AIR EMISSIONS MEASUREMENT OF MSW COMBUSTION

Jeffrey L. Hahn, P.E.
Vice President
Cooper Engineers, Inc.
Richmond, California 94804

ABSTRACT

The rationale and protocol for air emissions measurements of MSW in the O'Connor Rotary Combustor at Gallatin, TN are presented, along with the associated data. Computer analysis of the data is presented regarding formations of NO_x, CO and SO_2 as functions of MSW combustion parameters.

The protocol of the recent testing in Japan of the Teller Environmental Systems, Inc. (TESI) dry scrubber, dry venturi and baghouse operating on two 165 TPD Martin incinerators buring MSW is presented, along with some preliminary results.

INTRODUCTION

During the past five years, the study of feasibility and preliminary design of a plant converting sewage sludge and municipal solid wastes to usable energy have been underway in western Contra Costa County, near San Francisco, California. If feasible, the waste-to-energy project would supply electricity (and possibly steam) from sources other than oil and natural gas-fired equipment.

The concept originated from the intent of the West Contra Costa Sanitary District (WCCSD) to seek lower cost electricity for its wastewater treatment plant and less expensive sludge disposal. After an initial study in 1978, the West County Agency of Contra Costa County (WCA) assumed sponsorship of the project. (The WCA is a joint powers agency of the WCCSD and the City of Richmond Municipal Sewer District.

The WCA received funds in 1981 and 1982 from the California Waste Management Board (CWMB), formerly the State Solid Waste Management Board, to conduct an air emissions test of the Gallatin, Tennessee, waste-to-energy facility and a Japanese facility using a dry scrubber and baghouse. Test results from the Gallatin rotary combustor/boiler facility will provide key, unabated air emissions data for a similar combustion system proposed for the WCA waste-to-energy plant, while the testing in Japan will provide data regarding the WCA's choice of a TESI dry scrubber, dry venturi, baghouse as best available control technology (BACT) for the control of acid gases and particulate.

SCOPE OF WORK FOR THE AIR EMISSIONS TESTING AT GALLATIN, TN

The West County Agency received initial funds from a Step I Clean Water Grant from the State Water Resources Control Board (SWRCB) to conduct those activities necessary to determine the feasibility of a sewage sludge co-disposal waste-to-energy project and do the inital planning for the facility. Additional grants from the CWMB expanded the scope to include air emissions testing of a rotary combustor/boiler facility in Kure, Japan. The primary objective of those tests was to develop air emission factors that represent the unabated emissions from the combustion of unprocessed municipal solid waste and the abated emissions from an electrostatic precipitator (ESP) and a wet scrubber, the Turbulent Contacting Absorber (TCA). The results of the test are presented in a 1981 report prepared by Cooper Engineers, formerly Cooper & Clark Consulting Engineers. The additional air emissions tests at Gallatin were funded by a subsequent CWMB grant whose objectives are described below.

PRIMARY OBJECTIVES OF THE GALLATIN AIR EMISSIONS TESTING

The primary objective of the Gallatin air emissions testing was to assess the reduction of oxides of nitrogen (NO_x), non-methane hydrocarbon (NMHC) and carbon monoxide (CO) emissions by operating the rotary combustor under automatic combustion control (ACC). This was not assessed at Kure; although that facility does have ACC, it was operated during the air emissions testing in the manual mode by the City. However, Ishikawajima-Harima Heavy Industries Company, Ltd. (IHI), the plant engineers, have successfully operated the Kure facility on the ACC system. Lower NO_x and CO emissions by combustion control is a critical factor in obtaining an Authority to Construct and a Permit to Operate from the San Francisco Bay Area Air Quality Management District (BAAQMD).

Another objective of the testing was to measure unabated acid gas emissions. These data are needed to develop design and operational criteria for the proposed dry scrubber and baghouse air pollution control equipment selected as BACT for the WCA project.

Additional test data from Gallatin requested by the regulatory agencies to compare with that obtained at Kure include emissions of total heavy metals and their characterization by particle size ranges. Non-methane hydrocarbons were to be determined on a continuous basis using U.S. EPA Method 25.

The Gallatin testing also measured the efficiency of the Apitron electrostatically-assisted fabric filter. If proven, this type of particulate control system could be installed in California, as discussed in a 1980 publication by the California Air Resources Board on air pollution control from resource recovery plants.

CALIFORNIA AIR RESOURCES BOARD REVIEW OF GALLATIN AIR EMISSIONS TESTING SCOPE OF WORK

The California Air Resources Board (CARB) is the state agency with the responsibility to review the granting of air permits by the regional air quality management and air pollution control districts such as the BAAQMD. Having this important review capacity, especially regarding the choice of BACT, the scope of work and testing protocol were reviewed by CARB at the request of the CWMB. The following is a synopsis of their comments:

- The five-stage in-stack cyclone sampler designed by Southern Research Institute should be used to measure particle size and collect sufficient particulate in the different size ranges for heavy metal analyses in lieu of using the Anderson In-Stack cascade impactor.
- Particle analysis should include analyses of the heavy metals, such as; arsenic, beryllium, cadmium, chromium, copper, mercury, manganese, molybdenum, nickel, lead, antimony, selenium, tin, vanadium and zinc.
- HCl concentrations should be obtained by continuous analyzer, if possible.
- HF should be sampled by U.S. EPA Method 13B.
- Low molecular weight and high molecular weight organic compounds should be identified.
- Mercury should be tested using U.S. EPA Method 101.

Most of CARB's recommendations were incorporated in the final testing protocol which is described below. The significant differences were that a continuous HCl analyzer, although available at the Kure facility, was unavailable in this country, that fluoride analysis by particle size and in the gaseous state was substitued for U.S. EPA Method 13B, and that separate analyses of trace organic compounds was too expensive for this program, either analyzed under this grant or analyzed separately by CARB with sampling performed under this grant.

FINAL TESTING PROTOCOL FOR GALLATIN, TENNESSEE

Table 1 shows the final testing protocol that was taken to Gallatin having been approved by CWMB and CARB. This testing protocol only differs from the actual testing schedule as to the sequence in which samples were taken.

AIR EMISSION TESTING METHODOLOGY AT GALLATIN, TN

PURPOSE

The air emissions testing of the Gallatin O'Connor rotary combustor was conducted to obtain the most representative air emissions factors possible for the West County Agency's waste-to-energy project. The Gallatin facility was chosen to present a comparison of the air emissions factors from American municipal solid waste versus the emission factors from the Kure, Japan waste because the two facilities' combustion systems are basically identical. The two Gallatin O'Connor units are 100 TPD each and the Kure O'Connor units are 165 TPD each. Because of the similar combustion configuration much of the air emissions testing and analyses performed were similar.

FINAL TESTING SCHEDULE

The testing schedule for the two weeks at Gallatin is described in Table 2. The testing schedule sequence differs somewhat from the schedule developed prior to arrival in Gallatin because the multiclone sampling had to be scheduled later in the week in order that a sampling port of sufficient size for the multiclone be installed.

The actual daily Continuous Emissions Monitor (CEM) testing schedule included approximately 23 hours of measurements with less than 1 hour for spanning, calibrating, and draining water from the sample conditioner. The calibration was typically done in the morning and evening as follows: NO_x was calibrated for 15 minutes at 0 and 98 ppm. The SO_2 was calibrated for 15 minutes at 525 ppm (or 93 ppm depending on SO_2 range) and 0 ppm_v. Oxygen was calibrated with the ambient air (21% O_2) and a zero oxygen gas. CO_2 was calibrated with 12.26 and zero percent span gases. The non-methane hydrocarbon analyzer was calibrated with a zero gas and a $CO/CO_2/CH_4/C_3H_8$ mix (47.9 ppm_v / 2.09%/ 50.5 ppm_v / 50.6 ppm_v). This mix would give a NMHC standard of 151.8 ppm_v, which is 50.6 x 3. CO was calibrated with a span gas cylinder at 2,089 ppm_v and 0 ppm_v. The number of hours of CEM testing for NO_x, CO, CO_2 SO_2, O_2 and non-methane hydrocarbons for the two week test was 216, 216, 216, 143, 216 and 32, respectively.

SAMPLING LOCATIONS

The sampling locations used for the testing are shown in Figure 1, a cross section of the plant. In this figure the different sampling points are noted. Sampling Point 3 is described as the "Combustor Outlet" on all of the air emissions test data table is actually at the gas air heater outlet.

Figures 2, 3, and 4 show the dimensions of the ducting and location of the sampling ports for the different sampling points.

SAMPLING METHODS

The sampling methods used to extract and analyze the gas samples from sampling points 1, 2, and 3 (on Figure 1) are too detailed for this paper. Sampling and analysis for initial moleular weight and percent water, velocity traverse and volumetric flow rate, particulate emissions, sulfur oxides, mercury, acid gases and aerodynamic particle size by the Andersen Mark II and the Flow Sensor Multiclone follow U.S. EPA, BAAQMD or CARB methods, when available. Otherwise manufacturers manuals were followed.

Heavy metals were analyzed by atomic absorption from samples taken from the particulate catch of each multiclone. The stages of the multiclone were combined, if necessary, to provide approximately 100 milligrams of sample.

Fluoride was analyzed from the particulate and flue gas by ion chromatagraphy.

Sample points 4 and 5 (on Figure 1) are where the collection of the municipal solid waste and residue, respectively were taken. The proximate, ultimate and calorific value analyses of the solid waste and residues were performed in accordance with ASTM Standard Methods D3172-73, D3176-74 and D2015-66 (reapproved 1972), respectively. The sampling and analysis of solid waste did not include separation into the various waste fractions because of cost considerations. After the solid waste was obtained by diverting a crane load from the feed chute, the following sequence was performed: breaking open all the material, mixing thoroughly and then quartering the pile; next the alternate quarters were discarded; the remainder was remixed, quartered again, discarding alternate quarters; the final opposite two quarters were mixed and a 15-20 lb sample double bagged in plastic and taken to the laboratory. On Tuesday, February 8, 1983, a sample from all four quarters was taken and analyzed to determine the representativeness of each quarter-pile. Residue samples were obtained for laboratory analysis from the combustion residue as it dropped from the ash drag conveyor into the residue bin.

The continuous emissions monitoring was performed in a mobile van. The following gases were analyzed using the equipment and methods as follows:

Gas	Analyzer	Analyzer Technique
O_2	Taylor Servomax OA 580	paramagnetic
CO	Infrared Industries IR-702	infrared
CO_2	" " "	"
NO_x	Monitor Labs 8430	chemilumescence
SO_2	Dupont 400	ultraviolet
NMHC	Byron 401GC/FID	

The sample lines for the monitors were connected to the cyclone outlet on February 6, 1983 and moved to the gas air heater outlet on February 10, 1983 for the remainder of the test. Each line was directed to a water knockout to prevent condensation. A separate heated sample line was used from a gas air heater outlet sample port to the Byron 401 analyzer.

SUMMARY OF AIR EMISSIONS TEST RESULTS AT GALLATIN, TN

TEST ARRANGEMENTS

Testing of air emissions from the rotary combustor/boiler system burning municipal solid waste was conducted in Gallatin, Tennessee. The Resource Authority in Sumner County operates two 100-ton-per-day (TPD) rotary combustors attached to waterwall-type boilers in a solid waste processing facility designed to produce a total of 45,000 pounds per hour of steam. The facility began operation in December, 1981. The air emissions testing was performed from February 6 to 21,1983. Permission to test the Gallatin facility was obtained through the efforts of the O'Connor Combustor Corporation and was approved by the Resource Authority in Sumner County.

DEVELOPMENT OF TESTING METHODOLOGY

The air emissions testing methodology emerged from a series of meetings with representatives of the Bay Area Air Quality Management District, the California Waste Management Board and the California Air Resources Board. Although U.S. Environmental Protection Agency (EPA) methods were utilized wherever possible, additional methods were applied to provide data that would be applicable to other air quality management and air pollution control districts in California. Emphasis was given to identifying "non-regulated" air pollutants as well as traditionally "regulated" air pollutants and process variables. The incoming municipal solid waste, residue, specially processed solid waste, and two separate incoming waste materials were also tested.

REGULATED AIR POLLUTANTS

A summary of the results of air emissions tests for the "regulated" or criteria air pollutants — those named in the New Source Review Rules and New Source Performance Standards — are shown in Table 2. The reader is referred to the Cooper Engineers report, "Air Emission Tests of Solid Waste Combustion in a Rotary Combustor/Boiler System at Gallatin, Tennessee" for the complete set of results. The unabated emissions are given in average values of four units of measure:

(1) Flue gas concentration of the air pollutant (grains per Standard Dry Cubic Foot (gr/SDCF) at 12% CO_2 or ppm_v dry at 7% O_2),

(2) Pounds of air pollutant per hour for the 100-TPD combustion unit (lb/hr),

(3) Pounds of air pollutant per ton of as-received municipal solid waste (MSW) burned (lb/Ton),

(4) Pounds of air pollutant per million Btu (lb/10^6 Btu) of heat input from the as-received municipal solid waste.

Table 4 gives the controlled, or abated, air emissions found at the Gallatin facility, as well as the control efficiencies of the facilities air pollution control equipment.

Anticipated air emissions at other planned rotary combustor facilities may be calculated by matching the unabated air emission factors reported here with the proposed plant's MSW mass or heat input and reducing the unabated emissions by the efficiencies of the planned air pollution control equipment (i.e., as required by BACT) where applicable. The maximum values, reported in ppm_v are the "rolling" averages of the "worst case" time periods and should be used only in Ambient Air Quality Impact Analyses (AAQIAs) for comparison with their corresponding short-term ambient air quality standards (e.g., the respective 1-hr or 3-hr standards).

NON-REGULATED POLLUTANTS

The results of air emissions tests for "non-regulated" air pollutants — those pollutants without a specific standard or regulation — are shown in Table 5. The data give average unabated air emissions values in a similar format as in Table 3.

HEAVY METALS EMISSIONS

The results of air emissions tests for heavy metals are shown in Table 6. Special tests for total mercury were performed, and the results are presented in Table 7. Table 8 shows the percentage of the specific heavy metals in three particle size ranges.

The forecast of abated heavy metal emissions for other projects is dependent on the efficiencies of the planned air pollution control equipment in each particle size range and the amount of heavy metals in that size range.

SOLID WASTE AND COMBUSTION RESIDUE CHARACTERISTICS

The municipal solid waste combusted during the week of February 7, 1983 in Gallatin had on the average the following higher heating value (HHV) and moisture:

7,210 Btu/lb Dry Basis - HHV
41.54% - Moisture
4,217 Btu/lb As Received - HHV

The residue from the combustor average the following heating value and moisture:

2,140 Btu/lb Dry Basis - HHV
59.16% - Moisture
649 Btu/lb To Landfill - HHV

The net average heat input to the combustor was 29.01×10^6 BTU/hr.

ACC VERSUS NO_x, CO AND SO_2 CONCENTRATIONS

Cooper Engineers, in association with Rigo & Rigo Associates have begun data reduction on the correlation of all process variables and pollutant concentrations. Table 9 gives a summary of the CEM data that, on 5-minute intervals, has been compiled with the following process variables: steam flow, pressure and temperature; rotary combustor, furnace and boiler temperatures; process excess air (wet and dry O_2); and type and weight of MSW fed. The CEM data were also transformed into lb/M Btu emission factors by using the average U.S. EPA F-factor from the ultimate analyses of the MSW sampled at Gallatin.

Initial results can be summarized as follows:

NO_x:
NO_x was analyzed as a function of boiler-firing rate (percent of design load), flue gas percentage of oxygen, and whether or not NRT fuel was being burned. Each of these parameters was utilized in its raw form and as a squared and cross product.

The most comprehensive run indicates that the minimum residual standard deviation is 0.001 and that an R of .78 is the limit. The progressive reduction in the data indicates that an R of .75 can be obtained using load, load squared and the product of load and oxygen in the flue gas. The result is most intriguing because NO_x increases with O_2 (as expected) but decreases with load. This effect is very strong and is consistent with previous findings that how a fuel is burned affects NO_x emissions. Particular attention should be called to the fact that the direction of the load effect precludes any significant thermal NO_x formation. Also, whether or not NRT fuel was being burned had no effect.

CO

The CO data was regressed against the same system parameters as the NO_x data. The initial results displayed a pronounced increase in residual variance with increasing CO response so that the CO data was transformed to ln (CO) before further analysis was undertaken.

These data are extremely noisy so that the maximum R that can be achieved is 0.50. An R of 0.45 and a residual mean square comparable to the maximum can be achieved by incorporating load, flue gas oxygen content, inverse flue gas oxygen (the parameter that describes CO formation in oil burners) and NRT. For CO, burning NRT fuel increases the intercept and generally has opposite sign on the combustion parameters to raw waste. The data indicate that the NRT fuel behaves differently in the O'Connor Rotary Combustor than raw waste.

SO_2

The SO_2 data had to be log transformed to eliminate increasing residual variance like the CO data. These data clearly show that how a fuel is burned affects how much sulfur is released. The lb/MBtu sulfur emission was also affected by whether or not NRT fuel was being burned. NRT fuel increased the intercept and had a consistently opposite sign affect on load, oxygen content and load O_2 product.

SCOPE OF WORK FOR DRY SCRUBBER AND BAGHOUSE TESTING IN JAPAN

Cooper Engineers has attempted to test a dry scrubber and baghouse operating on flue gas from MSW combustion for the WCA since 1981. Over 1½ years was spent developing a test protocol and negotiating with the Town of Framingham, MA. In October 1982, Framingham officially notified Cooper Engineers that the testing of its retrofitted TESI dry scrubber, dry venturi and baghouse on a 250 TPD Voland incinerator would not be possible. The acid gas, heavy metal and particulate testing protocol which had been developed and reviewed by both CARB and CWMB was then switched to two new TESI systems installed on two 165 TPD MHI-Martin incinerators in Japan.

In addition, CARB was able to secure funding to add PCDD and PCDF analyses to the dry scrubber inlet, baghouse outlet and fly ash. During final preparations, the Ministries of Environment and Energy from the Province of Ontario, Canada, joined the testing and greatly expanded the test protocol for PCDDs and PCDFs. Table 10 presents a summary of the test protocol, while Table 11 gives the daily events. The reader will have to wait for the complete Cooper Engineers report; however, Table 12 gives preliminary results for removal of particulate acid gases, and mercury across the TESI dry scrubber, dry venturi, and baghouse.

FIGURE 1

CROSS-SECTION OF FACILITY SHOWING SAMPLING LOCATIONS

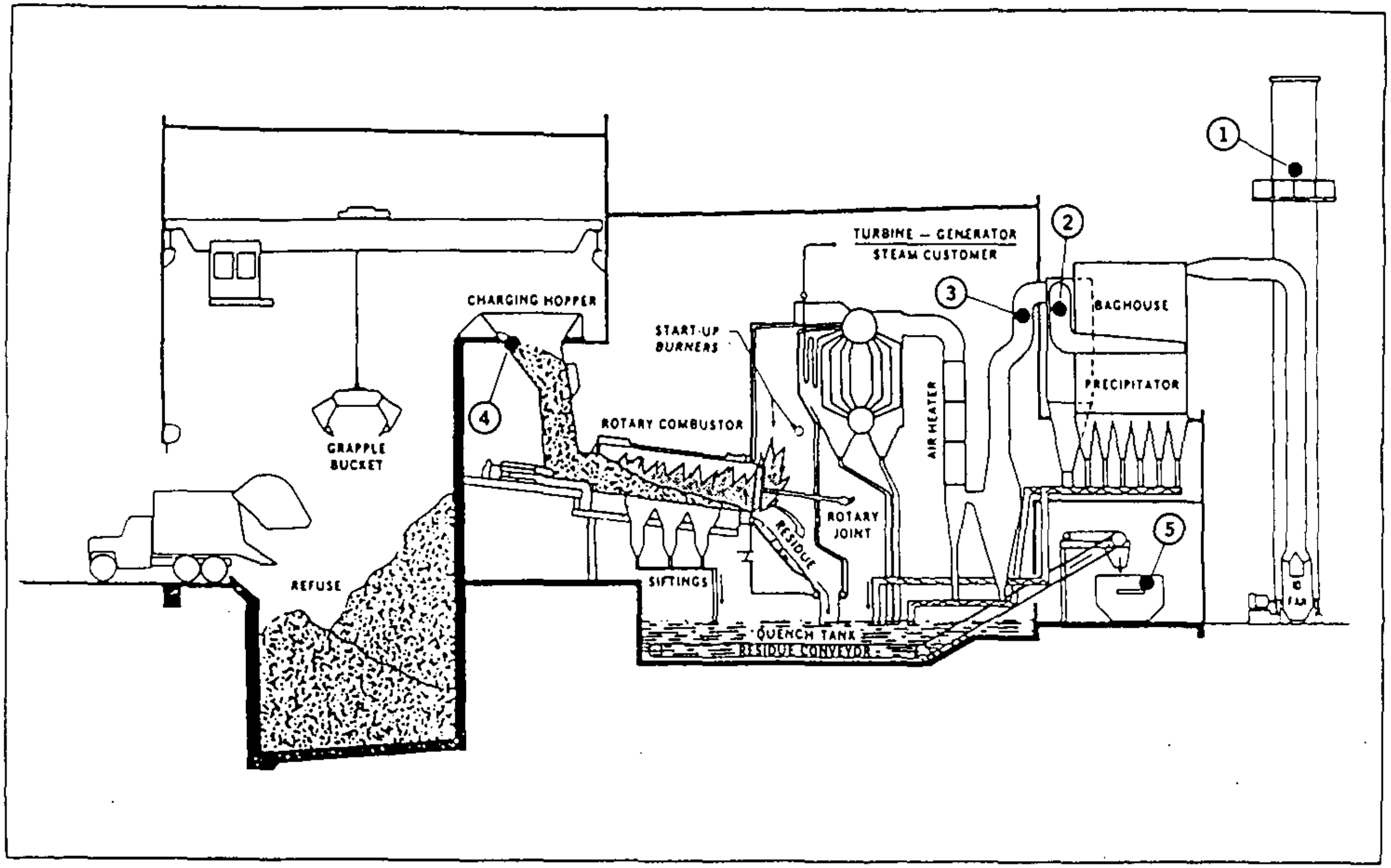


FIGURE 2

DIAGRAM OF SAMPLING POINT 3, GAH OUTLET

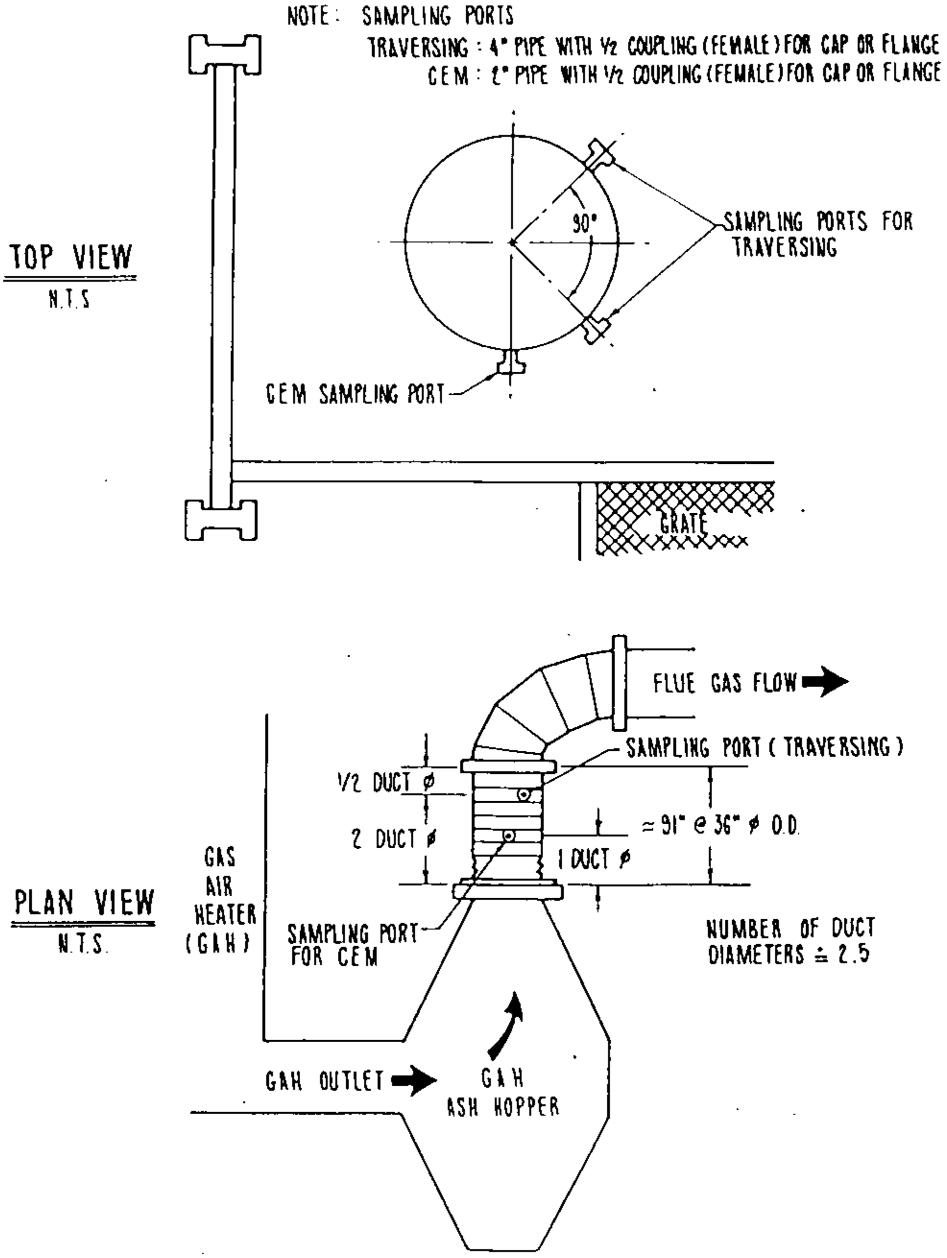


FIGURE 3

DIAGRAM OF SAMPLING POINT 2, CYCLONE OUTLET

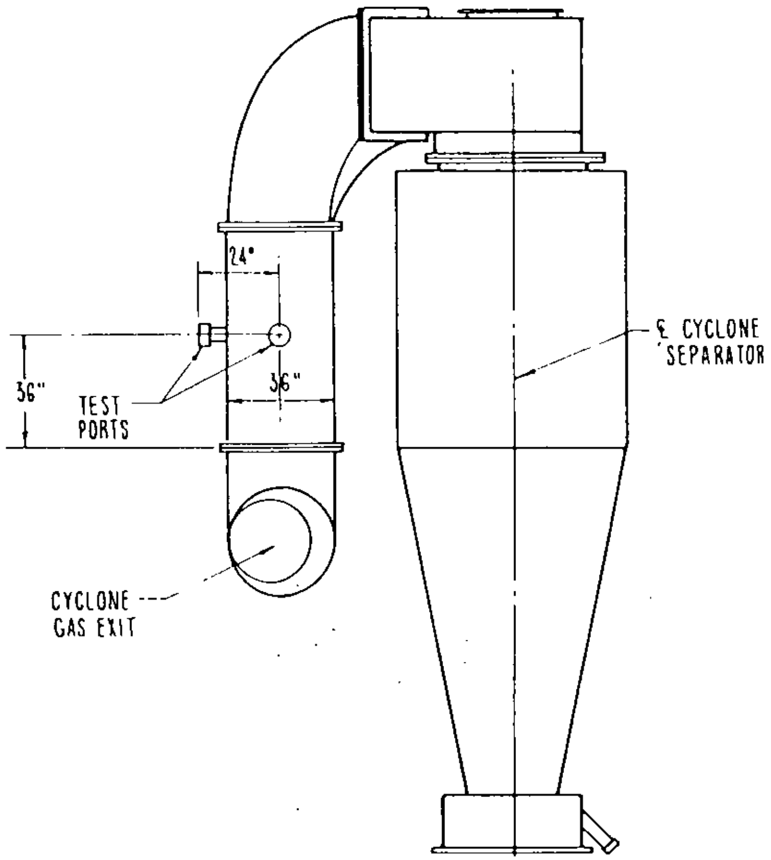


FIGURE 4

DIAGRAM OF SAMPLING POINT 1, MAIN STACK

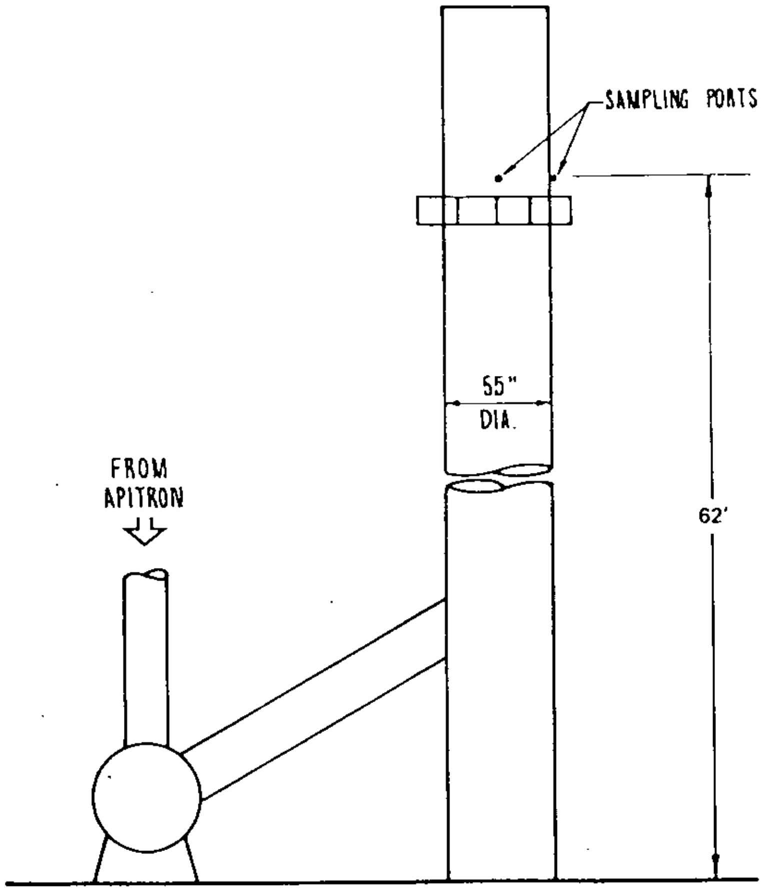


TABLE 1

FINAL TESTING PROTOCOL

	Sunday 2/6/83	Monday 2/7/83	Tuesday 2/8/83	Wednesday 2/9/83	Thursday 2/10/83	Friday 2/11/83	Sunday 2/20/83
SOURCE TESTING							
AM	Arrival	#1 HM, HF (Multiclone)	#3 HM, HF (Multiclone)	#3 Hg	#2 Method 5/8 In & Out	#3 Method 5/8 In & Out	
	Check Site	#1 HCl,HF,NH_3	#3 HCl,HF,NH_3	#7 MSW Sample #7 Res Sample	#11 MSW Sample #11 Res Sample	#15 MSW Sample #15 Res Sample	
		#1 MSW Sample #1 Res Sample	#4 MSW Sample #4 Res Sample	#5 HCl,HF,NH_3	#7 HCl,HF,NH_3	#10 HCl,HF,NH_3	
		#2 HM, HF (Multiclone)	#4 HM, HF (Multiclone)	#8 MSW Sample #8 Res Sample	#8 HCl,HF,NH_3	#11 HCl,HF,NH_3	
		#2 HCl,HF,NH_3	#4 HCl,HF,NH_3		#12 MSW Sample #12 Res Sample	#16 MSW Sample #16 Res Sample	
		#2 MSW Sample #2 Res Sample	#5 MSW Sample #5 Res Sample				
PM	Equipment Preparation	#1 Hg	#2 Hg	#1 Method 5/8 In & Out	#1 Andy In & Out	#2 Andy In & Out	
		#3 MSW Sample #3 Res Sample	#6 MSW Sample #6 Res Sample	#9 MSW Sample #9 Res Sample	#13 MSW Sample #13 Res Sample	#17 MSW Sample #17 Res Sample	
				#6 HCl,HF,NH_3	#9 HCl,HF,NH_3	#12 HCl,HF,NH_3	
				#10 MSW Sample #10 Res Sample	#14 MSW Sample #14 Res Sample	#18 MSW Sample #18 Res Sample	
CONTINUOUS MONITORING							
	Set-up and testing with O'Connor Combustor Corporation	Start 24 hr/day NO_x, CO, CO_2, O_2 and SO_2 Start 8 hr/day NMHC				End 8 hr/day NMHC	End 24 hr/day NO_x, CO, CO_2, O_2 and SO_2 Equipment Return

NOTES:

HM..........	Heavy metal sampling
MSW	Municipal solid waste
Multiclone ...	SoRI five-stage cyclone sampler
Andy	Andersen ten-stage cascade impactor
In & Out	Simultaneous testing of the inlet and outlet of the Apitron
NMHC.......	Non-methane hydrocarbon
Res	Ash residue sample

TABLE 7

AIR EMISSIONS TESTING AND SAMPLING SCHEDULE
GALLATIN ROTARY COMBUSTOR*
February 6-21, 1983

Sunday, February 6th

Test organization and equipment set-up (Chemecology)
EPA Method 1, 2, 3 and 4 at combustor outlet (gas air heater outlet) and cyclone outlet

Monday, February 7th

0800 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.
1042	3.	Solid wate sample taken for proximate and ultimate analyses.
1050 to 1437	4.	EPA Method 101, Hg at combustor outlet.
1120	5.	Residue sample taken for proximate and ultimate analyses.
1135 to 1722	6.	Continuous emissions monitoring at combustor outlet for NMHC.

Tuesday, February 8th

0800 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.
0855 to 1130	3.	EPA Method 101, Hg at combustor outlet.
0910 to 0930	4.	Four solid waste samples taken for proximate and ultimate analyses.
1000 to 1840	5.	Continuous emissions monitoring at combustor outlet for NMHC.
1015	6.	Residue sample taken for proximate and ultimate analyses.
1030 to 1056	7.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1122 to 1145	8.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1130	9.	Solid waste sample taken for proximate and ultimate analyses.
1321 to 1500	10.	EPA Method 5/8, particulate, sulfate, SO_2 at combustor outlet.
1322 to 1507	11.	EPA Method 5/8, particulate, sulfate, SO_2 at Apitron outlet.
1540	12.	Solid waste sample taken for proximate and ultimate analyses.
1640	13.	Residue sample taken for proximate and ultimate analyses.
1647 to 1825	14.	EPA Method 5/8, particulate, sulfate, SO_2 at combustor outlet.
1648 to 1830	15.	EPA Method 5/8, particulate, sulfate, SO_2 at Apitron outlet.
1700	16.	Solid waste sample taken for proximate and ultimate analyses.
1720	17.	Residue sample taken for proximate and ultimate analyses.

Wednesday, February 9th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 2400	2.	Continuous recording of combustor boiler process data.
0820	3.	EPA Method 2 - Velocity at Apitron outlet.
0940 to 1215	4.	EPA Method 101, Hg at combustor outlet.
0950	5.	Solid waste sample taken for proximate and ultimate analysis.
1019 to 1622	6.	Aerodynamic particle size distribution by Andersen Mark II at Apitron outlet.
1020	7.	Residue sample taken for proximate and ultimate analyses.
1107 to 1131	8.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1210 to 1237	9.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1219 to 1612	10.	Continuous emissions monitoring at combustor outlet for NMHC.
1321 to 1347	11.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1400	12.	Solid waste sample taken for proximate and ultimate analyses.
1400 to 1405	13.	Aerodynamic particle size distribution by Andersen Mark II at combustor outlet.
1420	14.	Residue sample taken for proximate and ultimate analyses.
1452 to 1513	15.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1544 to 1559	16.	Aerodynamic particle size distribution by Andersen Mark II at combustor outlet.

Thursday, February 10th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 2400	2.	Continuous recording of combustor boiler process data.
0855 to 2127	3.	Aerodynamic particle size distribution by Andersen Mark II at Apitron outlet.
0855 to 0904	4.	Aerodynamic particle size distribution by Andersen Mark II at combustor outlet.
0900 to 2240	5.	Continuous emissions monitoring at combustor outlet for NMHC.
0910	6.	Solid waste sample taken for proximate and ultimate analyses.
0920	7.	Residue sample taken for proximate and ultimate analyses.
1000 to 1020	8.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1019 to 1120	9.	Aerodynamic particle size distribution and heavy metals by Flow Sensor, five stage multiclone and acid gases (NH_3, HCl, HF) at combustor outlet.
1102 to 1129	10.	EPA Method 6, acid gases (NH_3, HCl, HF) at combustor outlet.
1217 to 1226	11.	Aerodynamic particle size distribution by Andersen Mark II at combustor outlet.
1345 to 1515	12.	Aerodynamic particle size distribution and heavy metals by Flow Sensor five stage multiclone and acid gases (NH_3, HCl, HF) at combustor outlet.
1410	13.	Solid waste sample taken for proximate and ultimate analyses.
1420	14.	Residue sample taken for proximate and ultimate analyses.

---

*All sampling designated as "combustor outlet" actually sampled at the gas air heater outlet.

TABLE 2 (Continued)

AIR EMISSIONS TESTING AND SAMPLING SCHEDULE
GALLATIN ROTARY COMBUSTOR*
February 6-21, 1983

Friday, February 11th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 2400	2.	Continuous recording of combustor boiler process data.
1000 to 1724	3.	Continuous emissions monitoring at combustor outlet for NMHC.
1007 to 1122	4.	Aerodynamic particle size distribution and heavy metals by Flow Sensor five stage multiclone and acid gases (NH_3, HCl, HF) at combustor outlet.
1300 to 1415	5.	Aerodynamic particle size distribution and heavy metals by Flow Sensor five stage multiclone and acid gases (NH_3, HCl, HP) at combustor outlet.
1552 to 1735	6.	EPA Method 5/8, particulate, sulfate, SO_2 at combustor outlet.
1554 to 1744	7.	EPA Method 5/8, particulate, sulfate, SO_2 at Apitron outlet.
1553 to 1732	8.	EPA Method 5, particulate at cyclone outlet.
1600	9.	NRT sample taken for proximate and ultimate analyses.
1630	10.	Residue sample taken for proximate and ultimate analyses.

Staturday, February 12th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 2400	2.	Continuous recording of combustor boiler process data.

Sunday, February 13th

0000 to 1500	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 1500	2.	Continuous recording of combustor boiler process data.

Monday, February 14th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.

Tuesday, February 15th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.

Wednesday, February 16th

0000 to 1100	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.

Thursday, February 17th

UNIT WAS DOWN ALL DAY

Friday, February 18th

0000 to 1600	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.

Saturday, February 19th

UNIT WAS DOWN ALL DAY

Sunday, February 20th

0000 to 2400	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0800 to 2400	2.	Continuous recording of combustor boiler process data.

Monday, February 21st

0000 to 0800	1.	Continuous emissions monitoring at combustor outlet: NO_x, O_2, SO_2, CO, CO_2.
0000 to 0800	2.	Continuous recording of combustor boiler process data.
0800		END OF TEST

---

*All sampling designated as "combustor outlet" actually sampled at the gas air heater outlet.

TABLE 3

AVERAGE UNABATED AIR EMISSIONS DATA FROM THE GALLATIN ROTARY COMBUSTOR

"REGULATED AIR POLLUTANTS"

Pollutant	Average Concentration	"Worst Case" Rolling Average Concentration (Time Period)	Average lb/hr	Average* lb/ton	Average** lb/10^6 Btu
Particulate:					
U.S. EPA and BAAQMD (without condensibles)	2.92 gr/SDCF at 12% CO_2	---	170.0	42.5	5.35
SCAQMD and Other California (with condensibles)	2.92 gr/SDCF at 12% CO_2	---	170.0	42.5	5.35
NO_x	147 ppm_v at 7% O_2	241 ppm_v at 7% O_2 (1 hr)	9.11	2.2	0.303
SO_2: U.S. EPA Method 8	154 ppm_v at 7% O_2	---	9.49	2.38	0.300
SO_2: Continuous Emission Monitoring	180 ppm_v at 7% O_2	651 ppm_v*** at 7% O_2 (1 hr) 454 ppm_v*** at 7% O_2 (3 hr)	11.41	2.8	0.424
NMHC	40.2 ppm_{wv} at 10% O_2 (wet)	124 ppm_{wv} at 10% O_2 (wet) (3 hr)	1.09	0.232	0.0369
CO	586 ppm_v at 7% O_2	2055 ppm_v at 7% O_2 (1 hr)	17.88	4.5	0.631
Hg	---	---	0.0067	0.00171	0.000216
Pb	---	---	1.024	0.274	0.0353
Be	---	---	<0.00018	<0.000048	<0.0000062

* Process feed weight approximately 92 TPD.

** Based on as-received MSW less the heating value of the residue.

*** Given high values because of high sulfur fuel.

TABLE 4

AVERAGE ABATED AIR EMISSIONS DATA FROM THE GALLATIN ROTARY COMBUSTOR

"REGULATED AIR POLLUTANTS"

Pollutant	Average Concentration	Average lb/hr	Average lb/ton	Average lb/10^6 Btu**
Particulate:				
U.S. EPA and BAAQMD (without condensibles)	0.0321 gr/SDCF at 12% CO_2	2.74	0.715	0.0949
SCAQMD and Other California (with condensibles)	0.0365 gr/SDCF at 12% CO_2	3.10	0.766	0.974
SO_2:				
U.S. EPA Method 8	141 ppm_v at 7% O_2	13.98	3.50	0.440

Air Pollution Control Equipment	Pollutant	Average Control Efficiency
Cyclone Only	Particulate	80.82% U.S. EPA-BAAQMD 78.47% SCAQMD-Other CA
APITRON		
Electrostatically Assisted Baghouse Only	Particulate	91.60% U.S. EPA-BAAQMD 91.53% SCAQMD-Other CA
Overall Apitron/Cyclone System	Particulate	98.39% U.S. EPA-BAAQMD 98.18% SCAQMD-Other CA

* Process feed weight approximately 92 tons per day.

** Based on as-received MSW less the heating value of the residue.

TABLE 5

AVERAGE UNABATED AIR EMISSIONS DATA FROM THE GALLATIN ROTARY COMBUSTOR

"NON-REGULATED AIR POLLUTANTS"

Pollutant	Average Concentration (ppm$_v$ at 7% O_2)	mg/kg[5]	Average lb/hr	Average lb/ton[1]	Average lb/10^6 Btu[2]
Total Sulfate	86.4	—	8.26	2.07	0.259
SO_3 (gaseous)[3]	40.3	—	3.85	0.97	0.121
$SO_4^=$ (particulate)[3]	46.1	48,000	4.41	1.10	0.138
HCl (gaseous)	509	—	19.8	5.27	0.761
Total Fluoride	10.22	—	0.232	0.0628	0.0099
HF (gaseous)[4]	5.11	—	0.116	0.0314	0.0050
F^- (particulate)[4]	5.11	1,110	0.116	0.0314	0.0050
NH_3 (gaseous)	29.2	—	0.458	0.121	0.0162

[1] Process feed weight approximately 92 tons per day.

[2] Based on as received MSW less heating value of the residue.

[3] Assumed that the SO_4 on the filter and before (front half) was particulate $SO_4^=$ and the back half was gaseous. Both calculated as H_2SO_4.

[4] Data based on multiclone data; gaseous HF assumed to be in the back half and F^- particulate in the front half.

[5] Milligrams of HF or H_2SO_4 per kilogram of total particulate emission.

TABLE 6

UNABATED (COMBUSTOR OUTLET) HEAVY METAL EMISSION RATES

Element	Average Weight %	Particulate Average lb/hr	Element E.R. (lb/hr)	Average Feed Rate TPH	Average Feed Rate 10^6Btu/hr	Emission Factors 10^{-3} lb/ton	Emission Factors 10^{-4} lb/10^{-6}-Btu
Arsenic (As)	0.0073	163.5	0.0119	3.74	29.01	3.18	4.10
Beryllium (Be)	<0.00011	163.5	<0.000180	3.74	29.01	<0.048	<0.062
Cadmium (Cd)	0.054	163.5	0.0883	3.74	29.01	23.6	30.4
Chromium (Cr)	0.018	163.5	0.0294	3.74	29.01	7.86	10.1
Selenium (Se)	<0.00033	163.5	<0.000540	3.74	29.01	<0.144	<0.186
Nickel (Ni)	<0.00076	163.5	<0.00124	3.74	29.01	<0.332	<0.427
Vanadium (V)	<0.0031	163.5	<0.00507	3.74	29.01	<13.6	<1.75
Zinc (Zn)	1.9	163.5	3.107	3.74	29.01	831	1,071
Lead (Pb)	0.626	163.5	1.024	3.74	29.01	274	353
Antimony (Sb)	0.085	163.5	0.139	3.74	29.01	37.2	47.9
Copper (Cu)	0.077	163.5	0.126	3.74	29.01	33.7	43.4
Manganese (Mn)	0.138	163.5	0.226	3.74	29.01	60.4	77.9
Molybdenum (Mo)	0.0037	163.5	0.00605	3.74	29.01	1.62	209
Tin (Sn)	<0.071	163.5	<0.116	3.74	29.01	<31.0	<40.0

TABLE 7

TOTAL MERCURY EMISSIONS AT THE COMBUSTOR OUTLET

	Date and Time			
	2/7/83 1050 to 1437	2/8/83 0855 to 1130	2/9/83 0940 to 1215	AVERAGE
EMISSIONS				
ug/NM^3 dry @ 12% CO_2	162	439	166	256
Lbs/Hr	0.0046	0.0107	0.0048	0.0067
MSW FEED RATE				
Tons/Hr	3.86	4.0	3.79	---
10^6 Btu/Hr	35.58	30.59	28.41	---
EMISSION FACTORS				
Lbs/Ton	11.9×10^{-4}	26.8×10^{-4}	12.7×10^{-4}	17.1×10^{-4}
Lbs/10^6 Btu	12.9×10^{-5}	35.0×10^{-5}	16.9×10^{-5}	21.6×10^{-5}

TABLE 8
HEAVY METAL DISTRIBUTION ON PARTICULATE

WEIGHT FRACTION

Size Range (u):	>3.9 u					1.0 to 1.8 u					<1.0 u				
	KURE	GALLATIN				KURE	GALLATIN				KURE	GALLATIN			
ELEMENT		#2	#3	#4	Ave.		#2	#3	#4	Ave.		#2	#3	#4	Ave.
Arsenic (As)	—	35.9	95.7	74.2	68.6	—	14.2	1.1	4.8	6.7	—	49.9	3.2	21.0	24.7
Beryllium (Be)*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Cadmium (Cd)	—	17.8	31.4	22.4	23.9	—	18.2	12.4	13.7	14.8	—	64.0	56.2	63.9	61.4
Chromium (Cr)	81.4	85.1	80.8	87.9	84.6	16.8	7.4	12.1	8.7	9.4	1.8	7.5	7.1	3.4	6.0
Selenium (Se)*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nickel (Ni)*	75.1	—	—	—	—	20.2	—	—	—	—	4.7	—	—	—	—
Vanadium (V)*	48.8	—	—	—	—	29.4	—	—	—	—	21.8	—	—	—	—
Zinc (Zn)	57.7	31.4	41.2	41.5	38.0	19.0	14.1	21.0	13.9	16.3	23.3	54.5	37.8	44.6	45.6
Lead (Pb)	35.1	20.8	38.0	30.1	29.6	25.5	16.3	11.2	13.0	13.5	39.4	63.0	50.8	56.9	56.9
Antimony (Sb)	—	8.2	3.0	11.9	7.7	—	5.3	18.1	9.8	11.1	—	86.5	78.9	78.3	81.2
Copper (Cu)	48.7	50.3	74.1	64.8	63.1	23.8	10.2	5.6	6.1	7.3	27.5	39.4	20.3	29.1	29.6
Manganese (Mn)	94.8	95.7	97.6	94.7	96.0	4.4	2.0	1.5	2.1	1.9	0.8	2.3	0.8	3.2	2.1
Molybdenum (Mo)	49.4	63.8	79.3	56.5	66.5	26.1	19.3	8.1	6.1	11.2	24.5	16.9	12.6	37.4	22.3
Tin (Sn)	32.5	9.2	5.1	16.0	10.1	28.9	21.4	26.8	16.9	21.7	38.6	69.4	68.1	67.1	68.2

*Gallatin levels of concentrations were below the level of detection.

