemical pilot plant should effectively reduce both the organic contaminants and the trace metal concentrations to levels acceptable for discharge to surface waters. The aerobic treatment process will probably require subsequent polishing via physical-chemical processes to remove trace metal contaminants

to levels acceptable for discharge to surface waters.

The waste streams produced in the condensation of gases and the separation of pyrolysis fuel oils from the scrubber oil are the most difficult to treat. Based on the very high BOD's and the low suspended solids from this WAF process, the anaerobic filter appears ideally suited for the initial treatment step. To date, the anaerobic filter has been utilized only once in full scale operations and consequently the pilot plant data will be especially valuable in the development of this innovative technology. The anaerobic contact process will run concurrently with the anaerobic filter for comparison between the two processes. Likewise, the aerobic pilot plant should be utilized with the pyrolysis waste streams and the results compared with those from the UNOX process utilized by the Union Carbide Company in treating their Purox wastewaters. Subsequent physical-chemical treatment may be required prior to discharge to surface waters for the removal of trace metals although these have not been specifically identified in the analysis of pyrolysis waste streams. (Figure 3.)

The wastewaters from the anaerobic digestion of MSW are the most poorly characterized because the process itself is only now undergoing full scale investigation. Depending on the oxygen demand of the waste streams, either the aerobic or the physical-chemical processes should be effective in its treatment. The aerobic process would generally be ineffective in the removal of trace metals and consequently, based on results of further testing, a physical-chemical process may be required to upgrade the effluent. (Figure 4.)



In conclusion, based on the results of our investigation, we feel that three pilot plant trailers should be designed, constructed, and operated in the field at WAF facilities. These three pilot plants, anaerobic, aerobic and physical-chemical, should be operated both in series and in parallel to obtain data on the relative efficiencies of the different processes. The operation of the anaerobic pilot plant should be especially valuable because of the innovative nature of the processes involved. In addition, the operation of the other pilot plants will provide valuable information on their respective removal efficiencies with respect to organic and trace metal priority pollutants. The successful operation of the pilot plants at WAF facilities will provide valuable information on the wastewater streams generated and the applicability of various treatment schemes in reducing the pollutant levels in these waste streams to acceptable levels.

#### ACKNOWLEDGEMENT

This study to characterize liquid pollutants produced at RDF-WAF facilities and to recommend treatment steps for their removal was funded by the Fuels Technology Branch, Industrial Environmental Research Laboratory, Environmental Protection Agency, Cincinnati, Ohio.

TABLE 1

SUMMARY OF SIGNIFICANT POLLUTANTS IDENTIFIED IN HYDRAPULPING WASTE STREAMS [1]

PARAMETER (mg/l)	BLOWDOWN	THICKENER WASTEWATER
Organic Surrogates		
B.O.D.	2,840	2,660
C.O.D.	8,954	6,799
T.S.S.	4,795	2,882
OIL and GREASE	*	*
Mineral Quality		
Na <sup>+</sup>	*	*
Ca <sup>+2</sup>	*	*
Total Alkalinity	*	*
Cl <sup>-</sup>	*	*
SO <sub>4</sub> <sup>-2</sup>	*	*
NO <sub>3</sub> <sup>-</sup>	NH <sub>3</sub> :N = 29	NH <sub>3</sub> : = 24
PO <sub>4</sub> <sup>-3</sup>	*	*
CY-	*	*
pH (units)	5.78	4.8
DO	*	*
Priority Pollutants		
Organics	*	*
Priority Pollutants		
Metals	*	*
Flow (liter/min)	290	110