TABLE 9
CEM DATA SUMMARY

SUMMARIES OF PLANT OPERATION INCLUDING DATA TAKEN DURING UPSET, STARTUP, SHUTDOWN, AND UNUSUAL FUEL CONDITIONS

FIRST WEEK TOTALS

		O_2	CO	NO_x	SO_2	HC	O_2
			(Corrected to) 7% O_2			(wet)	
		%	ppm	ppm	ppm	ppm	%
2-7	Mon.	9.5	278	174	81	9.5	6.6
2-8	Tues.	8.6	577	169	141	34	6.5
2-9	Wed.	9.8	622	147	266	47.4	6.2
2-10	Thurs.	11.2	598	140	171	23.4	5.5
2-11	Fr.	8.2	744	131	225	7.8	5.3
2-12	Sat.	7.8	636	122	—	—	5.3
2-13	Sun.	8.3	287	148	260	—	5.7
2-14	Mon.		PLANT UPSET				
Weighted Weekly Average		9.1	567	144	198	21.0	6.0
			ppm	ppm	ppm	ppm	
Worst							
1-Hr			2490	240	1328	—	
2-Hr			—	217	1069	—	
3-Hr			—	212	936	124	
Daily			744	174	266	47.4	
# Hours of Recorded Data			135	134	113	32	

SUMMARIES OF TYPICAL PLANT OPERATION

FIRST WEEK TOTALS

	O_2	CO	NO_x	SO_2	HC	O_2
		(Corrected to) 7% O_2			(wet)	
	%	ppm	ppm	ppm	ppm	%
Mon.	9.5	235	169	74	9.5	6.6
Tues.	8.6	577	169	141	34	6.5
Wed.	9.8	622	147	197	47.4	6.2
Thurs.	11.2	598	140	117	23.4	5.5
Fri.	8.2	668	128	228	7.8	5.3
Sat.	7.8	636	122	—	—	5.3
Sun.	8.3	287	148	260	—	5.7
Mon.		PLANT UPSET				
Weighted Weekly Average	9.1	554	143	180	21.0	5.9
		ppm	ppm	ppm	ppm	
Worst						
1-Hr		2055	211	651	—	
2-Hr		—	194	508	—	
3-Hr		—	193	454	124	
Daily		668	169	260	47.4	
# Hours of Recorded Data		132	129	97	32	

TABLE 9 (continued)
CEM DATA SUMMARY

SUMMARIES OF PLANT OPERATION INCLUDING DATA TAKEN DURING UPSET, STARTUP, SHUTDOWN, AND UNUSUAL FUEL CONDITIONS

SECOND WEEK TOTALS

		O_2	CO	NO_x	SO_2	HC	O_2
			(Corrected to) 7% O_2			(wet)	
		%	ppm	ppm	ppm	ppm	%
2-14	Mon.	11.3	494	186	—	—	7.2
2-15	Tues.	8.3	758	151	—	—	6.0
2-16	Wed.	11.7	2974	136	238	—	4.7
2-17	Thurs.		PLANT UPSET				
2-18	Fri.	12.8	1935	134	—	—	5.9
2-19	Sat.		PLANT UPSET				
2-20	Sun.	13.9	2501	108	—	—	5.3
2-21	Mon.	11.7	1407	116			5.8
Weighted Weekly Average		11.5	1532	142	238	—	5.8
			ppm	ppm	ppm	ppm	
Worst							
1-Hr			11,100	241	406	—	
2-Hr			—	218	342	—	
3-Hr			—	212	306	—	
Daily			2974	186	238	—	
# Hours of Recorded Data			81	81	11	—	

SUMMARIES OF TYPICAL PLANT OPERATION

SECOND WEEK TOTALS

	O_2	CO	NO_x	SO_2	HC	O_2
		(Corrected to) 7% O_2			(wet)	
	%	ppm	ppm	ppm	ppm	%
Mon.	11.3	494	186	—	—	7.2
Tues.	8.3	758	151	—	—	6.0
Wed.	11.7	779	138	178	—	4.7
Thurs.		PLANT UPSET				
Fri.	12.8	DATA UNUSABLE				5.9
Sat.		PLANT UPSET				
Sun.	13.9	DATA UNUSABLE				5.3
Mon.	11.7	DATA UNUSABLE				
Weighted Weekly Average	11.6	686	159	178	—	5.8
		ppm	ppm	ppm	ppm	
Worst						
1-Hr		1451	241	265	—	
2-Hr		—	218	215	—	
3-Hr		—	218	216	—	
Daily		779	186	178	—	
# Hours of Recorded Data		42	42	6	—	

TABLE 9 (continued)
CEM DATA SUMMARY

	SUMMARIES OF PLANT OPERATION INCLUDING DATA TAKEN DURING UPSET, STARTUP, SHUTDOWN, AND UNUSUAL FUEL CONDITIONS					SUMMARIES OF TYPICAL PLANT OPERATION			
	CO	NO_x	SO_2	HC		CO	NO_x	SO_2	HC
Worst Case:					Worst Case:				
Daily	2974	186	257	47.4	Daily	779	186	260	47.4
1-Hr	11,100	241	1328	—	1-Hr	2055	241	651	
2-Hr	—	218	1069	—	2-Hr	—	218	508	—
3-Hr	—	218	936	124	3-Hr	—	218	454	124
Two Week Daily Average	929	143	205	21.0	Two Week Daily Average	586	147	180	21.0
# Hours of Recorded Data	216	215	143	32	# Hours of Recorded Data	174	171	103	32

TABLE 10
SUMMARY OF TEST PROTOCOL

Test Number	Funding Responsibility	Test Description
1A1	CWMB	SO_2/SO_3
1A2	CWMB	SO_2/SO_3
1A3	CWMB	SO_2/SO_3
2A1	CWMB/CARB	% H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HCl, HF, sample weights for PM
2A2	CWMB/CARB	%H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HCl, HF, sample weights for PM
2A3	CWMB	Method 5, HCl, HF
2A4	MOE	PCDDs, PCDFs - Knockout flyash
4A1	CWMB	Hg
4A2	CWMB	Hg
2B1	CWMB/MOE	%H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HCl, HF, sample weights for PM
2B2	CWMB/MOE	% H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HCl, HF, sample weights for PM
2B3	MOE	PCDDs, PCDFs - Scrubber flyash
3B1 Sensor	CWMB/MOE	HCl, HF, heavy metals, PCDD/PCDF by particle size (less than or greater than 2 um) - Flow
3B2	CWMB	Particle size - Andersen
3B3 Sensor	CWMB/MOE	HCl, HF, heavy metals, PCDD/PCDF by particle size (less than or greater than 2 um) - Flow
3B4	CWMB	Particle size - Andersen
3B5	CWMB	HCl, HF, heavy metals, particle size
3B6	CWMB	Particle size - Andersen

TABLE 10
SUMMARY OF TEST PROTOCOL
(continued)

Test Number	Funding Responsibility	Test Description
1C1	CWMB	Part, Cond, SO_2/SO_3
1C2	CWMB	Part, Cond, SO_2/SO_3
1C3	CWMB	Part, Cond, SO_2/SO_3
2C1	CWMB/MOE	% H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HC1, HF, sample weights
2C2	CWMB	Method 5, HC1, HF
3C1 - 3C6	- - (same as 3B1 - 3B6) - -	
1D1	CWMB	Part, Cond, SO_2/SO_3
1D2	CWMB	Part, Cond, SO_2/SO_3
1D3	CWMB	Part, Cond, SO_2/SO_3
2D1	CWMB/CARB	% H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HC1, HF, sample weights PM
2D2	CWMB/CARB	% H_2O, Sample Vol, Orsat, etc. PCDDs, PCDFs, HC1, HF, sample weights
2D3	CWMB	Method 5, HC1, HF
2D4	CARB	PCDDs, PCDFs, flyash baghouse
3D1		Particle size distribution, HC1, HF, PCDDs, PCDFs (less than or greater than 2 um)
3D2	CWMB	Particle size - Andersen
4D1	CWMB	Hg (Method 101)
4D2	CWMB	HG (Method 101)
2E1	CARB	Sample Blank, PCDDs, PCDFs

Note:
CARB = California Air Resources Board
CWMB = California Waste Management Board
MOE = Ontario Ministry of the Environment
WSU = Wright State University
Cond = Condensible
Part = Particulates

TABLE 11

DAILY TESTING SCHEDULE FOR DS/DV/FF

DATE	SAMPLING LOCATIONS							
	A DS INLET		B DS OUTLET/DV INLET		C DV OUTLET/FF INLET		D FF OUTLET	
10/13/83	SO_2	U.S. EPA Method 6 (3 Runs)			PM SO_2	U.S. EPA Methods 5 and 8 with condensibles (3 Runs)	PM SO_2	U.S. EPA Methods 5 and 8 with condensibles (3 Runs)
10/14/83	PM HCl HF PCDDs PCDFs	U.S. EPA Modified Method 17 (2 Runs)	PM HCl HF PCDDs PCDFs	U.S. EPA Modified Method 5 (2 Runs)	PM HCl HF PCDDs PCDFs	U.S. EPA Modified Method 5 (2 Runs)	PM HCl HF PCDDs PCDFs	U.S. EPA Modified Method 5 (2 Runs)
10/15/83			Particle Sizing HCl, HF Heavy Metals & PCDDs PCDFs	Flow Sensor & Andersen Flow Sensor (3 runs each)	Particle Sizing HCl, HF Heavy Metals & PCDDs PCDFs	Flow Sensor & Andersen Flow Sensor (3 runs each)	Particle Sizing HCl, HF Heavy Metals & PCDDs PCDFs	Flow Sensor & Anderson Flow Sensor (1 continuous run each)
10/16/83	Hg PM condensibles only HCl, HF	U.S. EPA Method 101 (2 Runs) Gas Train (1 Run)					Hg PM HCl, HF	U.S. EPA Method 101 (2 Runs) U.S. EPA Method 17 with condensibles

TABLE 12

PRELIMINARY RESULTS FOR REMOVAL OF PARTICULATE, ACID GASES, AND MERCURY ACROSS A DRY SCRUBBER, DRY VENTURI, AND BAGHOUSE

Pollutant	Average Inlet to Dry Scrubber	Average Outlet of Fabric Filter	Removal Efficiency (percent)
Particulate - gr/SCDF			
U.S. EPA Method 5 **	2.26*	0.005	---
U.S. EPA Method 5 ** with condensibles	2.29*	0.027	---
Particulate - gr/SDCF @ 12% CO_2			
U.S. EPA Method 5**	4.74*	0.010	99.79
U.S. EPA Method 5** with condensibles	4.80*	0.055	98.85
HCl*** - ppm_{dv} @ 7% O_2	376	3.3	99.4
Outlet only	---	7.7	---
SO_2*** - ppm_{dv} @ 7% O_2	26	<0.2	> 99
HF**** - ppm_{dv} @ 7% O_2	1.54	0.42	72.7
Outlet only	---	0.54	---
Hg - ug/NM^3 (dry) @ 12% CO_2	280	196	30

---

* Inlet of Fabric Filter

** 3 of 5 tests

*** 1 of 3 tests

**** 1 of 3 tests - gaseous only

ASME'S ROLE IN DEVELOPING STANDARDS FOR MEASUREMENT OF DIOXIN EMISSIONS

Charles O. Velzy, P.E.
President
Charles R Velzy Associates, Inc.
Armonk, New York

Beginning in the late 1970's, investigators in Europe, and then the U.S. and Canada, reported finding dioxin in precipitator fly ash at energy from waste plants. Quantities reported were in the parts per billion and parts per trillion range. Identification of this material at these levels was only possible because of the development of new, highly sophisticated laboratory analysis procedures and equipment. The public hysteria surrounding reports in the popular press of finding such substances in stack discharges from energy from waste plants has raised serious concerns about implementation of such projects in different parts of this country. Thus, we are currently faced with a major problem in attempting to prioritize public health concerns related to implementation of resource recovery/energy from waste projects and potential emission of trace chlorinated hydrocarbons, such as dioxins and furans. Resolution of this problem requires the development, at the earliest possible date, of more definitive, sound, scientific information regarding conditions leading to formation, and destruction, of trace chlorinated hydrocarbons in waste fired energy recovery combustion processes.

In response to the first reporting of dioxin in a U.S. resource recovery plant at Hempstead, NY, and at the urging of industry representatives, the American Society of Mechanical Engineers (ASME) Research Committee for Industrial and Municipal Wastes commissioned a study on the current understanding of the technology of dioxin emissions from combustion processes. The basic study, undertaken by A.D. Little under contract to the ASME Research Committee, was critically reviewed by over twenty-five scientists/engineers, with the review comments responded to by A.D. Little. The entire dialogue, which was funded through support from government and industry, was published by ASME in February of 1981. A problem identified in this report was a lack of agreement on a standard method of test.

The subcommittee (which I chaired) that supervised this study for the ASME Research Committee, wrote a Foreword to the Report which attempted to place the public health risks from reported dioxin emissions in perspective. Based on available estimates of stack effluent concentrations of dioxin, mathematical calculations, and assumptions as to stack height, wind speed, and distance from the stack, a projection was made which indicated possible ground level concentrations of dioxin on the order of 0.1 pg/m^3 (0.1 x 10^{-12} g/m^3). This projection was then compared to extrapolations by NYS Health Department personnel for 2,3,7,8-TCDD in water and/or fish to arrive at a risk of one additional cancer case in a population of 1,000,000. To quote from the Foreword, "This projection, of course, involves a number of assumptions, the most important being, perhaps, that the population at the <u>point</u> of ground level concentration has an average daily breathing volume of 15 m^3 (530 ft.^{3}). This implies continuous exposure over one's lifetime (24 hrs./day for 70 yrs.) at the above concentration. Since the point of maximum ground level concentration changes with changes in wind direction, and a person normally moves from place to place in their daily activities, the assumption of continuous exposure is obviously a much more severe condition than would (ever) exist in practice. Another assumption in this attempt at risk assessment is that absorption of 2,3,7,8-TCDD through the lungs is equal to its absorption through the gastrointestinal tract." This assumption also appears to be ultra conservative. Thus, we feel these are extremely conservative worst case projections.

In October of 1981, the U.S. Environmental Protection Agency (EPA) issued their own evaluation of the health risks related to possible dioxin emissions from combustion of municipal solid waste based on tests of five solid waste combustion plants conducted in the early 1980's. Their conclusions closely paralleled those contained in the Foreword to the ASME Report issued six months earlier. The risk, very conservatively estimated as one additional cancer case per million of exposed population, was found to be so low that EPA indicated "that the emission levels of TCDD from these facilities do not present a public health hazard for residents living in the immediate vicinity." Further, interim evaluations at these five resource recovery facility locations indicated "that tetrachlorinated dioxin emissions from the combustion of municipal wastes are 'far below the level of a credible health risk.'"

However, these assessments of risk have not been widely accepted, largely because of: the extreme toxicity of dioxin inferred from animal studies; uncertainties in predicting emission levels from combustion sources due, at least partially to the lack of agreement on standard testing methods; and the absence of established "safe" emission limits. This lack of acceptance of risk has been evidenced recently nationwide by: moratoriums on energy from waste projects approved by voters in California; concerns in the news media in St. Louis; and proposed legislation in New York and New Jersey. Because of this continuing concern, two technical divisions within ASME, Air Pollution Control and Solid Waste Processing, called a meeting of engineers knowledgeable in the field on March 23, 1983, to discuss what role ASME might take in solving this problem.

The ad hoc Committee formed at this initial meeting, which has since met monthly, was organized into three subcommittees as follows: information gathering; technology transfer; and research. The research committee has developed the framework of an overall research program with short term, mid term, and long term objectives. Within the framework of the program outlined above, "near term" is meant to describe a period of 1 to 3 years, "mid term" means 2 to 5 years, and "long term" generally means 5 to 10 years, with health effects research probably continuing for 20 years or longer. The cost of such a program would be in the millions. Because of the general benefit to Society and the substantial program cost, major funding should be by the Federal government. The private sector, desirably through a Committee structure such as that currently in place within ASME, should retain a role in implementation of the total program to insure that the goals and objectives of the total program are achieved in a timely fashion within the priority needs of protecting the health of the general public and the realities of generating technically valid answers.

A workshop held January 24 and 25, 1984, in the Washington, D.C. area addressed Tasks 1-4 of Near Term Objective 1 of the research program noted above. The objective of these tasks was to reach a concensus among those currently active in the monitoring of dioxin and other trace chlorinated hydrocarbons on standard methods of sampling and laboratory analysis, including development of quality assurance programs. Such a workshop was deemed necessary in that, while methods currently exist to analyze for dioxin and other toxic substances in concentrations as low as parts per billion and lower, sampling and extraction procedures continue to be the subject of substantial discussion in the technical community. The implication of this is that, while over the past several years we have developed the capability to detect the presence of minute quantities of toxic substances, we are not too sure about the absolute quantity or the rate of discharge from combustion processes. Resolution of this problem requires the development, at the earliest possible date, of more definitive sound scientific information regarding conditions leading to formation, and destruction, of trace chlorinated hydrocarbons in combustion processes. This, in turn, requires the development of broadly accepted and used standard monitoring, sampling and laboratory analysis procedures.

Much discussion has taken place over the past several years, based on results at operating plants, as to the probable mechanism(s) of formation and destruction of PCDD (polychlorinated dibenzo-dioxin) and PCDF (polychlorinated dibenzo-furan). Thus, it has been suggested that PCDD and PCDF are formed as a result of combustion of PVC plastics contained in municipal solid waste. Recent investigations have demonstrated that this is an incorrect assumption. Thus, it is estimated that well over 50 percent of the chlorine found in municipal solid waste is associated with materials other than PVC. Several investigators have recently reported on studies which demonstrate that burning materials containing lignine, such as wood fiber, in the presence of a source of chlorine will result in generation of PCDDs and PCDFs. An attempt by one investigator to generate PCDDs and PCDFs by burning PVC alone were not successful.

An inspection of Table 1, particularly the results of tests by EPA in 1980 and Tiernan in 1983, clearly indicates that the formation of PCDDs and PCDFs is highly temperature dependent. The temperatures noted in the Table as furnace operating temperatures correlate well with reported destruction temperatures for PCDD.

Several other observations should be made regarding the test results presented in Tables 1 and 2. First, comparison of concentrations reported in several plants indicate five orders of magnitude variation in test results. Some of this variation appears to be related to differing furnace temperatures as noted above. However, other variations (Table 1, Tiernan's paper, Swedish and Dutch Plant, five orders of magnitude; and Table 2, German plants, approximately three orders of magnitude) appear due to potential differences in sampling or analytical procedures. Note, on Table 3, the variation in emission level of PCDD from various plants in micrograms per ton of waste burned.

TABLE 1

CDD AND CDF IN STACK EFFLUENT
(SUSPENDED PARTICULATE)

	EPA Tests - 1980					Tiernan Paper				Canada		ASME Report	
	RDF & Coal WW Blr. @1200°C	Modular w/waste Heat Blr. @1000°C	Refractory w/waste Heat Blr. @830°C	Mass Fired Waterwall @650°C	d-RDF w/coal WW Blr. ? Temp.	US Plant @550°C	Swedish Plant 400–600°C	Swedish Plant 680–1040°C	Neth. Plant 800–1050°C	Plant A	Plant B	Hempstead Res. Rec. Plant	German Incinerator
PCDD (μg/g)	0	---	---	0.25	---	15.6	38	0.76	17,060	0.69	0.47	2.75–8.25	---
TCDD (μg/g)	0	0.0026	0.0023	0.034	2.71	1.4	---	---	682	0.01	0	0.22–0.66	300
PCDF (μg/g)	0	---	---	2.5	---	30.2	---	---	---	1.98	1.05	---	---
TCDF (μg/g)	0	0.024	0.014	0.49	25.45	9.4	---	---	---	0.054	0.28	---	---
Particulate (g/m^3)	---	0.456	1.532	est. 0.183	0.011	est. 0.275	---	---	---	---	---	---	0.05

TABLE 2

CDD IN PRECIPITATOR FLY ASH

	ASME Report (18)					German Plants (19)					
	Swiss Plant	German Plant	Canadian Plant	Japanese Plant		SM 03.81	SM 283	SM 294	MA LfU	S LfU	LFI NW
				Plant 1	Plant 2						
PCDD (ug/g)	0.22	---	0.404	0.058	0.044	0	0.01	0.13	9.15	5.2	8.0
TECC (ug/g)	0.002	0.025	---	---	---	---	---	---	---	---	---

TABLE 3

TCDD/PCDD Emissions (ug/T)
from
European and USA Plants

Compound	Olie Netherlands	Benfenati Italy	Gizzi Italy	Swiss Federal Office	Redford USA	ADL USA	U.S. Plant	
							Test 1	Test 2
PCDD	10,508	2,330	2,405	675	209	2,121	20,166	13,186
TCDD	555		227	24	29	159	1,810	1,034
% of $\frac{\text{TCDD}}{\text{PCDD}}$	5.3		9.4	3.6	13.9	7.5	9.0	7.8

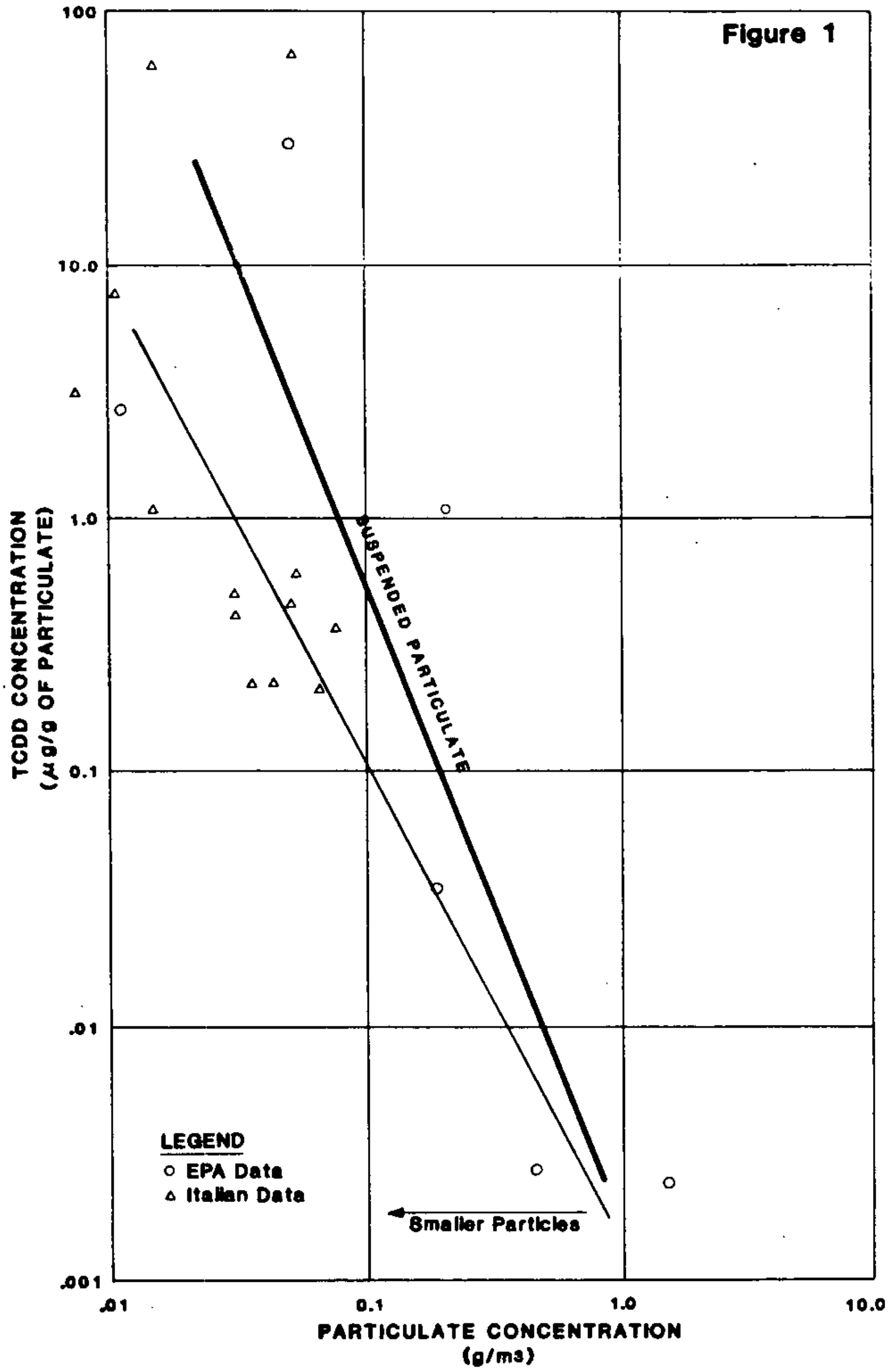
Another potential source of differences in concentration of TCDD and TCDF in suspended particles (reported in Table 1 as micrograms of TCDD or TCDF per gram of suspended particulate) is related to the tendency of the substances to concentrate in smaller particles. Thus, in the German plant and the plant burning dRDF with coal, particulate emissions were extremely low. This resulted in a high percentage of submicron particles in the suspended material. The reported TCDD concentration (not total emission) then, in the highly controlled plants, was several orders of magnitude higher than in those plants with less efficient control of particulate emissions resulting in larger particles in the flue gas discharges. This is graphically illustrated in Figure 1.

On both Figures 1 and 2, EPA test data and data reported by Italian investigators has been plotted. It may be observed that, while both sets of data exhibit the same general trends, there are substantial differences with respect to where on the Figures one might plot a "line of best fit" for the separate sets of data. One might surmise that the data was generated using different sampling methods or analytical procedures. Another problem is that nothing appears in the Reports about the specifics of monitoring "furnace temperatures". Thus, real average flue gas temperatures could vary by hundreds of °F from plant to plant.

Preliminary conclusions may be drawn from the data presented in Tables 1 and 2 and the discussion above. Maintenance of optimum combustion conditions, including maximum practicable furnace temperatures, will result in limiting PCDD and PCDF emission (along with all other hydrocarbons). Use of air pollution control devices that maximize reduction of particulate emissions will result in reducing the total mass of PCDDs and PCDFs discharged to the atmosphere, but will also result in higher concentration of these materials on the remaining smaller sized particulates. However, these general conclusions cannot be carried further, at this time with any degree of confidence, to make specific numerical predictions of emission levels under various operating conditions.

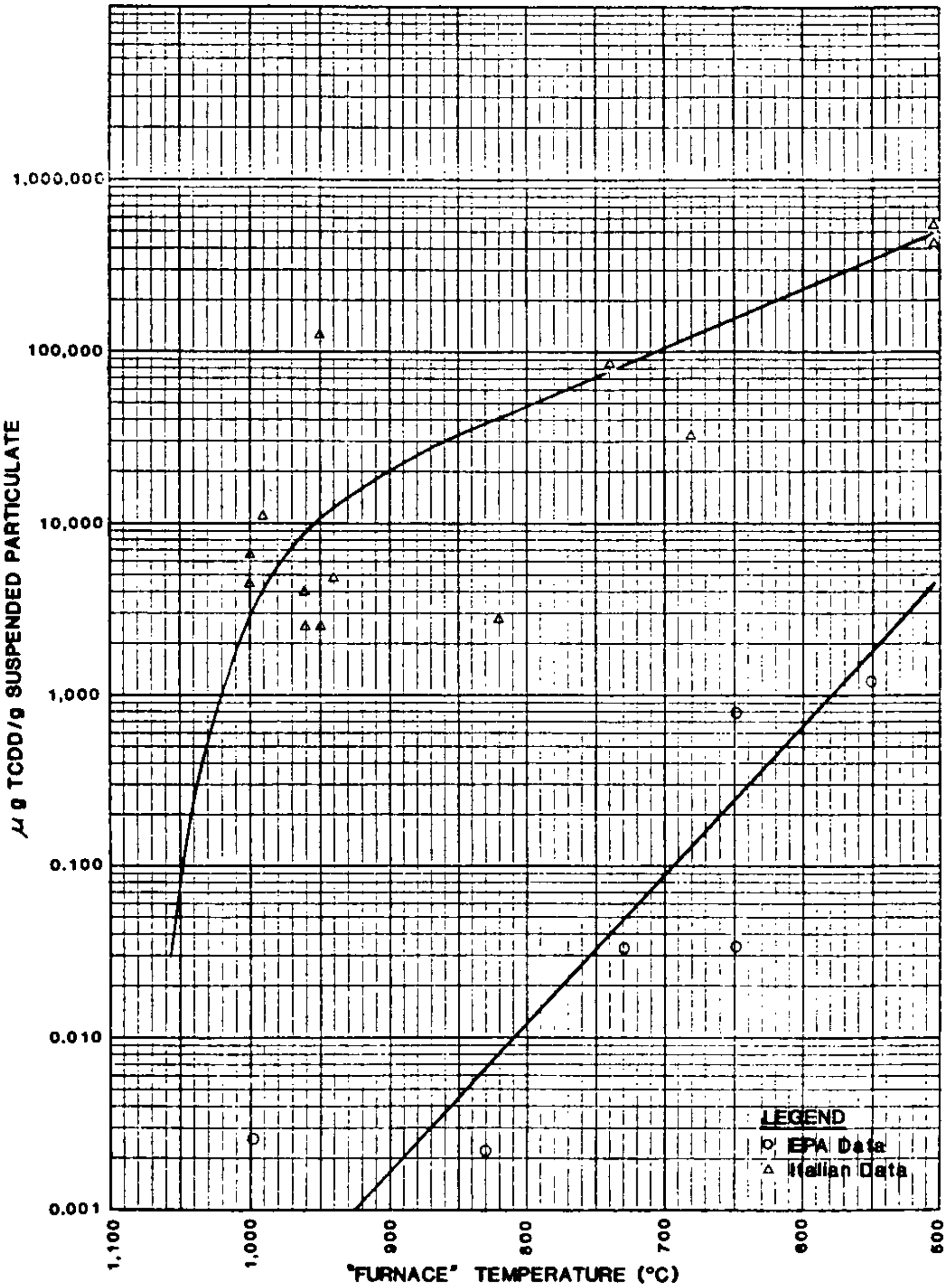
In another separate but related area, when problems have been encountered in obtaining satisfactory particulate acceptance test results, there is usually little data available with which to evaluate the results in light of variations in furnace combustion systems, variations in material being burned, and variations in furnace operation during tests. There is generally little or no information on the effect of design details and operational differences in air pollution control equipment on test results. There is little information on the chemical composition and size and shape of particulates carried in the flue gases in these installations. Test reports generally do not have information which would allow one to evaluate the effect on reported emissions of location and number of test points used, Orsat data generation and interpretation, effect of different sampling methods and techniques, and the method of calculating and expressing test results.

The primary objective of the January workshop was to come to a concensus agreement on a coordinated program of standardized testing methodology that would allow scientifically factual information to be developed over a period of time with respect to emissions of trace amounts of chlorinated



TCDD CONCENTRATION VS. PARTICULATE CONCENTRATION

Figure 2



TCDD CONCENTRATION vs. FURNACE TEMPERATURE hydrocarbons. Thus, at the end of two days of difficult deliberations, the participants reached a general concensus in the following areas:

1. The minimum acceptable amount of information to collect and record regarding furnace operating conditions during any test for trace chlorinated hydrocarbons.

2. The type and extent of furnace operating information that should be generated to allow optimization of combustion from the standpoint of minimizing emission of trace chlorinated hydrocarbons.

3. Standard source sampling procedure of use both in administering regulatory functions and in determining the most cost effective methods to minimize emissions of trace chlorinated hydrocarbons.

4. Standard laboratory procedures required to quantify the trace chlorinated hydrocarbons in the samples obtained by the source testing methods developed in 3. above.

In summary, a primary question facing resource recovery/energy from waste facilities presently ready for implementation is predicting, with scientific certainty, emission levels of trace pollutants such as heavy metals, dioxin, and other trace chlorinated hydrocarbons. Control of air pollution will only be achieved when emissions from a particular process are carefully characterized physically and chemically and quantified under varying combustion conditions such that selection of control techniques can be made on a sound technical basis. It must be possible to define design and operating parameters that will allow attainment of minimal discharge of trace pollutants such as dioxin (possibly zero with present day testing and analytical techniques), while minimizing discharge of other pollutants, with presently available waste fired energy recovery technologies. Present available data and regulatory acceptance testing methodology and reporting practices, do not seem to be adequate to meet the challenges of indicated future control requirements.

A secondary question (secondary only because of the time frame required to formulate scientifically based conclusions) is establishment of "safe" emission limits.

CHLORINATED DIBENZO-P-DIOXINS AND FURANS IN INCINERATION OF MUNICIPAL SOLID WASTE

David H. Cleverly
Research Scientist
New York City Department of Sanitation
51 Chambers Street; Room 830
New York, New York 10007

In 1977 Kees Olie, and Otto Hutzinger of the University of Amsterdam in the Netherlands reported finding chlorinated dibenzo-p-dioxins and dibenzofurans in emissions from garbage burning incinerators in Holland(1). At the time they were assessing hydrocarbon emissions and inadvertently discovered dioxins and furans. Because of the extreme toxicity of the compounds many other investigators began independent evaluations of stack emissions from municipal waste combustors (2,3,4,5). To date over 35 incinerators world-wide have been evaluated.

The discovery of what can be termed as "micropollutants" is a direct result of remarkable advances in analytical chemistry. Prior to 1970 the limits of detection for chemical compounds in stack effluents was one part per million. By 1980 the analytical sensitivity was reduced to one part per billion. Today the ability to detect specific isomers of dioxin is below one part per trillion, and in a few years it is expected that the level of detection will be down to an infinitesimal part per quadrillion (10^{-15} grams per gram). In addition there have been considerable advances made in the ability to separate individual isomers from the homologues in the sample. Only two isomers of the tetrachlorinted dioxins could be determined in 1974; today all 22 isomers can be analytically distinguished from each other.

Increasing the analytical sensitivity is the major reason dioxins and dibenzofurans have been discovered in combustion processes only within the past six years. A benefit of decreased detection limits is that formation and destruction theories of these compounds can be evaluated by laboratory experiment or in working incinerators.

This report is organized in the following manner: first the various theories of formation of dioxin will be discussed and evaluated; secondly the destruction of dioxins and furans during the incineration process will be discussed; next the operating conditions of modern incinerators as they apply to the destruction and inhibition of dioxin compounds will be discussed, and lastly there will be a discussion of emission rates of chlorinated dioxins and furans in waste-to-energy incinerators.

THEORY OF THERMAL FORMATION OF DIOXINS

The molecules found in garbage are complex and generally have too many atoms for combustion to proceed in any deliberate or preconceived fashion(6). In other words it is difficult to pedict how constituents present in the fuel will break apart, reform new compounds, disassociate into free radicals, or recombine with radicals and compounds under the influence of oxygen, turbulent mixing and temperature. The breakdown of molecules composing garbage and the formation of combustion products proceeds in long sequences of reactions, and each sequence involves only a small rearrangement of chemical bonds(7). Heat activates the collision of molecules, and high energy or violent collisions dissociates a molecule into fragmentary atoms called free radicals. These molecular fragments react with greater ease with other molecules or radicals yielding new intermediate combustion products. The intermediates collide, become dissociated into free radicals which sets up the process of creating intermediates. The repetition of the same molecular events is termed a chain reaction, and the atoms or radicals that cause the chain reactions are termed reaction centers. The chain reactions proceed by molecules reacting to form chain centers, and the more violent the collison the more likely the molecules will interact. The frequency and speed of these molecular encounters depends on the temperature of the gas(8). It usually only requires a small number of chain centers to lead to a large amount of chemical reaction. Thus chemical reactions and products are difficult if not impossible to predict with absolute certainty. For example water vapor is a product of combustion, but some 14 reactions have been identified that can possibly be responsible for H_2O formation. Methane, a simple compound of one carbon atom and four hydrogen atoms, may result in more than 100 elementary reactions when combusted. Therefore identifying all of the possible intermediate products of a fuel as complex as garbage may not be possible. It is possible however to identify the central chemical events in the formation of chlorinated dioxins which has been proposed through computer modelling, and through laboratory experiments under simulated incinerator conditions.

Current research is focused on several possible mechanisms for PCDD and PCDF formation in combustion. The theories include the following:

1. PCDDs and PCDFs exist as components of the raw fuel, ie: the refuse. Because of the relative thermal stablility of these compounds, they are not completely destroyed during incineration. Thus they are present in trace amounts in combustion effluents.

2. PCDDs and PCDFs are formed as a result of thermally induced reactions of certain precursor molecules present in the municipal waste. Some of these precursors are the result of oxidation-reduction reactions of stable compounds present in the waste, and the synthesis of dibenzo-p-dioxins and dibenzofurans occurs as a result of rearrangement of atoms, free-radical association, dechlorination and other molecular reactions.

3. PCDDs and PCDFs are formed in the combustion plasma or the gas plume because specific thermal degradation products arising from combustion are chlorinated by free radical chlorine present in the gases.

The first theory states that PCDD and PCDF compounds in the raw refuse fed into incinerators is responsible for dioxin and dibenzofuran emissions out the stack. Most investigations have not detected PCDD and PCDF compounds in the raw refuse(10,11). However, in September of 1983, researchers in Canada reported finding trace amounts of hepta and octachlorinated dioxins in the raw garbage fed into an incinerator in Toronto(12). Heptachlorinated dioxin ranged in concentration from 100ppt to 1ppb, and the concentration of octa-CDD ranged from 400ppt to 600ppt. The analyses is not considered statistically valid because only three samples of the input waste were taken.

The conditions of thermal stress imposed by incinerators discounts the liklihood of dioxins surviving the environment of the furnace at these trace levels. Generally, even the moderate temperature of 1472°F (800°C) is sufficient to cause the destruction of PCDD and PCDF compounds through the breaking of atomic bonds of the molecules. Thus dioxins and furans would have to be in ppm levels in the refuse feed to survive 99% destruction characteristic of modern incinerator conditions to be found in ppb or ppt levels in the flyash and particulate stack emissions(9). Even if commercial chemical products such as PCP, TCP, or phenoxy based pesticides and wood preservatives that have been found to contain ppb levels of TCDD, Penta-CDD, and Octa-CDD found their way into the refuse feed, these levels of dioxin would be greatly diluted when mixed with other constituents of the refuse. Hence the probability of PCDD concentrations to be present at levels that would impact PCDD emissions from the stack is quite low. Present knowledge of combustion kinetics discounts the validity of the first theory of formation occuring.

The second theory implies that the production of PCDD and PCDF compounds is a result of in-situ thermal degradation of precursor compounds present in the waste. Species of chlorophenols and chlorobenzenes are implicated as ideal precursor compounds. There are several examples of dioxin formed directly from the thermal degradation of precursors in laboratory experiments (10,13,14). Pentachlorobenzenes have been degraded in a pyrolytic atmosphere at 1150°F in sealed quartz ampoules, and have yielded ppb concentrations of tetra through octachlorinated dioxins. Pyrolysis of polychlorinated biphenyls (PCBs) has generated dibenzofurans in laboratory experiments at a rate of 1-5% of the PCB concentration. Trichlorophenolate has been successfully thermally degraded into PCDD using similar laboratory procedures. These laboratory procedures utilized reactive quartz ampules heated to between 900°F and 1200°F, and degradation was slowly induced in an oxygen deficient environment. Reducing the supply of oxygen during thermolysis increased the formation of dioxin(13). Higher temperatures significantly decreased the generation of dioxin(13). Increasing the chlorination of the precursor compounds, ie: chlorophenols, increased the resilience of the compound to thermal degradation(10). In each case high levels of precursors were used (200 micrograms to 500 micrograms) in order to generate ppb levels of PCDD. No precursors have been detected in the refuse at the ppm levels needed to induce the synthesis reaction to dioxins.

The exact mechanisms of PCDD and PCDF formation (in sita or de novo) are unknown at this time and can only be theorized. However, intensive research is being directed at the pathways of formation in full scale incinerators (10,11,18,23,25). Experiments in which full scale incinerators were fed chlorobenzenes and pentachlorophenols have not, so far, demonstrated a proportionate association between precursors present in the waste and stack emissions of PCDD and PCDF. For example Hutzinger and Olie have reported on adding hexachlorobenzene to a 96 metric tons per day refactory refuse incinerator in the Netherlands(16). About 200g of C_6Cl_6 per cubic meter of refuse was added to the incinerator over a 14 hour period. The furnace temperatures were between 760°C(1400°F) and 1050°C(1922°F). Hutzinger reports that, "No clear increase in either PCDD or PCDF was observed(16)." In another experiment the same scientists added wood treated with pentachlorophenol to a fluidized bed incinerator at a rate of 100kg/hour(16). They concluded that, "Addition of pentachlorophenol did not increase the level of chlorinated dioxins and dibenzofurans(16)." Micropyrolysis of pentachlorophenol, and PCBs in laboratory settings has yielded significant PCDDs and PCDFs including octa-CDD, hepta-CDD and hexa-CDD; it has been theorized that commercial chlorophenols or PCBs in the waste are precursors to PCDDs and PCDFs found in incinerator effluents (3,10). To date, this formation mechanism has not been clearly demonstrated in full scale refuse incinerators.

The third theory of dioxin formation involves thermal degradation products of combustion combining with chlorine in the gas plasma. Chloroganics and non-chlororganics thermally degrade to produce predioxin molecular structures that are then chlorinated by the influence of HCl, inorganic chloride, or organic chlorine present in the gases. Chlorobenzenes and chlorophenols have been observed in abundant quantity in municipal incinerators in the gas phase(5,12,13,17,19,25). These may thermally decompose, react, and reform into predioxin compounds which are then chlorinated by reaction with a chlorine ion.

In 1982, Hutzinger, Olie and others proposed that lignin in the raw refuse may thermally degrade into predioxins (10,11,16). Lignin is the non-cellulose component of vegetable matter that makes up about 20 to 30 percent of the dry weight of the woody tissues of plants. The predioxin compounds then undergo chlorination by interacting with HCl or another free chlorine radical. In an experiment, lignin sulfonate was burned in a quartz ampule tube in the presence of HCl or PVC (polyvinyl chloride). The reported combustion temperatures in the laboratory experiment did not exceed 590°C(1094°F). Low yields of PCDD and PCDF were generated in both experiments. When PVC was burned by itself no dioxins or furans were formed. This would indicate that the dioxins and furans were not produced in the thermal degradation of the PVC. In other investigations the complex lignin polymer was degraded under pyrolytic conditions into phenolic products (10). Thermal decomposition occurred at the temperature of 475°C (887°F). Altogether 26 phenolic compounds were observed. However no PCDDs or PCDFs were generated.

Liberti and Goretti have reported the generation of PCDD and PCDF from the combustion of pure vegetable extracts in the presence of chlorine(17). Pyrolytic degradation of extracts of chestnut, mimosa and tannic acid was accomplished in microscale in an unspecified manner under laboratory conditions. When the extracts were combusted without chlorine, phenols and cresol were detected in the combustion gas and particulates. When the extracts were burned in association with chlorine or PVC plastic, chlorophenols and PCDD and PCDF were formed. The researchers presumed that PVC was acting as a chlorine donor. Liberti concluded that heating vegetable matter breaks down the phenolics structure, yielding phenols. The phenols are chlorinated by chlorine present in the combustion atmosphere yielding chlorophenols. Pyrolysis of chlorophenols finally yields PCDD and PCDF. The general reaction he describes in the laboratory incinerator is a pyrolytic synthesis between a likely PCDD and PCDF precursor and a chlorine donor. Liberti speculates that PVC may act as the chlorine donating species. He suggests separating PVC would prevent chlorination of the plant phenolics present in vegetable matter, and thus precursor synthesis into pyrolytic products such as dioxins and furans would not happen.

The synthesis of dioxin is postulated to arise as a result of burning complex hydrocarbons along with the PVC consitutent in the refuse. This is thought to occur on two levels: either the PVC is acting as a chlorine doner when burned, or chlorobenzenes and chlorophenols as thermolysis products of PVC combustion are PCDD precursors(17,18). The primary product of thermolysis of pure PVC in laboratory experiments is hydrogen chloride gas(HCl)(13,10). Moreover, polycyclic aromatic hydrocarbons (PAH) like chlorobenzenes have been observed as PVC combustion products(13). No PCDD or PCDF compounds have been formed in degrading pure PVC(15,16). Other compounds measured as products of thermolysis have included: toulene, ethylbenzene, xylene, styrene, napthalene, and vinylchloride(15). Generally, increasing the termperature increases the formation of chlorinated hydrocarbons in pyrolytic combustion environments. Highest conversion efficiency occurred at temperatures between 1472°F to 2000°F. To date there have been no attempts to combust pure PVC in oxygen-rich environments under laboratory expermentation.

When working incinerators are observed, the theoretical association between the combustion of PVC and the chlorination of precursors into dioxins and furans is not as apparent or straight forward. For example, F.W. Karasek has recently reported on the controlled combustion of PVC added to the raw refuse fed into a Martin waterwall, resource recovery facility boiler in France(18). Sixty-two samples were collected in the precipitator hopper and analyzed for PCDD content. 300 kg (660 lbs) of PVC pellets were fed on an hourly basis into a 16 metric ton per hour furnace. The results showed that there were no differences in the emission levels of polychlorinated dioxins of the facility when combusting the normal refuse mix, and when combusting an additional 300 percent more PVC to the refuse. The experiment, using an actual working municipal waste incinerator designed for steam recovery, was repeated, and similar results were produced: the addition of PVC did not produce more dioxins. Furthermore, it must be noted that in Karasek's observations, no tetrachlorinated dioxins were detected either before or after the addition of PVC (at a detection limit of 0.1ppb). Under normal day-to-day operating conditions at this resource recovery facility no TCDDs were formed when a temperature greater than 900°C (1652°F), and when 12 to 14% oxygen in the combustion gas was sustained. Thus no 2,3,7,8-TCDD was found to be emitted.

A second example of the lack of a direct association with PVC and PCDD generation is a co-fired RDF combuster tested by the EPA in 1980(40). The Ames Iowa facility burned 85 percent coal and 15 percent refuse derived fuel(RDF) for the conversion of heat into electricity. The RDF was produced by removing the glass and metals from the garbage for recycling, and milling the remaining material. No paper or plastic was removed from the RDF. About 3 tons of RDF and 15 tons of coal were burned per hour; co-fired. The temperature of combustion was about 2,200^{o}F. The maximum RDF feed rate was about 9 tons/hour. No PCDDs or PCDFs were detected in any samples from this facility at a mean detection limit of 0.5ng/g in the flyash and 0.25 ng/dscm in the flue gas. No PVC or any other plastic was removed from the garbage prior to combustion.

In Oslo, Norway where PVC plastic is highly restricted and virtually no PVC was detected in the input refuse to a municipal incinerator, PCDDs and PCDFs were detected in the precipitator flyash(18). About 300 ppb of total PCDD was found, but no TCDD was detected. This compares with the French facility in which PVC was added with the refuse. About 580 ppb of total dioxins were detected in flyash at the Paris facility(18). The measurements between the two facilities are quantitatively different, but considering the level of detection, there is close agreement in the dioxin content of the flyash of both incinerators. Empirically one would expect a more profound reduction in total dioxin at the Olso incinerator if, indeed, the association between PVC in the waste and dioxin generation is strong.

It seems reasonable to assume that PVC is a significant source of chlorine in the refuse, but as the aforementioned examples have indicated, removing the PVC will not solve the problem of dioxin emissions. It is also important to note that hydrogen chloride is a common product of the thermolysis of many chloro-organic compounds, and these too are components of the refuse. As an example, a primary product of the pyrolysis of chlorobenzenes at 1100^{o}F is hydrogen chloride(HCl)(10). The refuse in urban areas contains an abundance of synthetic chlorinated organic compounds, many of which are benzene derivatives. Tanning agents for leather, flavoring, perfumes, paints and coatings, chemical solvents, photographic chemicals, pesticides, dyes, gasoline, food processing chemicals, and pharmaceuticals are a few examples of materials that may find there way into the refuse that contain chlorinated hydrocarbon compounds. Thus removing all the sources of chlorine in the waste would be difficult if not impossible to attain.

A critical question is, "What are the sources of chlorine in typical municipal solid waste?" Municipal solid waste contains as much as 0.66 dry weight percent chlorine(41,42). The plastic content of typical MSW is about 6% by weight(44). In the U.S. the PVC content of MSW has been observed to be as high as 10% of the total plastic fraction(43). It is assumed that the high density PVC contains 55% by weight chlorine. New York City generates approximately 28,000 TPD of MSW. Therefore, a conservative estimation of the chlorine contributed by PVC would be about 50%. Other research has indicated that only 36% of the chlorine in the waste can be accounted for by plastics(46). The remaining chlorine is from other components of the waste. Table 1 is a relative compositional analysis of the chlorine content in typical MSW from various fractions in the waste(47). It should become clear that removing PVC will not remove the sources of chlorine in garbage.

Table 1 Relative Content of Chlorine in the Various Fractions of Municipal Solid Waste as Percentage of the Total

Refuse Category	Chlorine (% by Dry Weight)
Textiles	5.55
Wood	0.73
Garden Waste	3.66
Rubber & Leather	14.17
Food Waste	17.04
Paper	22.98
Plastic	35.87
	100.00

Source: Reference 47

There is sufficient evidence to presume that even inorganic chloride (salt) is a source of chlorination of polycyclic aromatic hydrocarbons(46). Reaction kinetic experiments involving the formation of HCl have demonstrated that HCl can be formed not only from organic chlorides but also from inorganic chlorides(10,46). HCl has been demonstrated to form as a result of a reaction between sulfur dioxide and sodium chloride during incineration of refuse(48). The reaction is:

$$2\ NaCl + SO_2 + 1/2\ O_2 + H_2O \rightarrow Na_2\ SO_4 + HCl$$

HCl can also be liberated by the catalytic reaction of NaCl and a metal oxide(48). The general reaction is:

$$NaCl + H_2O + (A) \longrightarrow (B) + HCl$$

where (A) is a metal oxide, i.e.: Al_2O_3, Fe_2O_3.

Experiments of HCl formation in incinerators have shown that even when all of the plastic is removed from the waste prior to combustion, significant concentrations of HCl are still present in the flue gases(49). In an incinerator in Japan, plastic-free garbage was incinerated. The concentration of HCl in the flue gas was between 190 and 730 ppm with an average concentration of 450 ppm. The average value exceeded the HCl emission level established in Japan of 430 ppm. This supports the experimental evidence that PVC is not the only source of HCl gas during the combustion of municipal refuse.

Wood burning experiments have demonstrated that high concentrations of chlorinated aromatic hydrocarbons can be produced without the addition of HCl or PVC or Cl_2 during combustion(13,19,22). Ahling of the Swedish Air and Water Pollution Research Institute has burned pine in a conventional fireplace. Tetrachlorophenols and pentachlorophenol were formed in ppm levels in the combustion gas. It was presumed by Ahling that chlorination of phenolics in the wood fiber occurred as a result of liberation of chloride ions from inorganic chlorine (NaCl) contained in the wood since no chlorine was added to the combustion atmosphere(13). Olie and Hutzinger have produced PCDDs and PCDFs from the combustion of painted wood(16). The wood predated the evolution of phenoxy herbicides or chlorophenols and chlorobenzenes, and was estimated to be about 100 years old. The wood was burned in a fluidized bed incinerator at a rate of 220 pounds per hour without the addition of HCl or PVC, or other likely chlorine donors. PCDDs and PCDFs were detected in the flyash in ppb levels. Lamparski has reported on an analysis of the chimney gas of wood burning stoves in rural areas(20). The wood had not been exposed to dioxin precursor compounds such as chlorinated phenols. Random samples were taken from the eastern, central and western regions of the U.S. Average total dioxin levels in the flue gas were: 8.3ppb in the eastern region, 42.5ppb in the central region, and 9.9ppb in the western region. Caution should be used in interpreting the data since the researchers stated the findings were not statistically verified. However, the experiment does illustrate the potential of PCDD formation from wood burning without the addition of HCl or PVC during combustion.

There have been attempts to correlate the concentration of hydrogen chloride vapor in an incinerator with the emission of PCDDs and PCDFs. Currently, Dr. Ballschmiter is observing long term emissions of PCDDs from refuse incinerators in Germany(50). After one year of observation of 6 municipal incinerators Ballschmiter states, "We have tried to correlate this wide range of dioxin content in flyash with other measurable parameters... Our particular concern was focused on HCl emission, but there is no simple correlation with PCDD formation. The results even suggest no correlation at all(48)."

In October, 1983, researchers Gizzi and Benati of Milan, Italy reported on a correlational study of PCDD and PCDF emissions from a refuse incinerator and the emission of HCl, SO_2, NO_x and CO(51). The refuse incinerator was monitored over a 9-month period. The possible correlation between PCDD and PCDF concentrations and the emission of these other compounds were analyzed using the multiple regression method. No significant correlation was found between HCl, NO_x, SO_2, CO and the PCDDs and PCDFs emitted.

It is apparent from the aforementioned experiments involving the combustion of chlorophenolate formulations, wood and lignin that PCDD and PCDF can be formed from these substances under controlled laboratory procedures. It is important to summarize the basic determinations of these experiments. In microscale burning of pentachlorophenol it was observed that PCDDs were formed most effectively at temperatures of 500°C to 600°C (932°F to 1112°F) (9,10,11,17). At higher temperatures the amounts of PCDD decreased significantly. As an example in one experiment PCDD emissions decreased 50 times at an average furnace termperature of 840°C(1544°F) when compared to an average furnace temperature of 580°C(1076°F)(13). Likewise an increase in retention time at higher temperatures decreased the amount of PCDD in the flue gases(13). Overall the researcher noted that combustion of pentachlorophenol resulted in low PCDD emissions, "except when burned with insufficient oxygen suppy when PCDD with four to eight chlorine atoms appeared in the flue gases"(13).

Temperatures exceeding 800°C weigh the kinetic reactions in favor of destruction of PCDD compounds(24,25,18). Pyrolysis of PCBs in laboratory glassware yields PCDFs in the 1-5% range within the temperature range of 600°-800°C(10). The formation of PCDDs from chlorobenzenes follows similar procedures. It was noted that high concentrations of chlorobenzenes were needed to effect low yields of PCDD. Wood burning experiments have yielded appreciable quantities of chlorinated benzenes and phenols through the reaction of degradation products with inorganic chlorine in the fiber(13,20). Experiments involving lignin pyrolyis gives strong evidence that PCDD formation can occur via de novo synthesis in the presence of chlorine and at low temperatures(16,17,25). These experiments give substantial evidence to the hypothesis supporting theory 3 of PCDD formation. The pyrolysis of chlorinated and non-chlorinated and even chemically unrelated compounds in the presence of organic or inorganic chlorine can result in the de novo synthesis of polychlorinated dioxins and dibenzofurans. Thus even natural substances such as lignin can, if the hypothesis is correct, form PCDDs.

It is important to realize that not all these potential sources of dioxin formation can be separated from the refuse. Lignin, for example, is the second most prevalent compound found on earth. Likewise, chlorine is ubiquitous in the waste. One can, however, infer from the various microscale, pilotscale and fullscale experiments involving PCDD formation from precursors that the critical parameters to PCDD formation are: low temperatures, short retention times, and an insufficiency of oxygen during combustion. Therefore it can be assumed that PCDD inhibition during the incineration of complex chloro-organic mixtures can be best achieved by: sustained elevated temperatures, controlled residence time, and effective turbulent mixing of oxygen in the combustion gas. Correlational analysis has demonstrated an association between low combustion temperatures (below 900°C) and PCDD emissions(51).

DESTRUCTION OF CHLORINATED DIOXINS AND DIBENZOFURANS DURING INCINERATION

Destruction of chlorinated dioxins and furans is really a dissociation of the chemical bonds to the molecule by the energy of heat and by the attack of hydroxyl radicals. Destruction is a stepwise breakdown of the molecule into smaller oxygenated species(9). Residence time or the time period (usually in seconds) the molecules are kept at temperatures of destruction also plays an important role in decomposition. Regardless of the mechanisms of formation, the best way to deal with the possibility of formation of PCDDs and PCDFs is to sustain combustion parameters within the realm of molecular dissociation. Researchers at the National Bureau of Standards have been investigating the thermodynamics of decomposition of hazardous compounds for several years. Their research has yielded valuable insight into the atomic breakdown of chemical bonds(9, 26, 27). In terms of thermodynamic decomposition, there is no single compound with any special characteristics that would make it insensitive to thermal destruction. This is an important fact to keep in mind, for often it is said that chlorinated dioxins are so stable as to be completely resistant to thermal destruction.

Destruction can occur either as a unimolecular or bimolecular reaction. A unimolecular reaction involves the decomposition of the dioxin molecule by simple bond rupture. The bond rupture is predicted to occur along the weakest bond, and is activated by the energy of heat. The weakest bond appears to be the bond between carbon and oxygen atoms. Short-term (seconds) decomposition requires high temperatures, thus the association between high temperatures and short retention times. Computer modeling has shown the bond dissociation energy of the carbon-oxygen bond in dioxin to be around 80 kcal/mol(28). Given this observation, 99.99% destruction or decomposition of PCDD in the gas phase would occur at 977°C (1790°F) with a retention time of one second; 1000°C (1832°F) with a retention time of one-half second; 1227°C (2240°F) with a retention time of 4 millisecond(s), and at 1727°C (3140°F) with a retention time of 5 microsecond(s)(9). Modern waste-to-energy incinerators typically operate at temperatures between 1790°F and 1832°F. Unimolecular destruction of PCDDs and PCDFs should occur at the 99.99% level of efficiency if the compounds are held at these temperatures for at least one second.

Bimolecular destruction occurs by thermal activation along with attack by inorganic radicals. Stoichiometric conditions prevalent in incineration in which excess air is a fundamental aspect of combustion, favors the formation of hydroxyl radicals(OH) and oxygen atoms. The rates of attack by the OH radical groups on organic compounds in the combustion gases is dependent on temperature (as activation energy) and retention time. Computer modelling has indicated that the destruction of the various dioxin isomers by OH attack in order to effect 99.99% dissociation of the atom bonds occurs at a temperature of about 957°C (1755°F) and a retention time of one second(9).

PCDD AND PCDF EMISSIONS FROM MODERN RESOURCE RECOVERY FACILITIES

Examination of dioxin analyses of municipal incinerators gives solid evidence that when operating conditions are poor, dioxin emissions are at their highest levels. The furnace lapses into conditions where carbon monoxide increases, average furnace temperatures fall below thermal destruction temperatures, and polynuclear aromatic compounds increase in concentration in the flue gas. The excessive formation of soot could impede the heat balance or the transfer of heat to all areas of the furnace. Localized pyrolytic conditions could prevail along the incinerator walls or above the combustion radiant zone. Low incinerator efficiency could significantly increase particulates, and this could overload the design capabiltiy of an electrostatic precipitator. Thus reports indicating higher levels of PCDDs and PCDFs than what is usually found is probably due to one or more of these factors.

In October, 1983 Benfenati and Gizzi reported the measurement of PCDDs and PCDFs from a municipal incinerator near Milan, Italy(51). The Como facility is a 100TPD refractory incinerator with no heat recovery. The purpose of the study was to correlate the main parameters of combustion involved in the formation of PCDDs and PCDFs. Incinerator operating temperature, exhaust gas temperature, exhaust gas flow rate, and tons of refuse burned were recorded. The only significant correlation between PCDD and PCDF concentrations in stack emissions and an operating parameter was the minimal temperature of combustion reached during sampling. On the sampling period of highest emissions, PCDD and PCDF concentrations per ton of refuse burned were almost 200 times greater than the sampling period of lowest emissions. During the period of highest emissions, the minimum combustion temperature was only 320°C (608°F), and the average combustion temperature was 627°C (1161°F). This can be compared with the period of lowest emissions. The miminal combustion temperature was 960°C(1760°F), and the average temperature was 1832°F(1000°C). Although there was no statistical correlation with the other combustion parameters and dioxin and furan emissions, there was empirical association between emissions and CO. This is not surprising because carbon monoxide predominates when oxygen levels are low during combustion. CO was over 1300 times greater in concentration during the period of highest PCDD and PCDF emissions when compared to the period of lowest emissions.

In September 1983, the Canadian government issued a report on PCDD and PCDF emissions from a refuse incinerator in Ontario(32). The 600TPD incinerator burns refuse derived fuel in a suspension fired boiler. Glass and metals are presorted from the refuse, and the remainder is milled into RDF. Micropollutant emissions of dioxins and furans were empirically related to low average furnace temperature of 650°C(1200°F), low oxygen levels in the combustion gas and high levels of carbon monoxide. Engineers found that the nozzles that deliver secondary air (overfire air) to the radiant zone above the combustion grate were out of operation. No oxygen was being injected into the secondary zone of combustion. This situation was ideal for oxygen lean conditions to prevail in the combustion gas thus enhancing the likelihood of the pyrolytic degradation of organic compounds to occur. Incomplete combustion of thermolysis products in the radiant zone would also occur. High carbon monoxide is indicative of low oxygen in the combustion gas.

Tiernan has recently (1983) reported on PCDD and PCDF emissions from a 120 TPD mass burn resource recovery facility(19). Sampling was done over a 2 week period in conjunction with an EPA contract. Exceedingly poor combustion conditions were observed in this particular facility. On one sampling day the boiler did not produce steam because ignition and combustion of the refuse was not sustained to cause elevated temperatures sufficient to generate steam. PCDD and PCDF and other PAH emissions can be empirically associated with low combustion temperatures. During the stack sampling period in which the highest concentration of dioxins and furans was recorded, the average furnace temperature was only 550°C(1022°F). By comparison, during the sampling period in which the highest average furnace temperatures were reached, 1342°F(734°C), the PCDD emissions dropped by 33 percent. In addition the concentration of chlorophenols and chlorobenzenes was about 400 times less during the highest average furnace temperature. During the period of lowest temperature the emission of particulates was three times the perimtted federal standard for incinerators.

These examples of correlational analyses of operating facilities suggest that temperature and oxygen are two important parameters to inhibit formation and to encourage destruction of PCDD and PCDF compounds. The injection of an air supply into the radiant zone above the combustion zone is extremely important for the maintenance of minimal oxygen levels to support secondary combustion of products of thermolysis not completely destroyed during primary combustion.

CALCULATED EMISSION FACTORS OF PCDD AND PCDF FOR THE BROOKLYN NAVY YARD PROJECT

When evaluating emission rates of PCDDs and PCDFs from various reports of tested incinerators, it is important to observe the operating conditions at the time of the test. Poor conditions will not yield a true indication of what levels of the compounds are _typically_ found in incinerator emissions. Therefore, in the following extropolation of an emission factor, data derived from less than design intended conditions was not used. In this section, the criteria for determining an emission factor are discussed, and an emission factor for PCDDs and PCDFs of the proposed Brooklyn Navy Yard Resource Recovery Facility is determined. New York proposes to build a 3000TPD (2721MT) massburn, waterwall incinerator using the Martin grate. Steam will be sold for district heating.

An examination of the technical literature reveals that there are large discrepancies in how dioxin and furan data were reported; how the facilities were tested; the age of the facilities; the type of combustion units; the duration of testing; the extraction methodology for getting PCDD and PCDF compounds out of the fly ash matrix, and even whether or not energy was produced from burning municipal waste. In order to determine a realistic emission factor, certain criteria for reviewing the literature should be employed. For purposes of this emission analysis, the following criteria were used to determine which of the reported data were suitable for inclusion in a data base:

(1) The homologues of chlorodibenzo-p-dioxin and dibenzofurans were reported from tetra through octa-species either as concentration in the precipitated flyash or as emissions in the flue gas from the stack.
(2) The fuel for incineration was clearly identified as municipal solid waste.
(3) Energy was recovered from the heat of combustion to be sold as steam or hot water.
(4) The sampling included more than one "grab" sample. Only reports of multiple sample protocols were used.
(5) The data base was separated into two categories: data that was derived from analysis of precipitator flyash; data that was derived by testing actual stack emissions.
(6) The incinerator must have been built no earlier than 1965 to reflect growing concern for air pollution abatement.
(7) No data was used in which the author of the report acknowledged that sampling occured under poor operating conditions, i.e.: low furnace temperature, loss of secondary air flow; inoperative air pollution control system.

In addition to the criteria used to screen the literature, the actual emission calculations from the data were predicated on certain conservative factors.

1. The relative concentration of PCDD and PCDF per unit mass is 10 times greater on emitted flyash particles than on particles collected by the air pollution control equipment.
2. For purposes of calculating from flyash data, the particle collection efficiency of the air pollution control device is assumed to be 99.19%.
3. For puposes of calculating from flyash data the uncontrolled particulates are 62.2 lbs per ton of refuse burned.
4. For purposes of calculating from flyash data it is assumed that PCDFs and PCDDs have a high affinity for absorption to flyash particles.

The following serves as the data base for the calculation of an emission factor.

A. Precipitated Flyash Data

PCDD and PCDF Emission Factors
For Flyash Data

1. Lustenhouwer data on 25 unspecified incinerators for PCDD

	low		medium		high	
CDD	ng/g	ug/MT	ng/g	ug/MT	ng/g	ug/MT
Tetra	5	12.57	54	135.80	110	276.62
Penta	31	77.96	182	457.69	488	1227.20
Hexa	80	201.18	326	819.81	1200	3017.71
Hepta	190	477.80	288	724.25	902	2268.31
Octa	110	276.62	106	266.56	266	668.93
PCDD	416	1046.14	956	2404.11	2966	7458.77

Notes:

1. ug/MT = micrograms per metric ton of refuse burned at 2721MTPD
2. ng/g = nanograms per gram of precipitator flyash.
3. 25 incinerators were tested throughout Europe. The name, size or type of incinerator was not indicated. However only 3 incinerators were equipped for energy recovery.
4. Source: Reference 38

2. Amsterdam, The Netherlands
Design: Martin, Water wall; 4 lines
Built: 1969
Capacity: 2116 MT/D; 22 MT/hr per line
Tested by: reference 10
Date Tested: 1978
Energy: Steam for district heating

CDD	PCDD ng/g	ug/MT	CDF	PCDF ng/g	ug/MT
Tetra	9.4	23.63	Tetra	38.8	97.57
Penta	39.2	98.58	Penta	62.2	156.42
Hexa	113.6	285.66	Hexa	114.4	287.69
Hepta	201.8	507.48	Hepta	82.4	207.22
Octa	235.8	592.98	Octa	17.8	44.76
PCDD	599.8	1508.35	PCDF	315.6	793.66

3. Paris-Issy
   Design: Martin, water wall; 4 lines
   Built: 1965
   Capacity: 1632 MT/d; 17 MT/hr per line
   Tested By: reference 18
   Date Tested: over 1982
   Energy: Steam for electricity

CDD	PCDD ng/g	ug/mt
Tetra	N.D.	N.D.
Penta	12.5	31.43
Hexa	49.3	123.98
Hepta	148.6	373.69
Octa	370.2	930.96
PCDD	580.6	1460.07

Note: N.D. = Not Detected

4. Zurich-Hagenholtz; Switzerland
   Design: Martin, water wall; 1 line
   Built: 1973
   Capacity: 474 MT/d; 18.73 MT/hr.
   Tested by: reference 3
   Date Tested: 1978
   Energy: steam for electricity

CDD	PCDD ng/g	ug/mt	CDF	PCDF ng/g	ug/mt
Tetra	2	5.03	Tetra	1	2.51
Penta	8	20.12	Penta	4	10.06
Hexa	30	75.44	Hexa	30	75.44
Hepta	60	150.89	Hepta	40	100.59
Octa	120	301.77	Octa	10	25.15
PCDD	220	553.25	PCDF	85	213.75

5. Roosendaal, The Netherlands
   Design: B&S, refractory, 2 lines
   Built: 1975
   Capacity: 192 MT/d; 8 MT/hr per line
   Tested by: Reference 10
   Date Tested: 1980
   Energy: hot water produced but not sold

	PCDD			PCDF	
CDD	ng/g	ug/MT	CDF	ng/g	ug/MT
Tetra	40	100.59	Tetra	110	276.62
Hexa	330	829.87	Hexa	150	377.21
Octa	190	477.80	Octa	40	100.59

6. Rotterdam, The Netherlands
   Design: Martin, water wall, 4 lines
   Built: 1965
   Capacity: 1654 MT/d; 17.2 MT/hr per line
   Tested by: reference 10
   Date Tested: 1980
   Energy: Steam

CDD	ng/g	ug/MT	CDF	ng/g	ug/MT
Tetra	18	42.27	Tetra	70	176.03
Hexa	140	352.07	Hexa	70	176.03
Octa	190	477.80	Octa	20	50.30

7. Nashvill Thermal, U.S.A.
   Design: Babcock & Wilcox, Water wall; 2 lines
   Built: 1974
   Capacity: 720 MT/d; 15 MT/hr per line
   Tested by: reference 39
   Date Tested: 1978
   Energy: steam for district heating

	PCDD	
CDD	ng/g	ug/MT
Tetra	7.7	19.36
Hepta	14	35.21
Hexa	28	70.41
Octa	30	75.44

Note: Penta CDD not quantified

B. PCDD and PCDF Emission Factors From Flue Gas Data in Micrograms per Ton of Refuse Burned.

1. Chicago, N.W.; U.S.A
   Design: Martin, water wall; 4lines
   Built: 1971
   Capacity: 1572 MT/d; 16.375 MT/hr per line
   Tested by: reference 5
   Date Tested: 1980
   Energy: Steam for industrial heating

PCDD

CDD	ng/dscm	ug/hr	ug/MT	BNY ug/s
Tetra	6.3	540	32.98	0.85
Penta	N.R.	N.R.	-----	---
Hexa	16.0	1400	85.50	2.16
Hepta	7.6	640	39.08	1.03
Octa	2.5	220	18.44	0.34
PCDD	45	3900	238.17	6.08

PCDF

CDF	ng/dscm	ug/hr	ug/MT	BNY ug/s
Tetra	90	7600	464.12	12.16
Penta	N.R.	-----	-----	-----
Hexa	62	5200	317.56	8.37
Hepta	7.2	640	39.08	0.97
Octa	0.6	52	3.18	0.08
PCDF	460	39492	2411.73	62.13

2. Zurich Josefstrasse; Switzerland
Design: Martin, water wall, 1 line
Built: 1978
Capacity: 511 MT/d; at time tested;
14.3 MT/hr
Tested by: Reference 37
Date Tested: 1979
Energy: Steam for electricity

Note: reported gas flow rate: 94,000scm/hr.

PCDD

CDD	ng/dscm	ug/hr	ug/MT	BNY ug/s
Tetra	4	376	26.29	0.54
Penta	11	1034	72.31	1.48
Hexa	24.9	2340.6	163.68	3.35
Hepta	24.1	2265.4	158.42	3.24
Octa	49.1	4615.4	377.76	6.61
PCDD	113.1	10631.4	743.45	15.23

PCDF

CDF	ng/dscm	ug/hr	ug/MT	BNY ug/s
Tetra	22.3	2096.2	146.59	3.00
Penta	27.3	2566.2	179.45	3.68
Hexa	18.7	1757.8	122.92	2.49
Hepta	12.4	1165.6	81.51	1.67
Octa	8.2	770.8	53.90	1.10
PCDF	88.9	8356.6	584.38	11.97

Table 3: Average Emissions of PCDD and PCDF For the Brooklyn Navy Yard Project Based on Flue Gas Concentrations of Tested Resource Recovery Facilities in Micrograms Per Second (ug/sec)

Dioxins	Chicago, N.W. (1)	Zurich-Josef (2)	Arithmetic Mean
Tetra	0.85	0.54	0.70
Penta	N.R.	1.48	1.48
Hexa	2.16	3.35	2.76
Hepta	1.03	3.24	2.14
Octa	0.34	6.61	3.48
PCDD	6.08	15.23	10.66
Furans			
Tetra	12.16	3.00	7.58
Penta	N.R.	3.68	3.68
Hexa	8.37	2.49	5.43
Hepta	0.97	1.67	1.32
Octa	0.08	1.10	0.59
PCDF	62.13	11.97	37.05

Notes:
1. BNY gas flow rate is 8103.9 dscm/min at 12% CO_2, 489^{o}K
2. BNY gas flow rate is 8077.4 dscm/min at 519^{o}K and 10.5% CO_2
3. ug/s = BNY gas flow rate x ng/dscm (PCDD or PCDF)

Lustenhouwer has tested 25 refuse incinerators for the presence of PCDD in precipitated fly ash collected by the electrostatic precipitator. The data is displayed as number 1 under the data base for fly ash. The data is arranged by category and assigned a relative weight either as low, medium or high values. This data array is one of the most comprehensive assessments made by any investigator on the magnitude and variability of dioxin in refuse incinerators. However, only three of the 25 incinerators were resource recovery facilities.

The Lustenhouwer study serves as a baseline for evaluating the relative magnitude of dioxin concentrations measured at other resource recovery incinerators. Table 2 is a compilation of emission factors for five waste-to-energy incinerators ranging in size from 474 to 2116 metric tons of refuse per day. The facilities can be compared because PCDD and PCDF concentrations were converted into micrograms of the compounds per metric ton of refuse burned. The total PCDD emission factor resulted in a mean of 1173.89 ug/MT. This compares favorably to the PCDD emission factor of 1064.14 ug/MT discerned using the Lustenhouwer data corresponding to the "Low" column of PCDD concentration from 25 incinerators. On the other hand, the Roosendaal refractory incinerator produced an emission rate of total TCDD, hexa-CDD and octa-CDD that compares favorably to the Lustenhouwer data in the "medium" emission column. This incinerator does not produce energy for any energy market.

Analyses of flue gas data shows similar results. Well operated waste-to-energy facilities produce dioxin levels that are at or below the "low" values in Lustenhouwer's report of 25 incinerators. For example, the actual emission factor of total PCDD from the Chicago, N.W. resource recovery facility is 238.17 ug/MT, and this is considerably below the "low" factor of 1046.14 ug/MT in the Lustenhouwer study. Likewise the Zurich Josefstrasse facility that was tested by the Swiss EPA produced an emission factor for total PCDD to be 743.45 ug/MT; this is below the low emission factor in Lustenhouwer's report.

However, the Como refractory facility in Italy produced an emission factor of PCDD that fit well with the medium emission factor column of Lustenhouwer's study: 2349.2 ug/MT. The incinerator does not produce energy from the burning of garbage.

It is apparent that waste-to-energy incinerators produce significantly less PCDD than incinerators not equipped for energy production. Analysis of fly ash and flue gas data shows that flue gas emission rates are lower than the calculated emission rates that were derived from precipitated fly ash data. Table 2 presents dioxin and furan concentrations found in the precipitated flyash from five waste-to-energy facilities which are similar to the facility proposed for the Brooklyn Navy Yard project. The last column depicts the emission rate of the compounds (micrograms per second) utilizing the mean of the concentrations tested at these five waste-to-energy incinerators. It is important to note that the dioxin and furan concentrations found at these facilities are comparable and represent the work of four independent researchers. This tends to give confidence to the data. One problem, however, is that the emission rate is inferred from a measurement of the concentration of the dioxin found on the flyash collected by the electrostatic precipitator rather than being a direct measurement. Unfortunately most of the available experimental data is taken from precipitator flyash measurements, and there are only a limited number of direct measurements made on flue gas emissions from the stack.

The validity of using flyash measurements to calculate flue gas emissions has been brought into question by the recent work (1982) of Rghei and Eiceman(23). Their experiment gives evidence to the possibility that dioxins adsorbed on flyash particles may undergo further chemical reaction in the stack or plumes of incinerators when exposed to HCl in the flue gas. The experiment suggests that characterizing the distribution of PCDD homologues from precipitator flyash may not be an accurate determination of PCDD emissions. Eiceman concludes that, "PCDD distribution in flyash from the ESP of incinerators may not accurately describe PCDD content in airbourne particulate matter released into the atmosphere even if flyash analysis has been corrected for size fractionation. Thus, extrapolation of analytical results using flyash from ESP to possible environmental impact will be incorrect without description of these reactions(23)." Fortunately, actual flue gas measurements are available from two waste-to-energy systems utilizing the Martin grate system that has been proposed for the Brooklyn Navy Yard. The USEPA has performed actual flue gas measurement at the Chicago, N.W. resource recovery facility, (5) and the Federal Environmental Agency of Switzerland has conducted similar tests on the Zurich Josefstrasse facility (37). Table 3 presents the results of these measurements. The comparison of Table 3 to the predictions made for the Brooklyn Navy Yard in Table 2 show that the arithmetic mean for these two facilities for total PCDD was found to be 10.66 ug/scc versus the 36.39 ug/scc sec predicted fo the Brooklyn Navy Yard by using flyash data. In the case of PCDF, the arithmetic mean for the actual flue gas measurements was found to be 37.05 ug/sec versus 15.61 ug/sec. The comparability of these numbers suggests that even if some dioxin is being formed after the precipitator that this factor appears to be taken into account by the conservative methodology used to infer the emission rate from the flyash data. Therefore, while additional research would certainly be welcome in the area of dioxin emission, it has been shown that when measurements are made on modern incinerators designed for efficient energy recovery that comparable results are found by both European and American researchers. Further, that the literature shows good agreement between actual flue gas emissions and emission predicted or derived from flyash data.

For the purpose of estimating ground level impacts for the proposed Brooklyn Navy Yard facility, it is felt that the most appropriate data base is that derived from the Chicago, N.W. facility by the USEPA. The reasons for using this data are the following: (1) It represents a direct measurement of flue gas emission; (2) the data has been shown to be comparable to similar measurements made by the Swiss Environmental Agency and to measurements derived from independent analyses from flyash collected from US and European waste-to-energy facilities; and (3) the data is conservative in that it shows the highest emission rate (of the 7 large-scale waste-to-energy facilities for which data is available) for the Tetra homolgue which contains the isomer greatest toxicity and concern.

REFERENCES

1. Olie, K., P.L. Vermeuleu, O. Hutzinger. "Chlorinated-p-Dioxins and chlorodibenzofurans are trace components of Fly Ash and Flue Gas of Some Municipal Incinerators in the Netherlands." Chemosphere 6, 455-459, 1977.

2. Lustenhouwer, J.A., K. Olie, O. Hutzinger. "PCDD and Related Compounds in Incinerator Effluents." Chemosphere 9, 501, 1980.

3. Buser, H., H. Bosshardt and C. Rappe. "Identification of Polychlorinated Dibenzo-p-Dioxin Isomers Found in Fly Ash." Chemosphere 7, pp. 165-172, 1978.

4. Cavallaro, A., et.al. "Sampling, Occurence and Evaluation of PCDDs and PCDFs from Incinerated Solid Urban Waste." Chemosphere 9, pp. 611-621, 1980.

5. Redford, D., C. Haile, R. Lucas. Emissions of PCDD and PCDF From Combustion Sources. Presented at the International Symposium on Chlorinated Dioxins And Related Compounds, Arlington, Va., October 25-29,1981.

6. Gardiner, William."The Chemistry of Flames." Scientific American, Feb., 1982, p. 112.

7. Ibid.

8. Ibid., p. 113.

9. Shaub, W.M., W. Tsang. "Physical And Chemical Properties of Dioxins In Relation To Their Disposal." Human and Environmental Risks of Chlorinated Dioxins and Related Compounds. Edited by Richard Tucker; Alvin Young. In Press. Plenum Publishing Corp. 1983.

10. G.G. Choudhry, K. Olie, O. Hutzinger. "Mechanisms In The Thermal Formation of Chlorinated Compounds Including Polychlorinated Dibenzo-p-Dioxins." In Chlorinated Dioxins and Related Compounds: Impact on the Environment. Pergamon Press, New York., 1982., pp. 275-301.

11. Liberti and Brocco. "Formation of Polychlorodibenzo-Dioxins And Polychlorodibenzo-Furans In Urban Incinerator Emissions." In: Chlorinated Dioxins and Related Compounds: Impct on the Environment. Edited by O. Hutzinger, R. Frei, E. Merian, F. Pocchiari. Pergamon Press, New York, New York 1982, pp. 245-251.

12. Tosine, H., R. Clement, V. Osvacic, J. Osborne, C. Wong. "Levels of Chlorinated Organics in a Municipal Incinerator." Presented before the Division of Environmental Chemistry, American Chemical Society 186th National Meeting, September 1, 1983.

13. Ahling, B., A. Lindskog. "Emission of Chlorinated Organic Substances From Combustion." Swedish Air and Water Pollution Research Institute, Stockholm, Sweden.

14. Shaub, op.cit, p. 743.

15. Ibid, p. 744.

16. Olie, Berg, Hutzinger. "Formation and Fate of PCDD and PCDF from Combustion Processes." Chemosphere, 12, pp. 627-638, 1983.

17. Liberti, A., Goretti, Russo. "PCDD and PCDF Formation in the Combustion of Vegetable Wastes." Chemosphere 12, #4/5, pp. 661-638, 1983.

18. Ongoing research of F.W. Karasek, U. of Waterloo, Ontario, Canada. Not published; reprinted by permission of Dr. Karasek.

19. Tiernan, T.O., M. Taylor et.al. "Chlorobenzodioxins, Chlorodibenzofurans and Related Compounds in Effluents From Combustion Processes." Chemosphere, 12, #4/5, 1983.

20. Nestrick, T.J., L. Lamparski "Assessment of Chlorinated Dibenzo-p-Dioxin Formation and Potential Emission to the Environment From Wood Combustion." Chemosphere 12, #4/5, pp. 617-626, 1983.

21. Shaub, op.cit., "Physical and Chemical Properties of Dioxin." p. 740.

22. Ibid, p. 740.

23. Eiceman, G., H. Rghei, "Chlorination Reactions of 2,3,7,8-Tetrachlorodibenzo-p-dioxin on Fly Ash with HCl in Air." Chemosphere 11, #9, pp. 833-839, 1982.

24. Shaub, "Physical and Chemical Properties of Dioxin," p. 736.

25. Shaub, W., W. Tsang. "Dioxin Formation in Incinerators." Chemical Kinetics Division, NBS, Wash., D.C., December 1983, Environmental Science and Technology.

26. Shaub, W. "Estimated Thermodynamic Functions for Some Chlorinated Benzenes, Phenols and Dioxins." Thermochimica Acta, 58, pp. 44, 1982.

27. Shaub, "Physical and Chemical Properties of Dioxins," p. 737.

28. Ibid., p. 739.

29. Karasek, F.W., R. Clement, A. Vian. "Distribution of PCDDs and Other Toxic Compounds Generated on Fly Ash Particulates in Municipal Incinerators." Journal of Chromatography, 239, p. 179, 1982.

30. Tiernan, op.cit. , p. 601.

31. An Overview of Chlorinated Dibenzo-p-Dioxin and Dibenzofuran Compounds Relative to the Essex County Resource Recovery Facility. Report to the Port Authority of New York and New Jersey. Camp Dresser and McKee, March, 1983., Appendix.

32. Ministry of Environment, Ontario, Canada. "Hamilton SWARU Dioxin Tests Fact Sheet." Tricil Limited, Engineers. May 2, 1983.

33. Gizzi, F., R. Riginate, Benfenti, Fanelli. "Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans in Emissions From an Urban Waste Incinerator." Chemosphere 11, #6, pp. 577 - 583, 1983.

34. Tiernan, op.cit., p. 602.

35. Technical Proposal for the Proposed Brooklyn Navy Yard Project, City of New York. UOP Waste Systems, Des Plains, Ill., May 20, 1981. p. 31.

36. Kemp C., "Notes on Polychlorinated Dibenzo Dioxins and Polychlorinated Dibenzo Furans in Connection with Waste-to-Energy Plants." Browning Ferris Industries, April 1983, p. 14-18.

37. "Environmental Pollution Caused by Dioxins and Furans From Communal Refuse Incinerator Plants." Swiss Federal Office for Environmental Protection, Bern, June 1982.

38. Lustenhouwer, J., K. Olie, O.Hutzinger. "Chlorinated Dibenzo-p-Dioxins and Related Compounds in Incinerator Effluents. A Review of Measurements and Mechanisms of Formation." Chemosphere 9, 1980, pp. 501-522.

39. Polychlorinated Dibenzo-p-dioxins: Criteria For Their Effects on Man and His Environment. National Research Council, Canada. Ottawa, Canada, 1981, p. 29.

40. Haile, Clarence, Robert Lucas, et al., Comprehensive Assessment of the Specific Compounds Present in Combustion Processes, EPA-560/5-83-004, Office of Toxic Substances, Wash., D.C., June 1983.

41. Air Pollution Control at Resource Recovery Facilities, draft document dated November 15, 1983, California Air Resources Board, p. 40.

42. Trinklein, Barbara, "An Applied Statistical Approach to Refuse Composition Sampling," 1982 National Waste Processing Conf., ASME, p. 370.

43. Air Pollution Control at Resource Recovery Facilities, op.cit, p. 44.

44. Ibid., p. 43.

45. Personal communication with Daryl Mills, California Air Resources Board, Sacramento, California, on 12/15/83.

46. Alter, Harvey, "Resource Recovery From a Chemical Viewpoint," in _Materials From the Chemical Viewpoint,_ American Chemical Society, Wash., D.C., March, 1979, p.41.

47. Alter, Harvey, "Chemical Analysis of the Organics Portions of Household Refuse," _Solid Waste Management,_ Vol. 64, #12, December 1974, p. 710.

48. Nchida, Shigeo, Hiroshi Kamo, "Reaction Kinetics of Formation of HCL in Municipal Refuse Incinerators," Ind. Eng. Chem. Process Des. Dev., 1983, Vol. 22, pp.144-149.

49. _Ibid_., P. 144.

50. Ballschmiter, K., et.al, "Occurrence and Absence of Polychlordibenzofurans and Polychlorodibenzodioxins in Fly Ash From Municipal Incinerators," _Chemosphere_, Vol. 12, #4/5, 1983, pp. 585-594.

51. Benfenati, E., F. Gizzi, et.al.,"Polychlorinated dibenzo-p-dioxins and Polychlorinated dibenzofurans in Emissions From an Urban Incinerator. Correlation Between Concentration of Micropollutants and Combustion Conditions," _Chemosphere_, Vol. 12, #9/10, 1983, pp 1151-1157.

Co-firing of Coal and Refuse Derived Fuel at the Ames Municipal Electric Utility

Alfred W. Joensen

Introduction

The Ames Solid Waste Recovery System has been in commercial operation 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 existing municipal electric utility power plant. The process flow line arrangement is shown in Figure 1.

Municipal solid waste (MSW) originally entered a 50 tons/hr process line where primary shredding, ferrous removal and secondary shredding occurred. The RDF produced from the air density separator (ADS) is transported 500 feet to the 500 ton Atlas storage bin through a 14.0 inch diameter pneumatic transport line. The RDF was originally reclaimed from the storage bin pile by four bucket sweep and an associated pull-ring drive system. The sweep buckets dropped the material into two infeed drag conveyors which supplied two airlock feeders. The material was pneumatically transported 200 feet underground for injection into two opposite corner burners of the CE Unit No. 7.

Conceptual design as engineered in 1973 anticipated burning RDF with coal in the 35 MW tangentially fired pulverized coal fired Unit No. 7 at firing rates up to 20% by heat input or 8 tons/hour of fluff injection. Initial operation in October 1975 resulted in a high dropout of unburned material into the bottom ash hopper. The power plant began co-firing RDF with coal in the 7.5 or 12 MW spreader stoker boilers which had also been modified for this firing mode. The problem of high unburned material dropout in the 35 MW unit was solved by the installation of a CE dump grate at the furnace bottom. This retrofit was completed by April 26, 1978, and RDF was successfully co-fired in this unit up through the spring of 1982. At this time, the 70 MW B&W suspension fired Unit No. 8, especially designed for RDF co-firing, went operational and became the main unit for burning the fluff fuel.

This paper will present a summary of the co-firing experience in the suspension fired boiler plus other major highlights of the Ames Solid Waste Energy Recovery System.

A three year field evaluation of the Ames Solid Waste Recovery System began in February, 1976 and ended in February, 1979. This was a combined research effort between the City of Ames, EPA, the DOE, Ames Laboratory, Iowa State University and the Midwest Research Institute. Results of the evaluation of co-firing in the stoker units have been previously reported [2,3,4]. Results of the testing on Unit No. 7 is also available [5]. Further detailed discussion of co-firing in Units No. 7 and 8 have been published [7,8,9].

Process Plant Retrofit

The initial operation of the process flow line did not remove the glass fines and grit as anticipated. The presence of a large amount of glass fines resulted in excessive erosive wear in all of the plant mechanical equipment and in the pneumatic transport pipelines to the Atlas Bin and to the steam generators. In addition, the low melting temperature glass fines in the RDF tended to cause furnace wall buildup immediately above the corner tangential burner.

In October-December, 1978, two rotary disc screens and associated conveyors were installed between the primary and secondary shredders. The primary shredder discharge passes between the electromagnet and on to a scalping disc screen. The oversized (+ 1 1/2 inch) material is delivered to the secondary shredder for further size reduction to - 1 1/2 inch. The disc screen bottoms (- 1 1/2 inch) are conveyed to the second disc screens for fines separation. The bottoms from this screen (- 3/8 inch), consisting of ground glass, grit, and dirt, are transported to a waste storage bin and ultimately trucked to landfill. The oversized material from this second disc screen (+ 3/8 inch to - 1 1/2 inch) is bypassed around and mixed with the secondary shredder discharge. The shredded waste is then conveyed to a surge bin and then to the air density separator. The improvement in RDF quality has been reported in greater detail [6]. The revised flow arrangement is shown in Figure 2.

Other major improvements included the installation of a dust removal and associated bag house system. Air lock feeders were replaced with new units containing replaceable liners.

<u>Atlas Bin</u> From 1975-1978 only two drag infeed conveyors at the Atlas Bin were used to deliver RDF to the airlock feeders (in the basement) for subsequent pneumatic transport and injection to the appropriate boiler. In December, 1978 two screw conveyors were installed at the discharge of the North and South drag infeed conveyors just above the airlock feeders. This, in turn, allowed the drag sweep buckets and pull ring to operate at lower speeds to reduce wear.

In June 1978, the bin floor was resurfaced with trap rock and epoxy binder. Further experimentation with floor surface material resulted in the use of asphalt street mix as the best type of repair. In June, 1981 a sealing floor was installed above the pull-ring drag sweep bucket drive system.

Power Plant Boilers

Unit No. 7 This boiler is a C.E. Type VU-40 steam generator rated at 360,000 lbs/hour of steam flow at 850 psig/900°F. The unit is of the balanced draft type with two pulverizers and four corner sets of non-tilting tangential burners (2 coal nozzles/set). The unit was originally designed to burn Iowa coal (17.1% moisture, 13.5% ash and 9500 Btu/lb). The furnace volume is 27,000 ft^5, the furnace width and depth is 19'-11" x 19'-11". Furnace heat release rates are 1.224×10^6 Btu/hr-ft^2 plan area, 18,000 Btu/hr-ft^3 and 90,000 Btu/hr-ft^2 EPR. The RDF port was originally installed 14 in. above the upper coal port and later relocated 14 in. below the lower coal port. An elevation cross-section is shown in Figure 3.