TABLE 2

## SUMMARY OF SIGNIFICANT POLLUTANTS IDENTIFIED IN INCINERATOR WASTE STREAMS [2-8]

PARAMETER (mg/l)	QUENCH WATER	SCRUBBER WATER
Organic Surrogates		
B.O.D.	*	15-400
C.O.D.	*	20-790
T.S.S.	4-4,070	90-13,000
Oil and Grease	*	*
Mineral Quality		
Na <sup>+</sup>	3.36-1,306	14-1,621
Ca <sup>+2</sup>	66-517	19-1,499
Total Alkalinity	0-835	0-2,630
Cl <sup>-</sup>	98-1,920	180-3,540
SO <sub>4</sub> <sup>-2</sup>	25-5000	20-1,250
NO <sub>3</sub> <sup>-</sup>	35-100	10-710
PO <sub>4</sub> <sup>-3</sup>	1-21	1-51
CN <sup>-</sup>	*	5.2
pH (Units)	3.6-11.5	1.8-11.9
DO	*	*
Priority Pollutants		
Organics	*	*
Priority Pollutants		
Metals	*	Hg 0.03-11 AS 0.2-7 T-Cr 1-200 Cr <sup>6+</sup> 0.06-7 Pb 13-500 Cd 1.2-20 Fe 40-3,600 Cu 1-52 Zn 30-1,050 Mn 5-65
Flow (liter/min)	Combined flows up to 2,000 l/m	

TABLE 3

## SUMMARY OF SIGNIFICANT POLLUTANTS IDENTIFIED IN PYROLYSIS WASTE STREAMS (9-11)

PARAMETER (mg/l)	PYROLYSIS CONDENSATE and GAS SCRUBBER WATER	
Organic Surrogates		
B.O.D.	50,000-77,000	
C.O.D.	30,000-52,000	
T.S.S.	30-112	
Oil and Grease	500-1,000	
Mineral Quality		
Na <sup>+</sup>	89-170 <sup>+</sup>	
Ca <sup>+2</sup>	84-135 <sup>+</sup>	
Total Alkalinity		
Cl <sup>-</sup>	360-690 <sup>+</sup>	
SO <sub>4</sub> <sup>-2</sup>	44-62 <sup>+</sup>	
NO <sub>3</sub> <sup>-</sup>	•	
PO <sub>4</sub> <sup>-3</sup>	•	
CN <sup>-</sup>	2-8 <sup>+</sup>	
pH ( units )	3.7+	
DO	2.4-3.7+	
Priority Pollutants		
Organics	Phenol	20-50+
	2-4 Dimethyl Pheno	0.6-9+
	Benzene	4+
	Toluene	1+
	Ethylbenzene	1+
	Naphthalene	3+
Priority Pollutants		
Metals	Lead	0.3-0.8+
	Zinc	2.8-15+
Flow (liter/min)	Up to 250-reports differ	

TABLE 4

SUMMARY OF SIGNIFICANT POLLUTANTS IDENTIFIED  
IN DIGESTER SUPERNATANT/FILTRATE [12-13]

PARAMETER (mg/l)	DIGESTER SUPERNATANT/FILTRATE
Organic Surrogates	
B.O.D	500-10,000
C.O.D.	1,000-30,000
T.S.S.	200-15,000
Oil and Grease	*
Mineral Quality	
Na <sup>+</sup>	*
Ca <sup>+2</sup>	*
Total Alkalinity	100-2,700
CL <sup>-</sup>	*
SO <sub>4</sub> <sup>-2</sup>	*
NO <sub>3</sub> <sup>-</sup>	*
PO <sub>4</sub> <sup>-3</sup>	*
CN <sup>-</sup>	*
pH (units)	6.4-7.2
DO	*
Priority Pollutants	
Organics	Total volatile solids 650-3,800
Priority Pollutants	
Metals	*
Flow (liter/min)	*

TABLE 5

EFFICIENCY OF TREATMENT PROCESSES IN REMOVING SIGNIFICANT  
POLLUTANTS FROM PERTINENT INDUSTRIAL DISCHARGES (20-22)