Unit No. 8 This unit is a B&W Sterling boiler rated at 1250 psig 905°F 620,000 lbs/hr steam flow operating with a GE 70 MW turbine generator. Four levels of coal burners, with separate compartmented windboxes are located at elevations 127'-3", 136'-11", 146'-7", and 156'-3", while NO_x fans are located at elevation 164'-9". Each level of four burners are supplied by one pulverizer which has a capacity of 30,000 lbs/hr. The boiler front wall coal firing occurs West to East. An elevation cross-section is shown in Figure 4.

An eight inch diameter RDF injection port is installed in the North and South furnace wall at elevations 131'-0" and 137'-1/2". The upper RDF ports are currently being used to fire the RDF and this injection occurs perpendicular to the coal firing flame trajectory. This unit was designed to burn Gillette Wyoming sub-bituminous coal (30.0% moisture, 5.8% ash and 8150 Btu/lb).

A Detroit Stoker Company dump grate is used to complete the combustion of any bottom drop of RDF. Combustion air is ducted into the ash hopper for ungrate air and into plenums for overfire air as shown in Figure 6. Mixed grate air from hot and cold air ducts is currently supplied at about 218°F and is simultaneously controlled from a grate air master control. At present, the hot and cold air mixing must be manually biased.

Power Plant Retrofit

As previously discussed, bottom dropout of unburned material in Unit No. 7 resulted in the installation of dump grates which was completed on April 26, 1978. This retrofit utilized a design originally used by the boiler manufacturer in units used for the co-firing of shredded bark and coal in paper nulls. Approximately 2500 cfm of undergrate air and 1300 cfm of overfire air is supplied to the dump grates. An elevation view of the dump grate arrangement is shown in Figure 5.

In September 1978, the two RDF injection ports, originally installed above the two coal pipes in each corner of Unit No. 7 were relocated below the lower coal port. This was done to satisfy the emission offset level required for the anticipated new 70 MW Unit No. 8. In June 1981 the end wall overgrate combustion air source was modified to use some of the hot primary air being supplied to the No. 7 coal mills.

Operational Performance

RDF Properties   Material composition of MSW processed at Ames during 1977-1978 is shown in Table 1. Material composition and size distribution of RDF before and after the disc screen installation is given in Table 2. Total tons of RDF co-fired at the power plant through December 1982 is shown in Table 3. Ultimate analyses of RDF obtained during various testing periods is listed in Table 4.

Coal Properties   Ultimate analysis of the coal used during the 1978 Unit No. 7 boiler tests is shown in Table 5. The fuel properties of the coal used during the Unit No. 7 1982 boiler acceptance test is listed in Table 6.

Unit No. 7 Boiler Tests   The resultant boiler efficiencies associated with co-firing tests performed in 1978 are listed in Table 7. Corresponding environmental emissions measured during these boiler tests are listed in Table 8 and elemental analysis of ESP fly ash are listed in Table 9.

Unit No. 8   The only comprehensive co-firing tests performed on this unit was the ESP evaluation (July 1982). Results of this test series is shown in Table 10.

ESP   Average ESP collection efficiencies for lists performed on Units No. 7 and 8 are shown in Table 11.

Metal Wastage   The only metal wastage experience was on Unit No. 7 in July 1980. Approximately 11 tubes at opposite ends of the furnace water wall throat just above the dump grate experienced failure and were repaired using window patches. The original dump grate retrofit installation in 1978 made no provision for the introduction of overfire air along the full depth above the dump grate. Visual observation of the RDF firing reveals a burning pattern where all of the fluff does not completely penetrate the fireball but appears to be swept around the periphery and piles up on the grate in the corner opposite to the injection port. Thus the metal wastage can be attributed to severe piling and lack of sufficient combustion air.

Acknowledgments

The data and information summarized in this paper is derived from many sources. Unit No. 7 and stoker boiler test data are results obtained from a research project performed by the Engineering Research Institute of Iowa State University with sample analytical support by DOE-Ames Laboratory. This was a project funded by EPA and DOE. Additional technical support was provided by the Midwest Research Institute.

Special thanks go to Douglas E. Fiscus of Midwest Research Institute. He has provided much professional support since 1976 during our interaction on co-firing experiences. Further discussion of electric utility co-firing performance has also been documented [7,8,9].

Continued narratives on operational performance has been supplied by: Mr. Arnold Chantland, Public Works Director; Mr. Carl Baker, Power Plant Superintendent; Mr. Gary Titus, Assistant Electric Utility Director. The contribution of other power plant utility personnel is also gratefully acknowledged.

References

1. Even, J. C., S. K. Adams, P. Gheresus, A. W. Joensen, and J. H. Hall. Evaluation of the Ames Solid Waste Recovery System: Part I - Summary of Environmental Emissions, Equipment, Facilities, and Economic Evaluations. EPA-600/2-77-205, U.S. Environmental Protection Agency, Cincinnati, Ohio, November 1977.

2. Van Meter, D. B., A. W. Joensen, W. L. Larsen, R. Reece, and J. L. Hall. Evaluation of the Ames Solid Waste Recovery System: Part II - Performance of the Stoker Fired Steam Generators. EPA-600/7-79-229, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

3. Hall, J. L., A. W. Joensen, D. B. Van Meter, R. Wehage, G. Severns, and R. Reece. Evaluation of the Ames Solid Waste Recovery System: Part III - Environmental Emissions of the Stoker Fired Steam Generators. EPA-600/7-79-222, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

4. Hall, J. L., A. W. Joensen, D. B. Van Meter, J. C. Even, W. L. Larsen, S. K. Adams, P. Gheresus, and G. Severns. Evaluation of the Ames Solid Waste Recovery System: Refuse Processing Plant and Stoker Fired Steam Generators. U.S. Environmental Protection Agency, Year II Report, Cincinnati, Ohio, November 1979.

5. Joensen, A. W., J. L. Hall, J. C. Even, D. B. Van Meter, P. Gheresus, G. Severns, S. K. Adams, and R. White. Evaluation of the Ames Solid Waste Recovery System: Refuse Processing Plant and Suspension-Fired Steam Generators. Year III Report, EPA Grant R803903, February 1980.

6. Fiscus, D. E., Joensen, A. W., Chantland, A. O., and Olexsey, R. A., Evaluation of the Performance of the Disc Screens Installed at the City of Ames, Iowa Resource Recovery Facility. 1980 Proceedings ASME National Waste Processing Conference, Washington, D.C., May 11-14, 1980.

7. Fiscus, D. E., Ege, H. D., Petersen, R. D., Glaub, J. C., Savage, G. M. and Joensen, A. W. Study of Existing Co-firing Experience - Phase I. Volume I. Final Report. Midwest Research Institute to Argonne Laboratory. October 31, 1983.

8. Fiscus, D. E., Ege, H. D., Petersen, R. D., Glaub, J. C., Joensen, A. W., Wolfs, K. E. and Savage, G. M. Study of Existing RDF Co-firing Experience - Phase I, Volume II - Appendixes Final Report, Midwest Research Institute to Argonne Laboratory. October 31, 1983.

9. Fiscus, D. E., Ege, H. D., Petersen, R. D., Glaub, J. C., Wolfs, K. E., Joensen, A.W. and Savage, G. M. Study of Existing RDF Co-firing Experience - Phase II, Volume III. Final Report, Midwest Research Institute to Argonne Laboratory, October 31, 1983.

Table 1. Municipal Solid Waste (MSW) Properties[a]

As Received MSW	Yearly Avg[b] (July 5, 1977 to July 13, 1978)	Standard Deviation
Composition - % by wt		
Cardboard	12.2	12.46
Paper	34.4	12.91
Plastic	3.2	2.45
Wood	6.4	6.07
Glass	9.5	5.60
Ferrous metal	5.5	12.72
Nonferrous metal	0.9	3.11
Natural organics	6.6	6.26
Cloth	1.7	3.78
Tar	0.7	1.39
Miscellaneous	18.9	7.38
	100.0	
Heating value - Btu/lb	4831	433
Moisture - % by wt	24.20	6.54
Ash - % by wt	22.65	7.66

---

[a] Weekly composite samples taken at primary shredder discharge. Some moisture loss may have occurred.

[b] Average of 52 weekly composite samples.

Table 2. Average Material Composition and Size Distribution of RDF[a]

As Received Value		Before Disc Screen (Year 1978)	After Disc Screen (Year 1979)
Bulk density (lb/ft^3)		5.27	2.60
Size - % by Wt. Square Screen Size - in.			
	+2.5	4.29	4.83
-2.5	+1.5	9.81	13.94
-1.5	+0.75	15.34	33.21
-0.75	+0.375	20.45	24.80
-0.375	+0.188	16.59	10.53
-0.188	+0.094	11.35	4.86
-0.094		22.17	7.83
		100.00	100.00
Composition - % by Wt.			
Cardboard		10.43	29.26
Other paper		42.44	49.50
Plastic		3.95	5.13
Wood		8.21	4.28
Glass		6.05	1.44
Ferrous		0.21	0.14
Nonferrous		1.29	0.58
Natural organics		4.21	1.49
Cloth		3.54	1.59
Tar		0.23	0
Miscellaneous		19.44	6.59
		100.00	100.00

---

[a] Similar sampling periods in Spring, 1978 and Spring, 1979

Table 3. Total RDF Co-fired, Tons

Year	Stoker Units 5 and 6	Suspension Unit 7	Suspension Unit 8	Total Total	Firing Rate t/h
1975	7,058 (first RDF produced August 30, 1975)			7,058	
1976	34,465			34,465	
1977	40,890			40,890	
1978		28,488		28,488	
1979		23,059		23,059	
1980		26,797		26,797	
1981		26,818		26,818	
1982		6,519	17,437	23,956	6 avg (13 max)
TOTAL			17,437	211,531	

Table 4. RDF Properties - As Received

	1978[a/]	1978[b/]	Unit No. 8 Design	1979[c/]	1982[d/]
No. of Samples	12	N/A	N/A	8	3
Heating Value, Btu/lb	5602	4905	5610	6113	6356
% by Wt.					
Moisture	24.04	22.06	23.0	18.4	22.5
Ash	13.06	20.99	17.4	9.6	8.5
Carbon	30.66	28.45	30.9	29.9	35.5
Hydrogen	4.51	6.85	4.8	6.0	5.0
Sulfur	0.32	0.34	0.4	0.2	0.3
Chlorine	0.35	0.23	N/A	0.2	0.3
Oxygen	27.04	42.75	---	35.2	27.6

[a/] Sampled during Summer 1978 Unit No. 7 boiler tests

[b/] Spring 1978 into Atlas Bin (weekly composite)

[c/] Spring 1979 into Atlas Bin (weekly composite) after disc screen

[d/] July 1982, Unit No. 8 installation boiler acceptance tests

Table 5. 1978 Coal and RDF Properties, As Fired[a]

	Coal		RDF	
No. of Samples	18		12	
	Average	Std. Dev.	Average	Std. Dev.
Heating Value, Btu/lb	10,156	224	5602	359
% by Weight				
Moisture	16.60	1.20	24.04	3.06
Ash	9.74	2.23	13.06	2.72
Carbon	56.60	1.50	30.66	2.92
Hydrogen	4.01	0.19	4.51	0.44
Sulfur	2.79	0.81	0.32	0.05
Chlorine	0.21	0.12	0.35	0.15
Oxygen	9.08	2.26	27.04	2.87

[a] 1978 Unit No. 7 boiler tests

Table 6. Coal Ultimate Analysis

	Average
As Received	
Heating value - Btu/lb	8112
Ultimate analysis - % by wt	
Moisture	29.10
Ash	6.49
Carbon	47.05
Hydrogen	3.81
Nitrogen	0.69
Oxygen	12.30
Sulfur	0.53
Chlorine	0.03
	100.00

[a] July 1982 Boiler #8 acceptance tests, 6 samples

Table 7. Unit No. 7 Boiler Efficiency - ASME Loss Method

	80% Boiler Load			100% Boiler Load		
Ames Unit 7 1978 Boiler Tests[a]	Coal Only	10% RDF	20% RDF	Coal Only	10% RDF	20% RDF
Heat losses, %						
Dry gas	7.18	7.59	8.33	7.23	7.03	6.68
H_2 and H_2O in fuel	5.90	7.01	7.66	5.93	6.73	7.70
Moisture in air	0.29	0.24	0.24	0.30	0.26	0.27
Unburned combustibles	0.23	0.45	0.59	0.39	0.38	0.53
Radiation	0.41	0.41	0.41	0.30	0.30	0.30
Unaccounted for loss	1.50	1.50	1.50	1.50	1.50	1.50
Total heat loss	15.51	17.20	18.73	15.65	16.20	16.98
Boiler efficiency, %	84.49	82.80	81.27	84.35	83.80	83.02
Percentage points efficiency reduction due to co-firing		1.69	3.22		0.55	1.33
Orsat (before air heater), %						
CO_2	13.10	--	13.17	13.02	--	13.89
O_2	4.38	--	4.67	4.96	--	3.95
N_2	82.52	--	82.17	82.03	--	82.16
		--				
Air Heater Exit Gas Temperature, °F	367°F		422°F			390°F

---

[a] Prior to disc screen installation

Table 8. Stack Emissions - Unit No. 7 Tests (1978)

Parameter	Units	80% Load			100% Load		
		0% RDF	10% RDF	20% RDF	0% RDF	10% RDF	20% RDF
Particulates (controlled)	lb/10^6Btu	0.21(0.05)[a]	0.37(0.09)	0.37(0.07)	0.42(0.21)	0.44(0.07)	0.53(0.09)
Particulates (uncontrolled)	lb/10^6Btu	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_x	lb/10^6Btu	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_x	lb/10^6Btu	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	lb/10^9Btu	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	lb/10^9Btu	8.37(14.0)	12. (207.)	0.77(0.42)	0.19(0.33)	1.44(0.72)	0.42(0.19)
Methane	lb/10^9Btu	5.30(2.65)	6.07(1.58)	3.77(0.30)	3.35(0.93)	4.58(1.44)	2.47(0.58)
Fly Ash Resisivity ohm-cm		2.2 x 10^{10}		3.5 x 10^{10}	3.0 x 10^{10}		5 x 10^{10}

[a] Values in parentheses are ± one standard deviation

Table 9. Analysis of ESP Unit No. 7 Fly Ash (1978)

	80% Load			100% Load		
	0% RDF	10% RDF	20% RDF	0% RDF	10% RDF	20% RDF
Carbon	1.85 (0.55)[a]	2.43 (0.35)	2.54 (0.05)	1.92 (0.78)	2.41 (0.49)	2.40 (0.40)
Hydrogen	0.10 (0.02)	0.11 (0.01)	0.17 (0.05)	0.10 (0.02)	0.11 (0.01)	0.11 (0.02)
Sulfur	0.70 (0.34)	0.69 (0.13)	0.86 (0.14)	1.02 (0.51)	0.82 (0.21)	0.83 (0.13)
Chlorine	0.01 (0.01)	0.01 (0.00)	0.03 (0.01)	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)
Mineral	97.3 (0.55)	96.8 (0.46)	96.4 (0.09)	97.0 (0.39)	96.6 (0.59)	96.6 (0.30)

[a] Values in parentheses are ± one standard deviation

Table 10. Summary Tests - Unit No. 8[a/]

	Coal	Coal + RDF
Particulate Stack Emissions, lb/10^6 Btu	0.0053	0.0306
Air Heater Exit Gas Temperature, °F	282	298
Orsat Boiler Outlet, %		
O_2	4.2	5.7
CO_2	15.0	13.7
Total Heat Input 10^6 B/hr	745.72	829.68
RDF Heat Input, %		21.05
RDF flow, tons/hr		14.05
feedwater flow, 10^3 lb/hr	620.0	619.7

[a/] Full load tests

Table 11. Average Electrostatic Precipitator (ESP) Efficiency

Unit No.	Boiler Test Date	Nominal Boiler Load %	Average ESP Efficiency Coal Only %	Average ESP Efficiency Coal + RDF, %	RDF Heat Input %	Reduction Percentage Points
7	1978[a/]	80	96.8	95.1	10	1.7
		80	96.8	95.5	20	1.3
		100	94.7	93.9	10	0.8
		100	94.7	92.8	20	1.9
8	1982	100	99.9	99.4	22	0.5

[a/] 1978 boiler tests prior to disc screen installation

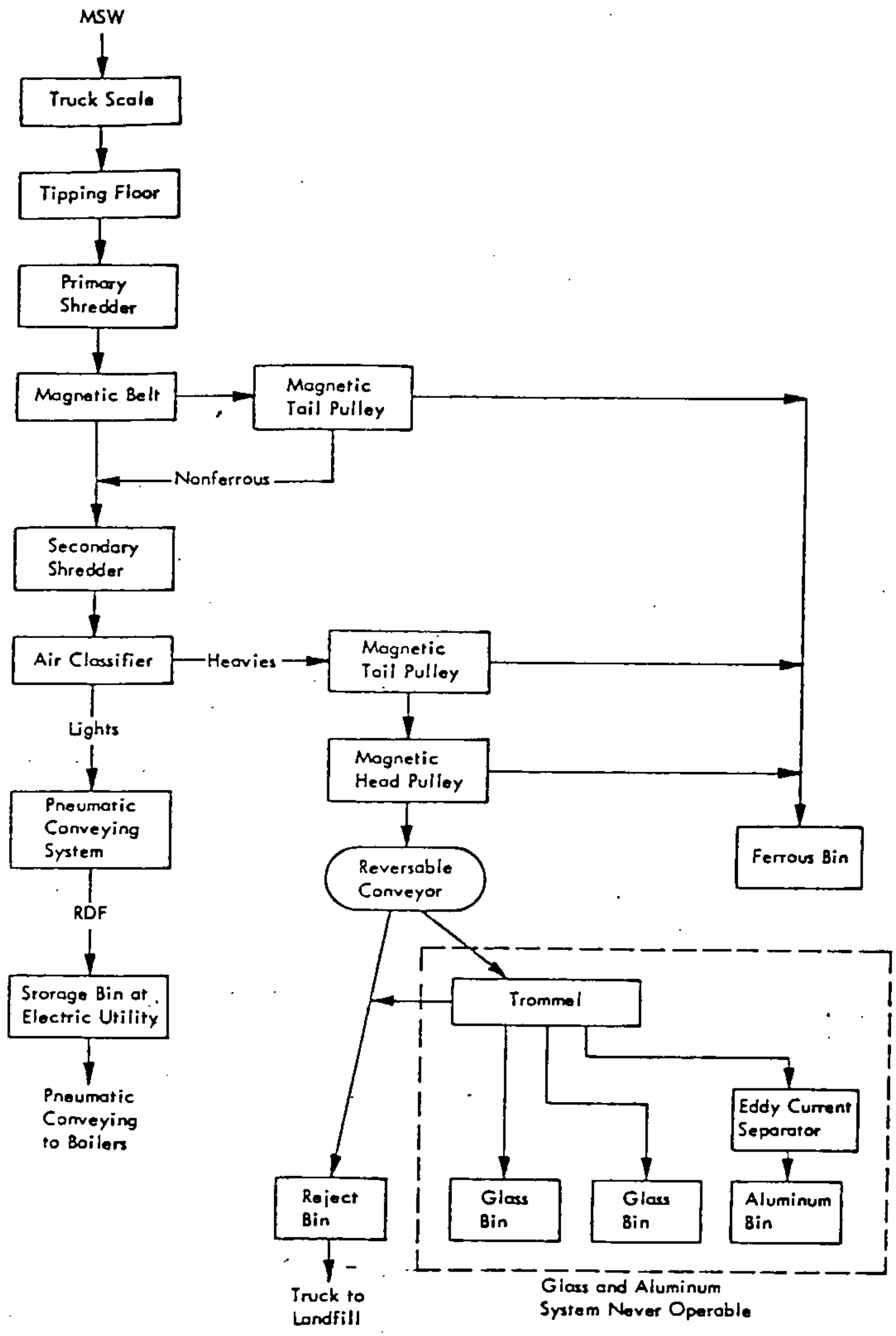


Figure 1. Ames RDF Process Plant Flow Diagram (Before Disc Screen).

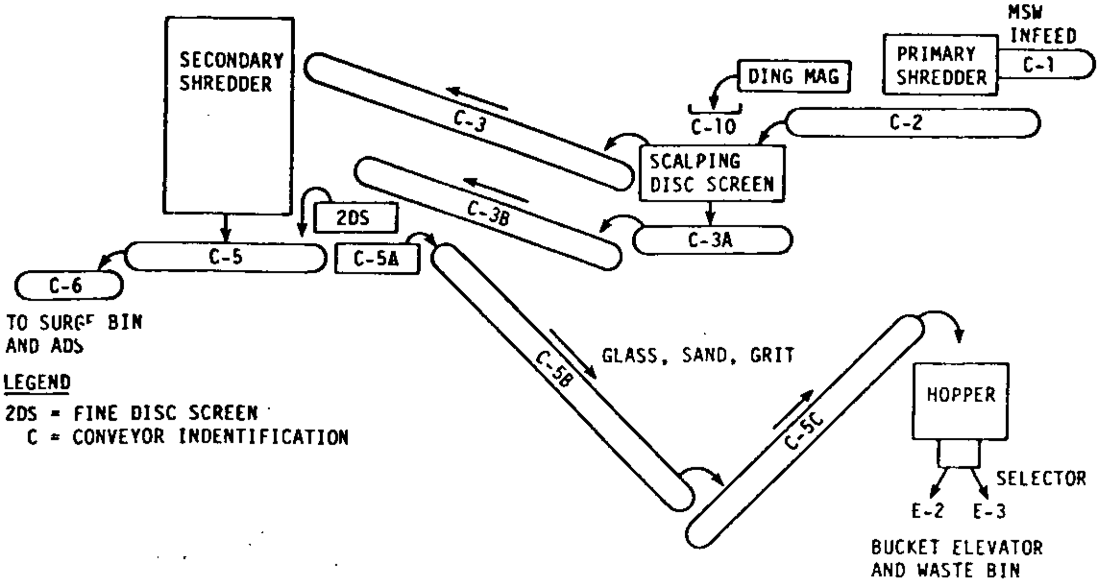


Figure 2. Process Plant Disc Screen Installation.

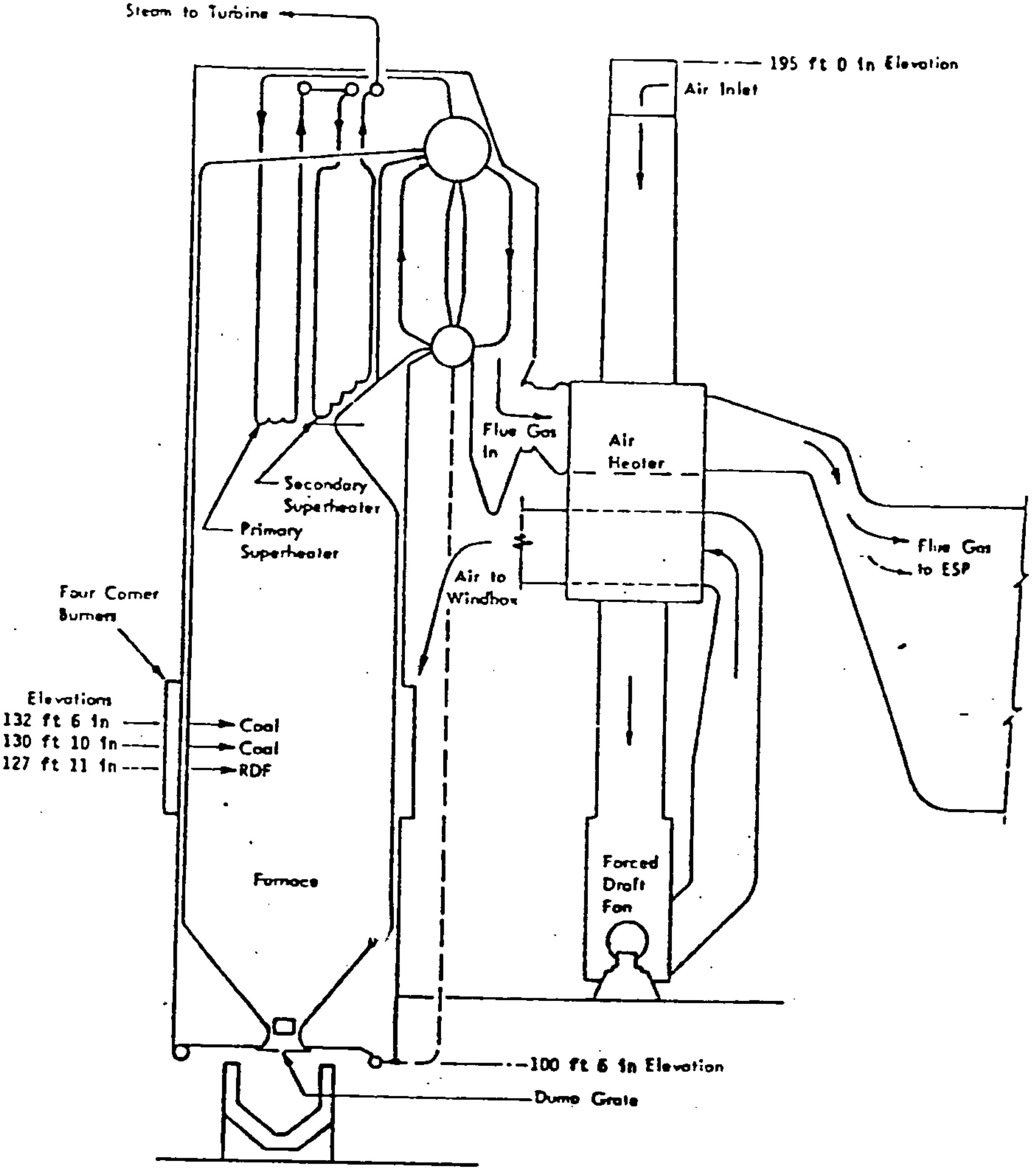


Figure 3. Unit No. 7 Elevation Cross-Section.

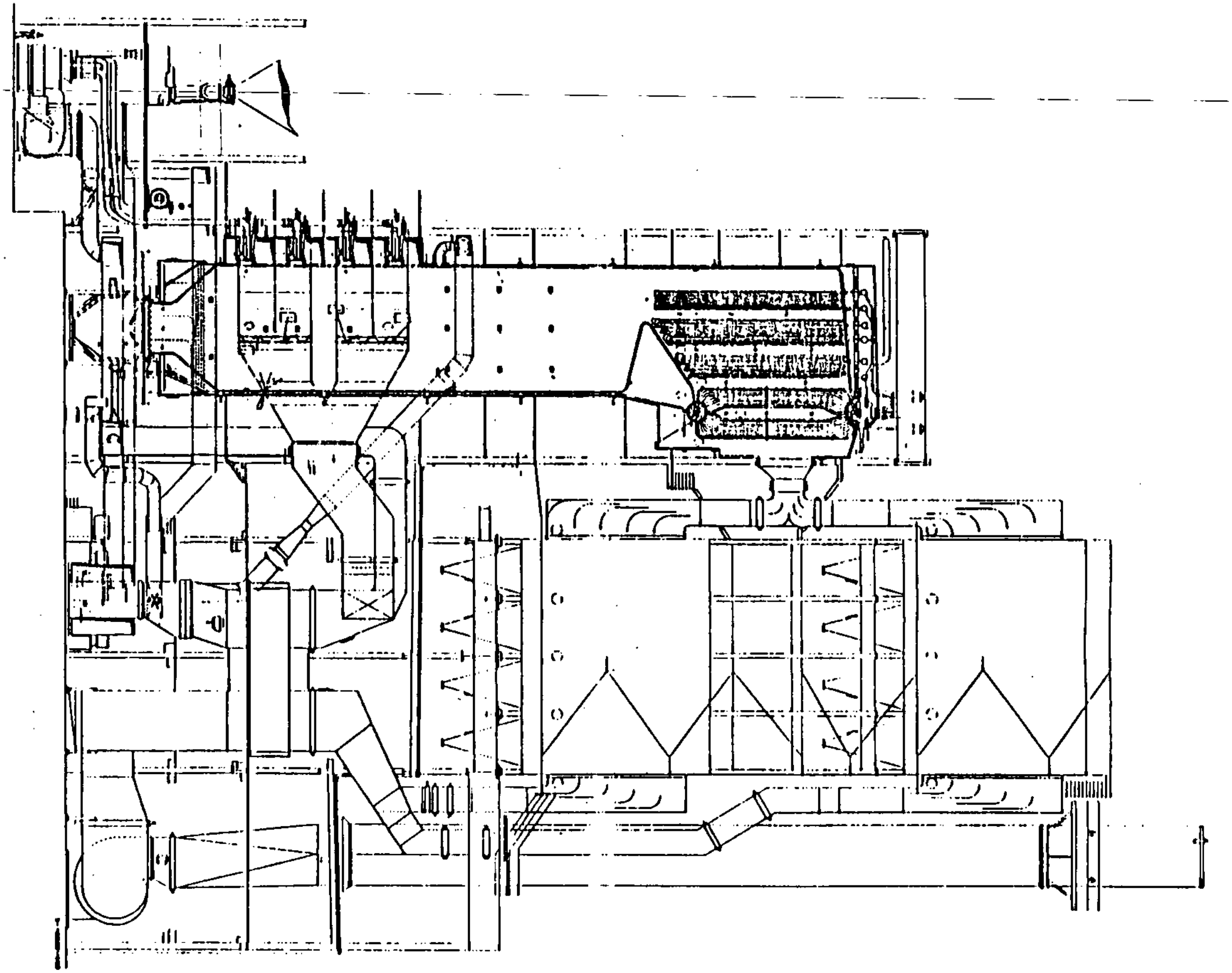


Figure 4. Unit No. 8 Cross-Section.

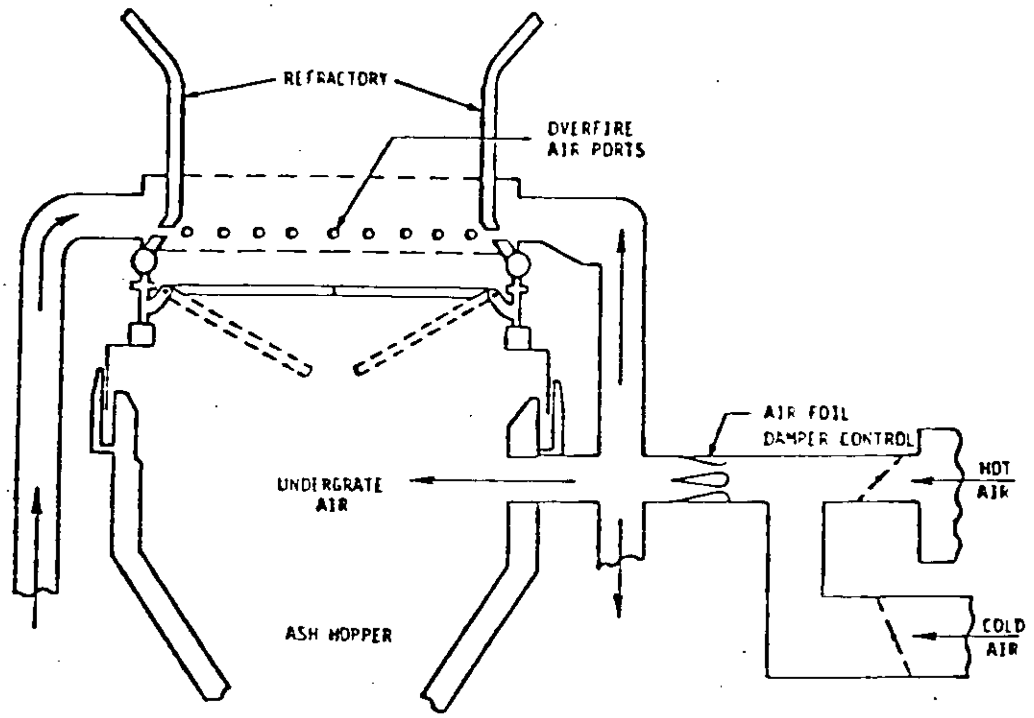


Figure 6. Unit No. 8 Dump-Grate Arrangement.

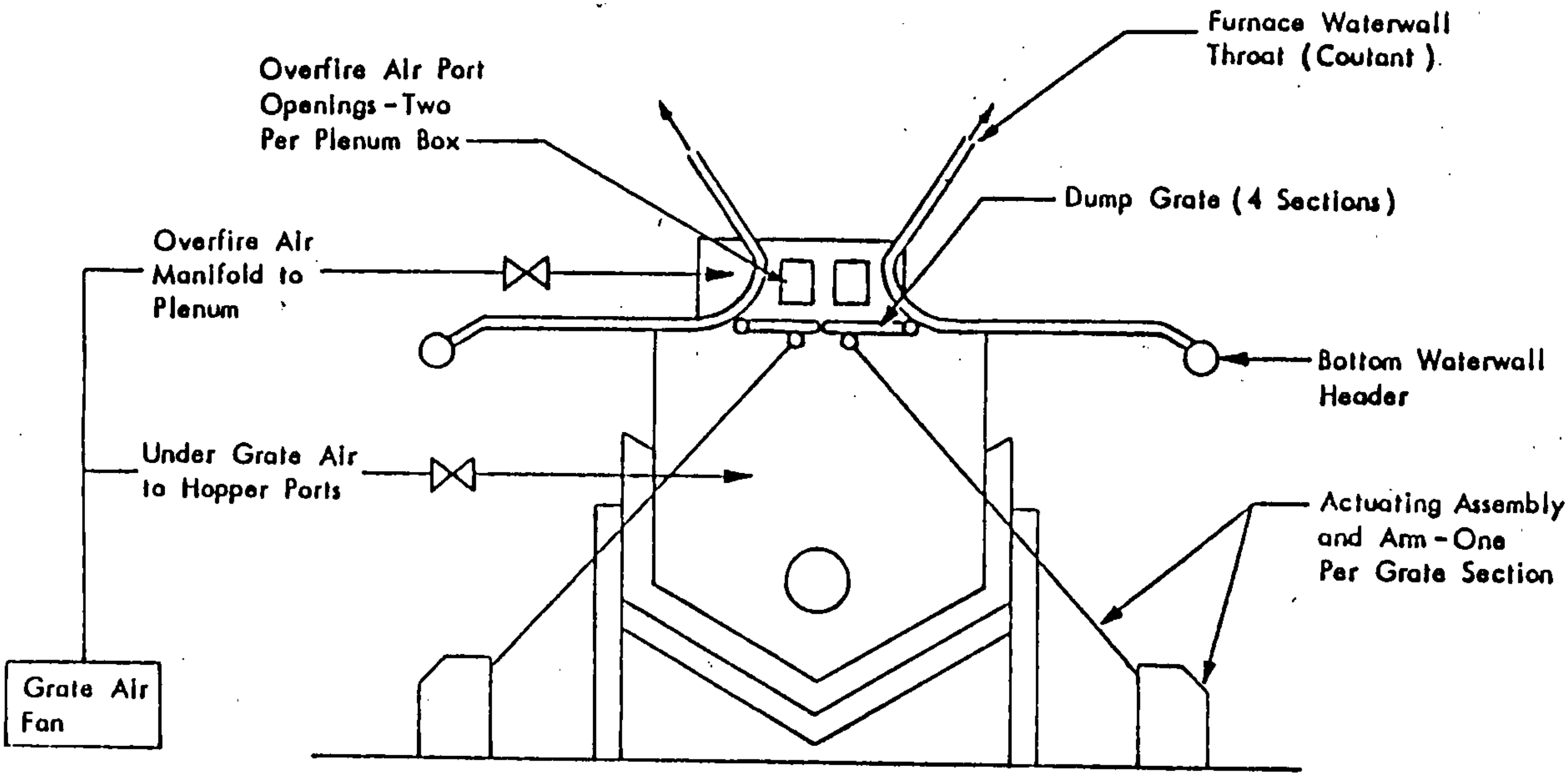


Figure 5. Unit No. 7 Dump-Grate Arrangement.

CO-FIRING OF COAL AND REFUSE DERIVED FUEL AT THE AMES MUNICIPAL ELECTRIC UTILITY

Alfred W. Joensen
Associate Professor
Department of Mechanical Engineering
and Engineering Research Institute
Iowa State University
Ames, Iowa

INTRODUCTION

The Ames Solid Waste Recovery System has been in commercial operation 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; the nominal 150 ton/day process plant, the 500 ton Atlas storage bin, and the existing municipal electric utility power plant. The process flow line arrangement is shown in Figure 1.

Municipal solid waste (MSW) originally entered a 50 tons/hour process line where primary shredding, ferrous removal, and secondary shredding occurred. The RDF produced from the air density separator (ADS) is transported 500 feet to the 500 ton Atlas storage bin through a 14.0 inch diameter pneumatic transport line. The RDF was originally reclaimed from the storage bin pile by a four bucket sweep and an associated pull-ring drive system. The sweep buckets dropped the material into two infeed drag conveyors which supplied two airlock feeders. The material was pneumatically transported 200 feet underground for injection into two opposite corner burners of the CE Unit No. 7.

Conceptual design, as engineered in 1973, anticipated burning RDF with coal in the 35 MW tangentially fired pulverized coal fired Unit No. 7 at firing rates up to 20% by heat input or 8 tons/hour of fluff injection. Initial operation in October 1975 resulted in a high dropout of unburned material into the bottom ash hopper. The power plant began co-firing RDF with coal in the 7.5 or 12 MW spreader stoker boilers which had also been modified for this firing mode. The problem of high unburned material dropout in the 35 MW unit was solved by the installation of a CE dump grate at the furnace bottom. This retrofit was completed by April 26, 1978, and RDF was successfully co-fired in this unit up through the spring of 1982. Then, the 70 MW B&W suspension fired Unit No. 8--especially designed for RDF co-firing--was operational and became the main unit for burning the fluff fuel.

A three year field evaluation of the Ames Solid Waste Recovery System began in February 1976 and ended in February 1979. This was a combined research effort between the City of Ames, the U.S. Environmental Protection Agency (EPA), the Department of Energy (DOE), the Ames Laboratory, Iowa State University and the Midwest Research Institute. Results of the evaluation of co-firing in the stoker units have been previously reported [1-4]. Results of the testing on Unit No. 7 are also available [5-6]. Further detailed discussion of co-firing in Units No. 7 and 8 have been published [7-9].

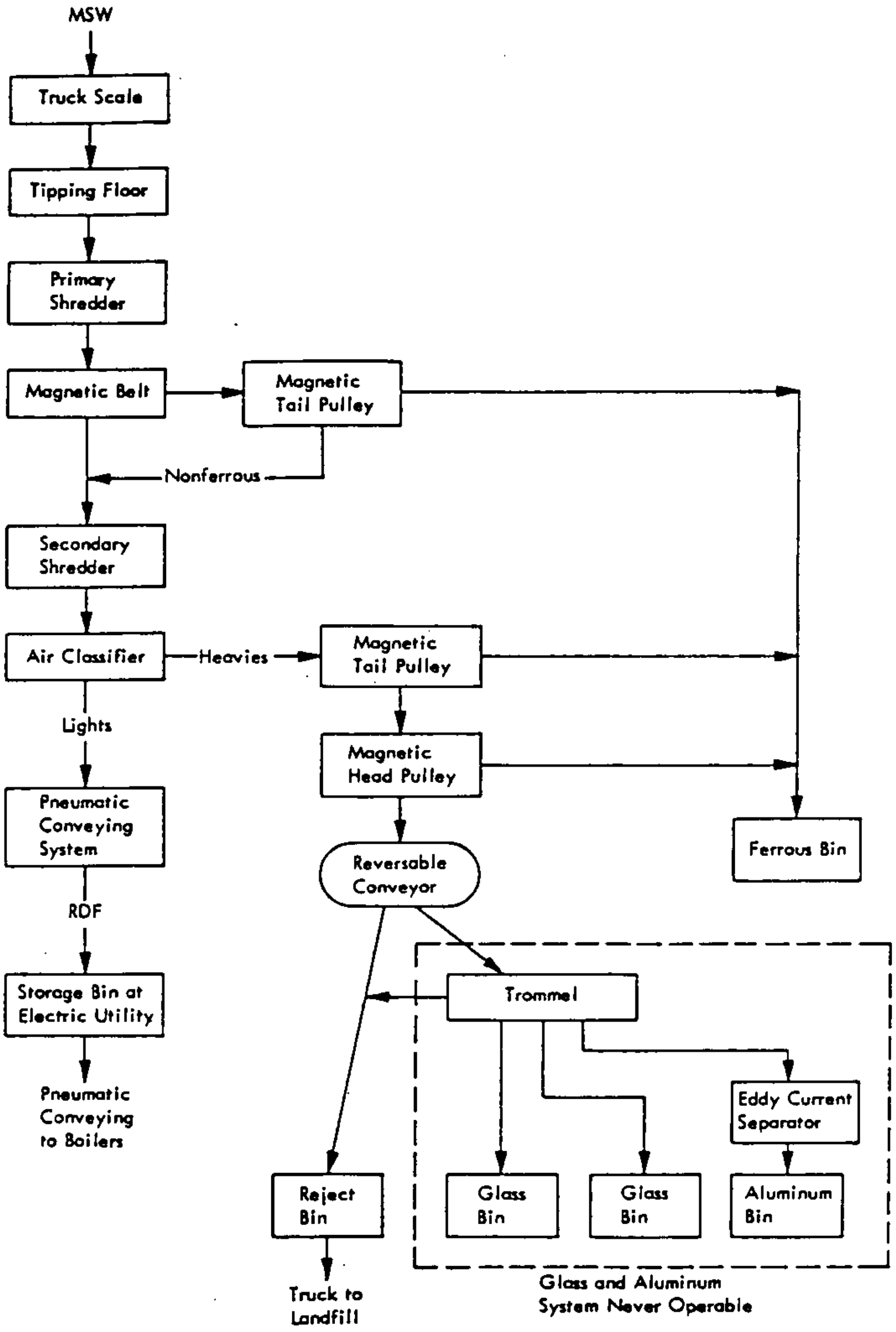


Figure 1. Ames RDF Process Plant Flow Diagram (Before Disc Screen).

This paper will present a summary of the co-firing experience in the suspension fired boiler plus other major highlights of the Ames Solid Waste Energy Recovery System.

PROCESS PLANT RETROFIT

Initial operation of the process flow line did not remove the glass fines and grit as anticipated. The presence of a large amount of glass fines resulted in excessive erosive wear in all of the plant mechanical equipment and in the pneumatic transport pipelines to the Atlas Bin and to the steam generators. In addition, the low melting temperature glass fines in the RDF tended to cause furnace wall buildup immediately above the corner tangential burner.

In October through December 1978, two rotary disc screens and associated conveyors were installed between the primary and secondary shredders. The primary shredder discharge now passes between the electromagnet and on to a scalping disc screen. The oversized (+ 1 1/2 inch) material is delivered to the secondary shredder for further size reduction to - 1 1/2 inch. The disc screen bottoms (- 1 1/2 inch) are conveyed to the second disc screens for fines separation. The bottoms from this screen (- 3/8 inch)--consisting of ground glass, grit, and dirt--are transported to a waste storage bin and ultimately trucked to landfill. The oversized material from this second disc screen (+ 3/8 inch to - 1 1/2 inch) is bypassed and mixed with the secondary shredder discharge. The shredded waste is then conveyed to a surge bin and then to the air density separator. The improvement in RDF quality has been reported in greater detail [6]. The revised flow arrangement is shown in Figure 2.

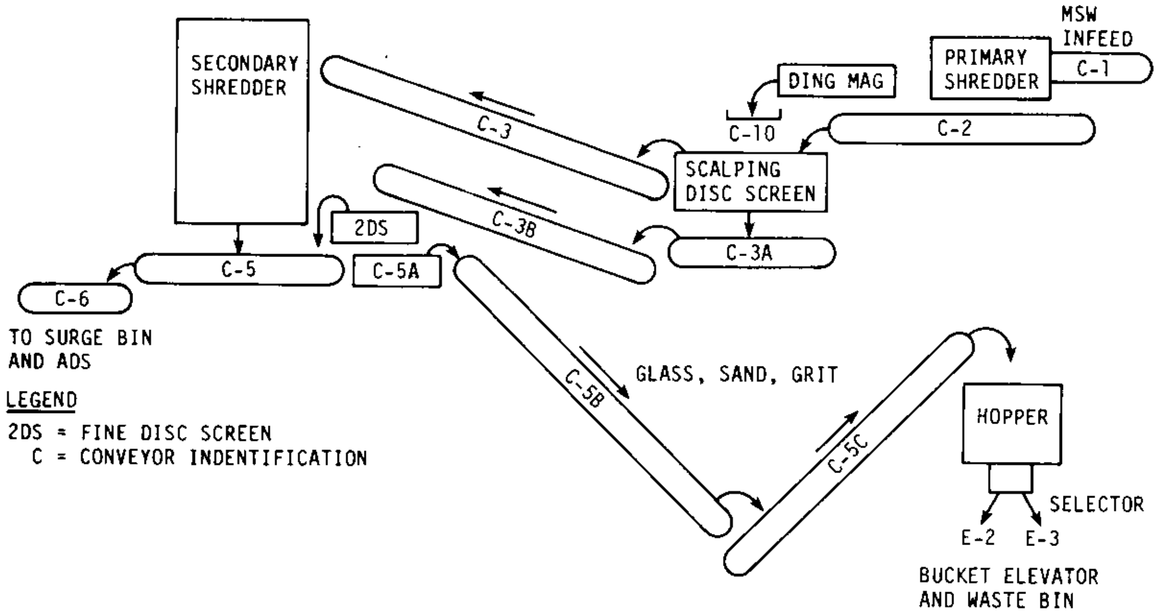


Figure 2. Process Plant Disc Screen Installation.

Other major improvements made in December 1978 included the installation of a dust removal and associated bag house system. Air lock feeders were replaced with new units containing replaceable liners.

ATLAS BIN

From 1975-1978 only two drag infeed conveyors at the Atlas Bin were used to deliver RDF to the airlock feeders (in the basement) for subsequent pneumatic transport and injection to the appropriate boiler. In December 1978, two screw conveyors were installed at the discharge of the north and south drag infeed conveyors just above the airlock feeders. This, in turn, allowed the drag sweep buckets and pull ring to operate at lower speeds to reduce wear.

In June 1978, the bin floor was resurfaced with trap rock and epoxy binder. Further experimentation with floor surface materials resulted in the use of asphalt street mix as the best type of repair. In June 1981, a sealing floor was installed above the pull-ring drag sweep bucket drive system.

POWER PLANT BOILERS

UNIT NO. 7

This boiler is a CE Type VU-40 steam generator rated at 360,000 lb/hr of steam flow at 850 psig/900° F. The unit is of the balanced draft type with two pulverizers and four corner sets of nontilting tangential burners (2 coal nozzles/set). The unit was originally designed to burn Iowa coal (17.1% moisture, 13.5% ash, and 9500 Btu/lb). The furnace volume is 27,000 ft^5, the furnace width and depth is 19' 11" × 19' 11". Furnace heat release rates are 1.224×10^6 Btu/hr-ft^2 plan area, 18,000 Btu/hr-ft^3, and 90,000 Btu/hr-ft^2 EPR. The RDF port was originally installed 14 inches above the upper coal port and later relocated 14 inches below the lower coal port. An elevation cross section is shown in Figure 3.

UNIT NO. 8

This unit is a B&W Sterling boiler rated at 1250 psig 905° F 620,000 steam flow operating with a GE 70 MW turbine generator. Four levels of coal burners with separate compartmented windboxes are located at elevations 127' 3", 136' 11", 146' 7", and 156' 3", while NO_x fans are located at elevation 164' 9". Each level of four burners are supplied by one pulverizer which has a capacity of 30,000. The boiler front wall coal firing occurs west to east. An elevation cross section is shown in Figure 4.

An eight inch diameter RDF injection port was installed in the north and south furnace wall at elevations 131' 0" and 137' 1/2". The upper RDF ports are currently being used to fire the RDF and this injection occurs perpendicular to the coal firing flame trajectory. This unit was designed to burn Gillette, Wyoming, sub-bituminous coal (30.0% moisture, 5.8% ash, and 8150 Btu/lb).

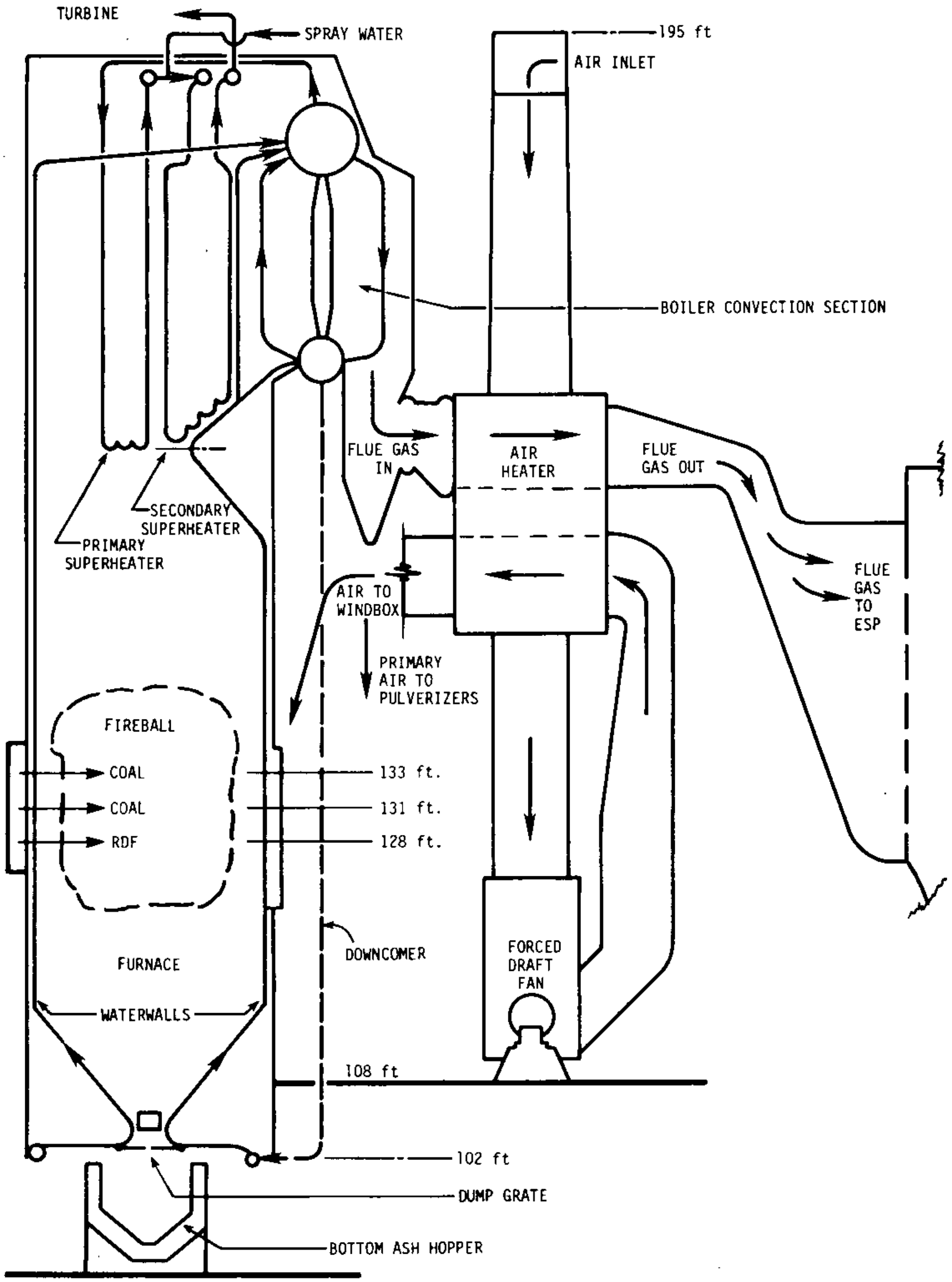


Figure 3. Unit No. 7 Elevation Cross Section.

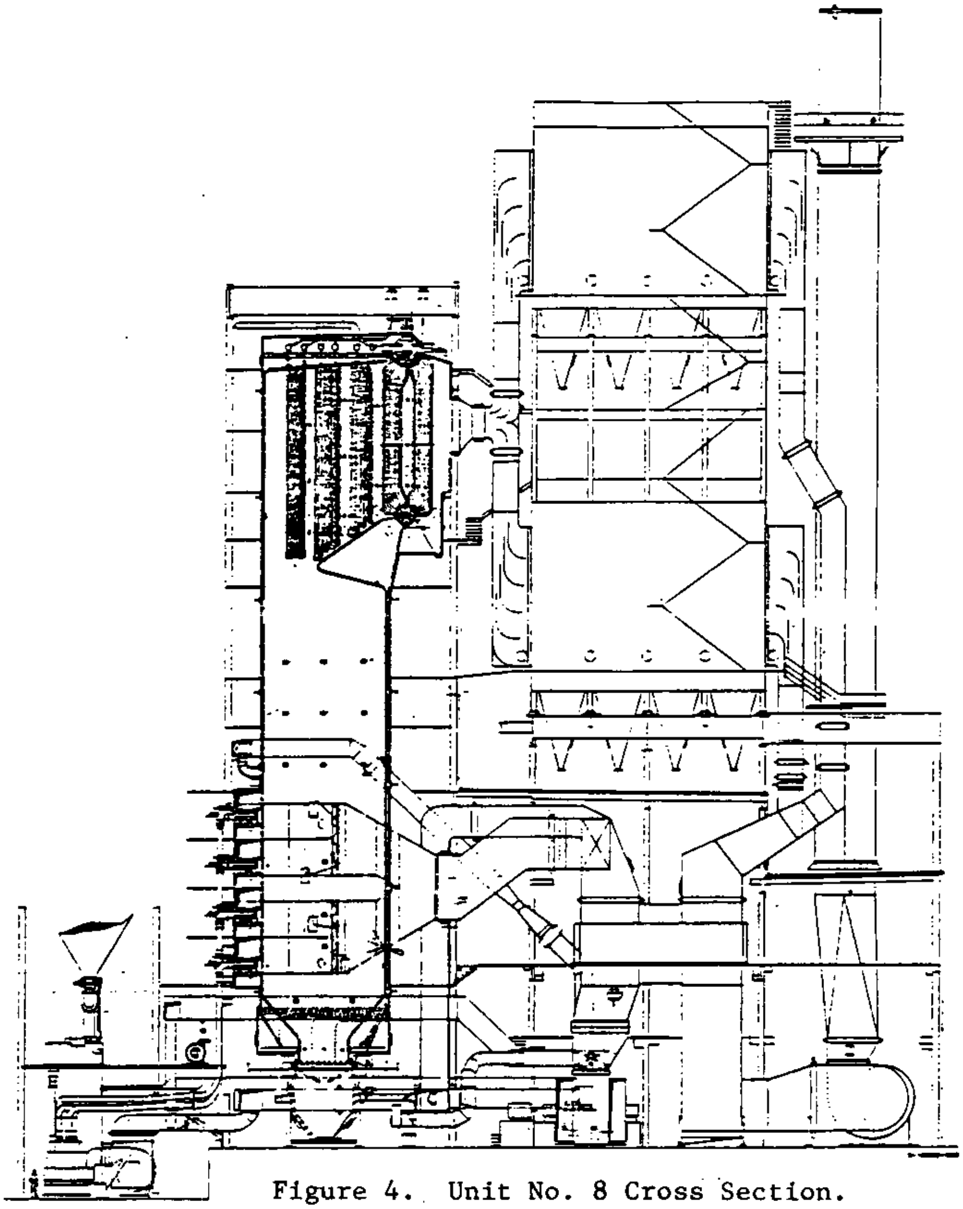


Figure 4. Unit No. 8 Cross Section.

A Detroit Stoker Company dump grate is used to complete the combustion of any bottom drop of RDF. Combustion air is ducted into the ash hopper for ungrate air and into plenums for overfire air as shown in Figure 5. Mixed grate air from hot and cold air ducts is currently supplied at about 218° F and is simultaneously controlled from a grate air master control. At present, the hot and cold air mixing must be manually biased.

POWER PLANT RETROFIT

As previously discussed, bottom dropout of unburned material in Unit No. 7 resulted in the installation of dump grates which was completed on April 26, 1978. This retrofit utilized a design originally used by the boiler manufacturer in units used for the co-firing of shredded bark and coal in paper nulls. Approximately 2500 cfm of undergrate air and 1300 cfm of overfire air is supplied to the dump grates. An elevation view of the dump grate arrangement is shown in Figure 6.

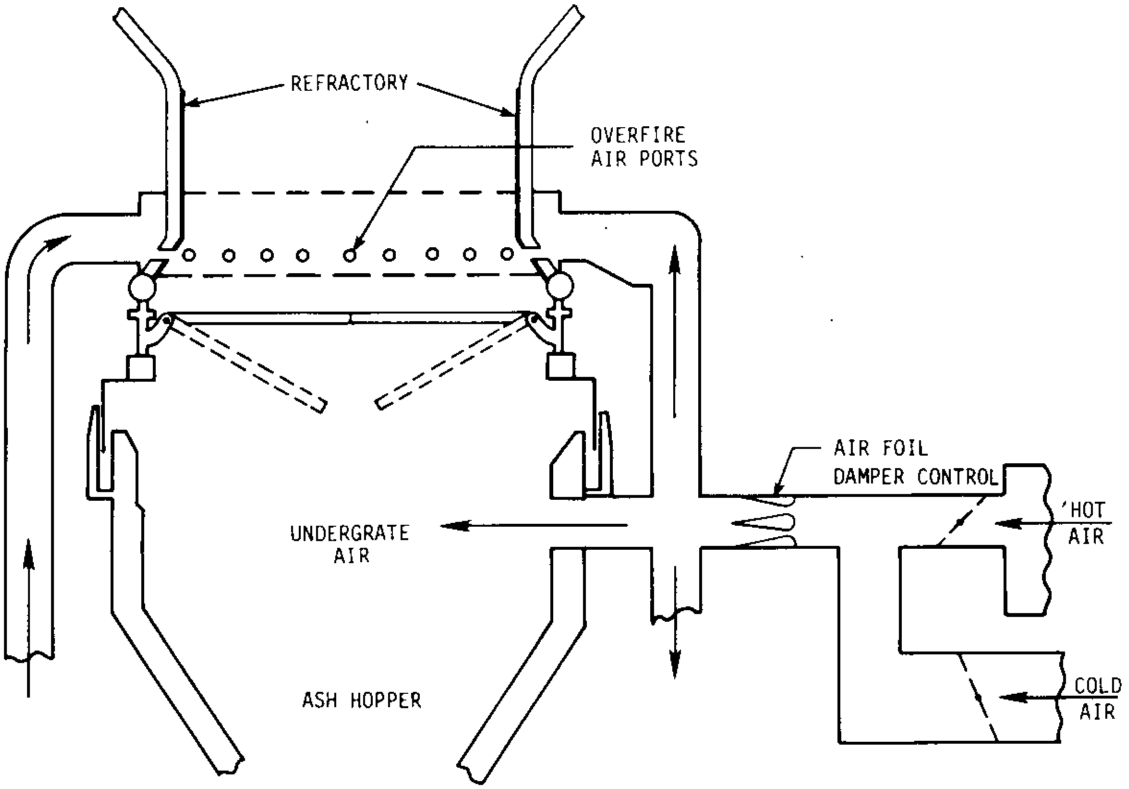


Figure 5. Unit No. 8 Dump-Grate Arrangement.

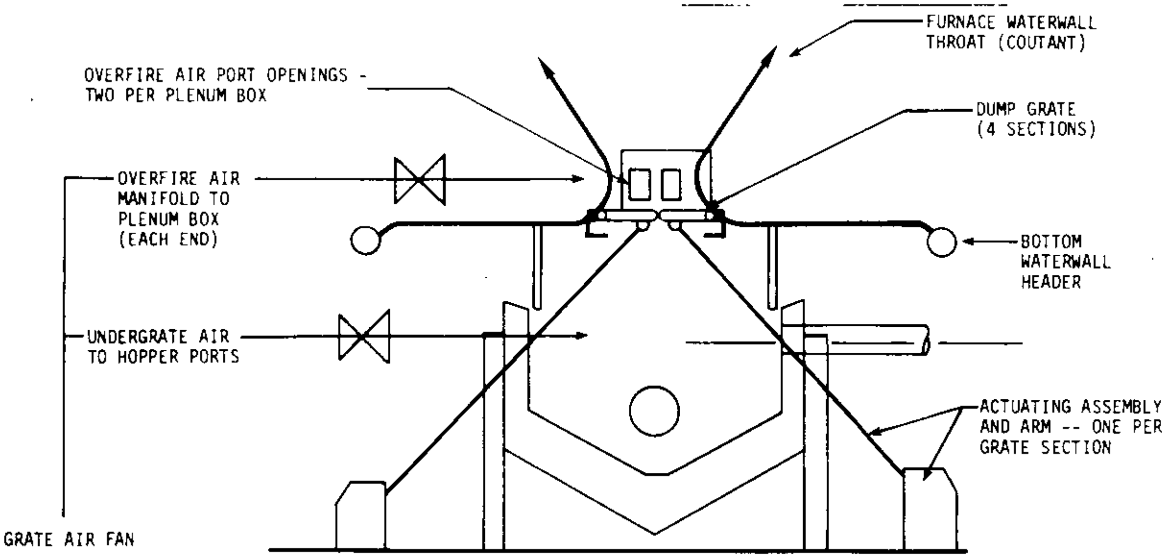


Figure 6. Unit No. 7 Dump-Grate Arrangement.

In September 1978, the two RDF injection ports, originally installed above the two coal pipes in each corner of Unit No. 7 were relocated below the lower coal port. This was done to satisfy the emission offset level required for the anticipated new 70 MW Unit No. 8. In June 1981, the end wall overgrate combustion air source was modified to use some of the hot primary air being supplied to the No. 7 coal mills.

OPERATIONAL PERFORMANCE

RDF PROPERTIES

Material composition of MSW processed at Ames from July 1977 to July 1978 is shown in Table 1. Material composition and size distribution of RDF before and after the disc screen installation is given in Table 2. Total tons of RDF co-fired at the power plant through December 1982 is shown in Table 3. Ultimate analyses of RDF obtained during various testing periods is listed in Table 4.

Table 1. Municipal Solid Waste (MSW) Properties.[a]

As Received MSW	Yearly Avg[b] (July 5, 1977 to July 13, 1978)	Standard Deviation
Composition - % by wt		
Cardboard	12.2	12.46
Paper	34.4	12.91
Plastic	3.2	2.45
Wood	6.4	6.07
Glass	9.5	5.60
Ferrous metal	5.5	12.72
Nonferrous metal	0.9	3.11
Natural organics	6.6	6.26
Cloth	1.7	3.78
Tar	0.7	1.39
Miscellaneous	18.9	7.38
	100.0	
Heating value - Btu/lb	4831	433
Moisture - % by wt	24.20	6.54
Ash - % by wt	22.65	7.66

---

[a] Weekly composite samples taken at primary shredder discharge. Some moisture loss may have occurred.

[b] Average of 52 weekly composite samples.

Table 2. Average Material Composition and Size Distribution of RDF.[a]

As Received Value		Before Disc Screen (Year 1978)	After Disc Screen (Year 1979)
Bulk density (lb/ft^3)		5.27	2.60
Size - % by Wt. Square Screen Size - in.			
	+2.5	4.29	4.83
-2.5	+1.5	9.81	13.94
-1.5	+0.75	15.34	33.21
-0.75	+0.375	20.45	24.80
-0.375	+0.188	16.59	10.53
-0.188	+0.094	11.35	4.86
-0.094		22.17	7.83
		100.00	100.00
Composition - % by Wt.			
Cardboard		10.43	29.26
Other paper		42.44	49.50
Plastic		3.95	5.13
Wood		8.21	4.28
Glass		6.05	1.44
Ferrous		0.21	0.14
Nonferrous		1.29	0.58
Natural organics		4.21	1.49
Cloth		3.54	1.59
Tar		0.23	0
Miscellaneous		19.44	6.59
		100.00	100.00

---

[a] Similar sampling periods in Spring 1978 and Spring 1979.

Table 3. Total RDF Co-fired, Tons.

Year	Stoker Units 5 and 6	Suspension Unit 7	Suspension Unit 8	Total Total	Firing Rate t/h
1975	7,058 (first RDF produced August 30, 1975)			7,058	
1976	34,465			34,465	
1977	40,890			40,890	
1978		28,488		28,488	
1979		23,059		23,059	
1980		26,797		26,797	
1981		26,818		26,818	
1982		6,519	17,437	23,956	6 avg (13 max)
	TOTAL		17,437	211,531	

Table 4. RDF Properties - As Received.

	1978[a]	1978[b]	Unit No. 8 Design	1979[c]	1982[d]
No. of Samples	12	N/A	N/A	8	3
Heating Value, Btu/lb	5602	4905	5610	6113	6356
% by Wt.					
Moisture	24.04	22.06	23.0	18.4	22.5
Ash	13.06	20.99	17.4	9.6	8.5
Carbon	30.66	28.45	30.9	29.9	35.5
Hydrogen	4.51	6.85	4.8	6.0	5.0
Sulfur	0.32	0.34	0.4	0.2	0.3
Chlorine	0.35	0.23	N/A	0.2	0.3
Oxygen	27.04	42.75	---	35.2	27.6

---

[a] Sampled during Summer 1978 Unit No. 7 boiler tests.

[b] Spring 1978 into Atlas Bin (weekly composite).

[c] Spring 1979 into Atlas Bin (weekly composite) after disc screen.

[d] July 1982, Unit No. 8 installation boiler acceptance tests.

COAL PROPERTIES

Ultimate analysis of the coal used during the 1978 Unit No. 7 boiler tests is shown in Table 5. The fuel properties of the coal used during the 1982 boiler acceptance test of Unit No. 7 is listed in Table 6.

Table 5. 1978 Coal and RDF Properties, As Fired.[a]

	Coal		RDF	
No. of Samples	18		12	
	Average	Std. Dev.	Average	Std. Dev.
Heating Value, Btu/lb	10,156	224	5602	359
% by Weight				
Moisture	16.60	1.20	24.04	3.06
Ash	9.74	2.23	13.06	2.72
Carbon	56.60	1.50	30.66	2.92
Hydrogen	4.01	0.19	4.51	0.44
Sulfur	2.79	0.81	0.32	0.05
Chlorine	0.21	0.12	0.35	0.15
Oxygen	9.08	2.26	27.04	2.87

---

[a] 1978 Unit No. 7 boiler tests.

Table 6. Coal Ultimate Analysis.

	Average
As Received	
Heating value - Btu/lb	8112
Ultimate analysis - % by wt	
Moisture	29.10
Ash	6.49
Carbon	47.05
Hydrogen	3.81
Nitrogen	0.69
Oxygen	12.30
Sulfur	0.53
Chlorine	0.03
	100.00

---

[a] July 1982 Boiler #8 acceptance tests, 6 samples.

UNIT NO. 7 BOILER TESTS

The resultant boiler efficiencies associated with co-firing tests performed in 1978 are listed in Table 7. Corresponding environmental emissions measured during these boiler tests are listed in Table 8 and elemental analysis of ESP fly ash are listed in Table 9.

UNIT NO. 8

The only comprehensive co-firing test performed on this unit was the ESP evaluation in July 1982. Results of this test series are shown in Table 10.

ESP

Average ESP collection efficiencies for lists performed on Units No. 7 and 8 are shown in Table 11.

METAL WASTAGE

The only metal wastage experience was on Unit No. 7 in July 1980. Approximately 11 tubes at opposite ends of the furnace water wall throat just above the dump grate experienced failure and were repaired using window patches. The original dump grate retrofit installation in 1978 made no provision for the introduction of overfire air along the full depth above the dump grate. Visual observation of the RDF firing reveals a burning pattern where all of the fluff does not completely penetrate the fireball but appears to be swept around the periphery and piles up on the grate in the corner opposite to the injection port. Thus, the metal wastage can be attributed to severe piling and lack of sufficient combustion air.

ACKNOWLEDGMENTS

The data and information summarized in this paper are derived from many sources. Unit No. 7 and stoker boiler test data are results obtained from a research project performed by the Engineering Research Institute of Iowa State University with sample analytical support by the DOE-Ames Laboratory. This was a project funded by the EPA and the DOE. Additional technical support was provided by the Midwest Research Institute.

Special thanks go to Douglas E. Fiscus of Midwest Research Institute. He has provided much professional support since 1976 during our interaction on co-firing experiences. Further discussion of electric utility co-firing performance has also been documented [7-9].

Continued narratives on operational performance has been supplied by: Mr. Arnold Chantland, Ames Public Works Director; Mr. Carl Baker, Ames Power Plant Superintendent; Mr. Gary Titus, Ames Assistant Electric Utility Director. The contribution of other power plant utility personnel is also gratefully acknowledged.

Table 7. Unit No. 7 Boiler Efficiency - ASME Loss Method.

Ames Unit 7 1978 Boiler Tests[a]	80% Boiler Load			100% Boiler Load		
	Coal Only	10% RDF	20% RFD	Coal Only	10% RDF	20% RDF
Heat losses, %						
Dry gas	7.18	7.59	8.33	7.23	7.03	6.68
H_2 and H_2O in fuel	5.90	7.01	7.66	5.93	6.73	7.70
Moisture in air	0.29	0.24	0.24	0.30	0.26	0.27
Unburned combustibles	0.23	0.45	0.59	0.39	0.38	0.53
Radiation	0.41	0.41	0.41	0.30	0.30	0.30
Unaccounted for loss	1.50	1.50	1.50	1.50	1.50	1.50
Total heat loss	15.51	17.20	18.73	15.65	16.20	16.98
Boiler Efficiency, %	84.49	82.80	81.27	84.35	83.80	83.02
Percentage points efficiency reduction due to co-firing		1.69	3.22		0.55	1.33
Orsat (before air heater), %						
CO_2	13.10	--	13.17	13.02	--	13.89
O_2	4.38	--	4.67	4.96	--	3.95
N_2	82.52	--	82.17	82.03	--	82.16
Air Heater Exit Gas Temperature, °F	367° F		422° F			390° F

---

[a] Prior to disc screen installation.

Table 8. Stack Emissions - Unit No. 7 Tests (1978).

Parameter	Units	80% Load			100% Load		
		0% RDF	10% RDF	20% RDF	0% RDF	10% RDF	20% RDF
Particulates (controlled)	lb/10^6Btu	0.21(0.05)[a]	0.37(0.09)	0.37(0.07)	0.42(0.21)	0.44(0.07)	0.53(0.09)
Particulates (uncontrolled)	lb/10^6Btu	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_x	lb/10^6Btu	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_x	lb/10^6Btu	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	lb/10^9Btu	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	lb/10^9Btu	8.37(14.0)	12. (207.)	0.77(0.42)	0.19(0.33)	1.44(0.72)	0.42(0.19)
Methane	lb/10^9Btu	5.30(2.65)	6.07(1.58)	3.77(0.30)	3.35(0.93)	4.58(1.44)	2.47(0.58)
Fly Ash Resistivity ohm-cm		2.2×10^{10}		3.5×10^{10}	3.0×10^{10}		5×10^{10}

---

[a] Values in parentheses are ± one standard deviation.

Table 9. 1978 Analysis of ESP Unit No. 7 Fly Ash.

	80% Load		
	0% RDF	10% RDF	20% RDF
Carbon	1.85 (0.55)[a]	2.43 (0.35)	2.54 (0.05)
Hydrogen	0.10 (0.02)	0.11 (0.01)	0.17 (0.05)
Sulfur	0.70 (0.34)	0.69 (0.13)	0.86 (0.14)
Chlorine	0.01 (0.01)	0.01 (0.00)	0.03 (0.01)
Mineral	97.3 (0.55)	96.8 (0.46)	96.4 (0.09)
	100% Load		
	0% RDF	10% RDF	20% RDF
Carbon	1.92 (0.78)	2.41 (0.49)	2.40 (0.40)
Hydrogen	0.10 (0.02)	0.11 (0.01)	0.11 (0.02)
Sulfur	1.02 (0.51)	0.82 (0.21)	0.83 (0.13)
Chlorine	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)
Mineral	97.0 (0.39)	96.6 (0.59)	96.6 (0.30)

---

[a] Values in parentheses are ± one standard deviation.

Table 10. Summary Tests - Unit No. 8.[a]

	Coal	Coal + RDF
Particulate Stack Emissions, lb/10^6 Btu	0.0053	0.0306
Air Heater Exit Gas Temperature, °F	282	298
Orsat Boiler Outlet, %		
O_2	4.2	5.7
CO_2	15.0	13.7
Total Heat Input 10^6 B/hr	745.72	829.68
RDF Heat Input, %		21.05
RDF flow, tons/hr		14.05
feedwater flow, 10^3 lb/hr	620.0	619.7

---

[a] Full load tests.

Table 11. Average Electrostatic Precipitator (ESP) Efficiency.

Unit No.	Boiler Test Date	Nominal Boiler Load %	Average ESP Efficiency Coal Only %	Average ESP Efficiency Coal + RDF %	RDF Heat Input %	Reduction Percentage Points
7	1978[a]	80	96.8	95.1	10	1.7
		80	96.8	95.5	20	1.3
		100	94.7	93.9	10	0.8
		100	94.7	92.8	20	1.9
8	1982	100	99.9	99.4	22	0.5

---

[a] 1978 boiler tests are prior to disc screen installation.

REFERENCES

1. Evan, J. C., S. K. Adams, P. Gheresus, A. W. Joensen, and J. H. Hall. Evaluation of the Ames Solid Waste Recovery System: Part I - Summary of Environmental Emissions, Equipment, Facilities, and Economic Evaluations. EPA-600/2-77-205, U.S. Environmental Protection Agency, Cincinnati, Ohio, November 1977.

2. Van Meter, D. B., A. W. Joensen, W. L. Larsen, R. Reece, and J. L. Hall. Evaluation of the Ames Solid Waste Recovery System: Part II - Performance of the Stoker Fired Steam Generators. EPA-600/7-79-229, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

3. Hall, J. L., A. W. Joensen, D. B. Van Meter, R. Wehage, G. Severns, and R. Reece. Evaluation of the Ames Solid Waste Recovery System: Part III - Environmental Emissions of the Stoker Fired Steam Generators. EPA-600/7-79-222, U.S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

4. Hall, J. L., A. W. Joensen, D. B. Van Meter, J. C. Even, W. L. Larsen, S. K. Adams, P. Gheresus, and G. Severns. Evaluation of the Ames Solid Waste Recovery System: Refuse Processing Plant and Stoker Fired Steam Generators. U.S. Environmental Protection Agency, Year II Report, Cincinnati, Ohio, November 1979.

5. Joensen, A. W., J. L. Hall, J. C. Even, D. B. Van Meter, P. Gheresus, G. Severns, S. K. Adams, and R. White. Evaluation of the Ames Solid Waste Recovery System: Refuse Processing Plant and Suspension-Fired Steam Generators. Year III Report, EPA Grant R803903, February 1980.

6. Fiscus, D. E., A. W. Joensen, A. O. Chantland, and R. A. Olexsey. Evaluation of the Performance of the Disc Screens Installed at the City of Ames, Iowa Resource Recovery Facility. 1980 Processing ASME National Waste Processing Conference, Washington, D.C., May 11-14, 1980.

7. Fiscus, D. E., H. D. Ege, R. D. Petersen, J. C. Glaub, G. M. Savage, and A. W. Joensen. Study of Existing Co-firing Experience - Phase I. Volume I. Final Report. Midwest Research Institute to Argonne Laboratory. October 31, 1983.

8. Fiscus, D. E., H. D. Ege, R. D. Petersen, J. C. Glaub, A. W. Joensen, K. E. Wolfs, and G. M. Savage. Study of Existing RDF Co-firing Experience - Phase I, Volume II - Appendixes Final Report, Midwest Research Institute to Argonne Laboratory. October 31, 1983.

9. Fiscus, D. E., H. D. Ege, R. D. Petersen, J. C. Glaub, K. E. Wolfs, A. W. Joensen, and G. M. Savage. Study of Existing RDF Co-firing Experience - Phase II, Volume III. Final Report, Midwest Research Institute to Argonne Laboratory, October 31, 1983.

THE AKRON RECYCLE ENERGY SYSTEM

Stanley D. Mark, Jr.
Vice President and General Manager
Tricil Resources, Inc.
Akron, Ohio
February 10, 1984

The purpose of this paper is to describe a project in Akron, Ohio, funded by the public sector and implemented by private industry, which incinerates municipal solid waste to generate energy for use by local customers.

INTRODUCTION

In 1971, the utility company which operated a steam production and distribution system in downtown Akron decided it was no longer going to continue in that business, leaving the City of Akron with the operation of the system. The City decided to build a modern resource recovery plant using North American technology to dispose of municipal solid waste and to generate the steam required for the system.

The plant is called the Akron Recycle Energy System (RES). It was originally financed through the issuance of $46 million in tax-exempt revenue bonds from the Ohio Water Development Authority (OWDA) and $10 million in general obligation bonds ($5 million from the City of Akron and $5 million from Summit County).

Plant construction was completed in mid-1979. Operating difficulties were discovered, however, during the commissioning process; and after two years, the plant performance was still well below its design capacity of 1,000 tons per day. During this start-up period, design changes were made requiring further significant capital commitment. By 1981, a decision point had been reached -- the alternatives being to modify the plant extensively, or to close it.

The City of Akron and the OWDA reviewed a number of alternatives to improve the operation and to reduce costs. An approach was developed requiring any future capital modifications to be guaranteed by a selected outside contractor. In June, 1981 Tricil was selected as the outside contractor. An agreement was signed by the City of Akron, the OWDA, the Ohio Citizens' Bank as trustee for the bondholders, and Tricil which required Tricil to:

- modify the RES at a fixed price of $11,450,000, backed by process performance guarantees, to process 800 tons per day of municipal solid waste
- initially operate the RES and its steam distribution system on natural gas and later on municipal solid waste, and

- negotiate and enter into a ten to twenty-year long-term operating contract.

The modified RES successfully completed its performance test in December 1982, processing up to 1,100 tpd during the month-long test. During 1983, it processed more waste, more consistently than ever before in its history. Today, the Akron modified RES can reliably receive and process 328,000 tons of municipal solid waste per year. The plant has a nominal design capacity of 1,000 tpd. Normal operation is based on processing waste an average of 900 tpd, 365 days per year, and satisfying customer steam requirements seven days per week, 24 hours per day. The plant currently employs 25 per cent fewer people than before the retrofit. Figure 1 is a photograph of the exterior of the RES plant as it looks today.

PROCESS DESCRIPTION

See Figure 2 which depicts schematically the processes employed at the RES plant. The RES operations are essentially divided into four major elements:

- Receiving
- Processing
- Combustion
- Steam Distribution

RECEIVING

Up to 160 waste hauling vehicles per day deliver waste to the plant. As the trucks enter the receiving area they are weighed to establish billing records before discharging their loads into one of the eight openings over the two receiving pits. This tipping floor is about the size of a football field. As the waste is dumped, it is diverted to the pits by an inverted "V" partition. Waste from either pit is moved toward its shredder by hydraulically-actuated multi-rams at the bottom of each pit. These rams transfer the waste forward to surge hoppers. A Gradall is used to break bridges in the receiving pits as they occur. A conveyor transports the waste from a surge hopper to the inlet of a shredder. A grapple crane picks and rejects unacceptable waste and assists in leveling the waste on the shredder infeed conveyors.

PROCESSING

Two 1500 hp shredders reduce the waste to a nominal 6" size and smaller. Each shredder is capable of processing up to 60 tph. Normally, only one shredder is run at a time. The shredded refuse then passes through a two-drum magnetic separation unit to remove ferrous metals from the waste stream. The ferrous fraction is cleaned by an air scrubbing system which removes loose tramp material before the metal is emptied into the load-out area. The tramp materials so removed drop back to the conveying line and rejoin the main waste stream enroute to the boilers.

COMBUSTION AREA

Fuel Distribution System

In the combustion area, a series of conveyors and fuel proportioners distributes the fuel to the three boilers. Air swept feeders direct the waste fuel into each boiler. This unique system assures that required quantities of waste are introduced to the boilers to match steam demand. Excess prepared fuel, not demanded by the boilers, is recycled back to the receiving pit from the fuel proportioner.

Boilers

Each of the three waterwall, spreader-stoker boilers is equipped with traveling chain grates and is capable of incinerating 20 tph of prepared refuse. Combustion air preheaters, economizers for feedwater preheating, and four-stage electrostatic precipitators for emission control are ancillary to the boilers.

Ash Removal

Bottom ash, fly ash, and soot are by-products of the waste incineration process. Bottom ash falls from the boiler grates and drops directly into water quench tanks immediately below the boilers. Soot recovered from the economizers is also conveyed to the quench tanks. Fly ash removed in the electrostatic precipitators is transported to a fly ash silo. From there it is directed to a pug mill for conditioning and then it is conveyed along with the bottom ash and soot to ash hauling vehicles for transport to a sanitary landfill.

MODIFICATION CONCEPT

The preceeding section describes the RES plant as it is today after being extensively retrofitted by Tricil. That work was initiated in June, 1981. It was based on a philosophy of municipal solid waste (MSW) materials handling, processing and incineration which is best described by the words:

- Simplicity
- Flexibility
- Reliability

These principles, when applied to plant design, result in minimized operating and maintenance costs. The original plant design was complex and inflexible; and, therefore, unreliable. Operating and maintenance costs were higher than expected. Efficient operations were hampered by inappropriately complex technology. The modifications focused on simplification of the materials handling system, improvements in certain other items of equipment, and installation of a microprocessor to control the process.

RECEIVING

Technical changes to the receiving area were minimal. The shape of the infeed surge bin was altered to allow improved refuse flow to the shredder infeed conveyors. The multi-ram system was sealed to improve housekeeping.

MATERIALS HANDLING

The original pneumatic materials handling system was replaced with a simple, reliable belt conveyor system designed by Tricil.

The interim prepared waste storage and retrieval system, as originally installed, was a constant cause of operating problems. It was replaced with the fuel proportioning system thus ensuring reliable, continuous feed to the boilers.

PROCESSING

Improvements to the processing area included the installation of shredder baffles to protect the shredder infeed conveyors. These baffles deflect the waste into the hammers creating a more homogeneous fuel. A steel, blast-protection wall was installed between the two shredders to improve operator safety and to reduce shredder downtime by allowing maintenance on one shredder while the second unit is operating. The original magnetic separator was removed and replaced with a stronger duty, double drum magnet and an air scrubber. The new magnets remove more and heavier ferrous items thereby offering greater protection for boiler grates. When passed through the air scrubber, entrained tramp materials are removed and ducted to a cyclone for return to the boiler feed conveyor. A higher quality ferrous fraction results. Once separated, the ferrous fraction is loaded onto awaiting trailers.

COMBUSTION

Combustion optimization was accomplished through the installation of two unique systems: the boiler fuel feed system, and an ash quench and removal system. The fuel feed system provides for variable rate delivery of prepared fuel to each boiler. The continuous ash quench and removal system was designed to eliminate infiltration air and thus assists in optimizing combustion conditions. The system eliminates the dangerous former practice of opening the boiler for manual ash removal.

PROCESS CONTROL

The process control system and the associated equipment were developed by Tricil to optimize the operation of the RES. A microprocessor-based control system was chosen to control critical operations such as:

- the waste to shredder infeed conveyor flow rate
- the boiler fuel proportioning system, and
- specific boiler operating requirements.

Major benefits of this electronic system versus the original pneumatic system are:

- superior boiler and process control
- lower operating and maintenance costs
- instantaneous response to changes in the operation
- provision of graphic operating data for future analysis.

In addition, a programmable logic controller was installed to provide control of specific conveyor functions such as limit switches, safety pull cords, and zero speed switches.

ENERGY DISTRIBUTION

STEAM

Steam produced by the boilers is distributed to a variety of outside customers. The major energy customers for the plant's steam are the University of Akron, three hospitals, and a BFGoodrich manufacturing plant. In addition there are about 200 steam customers in the City's downtown district. Leaving the boilers at 560 psi, the steam pressure is reduced to customer requirements. Instrumentation in the RES control room continuously monitors the steam flow and pressure.

The steam distribution system is maintained by RES personnel. That group also provides assistance and advice to customers in such areas as in-plant repairs, energy conservation, and efficient use of existing heating systems.

ELECTRICITY

Two back pressure steam turbines generate electricity for internal use. Steam demands for the feedwater deaeration system are provided by the low pressure steam exhausted from these units.

HOT WATER

Exhaust steam from the plant's two turbine generators is used to produce hot water at 210°F for supply to nearby customers. The water returns to the RES at 130°F.

FIRES AND EXPLOSIONS

The RES plant experienced a number of fires and explosions during 1983. Extensive damage resulted in some cases. There was no interruption in steam and hot water supply to RES customers, however, since the boilers were fired with natural gas during those periods when the supply of prepared waste was halted.

The likely cause of the fires and explosions was the presence of finely powdered resins and other organic fines in the waste. Such material was found in the investigations which followed each occurrence.

A program is underway to identify the sources of these reactive powders and to prevent their inclusion in waste which is handled by the RES plant.

RECENT OPERATING RESULTS

The Akron RES plant has been in continuous commercial operation since the beginning of 1983. The operating results for 1983 are described in the following sections.

MSW PROCESSING RATE

The RES plant processed MSW at an average daily rate of 600 tons throughout the year. The maximum daily rate was 1100 tons. It is believed that optimal operation of the plant would occur at an average daily throughput rate of 900 tons, but a shortage of refuse during winter months and lack of adequate energy demand by customers during the summer months restricted plant operations.

STEAM PRODUCTION

The average steam production throughout 1983 was 188,000 pounds per hour. The peak production was 400,000 pounds per hour. Of all the steam produced, 84% was derived from the combustion of municipal solid waste and 16% from the combustion of natural gas.

BOILER UTILIZATION

Of the three boilers in the RES plant, the actual utilization time ranged from 53% to 59%. The average boiler utilization factor was 55%. It is estimated that the availability for firing shredded waste in a boiler is 85%. Each boiler, therefore, had about 30% of its actual capacity go unused during 1983.

BOILER MSW RATE

During those periods of firing shredded waste in the boilers in the RES plant in 1983, the actual throughput rate was 355 tpd per boiler. It is known that each boiler can be fired on MSW at a rate of 400 tons per day. Thus, in addition to the utilization factor, firing the boilers with MSW at their nominal rate would provide about 13% of additional capacity.

ELECTRICAL POWER

Power consumption in the RES plant was equivalent to about 90 kwh per ton of waste processed. About 53% of that power was produced by the steam turbines in the plant.

SOLID BY-PRODUCTS

On a weight per cent basis, the RES plant produced solid by-products in the amounts indicated below:

- Rejects, 1.6%
- Ferrous, 4%
- Total Ash, 28.0% (wet basis)

PERSONNEL

The total staff requirement to maintain the RES plant in continuous operation during 1983 was:

Administrative	19
Operations	19
Maintenance	29
Total	67

Included in the above personnel listing are five people in the accounting and clerical category, seven people in the group which maintains the steam distribution system, and ten people who work continuously on housekeeping of the plant.

DETERMINING THE CALORIFIC VALUE OF MUNICIPAL SOLID WASTE: EXPERIMENTAL RESULTS FROM A 2.5 KILOGRAM-CAPACITY FLOW CALORIMETER

E.S. Domalski, K.L. Churney, A.E. Ledford, J.C. Colbert,
S.S. Bruce, T.J. Buckley,
Chemical Thermodynamics Division
Center for Chemical Physics

R. C. Paule, and
National Measurement Laboratory

M.L. Reilly
Temperature and Pressure Division
Center for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

ABSTRACT

A study has been made at the National Bureau of Standards to establish the limits of reliability of the calorific value of municipal solid waste (MSW) determined by the bomb calorimetric procedure currently used in commercial test laboratories. This procedure involves using gram-size samples derived from MSW that has been processed down to a particle size of 2 mm or less. Critics of the procedure argue that gram-size samples are too small to be representative of such a large quantity of so heterogeneous a material, and that processing MSW may also alter its composition.

To test the bomb calorimetric procedure, a 2.5 kg capacity combustion flow calorimeter was designed and constructed for the determination of the enthalpies of combustion of kilogram-size samples of MSW in flowing oxygen near atmospheric pressure.

Calorimetric data on processed MSW were obtained using both the kilogram-size flow and a gram-size bomb calorimeter. Intercomparison of results shows that the calorific value (on a dry basis) of gram-size test samples agrees, within the uncertainty of our experiments, with the corresponding values for their kilogram-size parent samples provided that the sample division technique used to obtain the gram-size samples is that described in this work. The average difference of the parent minus gram-size sample values (on a dry basis) is -0.1% with an imprecision (95% confidence interval) of ± 1.1% of the mean calorific value.

The effects of processing on sample composition were determined by intercomparison of flow calorimetric results on kilogram-size samples of processed and minimally processed MSW (150 mm or less particle size) that are nominally identical. The average difference of the unprocessed minus processed values (on a dry basis) is -0.5% with an imprecision (95% confidence interval) of ±2.9% of the mean calorific value.

1. INTRODUCTION

The work described in this paper was performed to assist in resolving an industrial problem formulated by members of the ASME Research Committee on Industrial and Municipal Wastes, the ASME Performance Test Code Committee (PTC-33) on Large Incinerators, and the ASTM Committee (E-38) on Resource Recovery. Incinerator-boiler systems which are used to dispose of municipal solid waste (MSW) are bought and sold on the basis of thermal specifications. To determine whether a system meets its thermal specifications, the calorific value of the input waste stream fed to the system must be known. At present, the calorific value is determined at commercial test laboratories using gram-size samples of the waste.

It has been the opinion of many combustion engineers that one cannot accurately sample a large, multiton quantity of MSW down to one or two grams and obtain a representative test sample. The calorific value determined from such a small sample would be suspect. Gram-size samples must be prepared from the bulk MSW by separation and milling techniques to provide a powdered test sample of approximately 2 mm or less particle size. Many combustion engineers feel that this processing may significantly alter the composition of the test sample and, hence, the calorific value. This might occur because of changes in composition due to excessive local heating associated with some milling operations or due to sampling and handling a material which is inhomogeneous and segregates easily.

The general question of whether or not the calorific value of a multiton quantity of MSW can be obtained by sampling down to one or two grams can be broken into two parts. The first part is: How should one sample a multiton pile or stream of raw waste in order to obtain increments of sufficient number and size to characterize the calorific value with a given precision? The second part is: How can one obtain representative gram-size samples that characterize these increments? The various issues in the dispute about the validity of the current method for determining the calorific value of MSW are primarily concerned with the second of these questions.

To address these issues, the National Bureau of Standards (NBS) initiated a research program in collaboration with the U.S. Department of Energy to develop test procedures for accurately determining the calorific values of refuse and refuse-derived fuels (RDF). This research also was part of the NBS response to the Resource Conservation and Recovery Act of 1976. Subtitle E of this legislation mandated NBS to provide guidelines for the development of specifications for classification of materials destined for disposal.

NBS made a commitment to develop a calorimeter to accommodate a sample of MSW which is larger than that currently used in commercial test laboratories. In addition, the MSW sample should be processed as little as possible. After many discussions with combustion engineers and statisticians, we decided that an acceptable sample size was about 2.5 kg and that the sample would be derived from dried RDF-2(+). In terms of the

---

(+) RDF-2 is MSW that has been processed to reduce the particle size so that 95 mass-percent passes through a 15 cm square mesh screen.

general sampling question, cited previously, the sample size adopted for the calorimeter is assumed to be a convenient fraction of a sampling increment for the waste stream.

After an initial study of the variability of MSW was carried out at NBS in 1980 [1], it was concluded that a calorimeter which could burn a kilogram-size sample with a total uncertainty of less than one percent in the enthalpy of combustion would satisfy our requirements.

A 2.5 kg capacity flow calorimeter was designed, fabricated, and placed in operation. A detailed description of the apparatus has been published [2]. Calorimetric measurements have been carried out in a study consisting of 26 experiments designed to resolve part of the dispute about the current method of determining the calorific value of MSW. A brief description of the main features of a typical experiment is given in section 2. The measurement protocol is discussed in section 3. Results are analyzed in section 4. Conclusions are given in section 5.

2. DESCRIPTION OF A TYPICAL FLOW EXPERIMENT

The isoperibol flow calorimeter consists of two basic parts: a constant temperature jacket and the calorimeter proper. The latter contains the sample combustor. Heat liberated in the combustion reaction is transferred to the stirred water in the calorimeter vessel, the outermost container of the calorimeter proper. The rise in temperature of the calorimeter water, after correction for heat exchange with the jacket and for heat transport by the flowing gases, is proportional to the enthalpy of combustion of the sample. The calorimeter is calibrated by determining the temperature rise produced by combustion of a known mass of microcrystalline cellulose whose enthalpy of combustion has been established by bomb calorimetry.