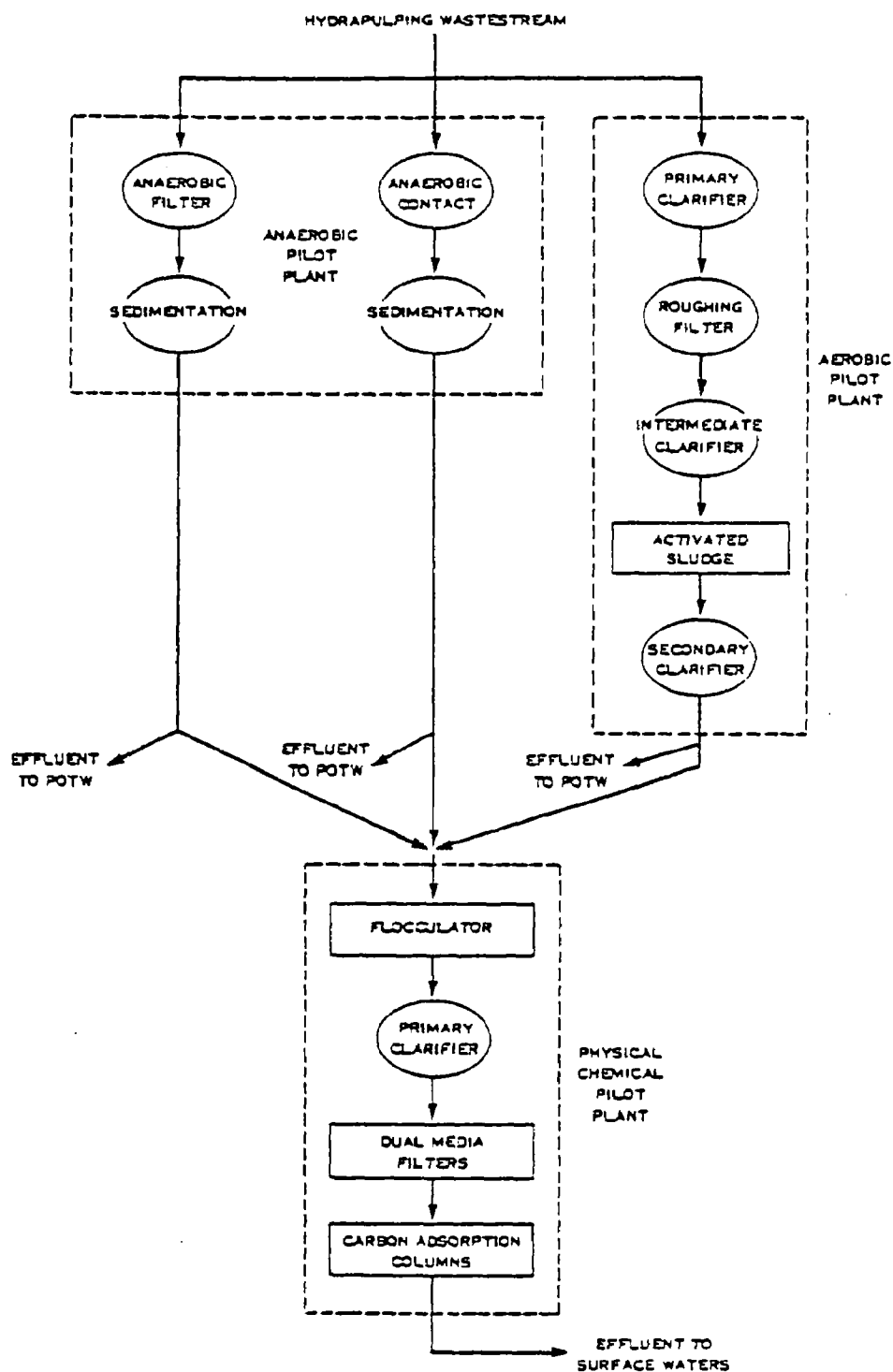
Industry/Level or Treatment	Percent Removal (%)							
	BOD	COD	SS	Oil & Grease	Phenol	Ammonia	Sulfide	Metals
<u>Petroleum</u>								
Primary	30-60	20-50	50-80	60-95	0-50			
Biological								
Secondary	40-99	30-95	20-85	50-99	60-99	0-99	70-100	
Filtration	40-70	20-55	75-95	65-95	5-20			
Carbon Adsorption	70-98	70-94	60-90	70-95	90-100			
Anaerobic Filter		10-13						
<u>Steam Electric Power</u>								
Primary				50-70				
Biological								
Secondary				70-90				
Anaerobic Filter								50-95
<u>Pulp &amp; Paper</u>								
Primary			95					
Biological								
Secondary	85-99							
Anaerobic Filter		73-94						
<u>Steam Supply &amp; Cooling</u>								
Precipitation & Coagulation								90-100
<u>Organic Chemicals</u>								
Biological								
Secondary	93	63-74						
Carbon Adsorption	90	69						
<u>Plastics &amp; Synthetics</u>								
Biological								
Secondary	80-99	90-95						
<u>Food Processing</u>								
Anaerobic Filter		55-86						
<u>Pharmaceutical</u>								
Anaerobic Filter		94-98						
<u>Wastewater Treat- ment Plant</u>								
Anaerobic Filter	85	76	45					