The RDF sample is burned in the form of a cylindrical compressed pellet (nominally 23 cm diameter and 15 cm high) rather than in loose form because this configuration simplifies quantitative collection of ash and prevents dispersion of the sample away from the main reaction zone.

Ten minutes prior to ignition, the combustor is flushed with oxygen. Oxygen is supplied to the sample by an array of nozzles arranged in five horizontal tiers of six symmetrically spaced nozzles located in the combustor wall. The tiers supply narrow jets of oxygen that are either directed at the sides of the sample or into the space above and below the sample. Additional oxygen dilutes the product gas as it leaves the collector to reduce the dew point of the product gas below room temperature. Typical flow rates are 160 lpm to the combustor and 110 lpm to dilute the product gas for a total flow of 270 lpm. Typical burning times were approximately 32 minutes for RDF-2 and microcrystalline cellulose samples, and about 40 minutes for RDF-4(+) samples.

(+) RDF-4 is MSW from which the metal has been removed and then processed to reduce the particle size so that 95 mass-percent passes through a 2 mm square mesh screen.

The hot combustion product gas passes through a ten-turn heat-exchange coil after leaving the combustor. The heat exchange coil transfers heat from the product gas to the stirred calorimeter water. Before leaving the calorimeter the product gas passes through a collector where most of the water formed in the combustion reaction is trapped.

A portion of the product gas is continuously withdrawn for analysis. Part of this gas is dried and passed through dedicated infrared detectors for CO and CO_2. A second part is passed through a scanning infrared detector used to monitor various trace components (hydrocarbons, SO_2, HCl, etc.). The remainder of this gas is passed through a cooled-mirror type of automatic dew point detector to monitor water vapor.

The CO_2, H_2O, and CO concentrations in the product gas during the combustion of an RDF-4 pellet are shown in Figure 1. The average CO_2 concentration over the first ten minutes of the combustion is 38 mole percent and corresponds to an oxygen supply rate of about 2.5 times stoichiometry. The H_2O concentration reaches a maximum of 2.4 mole percent (i.e. dew point of 16 °C) at 30 minutes; the abrupt fall in concentration at 42 minutes indicates that the combustor has been completely flushed of product gas. The occurrence of two peaks in the CO concentration versus time is typical of all the RDF samples. In Figure 1, the initial and final maximum CO concentrations are 0.016 and 0.027 mole percent, respectively. The initial peak always occurs near the time of the maximum rate of production of CO_2; the final peak occurs near the end of the visual burning when the ash tends to inhibit the combustion. The average CO concentration in a cellulose combustion is about a factor of fifty smaller than that shown in the figure.

The temperature of the product gas as it leaves the top of the combustor rises to about 400 °C within the first minute of the combustion, gradually increases to a maximum of about 450 °C between 12 and 15 minutes after ignition, and then decays exponentially thereafter. The peak values of the temperatures of the combustor wall within 25 cm of the sample are between 600 and 700 °C.

Before flushing the combustor and igniting the sample, the calorimeter water temperature is monitored for about one hour after the initial drift rate becomes constant. When the drift rate of the water temperature attains a steady value, about 150 to 180 minutes after ignition, readings are made for an additional hour which corresponds to the final drift period. A correction is made for the heat exchange between the calorimeter proper and the jacket during the three hour time interval between the two drift periods. This correction amounts to about 4% of the observed temperature rise which was between 6.0 and 9.5 °C for all experiments.

3. SAMPLE PREPARATION AND MEASUREMENT PROTOCOL

To resolve the dispute about the validity of the current method of determining the calorific value of MSW, two problems were addressed. The first is the sampling problem: How does one obtain a representative gram-size sample from a kilogram-size quantity of RDF-4? The second is the processing problem: Does processing MSW down to 2 mm particle size (RDF-4) alter its calorific value significantly (i.e. one percent or more)?

Both the sampling and processing problems were examined in context of the variability of MSW for two weeks, a time period appropriate to a specification test of an incinerator-boiler system. Thirteen to twenty-three kilograms of RDF-2 were obtained on each of ten consecutive working days (5 days per week for a 2 week period from January 10 to 21, 1983) from the Baltimore County Resource and Recovery Facility in Cockeysville, Maryland. Each sample was removed from the conveyor belt immediately beyond the primary shredder before any further processing occurred. The material was brought to NBS each day, dried for 12 hours at 105 °C to determine its initial moisture content, and then stored at 5 °C.

Ideally, the processing problem could be solved by comparing the calorific value of identical pairs of kilogram-size samples of dried RDF-2, one unprocessed and the other processed. We attempted to prepare such identical kilogram-size samples by hand sorting each day's material into eight categories and then reconstituting the material into 2.5 kg samples having the same relative mass composition as the whole.

The material of each day was hand sorted into metal, combustible, and noncombustible fractions. Metals were separated into magnetic and nonmagnetic components. The combustible fraction was separated into wood/vegetable matter, textiles, plastics, and paper. The noncombustible

Table 1. Composition of Four of Ten Day's Samples of Municipal Solid Waste Obtained from the Baltimore County Resource and Recovery Facility, January, 1983.

	Mass Percent (Dry)			
Day	4	6	7	9
1) Initial Moisture	27.6	34.3	25.1	22.0
2) Metal (Magnetic)	5.0	6.0	2.6	2.2
3) Metal (Nonmagnetic)	1.3	1.5	1.3	0.6
4) Wood, Vegetable	0.8	1.3	0.4	2.5
5) Textiles	1.6	3.2	5.2	13.8
6) Plastics	3.3	6.2	8.2	6.6
7) Paper	66.2	55.8	67.7	64.3
8) Glass, Ceramics	2.6	2.4	0.8	0.3
9) "Fines"	19.2	23.6	13.8	9.7
10) Metals	6.3	7.5	3.9	2.8
11) Combustible Content	71.9	66.5	81.5	87.2
12) Noncombustible Content	21.8	26.0	14.6	10.0
- Samples as Burned -				
13) Combustible Content	76.7	71.9	84.8	89.7
14) Noncombustible Content	23.3	28.1	15.2	10.3

fraction was divided into glass/ceramics and "fines" (primarily grit and sand). A summary of the results of hand sorting plus the initial moisture content for four of the ten day's material selected for our study are given in Table 1. The compositions according to main groups are given in lines 10 through 12. Metals were omitted from the reconstituted material. The combustible and noncombustible compositions of the samples actually burned in the flow and bomb calorimeters are listed in the last two rows of Table 1. Samples from days 6 and 9 were selected because they had the largest and smallest noncombustible content, respectively. Samples from days 4 and 7 had intermediate noncombustible contents.

Processed MSW consists of a low density component, fluff, which resembles chopped up cotton fibers, and a high density component which resembles sand or metal particles. Some high density material is entrained in the fluff; this entrainment is not uniform. Sampling problems arise because of segregation of the high and low density components. The sampling technique used in the first NBS study [1] of the variability of MSW for a two week period in January 1980 consisted of blending (in drums filled with steel balls), coning and quartering, and taking gram-size grab samples. This method was found to be unsatisfactory. In that study, the percent coefficient of variation(+), %CV, of the enthalpy of combustion on a dry basis was 3.2% for supposed identical gram-size samples of RDF-4 burned in a bomb calorimeter. The corresponding quantity for a pure (or truly homogeneous) material should be of the order of 0.1%.

For this study, we introduced a new technique for obtaining gram-size test samples. A Brinkmann Co. Sample Divider PTZ(++) was used. It consists of a central cup from whose bottom surface tubes extend outward and downward to collector bottles. In the model we used there are eight tubes and eight bottles. The cup, tubes, and bottles rotate around the central vertical axis of the cup. The sample is introduced into the divider through a funnel feeding a horizontal vibrating trough which teases the sample into the divider cup.

An initial assessment of the new sample division technique showed this method to be superior to the coning and quartering procedure used in the variability study [1]. This conclusion is confirmed by the results cited in section 4.

The measurement protocol adopted for our study is summarized in Table 2. Four bags of the reconstituted kilogram-size samples of RDF-2 were selected from each of the four days. The contents of two of the bags, designated A and B, were burned in the large flow calorimeter (Step 2C, Table 2) without further processing after drying to determine the residual moisture (Step 2A). A known amount of water was added to each of the samples and then each sample was compacted to form a pellet (Step 2B). The water was added to improve the cohesion of the pellet.

(+) 100 x (s / average) , where s is the standard deviation of a single measurement.

(++) The commercial sources cited in this paper are included to adequately describe the experimental procedures. Such identification does not imply recommendation or endorsement by the National Bureau of Standards.

Table 2. Measurement Protocol.

1. Select four 2.5 kg samples from each day.
   For example: Day 4, label samples A4, B4, C4, D4
2. A4, B4:
   - A) Dry.
   - B) Add water and pelletize.
   - C) Burn in flow calorimeter.
3. C4, D4:
   - A) Reduce to 2 mm particle size.
   - B) Blend, take grab sample (40 grams).
   - C) Divide to obtain test samples (2 grams each).
   - D) Recombine remainder of C4 and D4 to obtain two identical kilogram-size samples. Label E4, E′4.
   - E) Test samples: two sets of two combustion bomb calorimeter, two residual moisture, and two furnace ash determinations (one set for each bag).
4. E4, E′4:
   - A) Pelletize.
   - B) Burn in flow calorimeter.

The contents of the remaining two bags, designated C and D, were processed to 6 mm sieve size using a Williams Hammer Mill and then to 2 mm sieve size using a Wiley Mill (Step 3A). A diagram of the measurement protocol for bags C and D is given in Figure 2. Powdered dry ice was mixed with the material in the throat of the Wiley Mill to prevent excessive local heating. The resulting RDF-4 of each bag was then blended in a vee blender and a forty-gram grab sample was removed (Step 3B). (The grab sample was saved for future use in another study.) Gram-size test samples were then obtained from the milled, blended material of bag C and bag D using the Brinkmann Sample Divider (Step 3C). In Step 3D, the remainder of each bag was divided into two equal parts. One part of bag C and one part of bag D were combined to form the sample of bag E and similarly for identical bag E′. Kilogram-size pellets of RDF-2 (Step 2B) and RDF-4 (Step 4A) were prepared by placing the sample in a die piece and compressing it with a total force of 534 kN.

Masses of samples were recorded before, after, and during each step of the measurement protocol to account for sample loss. Individual measurements in sets made with either the bomb or flow calorimeter were carried out in a random order.

In subsequent sections of this paper, the labels C and D refer to the gram-size test samples withdrawn from bags C and D, respectively, before step 3D in which the remainder of bags C and D were split and recombined to obtain bags E and E′. The strategy behind step 3D was to take further advantage of the improved capability of the Brinkmann Sample Divider to divide the sample into identical parts. Having prepared identical gram-size samples in Step 3C, we prepared identical kilogram-size samples in Step 3D. Hence, differences in the enthalpy of combustion of each pair of

E and E′ samples for a given day afford a direct measure of the measurement precision of the new calorimeter on an actual sample of RDF (as distinct from a sample of pure cellulose which does not contain noncombustible components). While labels E, E′, A and B refer to kilogram-size samples, the samples of bags E and E′ differ from those of bags A and B in two important respects. Bags E and E′ contain processed material (i.e. RDF-4) while bags A and B contain unprocessed MSW (i.e. RDF-2). The samples in bags E and E′ are essentially exact replicates while those in bags A and B are only approximately identical (i.e. to the extent that hand sorting into general classifications given in Table 1 permits).

4. EXPERIMENTAL RESULTS

The experimental results are given in Tables 3, 5, and 7. Three important conclusions are drawn from these results. The first is concerned with the improvement in results obtained with the new sampling technique as compared to the coning and quartering technique used in the earlier variability study [1]. This is discussed in the analysis of the gram-size test results in Section 4.1. The second conclusion concerns whether or not gram-size test samples represent their kilogram-size parent samples of RDF-4. This is discussed in the comparison of flow and bomb calorimetry results in Section 4.2.1. The final conclusion concerns whether or not processing of RDF-2 to RDF-4 alters the calorific value. This is discussed in Section 4.2.2.

Table 3. Ash and Combustion Bomb Calorimetry Results for Two-Gram Test Samples.

Sample	Ash (Dry Basis), % Furnace %	 Bomb %	HHV2 MJ/kg	HHV3-B MJ/kg
C4	34.45	33.62	14.619	22.022
	34.54	33.50	14.555	21.886
D4	32.73	31.54	14.867	21.716
	32.30	31.21	14.857	21.598
C6	37.82	34.58	14.678	22.436
	37.19	35.67	14.546	22.612
D6	37.67	36.18	14.509	22.735
	36.89	35.51	14.714	22.817
C7	27.76	26.78	16.273	22.224
	28.30	26.58	16.506	22.480
D7	25.04	24.19	17.254	22.760
	25.49	23.13	17.253	22.443
C9	17.89	16.41	18.200	21.772
	17.68	16.31	18.221	21.773
D9	17.43	15.84	18.336	21.787
	17.55	16.57	18.325	21.966

4.1 COMBUSTION BOMB CALORIMETRY

The gram-size test sample results are listed in Table 3 for sampling days 4, 6, 7, and 9. They consist of duplicate results for each sample of the enthalpy of combustion (ASTM Method E711-81), bomb ash (dried residue from a combustion bomb experiment) and furnace ash (ASTM Method E830-81). All results were converted to a dry basis using moisture contents obtained with ASTM Method E790-81. In the furnace ash test, the sample is combusted in air in a furnace at 575 °C for two hours.

Table 4 summarizes the statistical analysis of the results; the methods are summarized in references [3] and [4]. The percent coefficient of variation, %CV, for the between-day, within-day, and within-bag variability are calculated for furnace ash, bomb ash and calorific values. HHV2 and HHV3 are the negative of the enthalpy of combustion on a moisture free and a moisture-ash free basis, respectively. HHV3-B refers to the use of the bomb ash value in the calculations; HHV3-F refers to the use of the furnace ash value in the calculations. For sake of comparison, the corresponding results for the 1980 variability study are given in the lower half of Table 4. The total %CV in column 6 is the square root of the sum in quadrature of the %CV's given in the preceding three columns.

Table 4. Summary of Statistical Analysis of Ash and Combustion Bomb Calorimetry Results for Two-Gram Test Samples.

Property (Dry basis)	Average	Components of Variability, %CV			
		Within Bag	Within Day	Between Days	Total
	January 1983 Study (4 days, this work)				
Furnace Ash, %	28.8	1.2	4.1	29.9	30.2
Bomb Ash, %	27.4	1.7	4.8	31.1	31.5
HHV2, MJ/kg	16.108	0.5	2.0	10.9	11.1
HHV3-B, MJ/kg	22.189	0.6	0.6	1.9	2.1
HHV3-F, MJ/kg	22.649	0.8	0.3	2.5	2.6
	January 1980 Study (10 days, [1])				
Furnace Ash, %	31.8	6.5	23.0	29.8	38.2
Bomb Ash, %	28.9	10.6	15.6	33.7	38.6
HHV2, KJ/kg	15.393	3.2	6.6	11.2	13.4
HHV3-B, MJ/kg	21.664	1.6	1.5	3.7	4.3
HHV3-F, MJ/kg	22.523	5.1	5.4	3.1	8.0

In this work, the within-bag %CV, which corresponds to the combined measurement and sampling error for gram-size samples, is substantially less for all properties than in the prior variability study [1]. The small value for the HHV2 within-bag %CV and its close agreement with the within-bag values for HHV3-B and HHV3-F indicates that the new sample division procedure has reduced our sampling error for gram-size samples to less than 0.8%. The within-day %CV for HHV2, 2.0%, suggests that the extra error introduced in failing to prepare equivalent kilogram-size samples (C and D) for each day by hand sorting and recombination is somewhat larger in size than the combined measurement and sampling error. (The label "within-day %CV" is the between-bags %CV estimated within days).

The fact that the within-day and within-bag %CV for HHV3-B are about the same while the corresponding values for HHV2 are not indicates that the hand sorting and reconstituting procedure failed to yield equivalent samples for each day primarily because the initial noncombustible contents were different. The lower between-day %CV for HHV3-B (or HHV3-F) as contrasted to that for HHV2 suggests that the primary variability in the MSW stream is in its ash (and initial moisture) content and not the calorific value of its combustible content. The latter was also a conclusion of the first variability study [1].

It should be noted that the total %CV reflects primarily the day-to-day variability and not the variability of the measurement processes being studied here. The latter is characterized by the within-bag and, to a certain extent, the within-day %CV.

It should also be noted that neither the within-day or between-day %CV of this work are strictly comparable to the corresponding parameters of the earlier variability study [1]. The values of the within-day %CV of this work have been deliberately altered by the hand sort and reconstitution procedure. The between-day %CV is for only four of ten days samples of MSW and the four days were not selected at random.

4.2 COMBUSTION FLOW CALORIMETRY

Six determinations of the energy equivalent (i.e. apparent heat capacity) of the flow calorimeter gave a %CV for a single measurement of 0.26%. The average energy equivalent was 4.509 MJ/K with an imprecision(+) of ±0.012 MJ which is 0.27% (0.26% x Student t $/\sqrt{n}$) of the mean.

In the calculation of the flow calorimetry results, we have omitted several minor calorimetric corrections (e.g. for small amounts of CO in the product gas, for small amounts of unburned sample in the ash, etc.). We do not expect the absence of these corrections to affect our results or conclusions in a practically significant manner. For convenience the results of the flow calorimetry will, henceforth, be referred to as flow results.

4.2.1 Flow Calorimetry of RDF-4.

The flow and bomb results on processed MSW (RDF-4) are summarized in Table 5. The columns labeled furnace ash, bomb ash, bomb HHV2, bomb HHV3 are calculated from the averages of the gram-size test measurements on C and D weighted by the amounts of sample from bags C and D which form the contents of bags E and E′.

(+) For this and all other statements labeled "imprecision", we are using the product of the standard deviation of the mean and the appropriate Student t factor at the 95% confidence level.

The analysis of the data in Table 5 is given in Table 6. The first four rows show the average and imprecision of the paired differences for values of flow ash minus furnace ash and flow minus bomb values for ash, HHV2 and HHV3. The day average rather than each of the paired differences of flow minus bomb values for ash, HHV2, and HHV3 were used to evaluate imprecisions as the differences tend to group themselves into within-day sets.

Table 5. Flow and Bomb Calorimetry Results on Processed MSW (RDF-4).

	Ash (Dry Basis), %			HHV2, MJ/kg		HHV3, MJ/kg	
Sample	Furnace(a)	Flow	Bomb(a)	Flow	Bomb(a)	Flow	Bomb(a,b)
E4	33.51	32.78	32.48	14.732	14.723	21.918	21.804
E′4	33.50	32.94	32.47	14.838	14.725	22.126	21.804
E6	37.43	36.17	35.49	14.458	14.612	22.650	22.650
E′6	37.43	36.32	35.49	14.489	14.612	22.752	22.650
E7	26.63	26.23	25.17	16.725	16.821	22.671	22.479
E′7	26.62	26.11	25.17	16.735	16.821	22.648	22.479
E9	17.63	17.20	16.28	18.425	18.272	22.253	21.826
E′9	17.64	17.11	16.28	18.295	18.271	22.070	21.825

(a) Calculated from averages of bomb calorimetry measurements on bags C and D and known mass fractions of C and D used to make up bags E and E′.

(b) HHV3-B

The first two rows of Table 6 show that the average flow ash is 2.7 ± 1.5% greater than the average bomb ash and is 2.5 ± 1.9% smaller than the average furnace ash. These differences are consistent with the relation between the combustion zone temperatures (i.e bomb > flow > furnace). They are also consistent with the observed variation in the amount of furnace ash formed as a function of furnace temperature [5]. The average difference of the flow minus bomb values for HHV2 is -0.1% of the average HHV2 flow value. This difference is not statistically different from zero as the 95% confidence interval is from -1.2 to +1.0%. The average difference of the flow minus bomb values for HHV3 is +0.9% of the average HHV3 flow value. The difference is statistically different from zero as the 95% confidence interval is from +0.1 to +1.7%. However, the interval misses zero by such a small amount that we do not regard the non-overlap to be practically important.

The average difference of the flow minus bomb values for HHV3 can be different from zero even if the HHV2 difference were zero, because, in this work the average difference of the flow minus bomb ash values is +0.8% which is 2.7% of the mean ash value. This causes the HHV3 difference to be +1.1% even if the HHV2 difference were zero. This is approximately what is observed in rows 3 and 4 of Table 8 (e.g. the average difference of the flow minus bomb values for HHV3 is 1.0% larger than the average difference of the flow minus bomb values for HHV2).

The difference of the flow minus bomb values for HHV2 completes the evidence for the conclusion, drawn in the previous section, that the new sample division technique provides representative gram-size test samples. The results of this section show that HHV2 is the same for the kilogram-size parent and the gram-size test samples; the results of the previous section showed that gram-size test samples from the same bag were practically the same.

Table 6. Analysis of Flow and Bomb Calorimetry Results on Processed MSW (RDF-4)

	Property Differences (Dry Basis)	Average	Imprecision(a)
1)	Flow Ash-Bomb Ash, %	+0.76 (+2.7%)(b)	0.41 (1.5%)
2)	Flow Ash-Furnace Ash, %	-0.69 (-2.5%)	0.54 (1.9%)
3)	HHV2 Flow-HHV2 Bomb, MJ/kg	-0.020 (-0.1%)	0.178 (1.1%)
4)	HHV3 Flow-HHV3(c) Bomb, MJ/kg	+0.197 (+0.9%)	0.187 (0.8%)

	Property (Dry basis)	Average	Components of Variability, %CV Measurement Error	 Between Day
5)	Ash, Flow, %	28.11	0.3	30.0
6)	HHV2, Flow, MJ/kg	16.087	0.4	11.3
7)	HHV3, Flow, MJ/kg	22.386	0.5	1.5
8)	Ash, Bomb, %	27.35		
9)	Ash, Furnace, %	28.80		
10)	HHV2, Bomb, MJ/kg	16.107		
11)	HHV3, Bomb, MJ/kg	22.189		

(a) product of Student t for the 95% confidence level and the standard deviation of the average.

(b) percent of flow value

(c) HHV3-B

The measurement errors given in the fifth through seventh rows of Table 6 are obtained from the analysis of the flow ash, HHV2, and HHV3 using paired differences from replicate samples E and E′ for each day. Between-day variability was computed in the usual manner [4]. The precision of a calorimetric measurement on kilogram-size samples of dry, processed MSW (0.4 to 0.5%) and on dry cellulose (0.3%) are comparable in magnitude. Confirmation of the assertion that E and E′ are replicate samples is obtained from the fact that the measurement error from the flow ash is small.

4.2.2 Flow Calorimetry of RDF-2

The flow results on unprocessed MSW (RDF-2) are summarized and compared with those on processed MSW (RDF-4) in Table 7. Results on the unprocessed samples A and then B for each day are given in columns headed "UNPR"; those on the processed samples E and then E′ for each day are given in columns headed "PR". An analysis of the data in Table 7 is given in Table 8. Average values and imprecisions in the differences of the unprocessed minus processed values for ash, HHV2, and HHV3 are given in the first three rows of Table 8. All differences have 95% confidence intervals

Table 7. Flow Calorimetry Results on Unprocessed (UNPR) and Processed (PR) MSW.

	Ash (Dry Basis), %		HHV2, MJ/kg		HHV3, MJ/kg	
Day	UNPR(a)	PR(b)	UNPR(a)	PR(b)	UNPR(a)	PR(b)
4	33.19	32.78	14.370	14.732	21.507	21.918
	34.39	32.94	14.306	14.838	21.806	22.126
6	36.06	36.17	14.432	14.458	22.570	22.650
	39.00	36.32	14.315	14.489	23.466	22.752
7	26.07	26.23	16.976	16.725	22.961	22.671
	24.00	26.11	17.039	16.735	22.418	22.648
9	16.97	17.20	18.350	18.425	22.100	22.253
	18.06	17.11	18.250	18.295	22.272	22.070

(a) results for each day are sample A and then B.

(b) results for each day are sample E and then E′.

Table 8. Analysis of Flow Calorimetry Results on Kilogram-Size Samples of Processed and Unprocessed MSW.

Unprocessed-Processed Property Differences (Dry Basis)	Average	Imprecision(a)
1) Ash, %	+0.36 (+1.3%)(b)	1.70 (6.0%)
2) HHV2, MJ/kg	-0.083 (-0.5%)	0.471 (2.9%)
3) HHV3, MJ/kg	+0.001 (+0.0%)	0.446 (2.0%)

		Components of Variability, %CV	
Unprocessed Property (Dry Basis)	Average	Within Day	Between Day
4) Ash, %	28.47	4.9	31.4
5) HHV2, MJ/kg	16.005	0.3	12.3
6) HHV3, MJ/kg	22.388	1.7	2.3

(a) product of Student t for the 95% confidence level at 3 degrees of freedom and the standard deviation of the average

(b) percent of average

that overlap zero and, thus, are not significantly different from zero (at this confidence level). The average effect of processing kilogram-size samples of RDF-2 to RDF-4 is such as to increase HHV2 by 0.5% and leave HHV3 unchanged. The 95% uncertainty intervals for the HHV2 difference, -3.4 to +2.4%, and the HHV3 difference, -2.0 to +2.0%, are larger than those for the differences of the flow minus bomb values given in Table 6 because hand sorting and reconstituting, as we carried it out, did not produce completely identical bags.

Our hand sorting process was subjective because personnel assisting in this task varied and composite materials (e.g. insulated wire or some types of shoes) were not separated into components prior to being assigned a category. Moreover, finer distinctions that might be significant calorimetrically were not made (e.g. distinction between hard and soft plastics or cotton and artificial fiber textiles). It is interesting to note that the day-averages of the percent ash content listed in Table 5 bear the same relation to each other as the total percent of nominally noncombustible contents listed in Table 2, line 14. However, the percent flow ash is larger in absolute magnitude than the value given in line 14 by 9.1 ± 2.4%. This is consistent with the fact that all components of our nominally combustible category produce some ash.

Within-day and between-day components of variability of the data for unprocessed samples are given in rows four to six of Table 8. Comparing these values with the corresponding bomb values listed in Table 4 shows the within-day %CV for HHV2 and HHV3 are in general agreement.

4.3 SUMMARY OF STATISTICAL RESULTS

(1) Replicate kilogram-size samples (i.e. samples E and E′) of processed RDF (RDF-4) have been prepared for the first time by a new sample division technique.

(2) The differences in the enthalpy of combustion (on a dry basis) of replicate samples E and E′ provided a %CV for a single measurement with the new flow calorimeter on an actual sample of RDF of 0.4%. (See Table 6.)

(3) The new sample division technique provides gram-size test samples, from the same kilogram-size parent sample, that have a %CV for a single measurement of 0.5% for the enthalpy of combustion (on a dry basis). (See Table 4.)

(4) The new sample division technique provided gram-size test samples from kilogram-size samples of RDF-4 which have the same average enthalpy of combustion (on a dry basis) as the kilogram-size parent sample to within 0.1%. The 95% confidence interval for the average difference in the enthalpy of combustion of parent minus gram-size test samples ranges from -1.2 to +1.0%. (See Table 6, line 3.)

(5) Processing of kilogram-size samples of MSW having a sieve size of minus 15 cm (RDF-2) down to a 2 mm sieve size (RDF-4) alters the enthalpy of combustion of the material (on a dry basis) by less than 0.5%. The 95% confidence interval for the average difference of the unprocessed minus processed values is from -3.4 to 2.4%. The main contribution to this

confidence interval is the variability in the supposed identical samples prepared by hand sorting. (See Table 8.)

(6) Kilogram-size samples of dried RDF-2 having the same enthalpy of combustion (on a dry basis) to about 2% can be prepared by matching the relative mass compositions according to the following categories of: metals, textiles, plastics, wood/vegetable matter, paper, glass/ceramics, and "fines" (residual grit and sand). (See Tables 4 and 8.)

5. DISCUSSION AND CONCLUSIONS

As indicated in the introduction, this work was performed as part of the effort to resolve the general question of whether or not the calorific value of a multiton quantity of MSW can be obtained by sampling down to one or two grams and obtain representative test samples. This general question can be divided into two parts. The first is: How should one sample a multiton pile or stream of raw waste to obtain a number of kilogram-size increments of sufficient number and amount to characterize the calorific value with a given precision? The second is: How can one obtain representative gram-size test samples that characterize these increments?

The first question is currently being investigated by ASTM Committee E-38 (+) and is beyond the scope of this paper.

The sample preparation and measurement protocol of this work were designed primarily to answer the second question. We assumed that the sample increment was, or could be, conveniently divided into bags containing between 2 and 2.5 kg of minimally processed MSW (RDF-2). To answer the second question, two problems were studied.

The first problem was the processing problem: Does processing of RDF-2 (MSW of 150 mm or less particle size) down to RDF-4 (MSW of 2 mm or less particle size) alter the calorific value of the waste?

The second problem was the kilogram-to-gram sampling problem: How does one obtain a representative gram-size test sample from a kilogram quantity of RDF-4?

Our results show that processing from 150 mm to 2 mm particle size does not alter the calorific value of the MSW within the uncertainty of our experiments. The average of the unprocessed minus processed difference in the calorific value on a dry basis is -0.5% and on a dry, ash-free basis is 0.0% of the corresponding mean calorific value. The imprecision in these differences are 2.9 and 2.0%, respectively of the corresponding mean calorific value. Most of the imprecision is due to the fact that completely identical pairs of samples were not prepared by our hand sorting and reconstituting of RDF-2. An important qualification is that excessive local heating of the RDF-2 during milling was avoided. In our case, powdered dry ice was added to the sample as is it was fed to a Wiley

---

(+) The subject and principles of the design of a sampling protocol, based on experimental test, are addressed in ASTM Method D 2234-76, Standard Method for the Collection of a Gross Sample of Coal. A variant of this method, as applied to MSW, is under study by the ASTM Committee E-38.

Mill in the final step of processing.

In regards to the kilogram-to-gram sampling problem, our results show that it is possible to obtain gram-size test samples that have the same calorific value as the kilogram parent of RDF-4 if one uses the new sample division technique described in this work. We show that different gram-size test samples taken from a single parent kilogram-size RDF-4 sample have the same calorific value as the parent within the uncertainty of our experiments. The average difference of the parent minus gram-size sample calorific values is -0.1% on a dry basis and +0.9% on a dry, ash-free basis of the corresponding mean calorific value. The imprecisions of the differences are 1.1 and 0.8%, respectively, of the corresponding mean calorific values.

The new sample division technique was successful because it is insensitive to the effects of segregation whereas our earlier coning and quartering method was not. Because the technique employed in this study is time consuming, it is recommended only as a reference procedure. An apparatus with more rapid throughput is needed for routine testing. We definitely do not recommend coning and quartering plus taking of grab samples as a technique for the preparation of gram-size test samples of RDF-4. However, it can be used if a within-bag %CV in the calorific value (on a dry basis) of three or more percent is tolerable.

In summary, this work shows that if 2.5 kg increments are collected to characterize the calorific value of a MSW stream, each increment can be processed (provided that excessive local heating is avoided) and then be sampled using the sample division technique cited here (or any other procedure sufficiently insensitive to segregation) to obtain representative gram-size test samples. Combining(+) the results on the processing to small particle size (see Table 8) and kilogram-to-gram sampling problem (see Table 6), we show that the average difference in the calorific values of the minimally processed (RDF-2) kilogram-size sample minus the processed (RDF-4) gram-size sample is -0.6% on a dry basis and +0.9% on a dry, ash-free basis of the corresponding mean calorific values. The imprecisions in these values are 3.1 and 2.2%, respectively, of the mean calorific values.

(+) Averages of the results on each basis (i.e. dry or dry, ash-free) were obtained by adding; the imprecisions were obtained as the square root of the sum of the squares, i.e.

$$\text{Dry:}\quad (-0.5) + (-0.1) \pm \sqrt{(2.9)^2 + (1.1)^2}\ \%$$

$$\text{Dry, ash free:}\quad (0.0) + (+0.9) \pm \sqrt{(2.0)^2 + (0.8)^2}\ \%$$

6. REFERENCES

[1] Kirklin, D.R., Colbert, J.C., Decker, P.H., Ledford, A.E., Ryan, R.V., and Domalski, E.S., "The variability of municipal solid waste and its relationship to the determination of the calorific value of refuse-derived fuels", Part A of NBSIR 82-2491, U.S. National Bureau of Standards, Washington, D.C. (1982).

[2] Churney, K.L., Domalski, E.S., Ledford, A.E., Colbert, J.C., Bruce, S.S., Buckley, T.J., Paule, R.C., and Reilly, M.L., "Assessing the credibility of the calorific value of municipal solid waste." NBSIR 84-2825, U.S. National Bureau of Standards, Washington, D.C. (1984).

[3] Mandel, J., and Paule, R.C., "Statistical analysis of sampling and measurement errors in the characterization of refuse-derived fuel", Proceedings of the Second International Conference on Materials and Energy from Refuse, Antwerp, Belgium, p6.25 (1981).

[4] Mandel. J., and Paule, R.C., "Interlaboratory evaluation of a material with unequal numbers of replicates", Analytical Chemistry, 42:1194 (1970) and Correction, Analytical Chemistry, 43:1287 (1971).

[5] Kirklin, D.R., Domalski, E.S., Kelly, R.V., and Robbins, C.R., "Ash content and X-ray analysis of selected RDF and coal samples as a function of temperature", Resources and Conservation, 9:243 (1982)

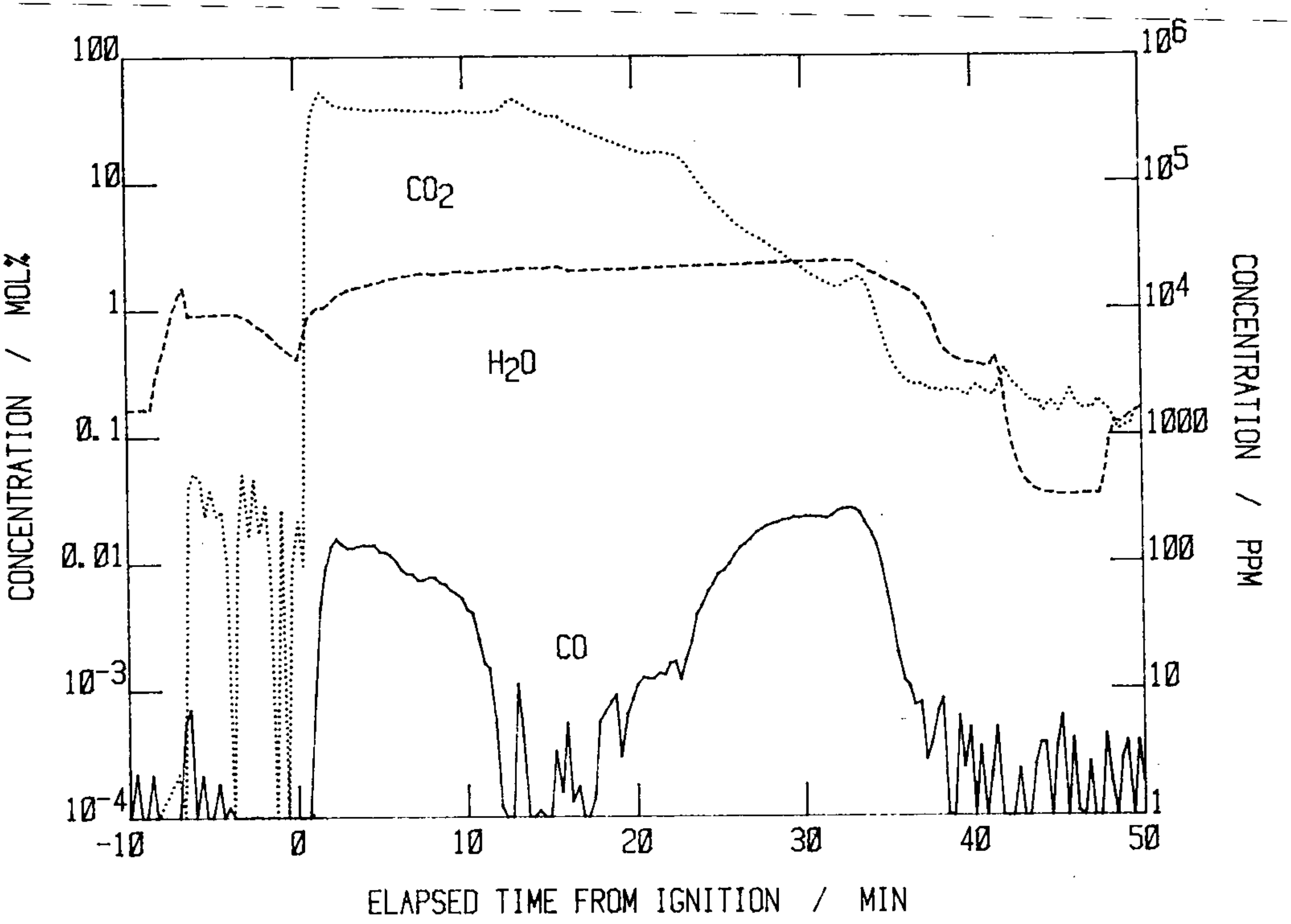


Figure 1. A plot of the concentrations of gaseous carbon dioxide, water, and carbon monoxide as a function of time for a typical experiment on RDF.

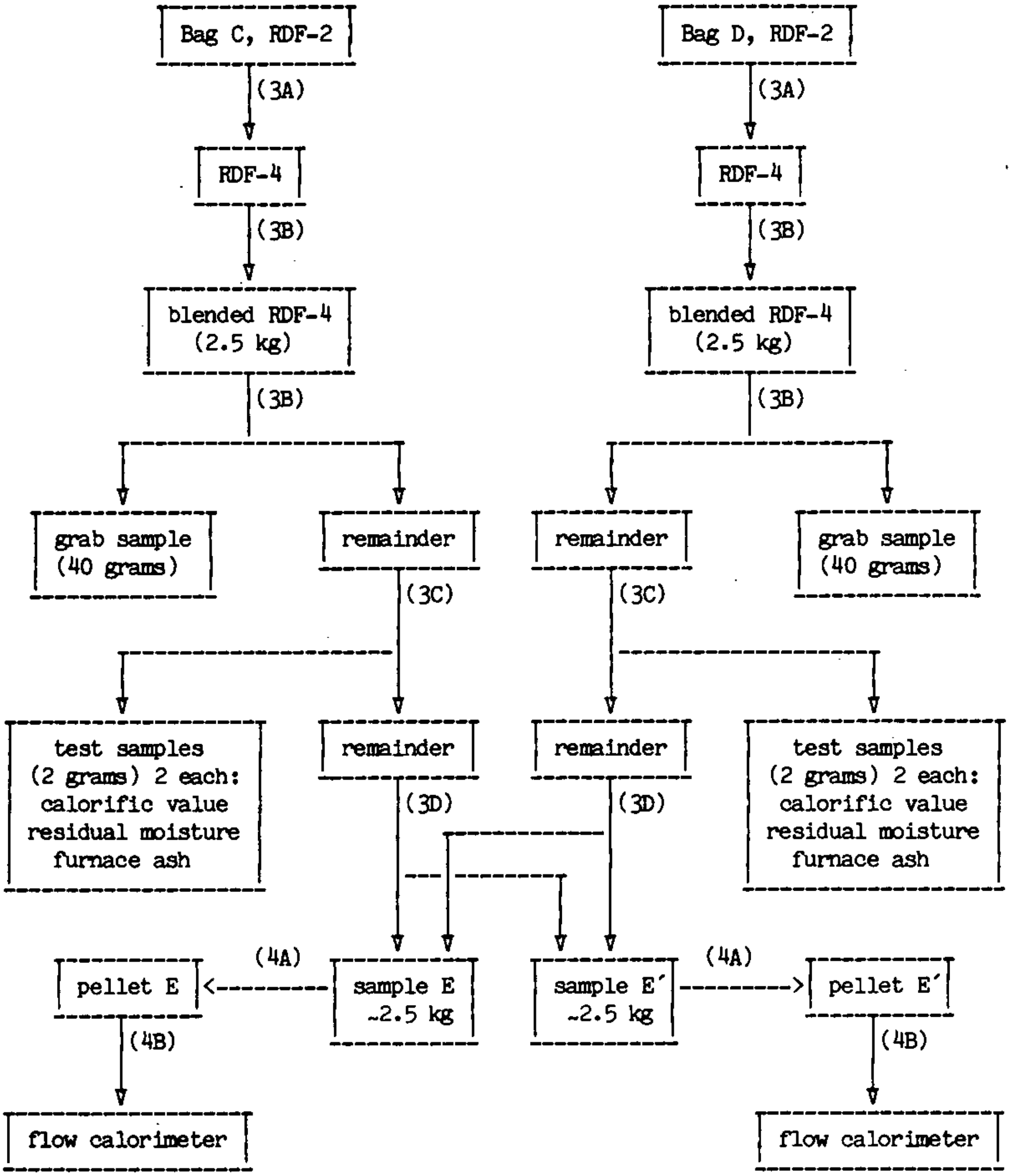


Figure 2. Diagram of the sample division technique used to prepare gram-size test samples (C and D) for the bomb calorimeter studies and kilogram-size samples (E and E′) for the flow calorimeter studies from 2.5 kilogram hand sorted and reconstituted samples in bags C and D. The steps given in Table 2 are indicated in the parentheses along the arrows.

HAZARDOUS WASTE ASPECTS OF MSW COMBUSTION

Wing Tsang
Research Chemist
National Bureau of Standards
Chemical Kinetics Division
Washington, DC 20234

This paper is concerned with organic emissions from MSW combustors. We will begin with a brief survey of the basic principles that govern the high temperature oxidative destruction of organic compounds. This will be followed by a survey of the existing data concerning organic emissions from such devices. Serious problems with respect to measurement methodology and inadequacies in the nature of the information base will be discussed. We will then consider the problem of dioxin emissions. Mechanisms for its formation and destruction will be described and the important controlling factors as well as major uncertainties indicated. We conclude by suggesting the type of laboratory measurements which can solve the many unanswered questions and the measurement strategies which may provide evidence for proper operation of MSW combustors.

INTRODUCTION

Over the past several years there have been numerous reports on the presence of dioxins and related compounds in emissions from municipal solid waste combustors (1). These have proved to be a major impediment to the use of municipal waste as a fuel in energy recovery units. In this report we outline the present state of knowledge on how organic compounds are formed or destroyed in an incinerator. We will relate the general principles to the operating variables that characterize the performance of such units. This will then be applied to the problem of dioxin emissions. The present data base of direct measurements and laboratory studies on this problem will be summarized. Various possible mechanisms for formation and destruction of dioxins will be presented. Directions for future studies will be indicated.

The present approach is a general one and the concepts can be applied to the whole range of possible hazardous organic emissions. As will be developed subsequently, although there are widespread reports of dioxin detection, there remain very important questions with regard to the meaning of such observations. In particular, studies relating dioxin levels to incinerator operating variables are only beginning to appear (2). Thus the data base for a satisfactory empirical solution does not exist. At a more fundamental level, however, work during the past twenty years in combustion kinetics has yielded a large body of information of how molecules are formed and destroyed under incinerator conditions (3). In view of the high costs of any program of physical testing, the use of the available information may provide insights that can lead to a shortening of the learning process and perhaps contribute to the strategy for physical testing.

COMBUSTION FUNDAMENTALS

Proper combustion in any practical device is controlled by chemical and physical kinetic factors. This has been demonstrated in an earlier report (3) where we have shown that under the usual range of incinerator conditions there are no thermodynamic barriers to the destruction of organic compounds. The consequence of this is the necessity of understanding the details of the combustion process. In the following we consider each of these facts.

(a) Chemical Kinetics: The detailed mechanism for the destruction of organic chemicals in an incinerator is extremely complex. In general terms, it involves the step-wise breakdown of the larger organic species to smaller fragments. In the course of this breakdown the organics become increasingly unsaturated. As a result, unless there is sufficient oxygen present to continue oxidation, the unsaturated substances will tend to polymerize leading ultimately to carbon. Thus, combustion can be considered to be a race between the two tendencies. For the present purposes, the step-wise breakdown and building-up offers numerous possibilities for the generation of hazardous organics. Fortunately, it is possible to effect considerable simplification by focussing on destruction mechanisms in terms of the rates of elementary processes that destroy stable and unstable organic compounds (3). As will be demonstrated subsequently, the latter probably represents an important element in the prediction of the products of incomplete combustion. The former is directly applicable to hazardous chemicals already present in the system.

In a previous communication (3) we have discussed the chemical factors involved in the incineration of hazardous wastes. Summarizing briefly, the chemical processes principally responsible for destruction are unimolecular decomposition and radical attack. The former is brought about by increasing the internal energy (temperature) of a molecule to such an extent that it exceeds the energy threshold necessary for decomposition. The latter involves a radical adding to, or abstracting an atom from, the compound of interest and thus changing the nature of the molecular entity. In more quantitative terms the differential equation for the destruction of any hazardous waste can be written as

$$-\frac{d(Hz)}{dt} = k_u(Hz) + \sum_i k_{bi}(Ri)(Hz)$$

where k_u and k_{bi} are unimolecular and bimolecular rate constants, for reactions given below. It should be emphasized that these are rate constants for elementary single step processes.

$$Hz \xrightarrow{k_u} \text{products}$$

$$Ri + Hz \xrightarrow{k_{bi}} \text{products}$$

Here Ri refers to a particular radical. It is necessary to draw a distinction between rate constants for these reactions and "global" rate constants. The latter represent the direct input necessary for the optimization of a particular system, but are extremely difficult to use in other contexts.

The former, inasmuch as they are direct reflections of the physical phenomena are applicable in all situations. To fully describe a system, however, a large number of such rate constants are required. Fortunately, many measurements on such rate constants exist and there are methods for making estimates. With some approximation one can make semi-quantitative predictions.