#### REFERENCES CITED

1. Young, J. C., and Johnson L., "Water Use and Wastewater Production at Solid Waste Processing/Energy Recovery Facilities," Engineering Research Institute, Iowa State University, Ames, Iowa, 1977.
2. Matusky, F. E., and Hampton, R. K., "Incinerator Wastewater," Proceedings National Incinerator Conference, 1968.
3. Achiger, W. C., and Daniels, L. E., "An Evaluation of Seven Incinerators," Proceedings National Incinerator Conference, 1970.
4. Wilson, D. A., and Brown, R. E., "Characterization of Several Incinerator Process Waters," Proceedings National Incinerator Conference, 1970.
5. Schoenberger, R. J., et al, "Characterization and Treatment of Incinerator Process Waters," Proceedings National Incinerator Conference, 1970.
6. Schoenberger, R. J., "Studies of Incinerator Operation," Proceedings National Incinerator Conference, 1972.
7. Cross, F. L., and Ross, R. W., "Effluent Water From Incinerator Flue Gas Scrubbers," Proceedings National Incinerator Conference, 1968.
8. Kaiser, E. R., and Carotti, "Municipal Incineration of Refuse with 2 Percent and 4 Percent Additions of Form Plastics: Polyethylene, Polyurethane, Polystyrene, and Polyvinyl Chloride," Proceedings National Incinerator Conference, 1972.
9. Engineering and Economic Analysis of Waste to Energy Systems, Ralph M. Parsons Company report to EPA Industrial Environmental Research Laboratory, June 1977.
10. Hoffman, D. A., Pyrolysis of Solid Municipal Wastes, EPA report 67012-73-039, Cincinnati, Ohio, 1977.
11. Ananth, C. et al, Environmental Assessment of Waste-to-Energy Process: Union Carbide Purex System, MRI report to EPA Industrial Environmental Research Laboratory, June 1978.
12. Malina, J. F., and Felipo, J. D., "Treatment of Supernatants and Liquids Associated with Sludge Treatment," Water and Sewage Works Journal, August 1971.
13. Sludge Treatment and Disposal, EPA Technology Transfer Manual, 1974.
14. Jennett, J. and Dennis, D., "Anaerobic Filter Treatment of Pharmaceutical Waste," Journal Water Pollution Control Federation, 47,1(January 1975).
15. Young, J. C., and McCarty, P. L., "The Anaerobic Filter for Waste Treatment," Journal Water Pollution Control Federation, 41, 5 (May 1969).

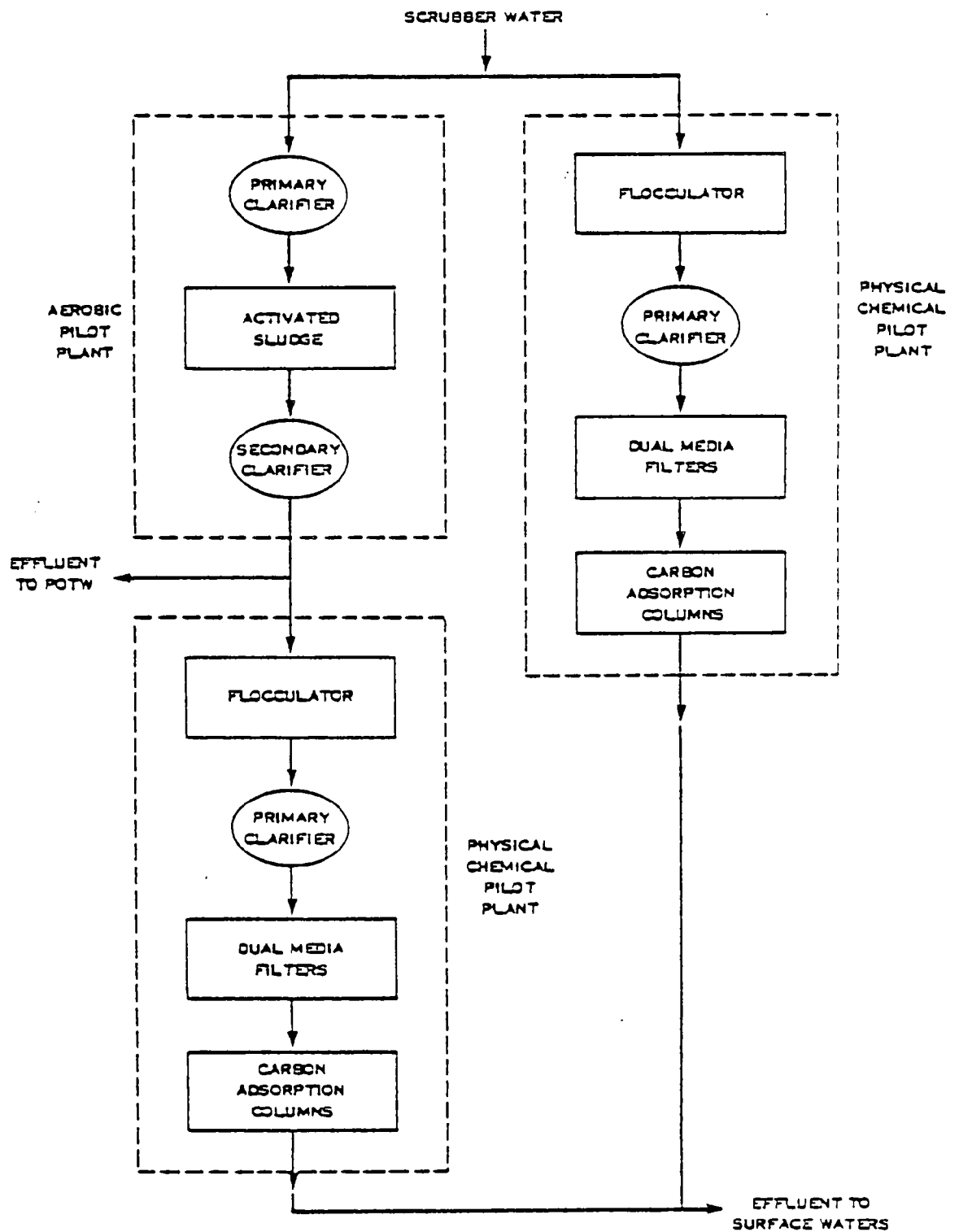
16. Taylor, W., Full-Scale Anaerobic Trickling Filter Evaluation, Food Waste Research Section, US EPA, Cincinnati, Ohio.
17. Hang, R. T., Raksit, S. K., and Wong, G. G., "Anaerobic Filter Treated Waste Activated Sludge" Water and Sewage Works Journal, 124, 2 (February 1977).
18. Sanders, F. A., and Bloodgood, D. E., "The Effects of Nitrogen-to-Carbon Ratio on Anaerobic Decomposition," Journal Water Pollution Control Federation, 37, 12 (December 1965).
19. Schoepfer, G. J., and Zeimke, N. R., "Development of the Anaerobic Contact Process, I, Pilot Plant Investigation and Economics," Sewage and Industrial Wastes, 31, 2 (February 1959).
20. State and Local Pretreatment Programs, Federal Guidelines, Volume I, US EPA, Municipal Construction Division, Washington, D.C. January 1977.
21. State and Local Pretreatment Programs, Federal Guidelines, Appendices 1-7, US EPA, Municipal Construction Division, Washington, D.C., January 1977.
22. Culp, R. L., Wesner, G. M., and Culp, G. L., Handbook of Advanced Wastewater Treatment, Van Nostrand - Reinhold Co., 1978.