Consider the situation with respect to dioxin in a well mixed isothermal reactor under near stochiometric conditions when the prime mode of radical attack will be by OH-radicals. The rate expressions can be estimated (4) as $k_b(OH + dioxin) \simeq 3 \times 10^{11}$ cc/mol-s and for unimolecular decomposition $k_u(dioxin) = 10^{15.5} \exp(-90000/RT)$/sec. With an OH concentration that is near the equilibrium value one finds 4-nines destruction can be achieved with 1 sec residence time at 1194 K. Similarly for hexachlorobenzene we find $k_u(C_6Cl_6) = 10^{16} \exp(-92000/RT)$ and $k(OH + C_6Cl_6) \sim 10^{11}$ cc/mol-sec leading to 4-nines destruction at 1323 K and 1 sec residence time. Although these numbers are rough estimates, they are not unreasonable. Also, for a series of compounds, it permits a rank ordering with respect to "incinerability". Thus, in the context of a "chemical" model, destruction of one chemical implies the destruction of a second compound in the mixture. On this basis, the important role of the rate constants in determining the resistance to chemical stress of any organic compound is clear. This can be demonstrated in even more graphic detail as follows. Assume that the substance of interest is being destroyed unimolecularly or pseudo-unimolecularly. Then the differential equation given above can be directly integrated. The result is,

$$\ln \frac{Ci}{Cf} = [k]t$$

where Ci and Cf are the initial and final concentrations respectively, k the rate constant, and t the heating time. Consider now the situation when we are concerned with two compounds (primed and unprimed), then on the basis of number of nines destruction efficiency we find (5)

$$(\# \text{ of nines})'/(\# \text{ of nines}) = k'/k$$

Destruction efficiencies are directly related to rate constants. A small difference in rate constants can have large consequences on destruction efficiency. For example, if one associates a destruction efficiency of 3-nines with a particular rate constant, then a compound with a rate constant for destruction that is a factor of 2 higher will in the context of this chemical model suffer 6-nines destruction. Strictly speaking, the above formalism is applicable only to hazardous compounds that are initially present in the waste. However, by suitable adjustment of the residence time, products of incomplete combustion can be brought into the framework. On the other hand, in view of the uncertainty regarding when such products are formed and the nature of the functional dependence discussed earlier, quantitative predictions become increasingly uncertain as more and more assumptions are involved.

We next consider mechanisms for the formation of hazardous chemicals. For this purpose it is most convenient to consider two categories of substances. The first are direct reaction products. These are the intermediates in the breakdown of complex organic compounds. Predictions are easy once the starting materials are known; for example, DDE from DDT, or in a grosser sense, HCl from PVC. A more difficult problem is the substances that are formed from reactions of unstable intermediates. However, some degree of ordering can be effected by considering the stability of the intermediates. For example, compounds derived from alkyl radicals are less likely to be formed than those derived from resonance stabilized species such as allyl, phenyl, benzyl, and phenoxy, since the instability (via unimolecular decomposition) of the former will lead to destruction prior to any subsequent reaction. On the other hand the stability of the latter leads to longer lifetimes, larger steady state compositions and thus greater opportunities for reaction. Phenoxy type radicals are particularly interesting, since dimerization will yield a dioxin type structure. Similarly, the stability of aromatic type radicals is probably responsible for soot and carbon particle formation.

(b) Physical Kinetics: The above treatment is based on the average properties of an incinerator, i.e. fixed residence time, composition and temperature. Serious errors are introduced in the averaging process. The temperatures in an incinerator range from ambient to that at the flame front. The environment varies from pyrolytic, immediately upon introduction of the waste, to highly oxidative in the post-flame region. This leads to the possibility that pockets of wastes may in fact experience different environments and residence times. The consequence is that different chemistries will be applicable. This is in essence the result of physical effects. For example under pyrolytic conditions, unimolecular decomposition and H-atom or organic radical attack will be the predominant modes of destruction. Since the latter are usually slower than OH-attack, a higher temperature will be required in order to effect the same degree of destruction. It is also possible that chemistry will no longer be the controlling factor. Consider the situation of a hazardous organic held within a particulate due to its low volatility. If the particulate is of a certain size, the hazardous substance may never experience the high temperatures characteristic of the incinerator environment. Alternatively, if the main destruction mode in an incinerator occurs at the high temperatures in the flame front, then high volatility organics in liquid or solid particles (6) may be preferentially desorbed and spend much less time in the reaction zone than the burning particle itself.

On the basis of the above, it is clear that physical properties relating to volatility such as the boiling point may well play an important role. Unfortunately, we have constructed scenarios which suggest that both light and heavy ends may escape destruction. In addition, it is clear that the mixing problem is dependent on the type of incinerator and mode of operation. One comes to the conclusion that it is highly unlikely that operational criteria such as average temperature, or residence time, or feed rates, etc., can guarantee destruction of hazardous chemicals that are formed during incineration. Validation of incinerator operation must depend on direct measurements on the incinerator. This does not mean that in the case of dioxin, for example, direct measurements must be made at all times. Indeed, as indicated above, there is considerable understanding of the various processes occurring within an incinerator. The real difficulty lies in assessing their relative importance. For this purpose the relative distribution of products may provide key insights. Basically, they represent testimony as to what has happened during incineration. This then leads to the question of the species that should be examined. Some suggestions in this direction will be described subsequently.

EXPERIMENTAL MEASUREMENTS

Junk and Ford (7) have recently reviewed the existing literature on organic emissions from combustion processes. Over two hundred organic compounds have been observed as effluents from waste incineration. Unfortunately, as noted by Junk and Ford (7), the general approach has been to "characterize sources according to the presence of pre-selected compounds such as PAH, priority pollutants and other components or classes of compounds. Such approaches generate numbers for interpretation and they yield some immediate results, but they are an oversimplifcation of a complex problem which requires more fundamental and extensive research". Furthermore they claim that "Current sampling procedures have proven inadequate for solving problems related to organic material in the vapor phase versus material sorbed on particulate matter, to organic component content versus particle size and particle composition, and to the possible chemical transformations within and outside the stack." Thus the quantitative significance of what has been observed must be regarded as highly uncertain. Nevertheless there are a number of observations which are of significance. For example, Ahling and coworkers report (8) extensive quantities of acids and aldehydes in emissions from MSW incinerators. This strongly suggests that under the conditions sampled by these molecules very little of the more thermally stable dioxin would be destroyed. If this is the case in general, then efforts on minimization of dioxin emissions should be directed towards prevention of their formation. The above is typical of the inferences that can be drawn from an analysis of emission products of incinerators. Indeed, given a complete and careful analysis of a number of selected compounds, it should be possible to give a complete scenario of what is happening.

Within the context of hazardous waste incineration a body of data is being accumulated (6,9,10). As expected, under sufficiently stressful conditions hazardous organic wastes can be totally destroyed. However, these conditions appear to be far more extreme than those usually encountered in a municipal solid waste incinerator. On the other hand, as mentioned earlier, temperature and residence time represent extremely uncertain properties. Indeed, if the recommended operational variables are for an isothermal well-mixed reactor, then the requirements are probably far in excess of what is needed. Data from laboratory experiments on hazardous waste destruction are now beginning to appear. They illustrate very well the range of possibilities that can exist. In one type of experiment premixed liquid droplets containing organics are rapidly passed through a high temperature flame. Under these condition physical effects appear to predominate. The chemistry can be considered to be infinitely fast and it would appear that high volatility materials are preferentially ejected from the droplet and thus are less easily destroyed than components which stay in the mixture and are then burned. A different type of experiment involved decomposing traces of a hazardous chemical in a hot air mixture. Through studies with a number of such compounds a relative ranking of "incinerability" can be established. The results are in fairly good accord with predictions based on chemistry as the predominant factor in incineration. However, the data must be regarded with caution since experiments are carried out in narrow quartz tubing and one expects that surface processes will be the predominant means for decomposition. This may not correspond to the situation in the post-flame region of an incinerator. On the other hand, the results suggest that decomposition on glass surfaces has rates that parallel the gas phase situation. The above is suggestive of the problems of carrying out laboratory studies in this area. The complexities of the phenomena are such that unless one designs the experiment to test one effect at a time results are frequently ambiguous. Unlike direct tests on a real system, laboratory results must be extrapolatable.

Much of the more recent emission measurements on incinerators has focussed on dioxins. The existing data have been summarized in numerous reviews (11,12). For the present purposes we will mention only a few salient points. The concentrations of dioxins are very low and extremely variable, ranging from less than 1 ppb (gram basis) (13,8) to hundreds of ppb (1). These variations are most pronounced in measurements of different incinerators. Nevertheless, even with the same incinerator replicate measurements can show variations of an order of magnitude or more (14). It is clear that the comments of Junk and Ford (7) on the measurements of organics in combustion emissions are applicable to dioxins. It is of course possible that the variations may be to some extent a manifestation of the extreme heterogeneity of municipal solid waste magnified by dioxins being formed by a high-order process. In the absence of validated procedures for sampling, the absolute magnitudes that are reported must be treated with caution. Relative concentrations of the dioxins and chlorinated aromatics are probably more reliable. On this basis it is clear that most if not all the dioxin isomers are formed during combustion (1). In addition, chlorinated dibenzofurans, chlorinated phenols and chlorinated benzenes (13,8) are usually detected with the dioxins. Single-ring aromatics are also present in significantly larger quantities and this has led to the surmise that they may be the precursors to the dioxins. It is clear that the product distribution offers a critical test for any proposed quantitative mechanism. On the other hand, direct addition of hexachlorobenzene and pentachlorophenol into waste mixtures does not appear to result in measurable changes in dioxin yields (15). Indeed, it has proved to be difficult to correlate dioxin yields with any other property of the incineration system. Such experiments are crucial to validating mechanisms and abatement strategies. They must however be carried out with great care and thought. Particular attention should be paid to the sensitivity of dioxin yields to the parameter to be varied. In view of the uncertainty in the measurements of dioxin concentrations in incinerators and the high costs of carrying out tests, large scale tests of this sort may well be premature.

The standard method for preparing dioxin in the laboratory involves pyrolysis of alkali metal polychlorophenoxide and the condensation of polychlorocatechol and polychloronitrobenzene (16). Temperature conditions approximating that used in the preparative process (250°C) are encountered in incinceration systems during the early pyrolytic phase of the destruction process. It is thus not surprising that in small-scale laboratory experiments that seek to simulate incinerator situations dioxins can be formed. Thus, dioxins have been found in laboratory experiments involving the combustion of a 2,4,5-T formulation (17), in the combustion and pyrolysis of chlorophenates (18), and from the combustion of chlorobenzenes (19). Unfortunately, all the available laboratory experiments were carried out with the aim of demonstrating that dioxin can be formed. Quantitative kinetic information was not obtained. Thus although the observations are very important, it is clear that much more careful laboratory data are needed if one seeks to build a quantitative kinetic model for dioxin formation in incinerators. Such a model is absolutely essential for the optimal control of dioxins.

The lack of quantitative laboratory data on dioxin formation makes it impossible to define the mode of its formation in an incinerator. From the most general point of view there are three possibilities. First, purely in the gas phase (20), through appropriate precursors such as the chlorophenols. We have demonstrated that in a well-mixed situation, gas phase formation is extremely unlikely since the likely precursors are in such trace quantities that the standard 1-2 second residence time is insufficient for the formation of dioxins in the quantities observed. A second possibility is formation through surface-catalyzed reactions on fly ash (21). This is a less remote possibility than gas phase formation in the sense that the required rate constants are reasonable. Finally, there is formation on the grate. The conditions encountered here may approximate some of the laboratory situations where dioxins are formed. Unfortunately the lack of rate information from these experiments makes it impossible to make firm conclusions. A particularly attractive feature of reactions on the grate is that with these solid state reactions, the heterogeneity of the mixture will be preserved. There may well be pockets of high concentrations of dioxin precursors thus facilitating its formation. Furthermore, ionic mechanisms, not possible in the gas phase, may be operative. In contrast, as noted earlier, the mechanism for dioxin destruction is probably well understood. There is thus undoubtedly a "window" in terms of temperature where dioxin formation is optimized. The task of future research must be to locate this "window".

DIRECTIONS FOR FUTURE WORK

We have outlined briefly the present state of knowledge with respect to dioxin formation and destruction in incinerators. It is clear that we are still lacking detailed quantitative information on many aspects of this problem. From the earlier discussion it is possible to divide problem areas into that which is associated with field testing, experiments in the laboratory or pilot level, and finally the bringing together of all the information in terms of monitoring protocols so as to validate the satisfactory performance of an incinerator.

With respect to field tests it is clear that there are large uncertainties in the sampling for dioxins. There is a great need for standardized and validated procedures (11). This will ultimately mean the certification of laboratories through performance tests on a standard pilot facility. Other important questions to be answered are the proper methodology for obtaining statistically valid samples and a better measure of the nature of the input stream. We do not believe that it has been absolutely established that dioxins are not initially present in the input stream. With regard to subscale experiments, they must be carefully conceived and carried out to answer specific quantitative questions regarding mechanisms and rates of dioxin formation and destruction. The general procedure must be that of standard bench or pilot scale kinetic experiments in seeking to isolate first a mechanism and then quantifying the results so as to permit extrapolation to full scale systems. This means working with well-defined materials and complete control of the experimental configuration. There is no longer any need for the qualitative experiments that report the presence of uncertain amounts of dioxins under ill-defined conditions.

The final question to be considered is the use of the information after it has been developed. In view of the complexity, cost, and nature of dioxin analysis we doubt that continuous or even high frequency periodic monitoring will ever be possible. Furthermore since input streams may vary, and there may be operational problems, there must be some method which will give the public some assurance that the incinerator is behaving properly in between direct testing. The simplest such procedure will be a temperature measurement. However, since the temperature in an incinerator is ill-defined, the results may be highly ambiguous. What is probably needed is many temperature measurements within the incinerator and a physical model linking these measurements with the operation of the incinerator. This will require extensive modeling and is probably at the frontier of the technology. Note that the need is for a general model since proper positioning of the thermocouples will depend on the configuration of the incinerator. We have suggested an alternative possibility (5). This involves monitoring the effluents from the incinerator and deducing from their nature and quantities whether significant quantities of hazardous organics can be destroyed or even be formed. Two types of tracers have been suggested, external or internal. The former as suggested by the name involves adding trace quantities of a tracer such as SF_6 whose destruction would imply destruction of dioxin-like compounds. Alternatively a compound such as CO, created during the incineration process, and the key intermediate during the oxidative degradation of practically all organic compounds, may serve a similar role. The basic advantage of a tracer is that a representative sample will contain molecules that have encountered all the possible environments in the incinerator. Thus from an understanding of the chemistry of the process, the conditions in the incinerator can be inferred. Of course obtaining representative samples is an important problem. However, unlike placing thermocouples throughout an incinerator, the need for effluent measurement is to completely sample one particular plane of the exit stack. Other internal standards are also possible. These include total hydrocarbon or carbon on fly ash. The former is more difficult to conceptualize since it involves a whole group of organic molecules. However, we suspect that an analysis of the distribution of lower molecular weight products may prove to be extremely useful. In all cases, however, considerable work is necessary in order to validate these conceptual models.

SUMMARY

From fundamental studies and gradually accumulating direct measurements an understanding of the physico-chemical processes in an incinerator is being developed. Such an understanding can help dictate the methodologies necessary to assure the public that an incinerator is being operated properly. There is a great need for careful laboratory and pilot scale work to develop the quantitative basis for proper measurement strategies. At the same time the quality of field measurements must be upgraded. If this can be achieved, a number of alternative strategies for monitoring incinerator effluents are possible. They can serve as substitutes for direct dioxin analysis.

REFERENCES

1. K. Olie, J. W. A. Lustenhouwer and O. Hutzinger, "Polychlorinated Dibenzo-p-Dioxins and Related Compounds in Incinerator Effluents in Chlorinated Dioxins and Related Compounds" (O. Hutzinger, R. W. Frei, E. Merian and F. Pocchiari, ed.) Pergamon Press, New York, 1982 pg. 227.

2. K. Olie, M. van den Berg and O. Hutzinger, Chemosphere, 12, 1983, 627.

3. W. Tsang and W. Shaub, "Chemical Processes in the Incineration of Hazardous Materials" in "Hazardous Waste Detoxification" (J. Exner, ed.), Ann Arbor Press, Ann Arbor, Michigan, 1982, pg. 61.

4. W. Tsang and W. Shaub, "Environmental Consequences Arising from the Combustion of Municipal Solid Wastes", in "Resource Recovery From Solid Wastes" (S. Sengupta and K. V. Wong, ed.), Pergamon, New York, 1982, pg. 219.

5. W. Tsang and W. Shaub, "Tracers for Quality Assurance in Municipal Solid Waste Combustion", Presented at the "Research Review on the Characterization of Municipal Solid Waste", National Bureau of Standards, Washington, DC, September 13, 1983, to be published.

6. S. Hanson, J. M. Beér and A. F. Sarofim, "Non Equilibrium Distillation Effect in Vaporizing Droplet Streams" in "Combustion of Synthetic Fuels" (W. Bartok, ed), ACS Symposium Series 217, American Chemical Society, Washington, DC 1983 pg. 95.
   J. C. Kramlich, M. P. Heap, J. H. Pohl, E. Poncelet, G. S. Samuelson and W. R. Seeker, "Laboratory Scale Flame-mode Hazardous Waste Thermal Destruction Research" Draft Final Report, Industrial Environmental Research Laboratory, 5995 Center Hill Road, Cincinnati, Ohio, 45224.

7. G. A. Junk and C. S. Ford, Chemosphere, 9, 1980, 187.

8. B. Ahling and A. Linskog, "Emission of Chlorinated Organic Substances from Combustion" in "Chlorinated Dioxins and Related Compounds, Impact on the Environment" (O. Hutzinger, R. W. Frei, E. Merian and F. Pocchiari, ed.), Pergamon Press, New York, 1982 pg. 215.

9. D. S. Duvall and W. A. Rubey, Laboratory Evaluation of High Temperature Destruction of Polychlorinated Biphenyls and Related Compounds, EPA-660/2-77-228 December, 1977, Municipal Environmental Research Laboratory, Office of Research and Development, US EPA, Cincinnati, Ohio, 45268.

10. J. F. Clausen, H. J. Fisher, R. J. Johnson, E. L. Moon, C. C. Shih, R. F. Tobias and C. A. Lee, "At Sea Incineration of Organochlorine Wastes Onboard the M/T Vulcanus", EPA-600/2-77-196, September, 1977, U. S. Environmental Protection Agency, Office of Research and Development, Washington, DC 20460.

11. Research Committee on Industrial and Municipal Wastes; The American Society of Mechanical Engineers; "Study on State of the Art of Dioxin From Combustion Sources", American Society of Mechanical Engineers, United Engineering Centers, 345 East 47th Street, New York, NY 10017.

12. O. Hutzinger, R. W. Frei, E. Morian and F. Pocchiari, "Chlorinated Dioxins and Related Compounds; Impact on the Environment", Pergamon Press, New York, 1982.

13. T. O. Tiernan, M. L. Taylor, J. H. Garret, G. F. Van Ness, J. G. Solch D. A. Deis and D. J. Wagel, Chemosphere, 12, 595, 1983.

14. F. Gizzi, R. Reginoto, E. Benfenati, and R. Fanelli, Chemosphere, 11, 577, 1982.

15. K. Olie, M. v. d. Berg and O. Hutzinger, Chemosphere, 12, 627, 1982.

16. A. J. Dobbs, J. Jappy and A. E. Wadham, Chemosphere, 12, 411, 1983.

17. B. Ahling, A. Lindskog, B. Jansson and G. Sundstrom, Chemosphere, 8 461, 1977.

18. C. Rappe, S. Marklund, H. R. Buser, H. P. Bosshardt, Chemosphere, 3, 219, 1978.

19. H. R. Buser, Chemosphere, 8, 445, 1979.

20. W. Shaub and W. Tsang, Environmental Science and Technology, in press.

21. W. Shaub and W. Tsang, "Hazardous Waste Aspects of Municipal Solid Waste Incineration", Presented at the Research Review in the Characterization of Municipal Solid Waste, National Bureau of Standards, Washington, DC 20234, September 13, 1983.

MASS FIRED ROTARY COMBUSTOR
AN INNOVATIVE COMBUSTION SYSTEM

Glenn A. Swinehart, Jr.
Manager of Marketing
O'Connor Combustor Corporation
Nashville, Tennessee

ABSTRACT

The patented O'Connor Water Wall Rotary Combustor combines the technology of the rotary kiln type furnaces which have been used for thirty years with the technology of water wall membrane type furnaces which are common in utility boilers. The unit is basically a rotary kiln with a membrane type water wall instead of the common refractory wall. The technology was conceived to offer long life under continuous duty while reducing maintenance, increasing thermal efficiency and increasing on line time.

INTRODUCTION

The Water Wall Rotary Combustor was conceived, designed and developed by Chadwell O'Connor, President of O'Connor Combustor Corporation and O'Connor Engineering Laboratories.

Thirty years of experience designing, building and operating municipal utility power plants as well as a municipal incinerator convinced Mr. O'Connor that there must be a better way to burn municipal waste than the traditional methods. He classified each of the major problems with existing technology with the idea in mind of designing a new approach which would eliminate or minimize these problems.

Today there are five mass burning plants in Japan, Thailand and the United States utilizing the O'Connor Rotary Combustor technology. Over 150,000 operating hours have been logged and the rotary combustor has proven to be all that was expected and more.

NEED FOR NEW TECHNOLOGY

PROBLEMS WITH SOLID WASTE/MASS BURN SYSTEMS

Historically, problems with mass fired incinerator systems have included the following:

1. High maintenance cost and considerable down time associated with refractory and fire brick.

2. Wear and burnout of reciprocating grates as well as high maintenance cost associated with the many moving parts and mechanisms required to move the grates.

3. Poor air to waste mixing resulting in poor combustion efficiency and requirement for high excess air.

4. Inability to burn waste with high moisture content without the use of auxiliary fuel.

5. Short life of boiler and superheater tubes due to metal wastage and corrosion caused by cyclic reducing/oxidizing products of combustion.

DEVELOPMENT OF THE ROTARY COMBUSTOR

ADDRESS TRADITIONAL PROBLEMS

The Rotary Combustor was conceived with the goal of eliminating or minimizing the traditional problems associated with mass burning incinerators while utilizing the principals and standards common in the utility boiler plant industry. See Figure No. 1.

NO REFRACTORY

The need for refractory was eliminated. It was decided early in the conceptual design phase that all required cooling would be accomplished using the water wall principal which is standard in the boiler industry. The water for cooling is an integral part of the boiler water circulation systems to maintain even temperatures and eliminate the need for a separate water circulating and cooling system.

NO MOVING GRATES

There are no moving grates associated with the design of the Rotary Combustor. Material is moved through the combustor by the rotating cylinder combined with a slight (6°) incline. Residence time of the waste material is controlled by varying the RPM of the cylinder.

Solid waste is fed into the elevated end of the cylinder by a hydraulically actuated ram system. The waste is tumbled and incinerated as it moves through the water wall cylinder. The lower end discharges into an integral water wall furnace and boiler section.

A closed-circuit forced circulation system circulates water from the bottom drum of the boiler, through the rotary combustor and to the boiler steam drum. Approximately 25% to 30% of the total system steam production is generated in the rotary combustor cylinder.

AIR-TO-WASTE MIXING

The Rotary Combustor walls are fabricated of steel boiler tubes connected by a steel place (or fin) to form a membrane wall. Air holes are provided in the plate between the tubes. A force draft fan circulates combustion air through an air preheater which uses otherwise wasted flue gas heat to preheat the combustion air to approximately 450° F. The preheated air is supplied to the windbox under the combustor cylinder where it is directed through the previously mentioned air holes and mixes with the solid waste. In this manner, air is intimately mixed with the tumbling waste and the need for high excess air is minimized. The Rotary Combustor system operates at 50% excess air average. See Figure 2.

This system of preheating and mixing of air and waste also allows the combustor to efficiently burn wastes containing high moisture content. Waste with moisture as high as 65% has been burned in this technology without the use of auxiliary fuel.

PREVENT METAL WASTAGE AND CORROSION

The intimate fuel-air mixing combined with very turbulent cyclone type burning results in a constant oxidizing atmosphere which is very "friendly" to the steel in the combustor/boiler system. Also, the system is designed to maintain tube and other steel surfaces above 350° F. and below 600° F. to minimize low temperature and high temperature corrosion.

With five plants (8 rotary combustor units) in operation, there have been no tube railures and no visual or measurable metal wastage or corrosion of the combustor or boiler tubes. Ultrasonic testing has been performed annually at three of the plants to monitor potential metal wastage. The current tests yield the same results as the initial tests.

HIGH THERMAL EFFICIENCY

Efficient combustion combined with relatively low excess air results in an overall system thermal efficiency which is unequalled in mass burning technology. Typical performance data is shown in the results of tests performed by the Tennessee Valley Authority on two Rotary Combustor systems in Sumner County, Tennessee. See Table 1.

CURRENT OPERATING FACILITIES

The O'Connor Water Wall Rotary Combustor/Boiler technology is currently utilized in six plants. Five of the six facilities were supplied with the rotary combustor system by IHI of Japan operating under a license agreement with the O'Connor Combustor Corporation.

Siam Kraft Paper Company, Ltd.

Location: Ban Pong, Thailand
No. Units: 2
Capacity per Unit: 132 tons per day
Waste: Bagasse and Industrial Refuse
Steam: 164 psig sat.
Year Completed: 1977

Kambara Tank Cleaning Service Company, Ltd

Location: Fukuyama, Japan
No. Units: 1
Capacity per Unit: 132 tons per day
Waste: Oil Sludge and Industrial Refuse
Steam: 228 psig sat.
Year Completed: 1977

IHI Yokohama Works

Location: Yokohama, Japan
No. Units: 1
Capacity per Unit: 55 tons per day
Waste: Municipal Solid Waste
Year Completed: 1978

Kure City

Location: Kure City, Japan
No. Units: 2
Capacity per Unit: 165 tons per day
Waste: Municipal Solid Waste
Steam: 228 psig
Year Completed: 1980

Resource Authority in Sumner County, Tennessee

Location: Sumner County, Tennessee
No. Units: 2
Capacity per Unit: 100 tons per day
Waste: Municipal Solid Waste
Steam: 425 psig, 504° F. (superheated)
Year Completed: 1982

ADVANTAGES OF THE ROTARY COMBUSTOR SYSTEM

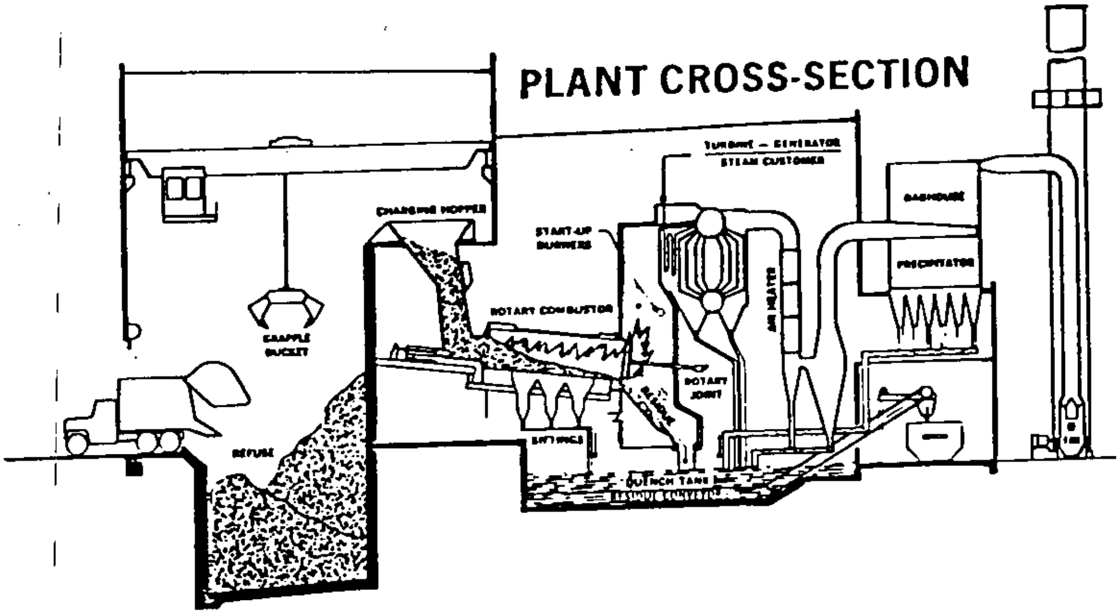
As previously indicated the development of the Water Wall Rotary Combustor was aimed at reducing or eliminating the problems normally associated with mass burning systems. This technology has successfully proven to offer the following advantages:

- High thermal efficiency for energy recovery.
- Ability to efficiently burn waste with high moisture content.
- Low corrosion/metal wastage--none experienced to date after 150,000 hours of operating time.
- High level of reliability--very few moving parts combined with utility plant type construction has resulted in 95% plus reliability.
- Low maintenance cost--in two years of operation at the Sumner County, Tennessee facility (2-100 tons per day units) the total maintenance cost associated with the Rotary Combustor/Boiler systems has been less than $12,000 total for two years.

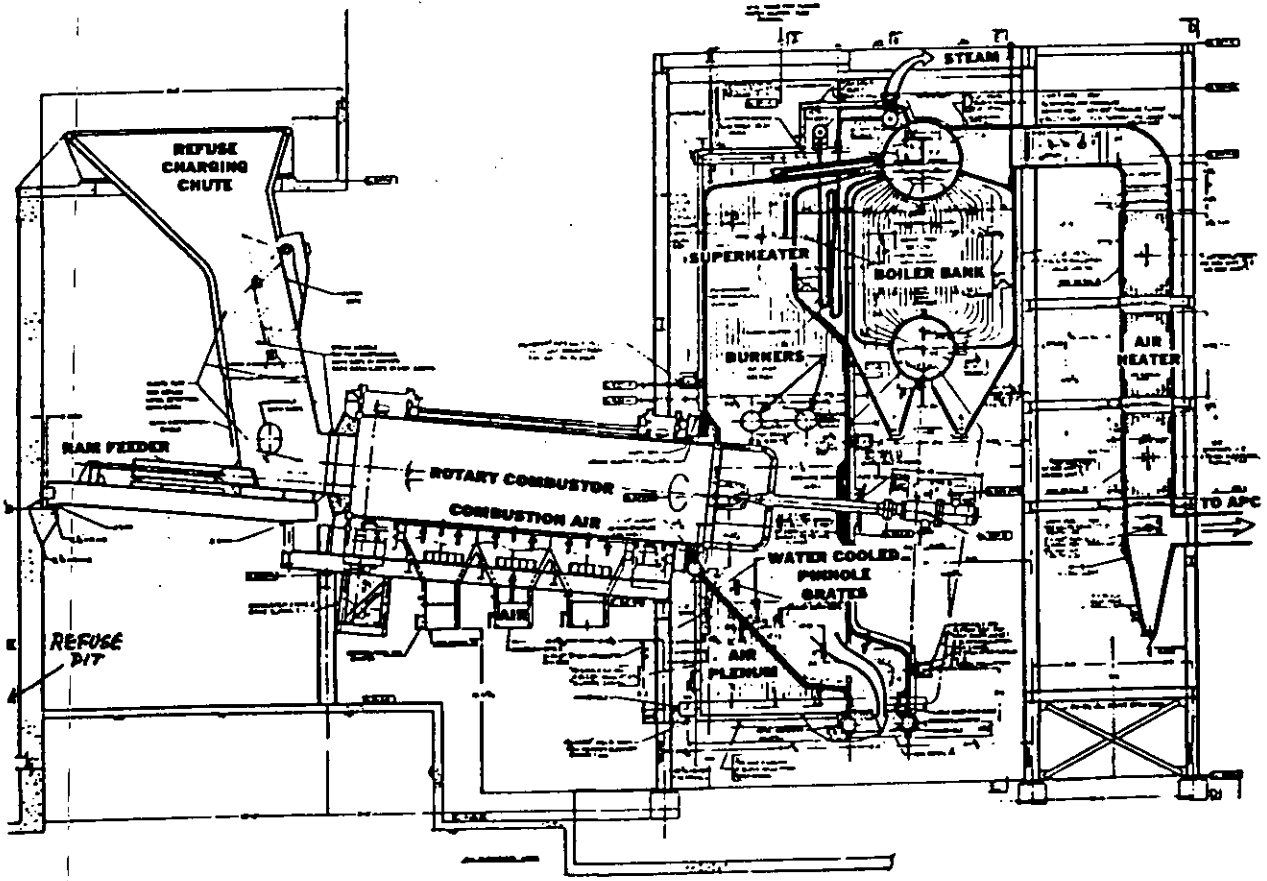
CONCLUSION

The O'Connor Water Wall Rotary Combustor is indeed an innovative technology for mass burning of various types of waste material. This technology is commercially available in a range of unit sizes from 60 TPD to 300 TPD. The inventor/developer of the Rotary Combustor has proved what he set out to do, that there is a better way to convert waste-to-energy, and that the better way is the O'Connor Water Cooled Rotary Combustor.

PLANT CROSS-SECTION

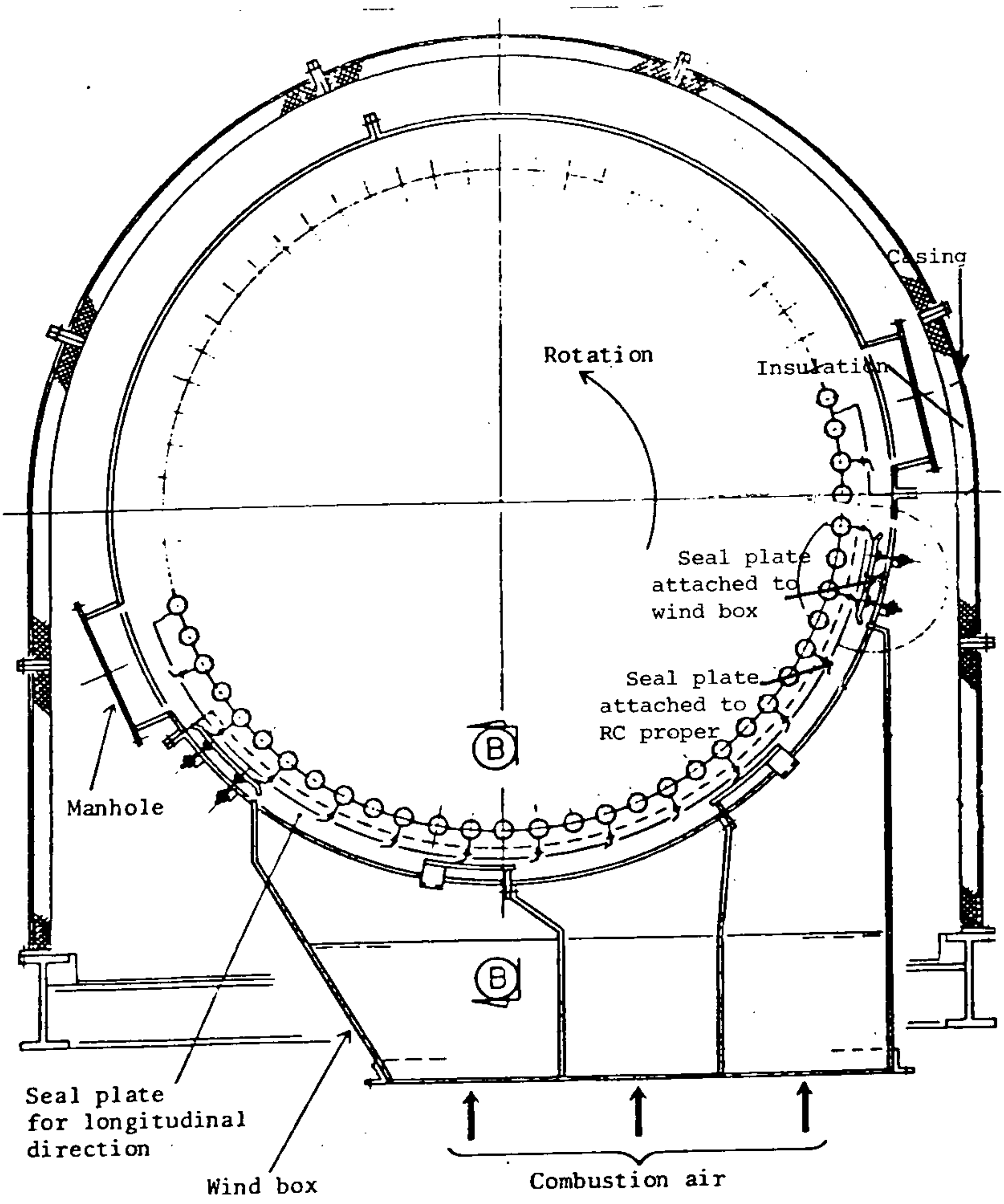


COMBUSTION SYSTEM CROSS-SECTION



200 TPD WASTE-TO-ENERGY PLANT
SUMNER COUNTY, TENNESSEE

Figure 1



Construction of air seal

Figure 2

TVA TEST RESULTS
SUMNER COUNTY WASTE TO ENERGY FACILITY
2 100 TPD ROTARY COMBUSTOR UNITS

DATE	TEST NO.	UNIT NO.	STEAM PRODUCED, LBS	WASTE BURNED, LBS	LBS STEAM PER LB WASTE	* CORRECTED LBS STEAM PER LB WASTE	TIME HRS	LBS STEAM PER HOUR	TONS MSW PER DAY
7/27/82	1	1	102,260	39,450	2.59	2.68	4.267	23,965	111
7/27/82	2	1	85,140	29,850	2.85	2.95	4.117	20,682	87
7/29/82	3	1	104,800	34,000	3.08	3.19	4.416	23,732	92
7/29/82	4	1	112,380	38,000	2.96	3.06	4.483	25,068	102
7/30/82	5	2	52,640	18,545	2.84	2.94	2.083	25,267	107
	Average		457,220	159,865	2.86	2.96	N/A	23,743	99.8

* Corrected for boiler blowdown

NOTE: Average calorific value of MSW 4270 btu/lb as fired
Average moisture content of MSW 38% as fired

TABLE NO. 1

MASSBURN TECHNOLOGIES--TECHNICAL CONSIDERATIONS

W. D. Turner, P.E.
Mechanical Engineering Department
Texas A&M University
College Station, TX 77843

INTRODUCTION

This paper is primarily concerned with the current and historical performance and problems of the 10 mass-burning, waterwalled facilities in the United States. Thermal efficiencies, pollution problems, corrosion problems, and mass and energy balances will be included as well as a discussion of research and development needs in the mass burning area. Nine of the 10 large-scale, mass-burning, waterwall facilities were visited in 1982. The data included herein are contained in an Argonne report on the U.S. plants (Turner, 1983). The 10 plants and their technical data are included in Table 1.

Table 1 Summary Data - United States Plants

Incinerator	Design Capacity tons/day	Year Built	Capital Cost (M$) (1981 $)	No. of Furnace Lines	Estimated Boiler Efficiency[b] %
Portsmouth, VA	145 (160)	1977	6.7	2	66
Hampton, VA	218 (240)	1980	14.4	2	66
Braintree, MA	218 (240)	1971	6.6	2	60
Norfolk, VA	327 (360)	1967	6.2	2	60-70
Harrisburg, PA	655 (720)	1972	17.6	2	64.5
Nashville, TN	655 (720)	1974	41.6	2	67.5
Oceanside, NY[a]	682 (750)	1974-1977	24.8	3	62.5
Saugus, MA	1091 (1200)	1975	88.5	2	70
Chicago NW, IL	1455 (1600)	1970	57.0	4	67
Pinellas Co,FL	1820 (2000)	1983	111.1	2	--

a 136t (150 tons) of the Oceanside plant are from a nonenergy recovery furnace unit.
b Systech Corp., 1982

MASS-BURNING TECHNOLOGIES

There are 10 large-scale, mass-burning facilities in the United States and dozens of smaller, modular-type incinerators. The technical status of these mass-burn systems are included in two Argonne reports (Turner, 1983), and (Hopper, et al, 1983). The latter report is largely concerned with the modular systems. There are common characteristics of both the waterwalled and the modular incinerators, but the main feature common to both is the fact that they are mass-burning systems. Little or no front-end processing of the refuse is required prior to incineration. The theoretical thermal efficiencies of the waterwalled systems are slightly better than the modular systems, either because of the higher amounts of excess air or auxiliary fuel required for complete combustion in the modulars. Reilly and Powers, 1980, compared the energy productivity of three resource recovery systems. Table 2 is a comparison of waterwalled incineration, modular incineration, and RDF production, based on a nominal 10.5 MJ/kg (4500 Btu/lb) refuse input (Reilly and Powers, 1980). In the Battelle report on modular incineration (Hopper et al, 1983) the steam produced per pound of refuse was compared for several modular incinerators. The average was 2.4 kg/kg (2.4 lb/lb) of refuse for modular incinerators and a range from 2.6 to 2.75 kg/kg (2.6 to 2.75 lb/lb) of refuse for waterwalled incinerators. Certified tests at the Hampton, VA waterwalled facility showed a conversion efficiency of 65 to 67% (Martin, 1982). Table 1 lists the estimated efficiencies of the various plants.

Table 2 Comparison of Energy Productivity of Three Resource Recovery Systems[a]

	Waterwalled Incineration (Unprocessed)		Modular Incineration		RDF Production	
	Btu/lb	MJ/kg	Btu/lb	MJ/kg	Btu/lb	MJ/kg
A. Energy Input	4500	10.5	4500	10.5	4500	10.5
B. Energy Requirements and Losses	1800	4.2	2050	4.8	2350	5.5
C. Net Energy (A-B)	2700	6.3	2450	4.8	2150	5.5
Energy Productivity Ratio (C/A)	60%		54%		48%	

a Reilly and Powers, 1980.

Few of the facilities weigh both incoming refuse and outgoing residue; therefore accurate mass balances are not always available. Two plants, Chicago NW and Hampton, VA do weigh both, and Table 3 shows average results for these two facilities.

Table 3 Mass Balances for Incineration Processes[a]

Plant	Time Period	Refuse in short tons	Residue Out short tons	% Reduction in mass	% Reduction in volume
Chicago, NW	1980-81	698,772	222,922	68%	95[b]
Hampton, VA	1981-82	140,551	62,568	55%	85

a Turner, 1983
b Estimated

Since the life of sanitary and residue landfills is of prime importance, the percent reduction in volume is a more important factor than the weight reduction. The refuse is reduced in volume by 85 to 95% in the incineration process. According to Hopper, mass balances and volume reductions for modular incinerators would fall within the same range as given by Table 3 for waterwalled incinerators.

Corrosion and pollution are two of the biggest problems facing incineration processes. Many of the problems are common to both modular and waterwalled incinerators. Modular incinerator problems have been discussed by Hopper and will not be covered here to any great extent. Summary performance of corrosion and pollution problems in the waterwalled units is taken from Turner, 1983.

CORROSION IN WATERWALLED UNITS

There are four basic types of corrosion in a waterwalled, refuse-burning facility. The first type is high temperature corrosion. The gas in the furnace will reach temperatures of 1367° K (2000° F), or higher. This high temperature causes problems with the grates, furnace walls, boiler tubes, and the superheater. Another type of corrosion which occurs is erosion corrosion. This occurs when gas molecules and particulates impinge on the tubes, literally wearing them away. It is particularly bad in regions where the gas stream impinges directly on bends in the tubes or locally where the gas velocity is high. Erosion corrosion also occurs on sliding grates due to the relative motion between them. Another type of corrision seen in some water-walled plants is internal corrosion in the economizer, largely due to untreated boiler feedwater. The fourth type of corrosive attack which can occur involves condensation of stack gases, either because of too low stack exit temperatures or by wet scrubbing of the gases. This condensation will cause the formation of dilute solutions of acids, principally HCl, HNO_3, and H_2SO_4, which will attack the surfaces on which they condense, (Turner, 1983).

Waterwall tube corrosion occurred near the grate system in early European incinerators. To protect this portion of the tubes, several methods are used. Cast iron armor blocks are sometimes added for several meters above the grates. Another solution is the use of a refractory material to protect the bottom of the tubes. The refractory may be in the form of bricks or castable silicon carbide. In the U.S. plants watertube corrosion is not a widespread problem although there have been some problems at individual facilities. Table 4 lists the type of protection on the lower tubes and also indicates whether or not any problems have been experienced.

Superheaters are particularly vulnerable to corrosion because they operate at much higher temperatures than the other components in the steam production system. The corrosion of superheater tubes has been attributed to several factors. One is the presence of CO in the gas stream, due to incomplete combustion. Sufficient overfire air is essential to complete combustion, and if the tubes are continually seeing alternating oxidizing and reducing atmospheres, corrosion can result. Control of the secondary combustion air will reduce incomplete combustion. Another factor which has a severe corrosive effect is the presence of chlorides in the waste stream. Polyvinylchloride (PVC) and other plastics contribute chlorides which are very harmful to the steel tubes. A third factor affecting corrosion is the presence of sulfur compounds in the refuse stream. At low temperatures, the presence of sulfur appeared to counteract the attack by chlorides, according to the Battelle research but at temperatures greater than 700° K

Table 4 Watertube Protection and Problems
(Turner, 1983 and Systech Corp., 1982)

Plant	Protection on Waterwall Tubes Armor Block	Refractory Block	Castable SiC	Comments
Braintree, MA		X		Original refractory still in place--few tubes repaired.
Chicago, NW			X	No recent problems. Good tube life.
Hampton, VA			X	Major changes. Original refractory blocks replaced after 18 months.
Harrisburg PA		X		Major watertube leakage problems. Refractory badly worn away in places
Nashville, TN			X	Extensive watertube failures occurred. Refractory was placed to 20' above grate and problems have greatly decreased.
Norfolk, VA	X			Armor block is replaced every 3-4 months. Only one watertube was welded in first 15 years of operation.
Oceanside, NY		X	X	Refractory block to 5' above grate. SiC to 55' above grate. Refractory problems are still occurring. No tube problems.
Pinellas County, NY			X	Not enough service life yet.
Portsmouth, VA		X		Armor blocks were originally used, but were not effective. No watertube problems
RESCO				Sidewall slagging was an early problem. Few tube problems are reported.

(800° F), the presence of sulfides increased the attack. The complex sulfide reaction is described by Kerekes, Bryers, and Somerland, 1976. Another factor which causes corrosion of the superheater and evaporator tubes is the presence of heavy metals, particularly lead and zinc. Zinc reacts with sulfates to form eutectic compositions which melt and form molten liquid layers on the tube surfaces. These molten layers penetrate the protective iron oxide layer and cause severe corrosion. Chlorides of zinc, sodium, and potassium also combine with lead chloride to form low-temperature corrosive melts in the temperature range of 670° to 720° K (750° to 840° F) (Kerekes, Bryers, and Sauer, 1977). The best solution of many of the superheater corrosion problems is to keep metal tube surfaces below 670° K (750° F), if possible. A fifth problem involves the carryover of particulates in the gas stream. These soft particles will adhere to the superheater tubes, forming deposits which sometimes lead to localized corrosion. Also, these particles impinging on the tubes can cause erosion to occur, particularly when the flow is perpendicular to the tubes. Good boiler design can reduce the carryover of these particles, and protective shields can sometimes be installed to eliminate tube erosion. Four of the 10 U.S. incinerators produce superheated steam. These are Harrisburg, Nashville, Pinellas County, and RESCO. Steam conditions and superheater corrosion problems are summarized in Table 5.