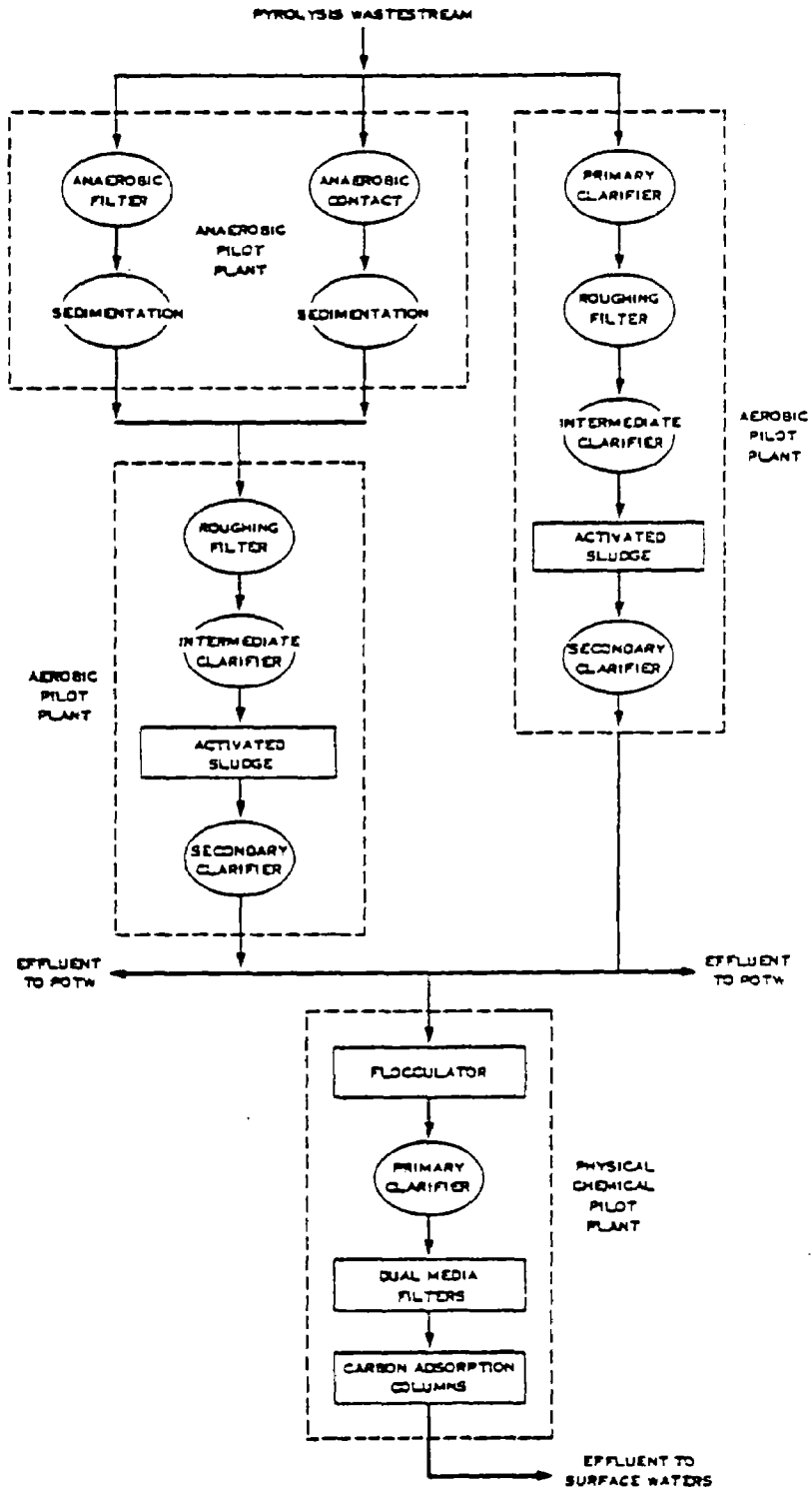
AEROBIC AND ANEROBIC TREATMENT PROCESSES,  
 FOLLOWED BY PHYSICAL CHEMICAL TREATMENT  
 SHOULD BE INVESTIGATED IN THE TREATMENT  
 OF HYDRAPULPING WASTESTREAMS (TABLE 1)

Figure 1

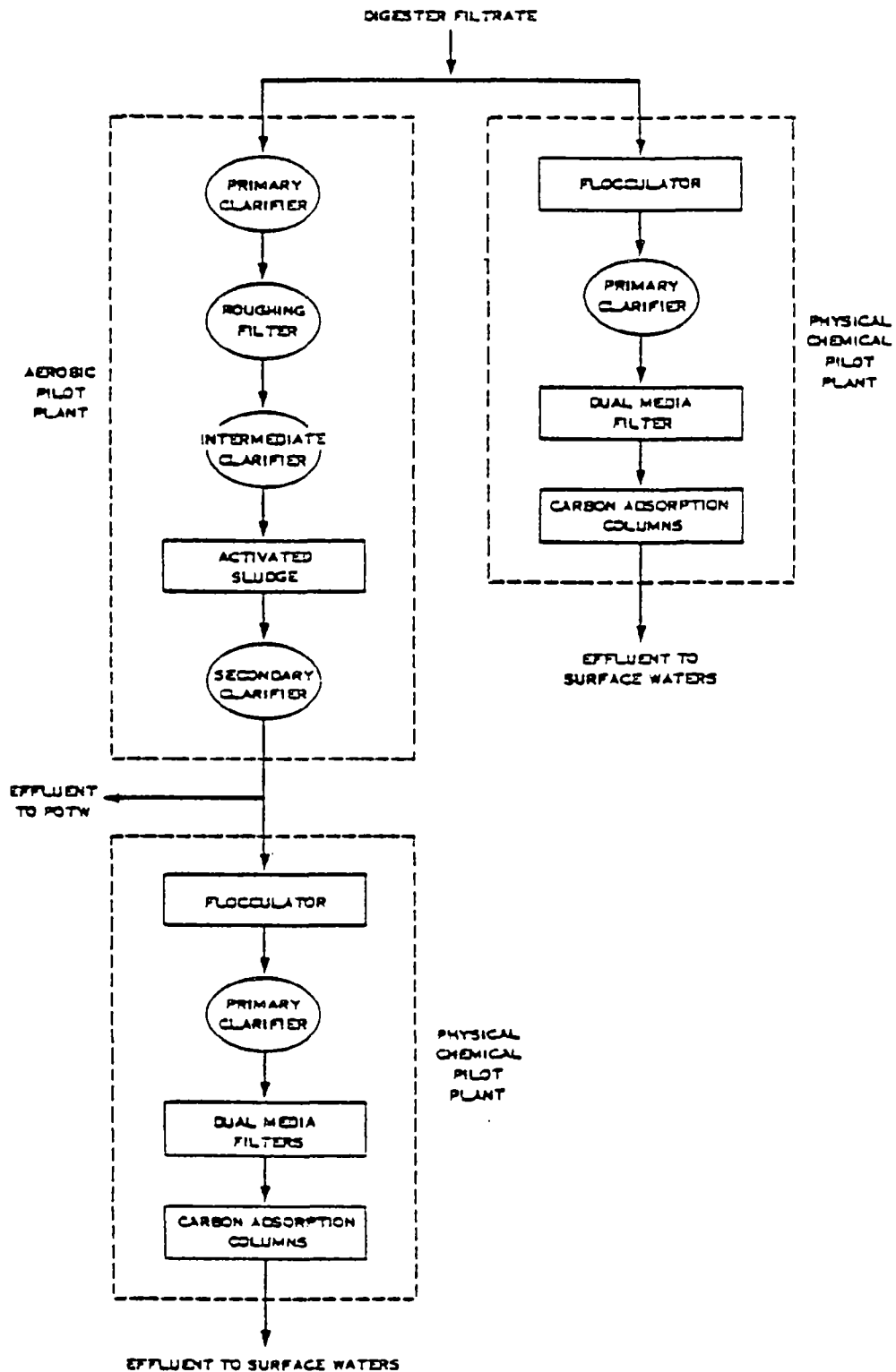


BOTH AEROBIC AND PHYSICAL CHEMICAL TREATMENT PROCESSES  
SHOULD BE INVESTIGATED IN THE TREATMENT OF  
SCRUBBER WATERS (Table 2)

Figure 2



AEROBIC AND ANAEROBIC TREATMENT PROCESSES, OPERATED IN SERIES AND IN PARALLEL, SHOULD BE INVESTIGATED IN THE TREATMENT OF PYROLYSIS WASTESTREAMS (Table 3)



AEROBIC AND PHYSICAL CHEMICAL TREATMENT PROCESSES  
SHOULD BE INVESTIGATED IN THE TREATMENT  
OF DIGESTER WASTESTREAMS (Table 4)

Figure 4

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Proceedings from a Technical Conference on Waste-to-Energy Technology Update - 1980		5. REPORT DATE September, 1980
		6. PERFORMING ORGANIZATION CODE G-8290
7. AUTHOR(S) G. Ray Smithson, Jr.		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle Columbus Division 505 King Avenue Columbus, Ohio 43201		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. R 806 653 010
12. SPONSORING AGENCY NAME AND ADDRESS Incineration Research Branch Industrial Pollution Control Division U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Proceedings
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		
16. ABSTRACT <p>The Technical Conference on Waste-to-Energy Technology Update-1980 was held at Cincinnati, Ohio, on April 51 and 16, 1980. The purposes of the technical conference were:</p> <ul style="list-style-type: none"> <li>o To review the status of relevant research and development activities being supported by U.S. EPA's Industrial Environmental Research Laboratory at Cincinnati, Ohio.</li> <li>o To consider the most effective means for the commercial exploitation of the results of this research.</li> <li>o To review areas for future research and to recommend strategies for the implementation of such research.</li> </ul> <p>The conference was presented in three technical sessions; these are Conversion Processes, Combustion, and Environmental Assessments and Pollution Control Technology. These proceedings incorporate copies of the papers presented by the conference speakers.</p>		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Waste-to-Energy RDF DRDF Energy Recovery Waste Disposal		
18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 227
	20. SECURITY CLASS (This page)	22. PRICE