The boiler tubes run at a lower temperature than the superheater tubes and are less susceptible to the higher temperature corrosion problems experienced by the superheaters. The boiler tubes will experience, however, some of the same problems. Harmful deposits will occur on the tubes which can result in localized corrosion, and erosion corrosion can also occur in areas where there is a high incidence of impingement on the tubes. Corrosion has been found on evaporator tubes apparently free from any scale or deposits (Kautz, 1977). The most important ways to reduce evaporator tube corrosion appear to be (1) good furnace design to reduce the flue gas temperatures in the convective section and to eliminate as much particulate carryover as possible, and (2) control of the refuse feed and firing characteristics by reducing the amount and the fluctuations of CO in the furnace gases. Major problems have occurred at only one of the incinerator plants. Others have experienced either minor or no problems. Table 6 summarizes the evaporator-tube corrosion problems at each facility.

The economizer should be the least troublesome of the components in the energy recovery system. It will generally be seeing gas temperatures of less than 811° K (1000° F), and ash deposits can generally be blown off fairly effectively. Harmful corrosion can occur if the inlet feedwater temperature from the deaerator heater drops below the condensation temperature on the gas side. Acids formed on the gas side could result in heavy corrosion to the tubes. Corrosion can also occur on the water side of the dissolved oxygen in the water is not completely removed by the deaerator or if the pH of the water is too low. If the feedwater inlet temperature is maintained above 394° K (250° F), the oxygen is removed, and the pH is kept between 10 and 11, no problems should occur on the water side. Keeping the inlet water temperature above 250° F (394° K) should also prevent condensation of flue gases, which should also keep corrosion from occurring on the gas side. Severe economizer problems have occurred at the Harrisburg plant, and lesser economizer problems have occurred at both Portsmouth and Braintree. The Harrisburg economizers corroded internally

Table 5 Superheater Corrosion Problems

Plant	Steam Conditions Pressure MN/m^2(psig)	°K(°F)	Corrosion Problems/Comments
Harrisburg, PA	1.8(260)	547(525)	Poor initial superheater performance with 6 month actual life. Material change increased life to 2 years. Soot blowing practices, erosion, and material selection were all considered problems.
Nashville, TN	2.8(400)	589(600)	Extremely poor superheater performance. Superheater is first component in gas stream. Failures due to poor combustion, erosion, and direct flame impingement prior to redesign of overfire system.
Pinellas County, FL	4.2(600)	672(750)	Not sufficient operating experience to date.
RESCO, Saugus, MA	4.3(625)	714(825)	Frequent corrosion, caused both by erosion and direct flame impingement, when located as first component in gas stream. Subsequent furnace redesign and relocation of superheater downstream of first convective bank has greatly reduced superheater corrosion.

as a result of a faulty deaerator. The problem went undetected for months, and the results were major outages due to economizer leaks. During the period 1979-82, there were 40 leaks, resulting in nearly 40% of the down time of the plant and requiring complete replacement of the economizers on both boilers. At Portsmouth, there was also a problem with the boiler feedwater, and both economizers had to be replaced. An external corrosion problem also occurred when fly ash deposited on the outside of the economizer got wet. Both problems have since been corrected. At Braintree two economizer tubes were replaced early in the plant's operation, but after a redesign of the tubes, no further problems occurred. With the exception of Norfolk, which has no economizer, all other plants still have the original economizers in place and report no problems (Turner, 1983).

The precipitator should also be relatively free from corrosion. The normal operational temperature seen by precipitators is in the range of

Table 6 Evaporator-Tube Corrosion

	Steam Produced		
	Pressure	Temperature	
Plant	MN/m^2 (psig)	°K (°F)	Corrosion Problems/Comments
Braintree, MA	1.7 (250)	478 (400)	Excellent performance of boilers. No tube repairs on one boiler in 10 years. A few tubes plugged on the second boiler.
Chicago, NW, IL	1.9 (275)	486 (414)	A few tubes plugged. Corrosion rates estimated at less than 1 mill/year.
Hampton, VA	2.5 (360)	499 (438)	No problems in three years of operation.
Harrisburg, PA	1.8 (260)	547 (525)	Few tube repairs needed. In a three-year period (1979-82), one boiler had no leaks, and 1 boiler had only three leaks.
Nashville, TN	2.8 (400)	589 (600)	Complete convective bank replacement was required in 1978, with tube life of 11,000 to 15,000 hours. Soot-blowing practices partly responsible, but poor combustion largely blamed.
Norfolk, VA	1.9 (275)	486 (414)	Very good boiler service. The boilers were replaced after 10 and 11 years of service. The initial tube repair of any kind was in 1974, after 7 years of operation.
Oceanside, NY	3.1 (450)	511 (459.5)	No tube failures have been reported on either boiler.
Pinellas County, FL	4.2 (600)	672 (750)	No problems reported yet.
Portsmouth, VA	0.9 (125)	452 (353)	Few tube failures to date.
RESCO, Saugus, MA	4.3 (625)	714 (825)	Convective tube failures occurred prior to furnace redesign. Few problems since 1979.

506°K (450°F) to 561°K (550°F), although higher temperatures do occur. This high temperature is well above the dew point of the gases in the waste stream; therefore, the condensation of harmful acids should not occur. Erosion corrosion might occur on some parts due to the impingement of the particulates in the gas stream, but this should not be a major problem. Removal of undesirable gases by wet scrubbing can cause major corrosion problems. Weak acid solutions are formed from condensed chloride, sulfates, and nitrides, which can be very destructive to steel. Only Oceanside is currently reporting any significant corrosion problems with the ESP's. Braintree did have a problem during the mid-1970's. This plant was operating on an intermittent basis with daily startups and shutdowns. Apparently condensation of the stack gases was occurring, the condition existing at Oceanside. The Braintree incinerator was taken out of service for several months in 1977-78 for ESP repair (Turner, 1983).

The other major corrosion area in the waterwalled incinerator is the grate system. As previously discussed, not all of the plants experience the same type of corrosion in the radiative and convective portions of the energy recovery system. All plants, however, experience grate burnout, and for some it represents one of the major maintenance items. There are essentially five different grate technologies used by the U.S. plants. Three plants use the Josef Martin reverse reciprocating grate, and one plant uses the Von Roll grate. Both of these grate systems are derivations from European mass-burning technologies. Four U.S. plants use grates designed by Detroit Stoker. Another plant uses a Flynn and Emrick rocking grate. All of these grates are inclined from front to rear to facilitate the refuse moving through the furnace. Only one plant uses a horizontal grate, the Riley traveling grate. Table 7 summarizes the grate systems for the various plants and discusses the grate burnout problems.

Figure 1 is a photograph of the interior of Nashville Thermal, showing the inclined and stepped Detroit Stoker grates. Figure 2 is a photograph of the Flynn and Emrick rocking grate system, and Figure 3 is a close up showing the burnout of one of the rocking grates. Figure 4 is a view of one of the Harrisburg furnaces showing the Martin grates.

POLLUTION PROBLEMS IN WATERWALLED INCINERATORS

The pollution problems in the incineration of refuse are related to emission of particulates, gaseous emissions, trace metals, thermal pollution, and water pollution. Another problem exists with the landfill residue. The following discussion is taken from Turner, 1983; Systech Corp., 1982, and Velzy, 1983. Velzy's paper applies to waste incineration, in general, and is not restricted to U.S. waterwalled incinerator results.

PARTICULATE EMISSIONS AND CONTROLS

The principal area where the standards are well-defined is in particulate emissions. The federal performance standard for new incinerators is 0.18 g/dscm (0.08 gr/dscf) corrected to 12% CO_2. States and local political entities may adopt a more stringent requirement, and several have. Maryland, for instance, has a particulate limit of 0.069

Table 7 Grate Corrosion Problems

Plant	Type of Grate	Features	Comments
Braintree, MA	Riley Traveling	Horizontal	High maintenance item, frequently requiring replacement of small cast iron cleats.
Chicago, NW, IL	Martin Reverse Reciprocating	26° Angle	High chrome castings. 60 to 70% of original grates still in place after 13 years. Grates are cleaned and rotated periodically.
Hampton, VA	Detroit Stoker	Inclined and stepped with 3 grate sections.	Poor performance of original cast iron knees between sections and of the grate bars. Less than a 6-month life time on burning grate. Stainless steel grate bars & knees are now being used.
Harrisburg, PA	Martin Reverse Reciprocating	26° Angle	Estimated that 40-50% of original grates are still in place. Principal failures are due to burnout in high temperature areas.
Nashville, TN	Detroit Stoker	Inclined and stepped with 4 grate sections.	Grate replacement on cast iron grates required 4 times a year. Chrome-nickel grate replacements have given better service.

Table 7 Grate Corrosion Problems, Cont'd.

Plant	Type of Grate	Features	Comments
Norfolk, VA	Detroit Stoker	Inclined and stepped with 3 grate sections.	Grate replacement on the second (burning) is high, estimated at 25 bars a week. The third grate requires overhauling every two weeks. Highest maintenance item in the plant.
Oceanside, NY	Flynn & Emrick Rocking Grate	Inclined	Overall performance is good, 1 year lifetime in burning grate area.
Pinellas County, FL	Martin Reverse Reciprocating	Inclined at 26°	Not enough operating data to date.
Portsmouth, VA	Detroit Stoker	Inclined and stepped with 3 grate sections.	Normally 6 to 10 grate replacement bars a month. Considered a major maintenance item.
RESCO, Saugus, MA	Von Roll	Inclined at 18° and stepped--3 grate sections.	Major maintenance item initially, but grate material was changed in first year. Many of the new grates are still in place. Grate rotation extends life of grate system.

g/dscm (0.03 gr/dscf) corrected to 12% CO_2, and Massachusetts has a limit of 0.115 g/dscm (0.05 gr/dscf).

The most common particulate capture system used on today's waterwalled incinerators is an electrostatic precipitator (ESP). Today's modern ESP typically consists of from two to four fields which capture 95 to 99% of the charged particles. A technology which has had very good success in controlling particulates is the use of fabric filters. Although the testing has been on a limited basis, with very little longtime tests results, some of the emission data are amazing. Emissions of less than 0.002 g/dscm (0.001 gr/dscf) have been reported. O'Connell et al. suggest that 0.058 g/dscm (0.025 gr/dscf) is a reasonable achievable result using fabric filters. Table 8 lists the emissions obtained from various tests of the U.S. waterwalled plants (Systech Corp., 1982 and Turner, 1983).

Table 8 Emissions from U.S. Waterwalled Incinerators

Plant	Particulate Emissions, gr/dscf	Comments
Braintree, MA	< .08	ESP's repaired in 1978 to meet standards
Chicago, NW, IL	.027, .057, .04	Rothemuehle ESP's first to be installed on a refuse-burning plant.
Hampton, VA	.0222, .0209, .0191	Precipitaire ESP's
Harrisburg, PA	.04-.07	Have also burned some raw sewage sludge
Nashville, TN	.007-.01	American Air Filter 4-field ESP's have lowest documented emissions in U.S.
Norfolk, VA	.029-.05	
Oceanside, NY	.03-.045	
Pinellas County, FL	N/A	
Portsmouth, VA	.22 to .33	Results prior to 1983. ESP's were upgraded and cyclone separators added.
RESCO, Saugus, MA	.025	Wheelabrator-Lurgi, 2-field ESP's

GASEOUS EMISSIONS AND CONTROLS

Gaseous emissions from incinerators include sulfur dioxide (SO_2), nitrogen oxides (usually reported as NO_x), carbon monoxide (CO), hydrochloric acid (HCl), fluorides, and several complex hydrocarbons. In the United States, there is a very limited amount of gaseous emission data, and these data are summarized in the O'Connell et al, 1982, and the Rigo et al., 1982, papers.

Sulfur Dioxide (SO_2): The amount of sulfur normally in municipal refuse is small, averaging less than 0.12%. Unlike coal, which can have a sulfur content of several percent, the SO_2 emitted from refuse is a very small percentage of the flue gas volume. Consequently, no municipal incinerators in the United States have controls to limit sulfur dioxide emissions. According to the O'Connell paper, some state and local agencies, particularly in California, are requiring acid gas controls on new incinerators. The older method of removing acid gases was by a wet caustic scrubbing technique. Newer installations in both Germany and Japan are using dry scrubbers, a technique which injects a powder into the gas stream which chemicallly attracts and collects the acid gases. There is a limited amount of performance data on these scrubbing devices, but manufacturer's data suggest SO_2 removal efficiencies of 48 to 88% (O'Connell, Stotler, and Clark, 1982).

Nitrogen Oxides (NO_x): The emissions of NO_x from municipal incinerators are quite small, and emission data from various incinerators can be found in both the O'Connell et al. and Rigo et al. papers. There is no NO_x control on municipal incinerators at the present time.

Carbon Monoxide (CO): Carbon monoxide levels in incinerators are determined by the combustion characteristics of the furnace, principally involving the overfire air and the combustion temperature. Emission levels from various incinerators are tabulated in both the O'Connell et al. and Rigo et al. papers. The maximum level of 150 ppm or 0.95 kg/t (1.9 lb/ton) of CO emitted was recommended by O'Connell et al. as a reasonable standard. Modern incinerator design should be able to improve on this recommendation, especially since reducing the CO content will also help reduce corrosion problems previously discussed. Velzy, 1983 indicates that the above recommendation is well below current levels achieved in actual testing.

Hydrochloric Acid (HCl) and Fluorides: The U.S. government does not have a standard for either hydrochloric acid or fluorides, often present as hydrofluoric acid (HF). A significant amount of HCl is present in the gas stream because of the presence of polyvinylchloride (PVC), but only trace amounts of HF are usually found. The U.S. government has only required the reporting of these gas levels, but states can and will set their own standards. California is requiring acid gas removal on new incinerator installations. Both HCl and HF can be removed by scrubbing techniques. A reasonable estimate of the HCl and fluoride emission levels are 200 ppm and 6.5 ppm, respectively (O'Connell, Stotler, and Clark, 1982).

Miscellaneous Gas Emissions: Also discussed in the O'Connell et al. paper are other substances such as dioxins, furans, polynuclear aromatic hydrocarbons, polychlorinated biphenyls (PCB's), asbestos, and vinyl chloride. No data are available for most of the substances in this group. Dioxins, specifically polychlorinated dibenzo-dioxins (PCDD), and furans, polychlorinated dibenzo-furans (PCDF) are receiving a great deal of attention because of their extreme toxicity. Velzy, 1983 discusses the limited testing conducted to date in refuse incineration. Although the results are not conclusive at this point, the indications are that the current emission levels of PCDD and PCDF do not constitute a significant public health problem. Velzy also points out that the formation of PCDD and PCDF during incineration is a temperature dependent process. High temperatures will destroy the formation of both PCDD and PCDF. Thus, good combustion practices, high temperature incineration, and good pollution control devices should prevent any serious problem with these particular emissions.

Trace Metals: Most of the metals found in municipal solid waste end up a residue in the bottom ash or fly ash. Except for mercury, less than three percent of the volatile metals (lead, cadmium, and zinc) are emitted and less than one percent of the nonvolatile metals are emitted. The O'Connell et al. paper tabulates the limited data available from incineration testing and states recommended emission levels for several metals.

Emissions Summary: Table 9 is taken from the O'Connell et al. paper and summarizes current emission levels. The BACT column is Best Available Control Technology and the LAER is Lowest Achievable Emission Rate.

A paper presented at the 1980 Waste Processing Conference in New York discussed a computer model which used data on emissions from the Braintree Municipal Incinerator (Olexsey, Freeman, and Brailey, 1980). The model predicted ground-level pollutants from waste-to-energy facilities and included arsenic, beryllium, cadmium, chromium, lead, mercury, sulfur dioxide, and chlorine in the analysis. The concentrations of each of these elements, based on the model, showed levels far below the toxic level for the small Braintree incinerator. Furthermore, scaling up the model to a larger plant, 900 t/day (1000 tons/day) or more, did not project hazardous levels for any of the pollutants. It should be emphasized that this paper was based on a model, and the authors are quick to point that out. Any extension of the results to plants other than the Braintree facility cannot be validated, Turner 1983.

Water Pollution Problems

The pollutant water from a waterwalled incinerator is usually very small. The burned-out residue from the furnace is cooled in some fashion, usually by quenching in water or by spraying with water. The actual amount of water used is small, generally only a few gallons (liters) per ton of refuse burned. This water is disposed of in different ways at the various incinerators. In most plants the water, ash, and residue are trucked to the landfill site. Other plants use some sort of sluice trough and/or holding pond scheme for their ash. While the water pollution problem is

Table 9 Summary of Emission Levels and State-of-the-Art Control Systems[a]

Pollutant	Attainable Maximum Emission Level	BACT	LAER
Particulates	.02 gr/dscf (.045 g/dscm)	ESP	ESP
Sulfur dioxide	80 ppm	None	Dry or Wet Scrubber
Nitrogen oxides	75 ppm	None	None
Carbon monoxide	150 ppm	Combustion Control	Combustion Control
Hydrocarbons	16 ppm	Combustion Control	Combustion Control
Hydrochloric acid	200 ppm	None	Dry or Wet Scrubber
Fluorides	6.5 ppm	None	Dry or Wet Scrubber
Lead	.012 lb/ton (.006 kg/t)	ESP	ESP
Mercury	.0064 lb/ton (.0032 kg/t)	None	None
Beryllium	5.6×10^{-8} lb/ton (2.8×10^{-8} kg/t)	ESP	ESP
Sulfuric acid mist	.04 lb/ton (.02 kg/t)	None	Dry Scrubber
Toxic dioxins	5×10^{-10} lb/ton (2.5×10^{-10} kg/t)	None	None
Polynuclear aromatics	10^{-5} lb/ton ($.5 \times 10^{-5}$ kg/t)	None	None
PCP's[b]	1.2×10^{-4} lb/ton ($.65 \times 10^{-4}$ kg/t)	None	None
Asbestos	-	None	None
Vinyl chloride	-	None	None
H_2S	-	None	None
Reduced sulfur	-	None	None

[a] O'Connell, Stotler, and Clark, 1982.

[b] Value should decline because manufacture of PCB's is banned.

not insignificant, it generally is considered much less of a problem than air pollution.

Thermal Pollution Problems

The incinerators will be discharging gases at temperatures in excess of 450°K (350°F) into the atmosphere, which does involve some thermal pollution. Some of this waste heat could be recovered, theoretically, by preheating combustion air, or by using some sort of secondary energy recovery (such as running a freon-driven turbine-generator). However, corrosion considerations dictate that if the gas stream contains potentially harmful acid gases, then the stack temperature should be greater than the dew point of these gases. Limited thermal pollution effects have to be tolerated.

Residue Landfill Considerations

The residue from the incineration process consists primarily of metals, glass, water, and ash. Ferrous metals are the dominant metal fraction in the residue, generally ranging from 10 to 25%. Various studies have been conducted to determine the metallic content of the residue (Schoenberger, 1972; Schoenberger and Bender, 1976). Nonferrous metals generally comprise about one percent of the MSW and consist mainly of aluminum, copper, zinc, and chromium. Only trace amounts of lead and tin were found in the residue testing conducted by Schoenberger and Bender. One of the concerns with the residue from the incineration process is water pollution from the leachate, particularly of heavy metals. In some areas, the residue may be classified as a hazardous material, and special landfill precautions may have to be taken. The end result of the incineration process achieves, however, a final residue greatly reduced in both mass and volume. It can be disposed of more easily and cheaply, and in less volume, than unprocessed refuse that is landfilled. The problems which may be encountered in the landfilling of the residue are generally less than those encountered by the landfilling of the raw refuse, Turner, 1983.

RESEARCH AND DEVELOPMENT NEEDS

Based on site visits to each of the U.S. waterwalled waste-to-energy plants, interviews with plant personnel, and reviews of the technical literature, there are a number of both short term and long-term needs. These are identified in Turner, 1983 and are taken directly from that report. Short term needs are:

1. The development of improved grate systems is a near-term need, particularly if the American grates are to compete favorably with the more-established European technologies. The improved grate systems should include improved grate materials, improved agitation, improved reliability, and longer service life.

2. Another goal would be to develop additional uses for the incinerator residue. This would prolong landfill life if unburnables only

had to be landfilled. Uses as roadbed material, as aggregate, and as daily cover for sanitary landfills are possibilities, but additional R&D efforts are needed.

3. Ferrous and other metals recovery from the incinerator residue is another area which needs to be explored. At Harrisburg, Chicago, and other plants where ferrous material is not normally recovered, there are literally thousands of tons of metal potentially recoverable.

4. The refuse feed system should be optimized. There is a definite need to develop better techniques for feeding the fuel into the furnace.

5. The need exists for improved instrumentation and controls throughout the incinerator plant, from refuse receipt through disposal of the residue. Only the Hampton plant can be considered automated, and the performance of the control systems in this plant should be carefully monitored. The newer plants will likely be automated to at least the same degree, and improved controls will be needed, especially when the newer plants will be scaled up in size an order of magnitude larger than Hampton.

6. Another short-term R&D area is in emissions control. More stringent air pollution requirements in Japan and Western Europe have caused engineers in those countries to develop improved methods of emission control, particularly dry scrubbing techniques. The bag house approach tested at RESCO and other places is apparently successful in reducing emissions below levels attainable with ESP's, but the method still needs further development. Dry scrubbing of the various acid gases is in its infancy, and the method will not be applicable to all of the various types of acid gases.

7. The optimum use of overfire and underfire air to improve combustion is needed. Because of the heterogeneous nature of refuse, a proper mix of primary and secondary air is required for good combustion. The current practices vary at the existing U.S. plants, ranging from copious amounts of underfire air without any secondary air to almost the opposite extreme.

8. A better knowledge of the corrosion mechanisms throughout the incinerator plant is needed. Most of the U.S. plants have been bothered by some type of corrosion, but the problems vary from plant to plant. Some have superheater problems; others economizer or boiler problems; some have water tube failures; all have erosion or wear problems with the grates; and all plants have some corrosion problems with the residue handling system. There needs to be a systematic study undertaken of the plant corrosion problems to determine acceptable solutions.

9. The long-term effects of co-burning both dry and liquid sewage sludge with refuse is still an unknown. The proper ratio of powdered and liquid sludge to refuse, the effects on combustion, the short-term corrosion problems, and long-term effects need to be addressed.

10. Improved ash and residue handling systems are an urgent need. Without exception, all U.S. plants had problems with the system. These problems are minimized at the plants by having redundant systems, but this

is not the solution. Improved materials handling systems would reduce costs and improve overall system reliability.

11. Slagging is a problem at most of the plants. R&D efforts are needed to determine the causes, and then efforts are needed to control the problem.

12. Education and training, particularly of the personnel needed for the future plants, are critical areas. There are very few skilled technicians in the U.S. trained in the operation of refuse-to-energy plants, and the future plants are going to be more complex, producing electrical power in many cases as well as steam. Whether the training will be conducted by the manufacturer, by technical organizations such as ASME, or by governmental agencies, such as the state or federal offices of solid waste management, is a near-term problem which needs to be addressed.

13. Another nontechnical problem which requires some attention is the length of time needed to hold all the hearings and acquire the necessary permits to start the construction of waste-to-energy plants. "Fast-track" implementation is needed and can only be accomplished with the full cooperation of all political entities involved. The long lead time barriers need to be investigated, and the entire process speeded up as much as possible. The very short time it took to construct the RESCO plant is an example of what can be done if the need is there.

There are several long-term needs, some of which could be considered extensions of the short-term needs discussed previously.

1. The characteristics of MSW as a fuel need to be determined. The Btu (Joule) range, not just the average, should be studied. Long-range studies of the trends in the refuse, including both energy content and expected amount to be generated per person, should be considered.

2. The overall combustion characteristics of MSW as a fuel need to be studied in more detail. There are too many problems existing with today's plants in the combustion area. Excessive emissions, grate burnouts, corrosion problems, lack of knowledge of gas profiles in the furnace, excessively high gas temperatures due to a changing MSW energy content, slagging, and other problems are related to the combustion of MSW. A long-term, systematic study of the combustion of the MSW is needed. Through improved grate systems, materials handling, combustion, and controls systems, the overall long-range goal should be to improve system availability to the 85-90% range. Currently 60-70% availability is a typical figure for most U.S. plants.

REFERENCES

1. Hopper, R. et al., Thermal Systems for Conversion of Municipal Solid Waste, Volume 3. Small-Scale Systems: A Technology Status Report, ANL/CNSV-TM-120, Vol. 3 (1983).

2. Kautz, K. M., The Causes of Boiler Metal Wastage in the Stadwerke Duesseldorf Incineration Plant, Proceedings of 1977 Conference on Ash

Deposits and Corrosion Due to Impurities in Combustion Gases, Henniker, NH, June 1977, pp. 437-444 (1978), R. W. Bryers, Editor.

3. Kerekes, Z. E., R. W. Bryers, and A. R. Sauer, The Influence of Heavy Metals Pb and Zn on Corrosion and Deposits in Refuse-Fired Steam Generators, Proceedings of 1977 Conference on Ash Deposits and Corrosion Due to Impurities in Combustion Gases, Henniker, NH, June 1977, pp. 455-472 (1978), R. W. Bryers, Editor.

4. Kerekes, Z. E., R. W. Bryers, R. E. Sommerland, Corrosion Mechanisms in Refuse-Fired Steam Generators Related to Superheader Tube Failures, Proceedings of the 1976 ASME Conference on Present Status and Research Needs in Energy Recovery from Waste, Oxford, OH, pp. 120-163 (Sept. 1976), R. A. Matula, Editor.

5. Martin, Timothy L., From Tipping Fee to Tipping Free, Solid Wastes Management, pp. 20-22, 24, 168 (Feb. 1982).

6. O'Connell, W. L., G. C. Stotler, R. Clark, Emissions and Emission Control in Modern Municipal Incinerators, Proceedings of the 1982 ASME National Waste Processing Conference, New York, NY, pp. 285-297 (May 1982).

7. Olexsey, R. A., H. M. Freeman, and P. A. Brailey, Estimated Ground Level Concentrations of Pollutants from Waste-to-Energy Facilities, Proceedings of the 1980 ASME National Waste Processing Conference, New Waste-to-Energy Plant Emissions, Proceedings of the 1982 ASME National Waste Processing Conference, New York, NY, pp. 305-328, (May 1982).

8. Reilly, T. C., and D. L. Powers, Resource Recovery Systems, Solid Wastes Management, pp. 38-44 (June 1980).

9. Rigo, H. G., J. Raschko, and S. Worster, Consolidated Data Base for Waste-to-Energy Plant Emissions, Proceedings of the 1982 ASME National Waste Processing Conference, New York, NY, pp. 305-328, (May 1982).

10. Schoenberger, R. J., Studies on Incinerator Operation, Proceedings of the 1972 ASME National Incinerator Conference, pp. 15-31 (1972).

11. Schoenberger, Robert, and Joel Bender, Analysis of Metals Found in Incinerator Residue, Proceedings of the 1976 ASME National Waste Processing Conference, Boston, MA, pp. 499-511 (May 1976).

12. Systech Corporation, An Overview of U.S. and Canadian Experience with European Mass Burning Waterwalled Incinerator Systems, U.S. EPA Contract #68-01-6071 (January 1982).

13. Turner, W. D., Thermal Systems for Conversion of Municipal Solid Waste, Volume 2, Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report, ANL/CNSV-TM-120, Vol. 2 (1983).

14. Velzy, C. O., Trace Emissions in Resource Recovery: Problems, Issues, and Possiblel Control Techniques. Proceedings of the DOE-ANL

Conference, State-of-the-Art and Emerging Technologies: A Waste-to-Energy Workshop (Nov. 28-30, 1983).

Figure 1 - Interior of Nashville Thermal Showing Detroit Stoker Grates

Figure 2 - Photograph of Flynn and Emrick Rocking Grate at Oceanside

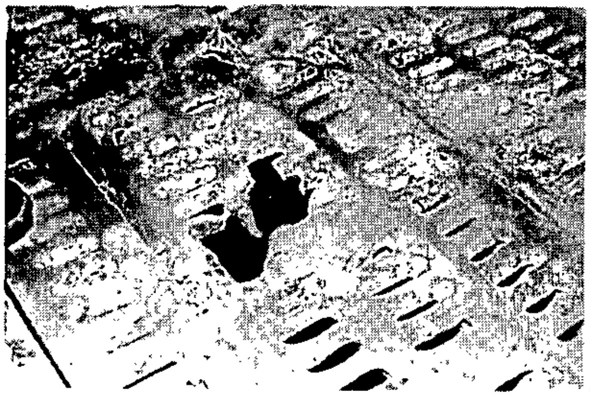


Figure 3 - Grate Burnout at Oceanside

Figure 4 - Martin Grate System at Harrisburg

RDF COFIRING IN UTILITY BOILERS

Charles R. McGowin
Technical Manager-Analysis
Electric Power Research Institute
Palo Alto, California 94303

INTRODUCTION

Energy recovery from municipal solid waste is being considered by many communities both as an alternative energy source and as a method of waste disposal. In some U.S. cities, landfill disposal space is disappearing, and the combination of waste disposal and energy recovery is an attractive alternative. Electric utilities provide an important function in most community energy recovery projects as customers for fuel, steam or electricity and, in some cases, as operators of refuse-to-energy conversion facilities.

This paper addresses the roles that utilities can serve in refuse-to-energy projects, utility experience with cofiring refuse-derived fuel with coal in utility boilers, institutional issues and utility incentives to participate, and the shift in interest toward dedicated refuse-fired facilities in recent years. In addition, the EPRI program on municipal solid waste utilization is summarized.

ALTERNATE ELECTRIC UTILITY ROLES

Alternate roles served by utilities in resource recovery projects include the following:

- Customer for refuse derived fuel (RDF)
- Owner/operator of power plant cofiring RDF and coal or oil
- Customer for steam or electricity
- Owner/operator of turbine/generator driven by refuse-generated steam
- Owner/operator of resource recovery facility
- Customer for gas recovered from landfills.

Since the 1970's, nine utilities have cofired RDF with coal or oil in their boilers. In most cases, the RDF was obtained from offsite resource recovery plants, and in one case (Lakeland), the resource recovery plant is located at the power plant. Utilities are also customers for steam and electricity from from dedicated plants, and, in some cases, own and operate the turbine generator driven by the steam (Hempstead, New York and Miami, Florida). Utilities are also purchasing gas and electricity generated from gas recovered at sanitary landfills (e.g. Staten Island, New York).

RDF COFIRING EXPERIENCE

The City of St. Louis and Union Electric Company conducted the first demonstration of RDF cofiring in the 140 MW Meramec Unit 1. As shown in Table 1, electric utility experience has principally occurred in suspension-fired boilers, both tangential and wall-fired, and there has been more limited experience in cyclone and stoker-fired utility boilers.

Utility experience has been extensively reviewed in an on-going project to develop guidelines for RDF cofiring, cosponsored by Argonne National Laboratory and EPRI. Collection and analysis of RDF preparation and cofiring data and experience has been completed under DOE/ANL sponsorship (1-5). The actual guidelines will be completed during 1985 under EPRI sponsorship.

RDF COFIRING STATISTICS

Since 1972, RDF has been cofired by nine utilities in at least sixteen units, ranging from 35 MW at Ames to 364 MW at Lakeland (5). Through 1982, 348,514 tons of RDF had been burned in suspension and cyclone-fired boilers, of which 48 percent was consumed at Ames. The fraction heat input supplied by RDF is typically 10 to 15 percent, although higher levels of heat input, up to about 50 percent, have been reached in specific cases. Of the locations listed in Table 1, only Ames, Madison, Rochester, and Lakeland are now cofiring RDF, and Baltimore and Columbus are converting an old unit and building a new unit, respectively, to cofire RDF and coal. New RDF cofiring projects are also being actively pursued in Hartford and Minneapolis. The remaining projects have been discontinued due to a variety of technical and economic problems.

RDF COFIRING PROBLEMS

Tables 2 and 3 summarize the operating problems and the relative severity of each, encountered in cofiring RDF in utility boilers (1-5). The seven most critical operating problems are marked "X" and include the following:

- o Upper furnace wall slagging - Ames, Milwaukee
- o ESP efficiency decrease - Baltimore

TABLE 1

Experience With RDF Cofiring In Large Utility Boilers

Location	Utility	Unit	MW	Primary Fuel	Date of Startup	Status/Comment
Tangentially-Fired Boilers						
St. Louis, MO	Union Electric Co.	Meramec 1	140	Coal	1972	Shutdown 1976
Ames, IA	Ames Municipal Electric System	Ames 7	35	Coal	1975	Operational 1978 with dump grate
Milwaukee, WI	Wisconsin Electric Power Co.	Oak Creek 7, 8	310 each	Coal	1977	Shutdown September 1980
Chicago, IL	Commonwealth Edison Co.	Crawford 7 + 8	208/325	Coal	1978	Shutdown 1979
Rochester, NY	Rochester Gas and Electric Corp.	Russell 1, 2, 3, 4	42/62/ /62/75	Coal	1981	Units 1 and 3 operational with dump grates
Cyclone-Fired Boilers						
Bridgeport, CT	United Illuminating Co.	Bridgeport Harbor 1	86	No. 6 Oil	1980	ECOFUEL II plant shutdown October 1980
Baltimore, MD	Baltimore Gas and Electric Co.	Crane	200	Coal	1980	Tested in 1980, conversion underway

TABLE 1 (continued)

Experience With RDF Cofiring In Large Utility Boilers

Location	Utility	Unit	MW	Primary Fuel	Date of Startup	Status/Comment
Wall-Fired Boilers						
Madison, WI	Madison Gas and Electric Co.	Blount Street 1&2	50 each	Coal	1979	Operational with dump grate
Lakeland, FL	City of Lakeland	McIntosh 3	364	Coal	1981	Operational with dump grate
Ames, IA	Ames Municipal Electric Systems	Ames 8	60	Coal	1982	Operational, new unit.
Stoker-Fired Boilers						
Ames, IA	Ames Municipal Electric System	Ames	7.5/12.5	Coal	1975	Operational
Columbus, OH	City of Columbus	Columbus	90	Coal	1984	Under construction for 1984 operation

TABLE 2

SUMMARY OF REPORTED UTILITY BOILER OPERATING PROBLEMS DUE TO RDF COFIRING (Ref. 5)

Problem	Ames Unit 7	Ames Unit 8	Balti-more	Bridge-port	Chicago	Lake-land	Madi-son	Mil-waukee	Roch-ester	St. Louis
Boiler Thermal Efficiency Decrease										
o Increased sensible heat loss due to high RDF ash content	0	0	0	0	0	0	0	0	0	0
o High RDF moisture content	0		0		0	0	0	0	0	0
o Increased unburned combustibles in ash	0	0	0		0	0	0	0		0
o Increased excess air required for RDF	0	0						0		
ESP Efficiency Decrease										
o Increased fly ash volume in flue gas	0	0	X		0			0		0
o Increased particulate size			X					0		
o Increased unburned combustibles in fly ash	0		X					0		
Unit Derating										
o Increases in flue gas volume exceeds induced draft fan capacity at full boiler load								0	0	
Boiler Slagging Increase										
o Upper furnace wall slagging	A				0			X	0	
Corrosion and Erosion of Boiler Tubing										
o Corrosion in localized area immediately above dump grate	B									

Legend: X = Severe problem. Persistence of problem would cause plant shutdown; therefore, RDF would be rejected.

0 = Moderate problem. Problem is manageable and cofiring could continue.

A = Slagging originally a severe problem in Ames Unit 7 but not a problem after disc screen system installation.

B = Corrosion originally a severe problem in Ames Unit 7 but not a problem after refractory lining installed.

TABLE 3

SUMMARY OF REPORTED ELECTRIC UTILITY MATERIAL HANDLING PROBLEMS DUE TO RDF COFIRING (Ref. 5)

Problem	Ames Unit 7	Ames Unit 8	Balti-more	Bridge-port	Chicago	Lake-land	Madi-son	Mil-waukee	Roch-ester	St. Louis
RDF Handling										
o Poor control of RDF feed rate	0	0	0		0	0	0	0	0	0
o Pneumatic conveying line pluggage	0	0	0		0		A	0	A	0
o RDF storage bin must be emptied weekly	0	0			0	0		0	0	0
o Pneumatic conveying system feeder pluggage					0	0	0	0	0	0
o Excessive abrasion of pneumatic conveying lines	0	0	0		0			0		0
o Excessive dust at RDF receiving station	0	0	0				0	0		0
o Fire from fuel leakage from pressurized boiler				0						
o Cold weather moisture condensation in RDF storage bin								0		
Bottom Ash Handling										
o Substantially more frequent bottom ash removal	B				X	C		0		C
o Large clinkers bridge dump grates	0					0	0		0	
o Clinker grinder jamming	0	0			0			0		
o Sluice line pluggage	0	0			0			0		
o Reduced performance of sluice water treatment system					0			X	0	
o Septic sluice water					X					D
o Pluggage of sluice water overflows by floating material					X			X		
o Bottom ash dewatering screens plugged					0			0		
o Increased dry ash system cyclone maintenance							0			

Legend: X = Severe problem. Persistence of problem would cause plant shutdown; therefore, RDF would be rejected.

0 = Moderate problem. Problem is manageable and cofiring could continue.

A = Pneumatic conveying line pluggage by metals a moderate problem at Madison and Rochester but not a problem after installation of magnetic separator at electric utility.

B = Bottom ash accumulation originally a severe problem in Ames Unit 7 but not a problem after dump grate installation.

C = Bottom ash accumulation originally severe problem at Lakeland and St. Louis but not a problem after air classifier used.

D = Septic sluice water in sluice pond originally a moderate problem at St. Louis but not a problem after aeration pump installed in sluice pond.

- Corrosion of boiler tubing - Ames
- High bottom ash accumulation rate - Ames, Chicago, St. Louis, Lakeland
- Reduced performance of sluice water treatment system - Milwaukee
- Pluggage of sluice water overflows by floating material - Chicago, Milwaukee
- Septic sluice water - Chicago

Upper furnace wall slagging was a problem at both Ames and Milwaukee. Ames Unit 7 experienced heavy slag accumulation when RDF cofiring began in April 1978. The slagging problem disappeared in late 1978, when disc screens were installed at the Ames resource recovery plant and the RDF ash content decreased from 21 to 9.6 percent. At Milwaukee, however, the slagging problem appears to be related more to the high heat release rates of the Oak Creek Unit 7 and 8 boilers. As shown in Table 4, these units have the highest plan area heat release rates of all the units in which RDF has been burned.

A decrease in electrostatic precipitator collection efficiency with RDF cofiring has been reported at Ames, Baltimore, St. Louis, and Milwaukee, which appears to be caused by a combination of increased flyash loading and modification of flyash properties. The causes and solutions of this problem are being addressed in the RDF cofiring guidelines project.

All locations except Ames have reported that boiler tube corrosion is not significantly affected by RDF cofiring. At Ames Unit 7, 22 tubes just above the bottom dump grate showed evidence of metal wastage, which appeared to be due to the presence of a reducing atmoshere around RDF particles on the dump grate and uneven distribution of overfire air. At Ames, the problem has been corrected by a refractory lining around the wall, 18 inches above the dump grate.

RDF cofiring also significantly increases bottom ash accumulation rate due to the high ash and low Btu content of RDF relative to coal. The increased volume of ash has overloaded the bottom ash handling system in cases where the RDF ash content was above about 20%, e.g. at St. Louis, Ames, Milwaukee, and Chicago. The problem has been reduced by air classification and trommel and disc screening of RDF to reduce ash content. At St. Louis, Ames Unit 7, and Milwaukee, the problem was increased by dropout of unburned combustibles from the RDF, which clogged the bottom ash hopper and the ash/sluice water separation system. A bottom dump grate was subsequently installed in the bottom of Ames Unit 7 to retain the combustibles in the furnace until combustion is completed. Bottom dump grates have since been installed in most of the RDF-cofired utility boilers operating today.

TABLE 4

RANKING OF BOILER SIZE (Ref. 5)

Location	Unit No.	Generating Capacity (MW)	Furnace Dimensions (ft)			Furnace Plan Area (ft^2)	Volume of All Furnaces[a] (ft^3)
			Height	Width	Depth		
Ames	7	35	84	19.9	19.9	396	27,300
Madison	8 & 9	55	89	20	21	420	28,000
Rochester	3	62	75	22.1	21.3	471	30,400
Ames	8	65	116.5	24.5	22.0	539	50,400
Bridgeport[b]	1	80	78	30	14	420	30,830
St. Louis	1&2	125	116	38.2	28.1	1,073	96,000
Baltimore[b]	2	200	114	26	22	572	60,580
Chicago	7	200	125	26.3	27.8	1,462[c]	149,000
Milwaukee	7 & 8	310	122	44.1	29.9	1,319	136,000
Chicago	8	325	141	39.6	28.1	2,226	254,000
Lakeland	3	364	156	43	45	1,935	210,000

Furnace Plan Area Ranking for Suspension Fired Boilers

Location	Unit No.	Furnace Plan Area Ratio (ft^2/MW)
Ames	7	11.3
St. Louis	1 & 2	8.6
Ames	8	8.3
Madison	8 & 9	7.6
Rochester	3	7.6
Chicago	7	7.3
Chicago	8	6.8
Lakeland	3	5.3
Milwaukee	7 & 8	4.3

Furnace Volume Ranking

Location	Unit No.	Furnace Volume Ratio (ft^3/MW)
Suspension Fired Boilers		
Chicago	8	782
Ames	7	780
St. Louis	1 & 2	768
Chicago	7	745
Lakeland	3	577
Madison	8 & 9	509
Rochester	3	490
Milwaukee	7 & 8	439
Cyclone Fired Boilers[d]		
Bridgeport	1	385
Baltimore	2	303

---

[a] Because of furnace configuration, furnace volume is not plan area times height.

[b] Dimensions, plan, area, and volume are for the main furnace, not the cyclone furnace.

[c] Chicago boilers are double furnace units, and plan area is twice width times depth.

[d] Main furnace plan area/MW does not apply to cyclone units as the RDF is combusted in the cyclone furnace. Main furnace volume/MW does apply to cyclone units because this is the space through which cofiring fly ash must pass.

Other operating problems included ash hopper fires, clogging of the ash/sluice water treatment system at Milwaukee, plugging of the sluice water overflow by floating debris at Chicago and Milwaukee, and high organic loading of the ash sluice water causing septic conditions at Chicago.

OPERATING PROBLEM SOLUTIONS

As discussed in the last section, most of the operating problems have been overcome by the utilities. The most severe problems and their solutions are summarized in Table 5. Reduction of RDF ash content, installation of bottom dump grates, and avoidance of boilers with high heat release rates appear to have eliminated most of the problems. An exception is the decrease in ESP collection efficiency, whose solution would require major modification of the ESP, replacement by a fabric filter, or some form of ESP augmentation, such as flue gas conditioning. These solutions will likely form the basis for the RDF cofiring guidelines being developed by Argonne and EPRI.

NONTECHNICAL ISSUES

Due to a number of nontechnical issues, there is little incentive in most cases for electric utilities to cofire RDF in utility boilers (6). These issues include:

- Utilities are not compensated for the increased risk of burning refuse in their boilers.
- Utilities can pay only a fraction of the value of coal or oil for RDF in order to not affect the cost of power generation to their customers.
- RDF cofiring may require derating of the unit and incur capacity and replacement power charges.
- An economic dispatch penalty may be charged if the unit is operated off peak to accommodate waste disposal.
- Higher revenues can be generated to offset the net cost of waste disposal by sale of electricity and cogenerated steam from a dedicated facility.

For example, as shown in Table 6, the price paid for RDF is the difference between the value of the fuel saved by substituting RDF for coal and the incremental operation and maintenance expense resulting from RDF cofiring (7). If the incremental O and M cost is high, the resulting RDF price paid by the utility becomes a fraction of the cost of the primary coal or oil fuel and can even be negative in some cases, i.e. the utility is paid to burn RDF. The result is low revenues from RDF sales and a high net waste disposal cost.

TABLE 5

SEVERE OPERATING PROBLEMS AND SUGGESTED SOLUTIONS

Problem	Cause	Suggested Solutions
o Upper furnace wall slagging	o Amount and slagging potential of RDF ash o High heat release rate vs. boiler plan area and volume	o Reduced RDF ash content o Avoid boilers with high heat release rates
o ESP efficiency decrease	o Increased volume and particle size of fly ash o Increased unburned combustibles in fly ash	o Replace ESP with baghouse o Augment ESP
o Corrosion of boiler tubes	o RDF ash in contact with tube wall in presence of reducing atmosphere o Uneven overfire air distribution	o Refractory lining above dump grate o Even distribution of overfire air
o High bottom ash accumulation rate	o High RDF ash content	o Reduced RDF ash content o Bottom dump grate
o Reduced performance of sluice water treatment, pluggage of sluice water overflows; fires in bottom ash hopper	o Floating material in bottom ash hopper	o Bottom dump grate
o Septic sluice water	o Unburned organics in bottom ash	o Bottom dump grate

TABLE 6

Example Calculation - Fluff RDF Cofiring In A Utility Boiler

Basis: 500 MW unit, 260,000 t/yr MSW, 1.75 x 10^9 kWh/yr

		Mills/kWh	10^6 $/yr
Reference cost of electricity			
o Coal @ 1.70 $/$10^6$ Btu		16.6	
o Variable O&M		3.5	
	Total	20.1	35.2
Less utility RDF firing costs			
o Added fixed charge		0.6	1.1
o Added fixed O&M		0.3	0.5
o Variable O&M		3.6	6.3
o Coal @ 1.70 $/$10^6$ Btu		15.0	26.3
		19.5	34.2
Equals utility RDF payment			
o 10^6 $/yr			1.0
o $/t MSW			3.9

		10^6 $/yr	$/t MSW
Municipal RDF process costs			
o Fixed charge		5.4	20.9
o Fixed O&M		2.8	10.8
o Variable O&M		1.5	5.7
	Total	9.7	37.4
Less utility RDF payment		1.0	3.9
Equals breakeven tipping fee		8.7	33.5

One exception appears to be the City of Lakeland, Florida's new McIntosh Unit 3, which was designed to cofire coal and RDF. The RDF is produced by a very simple low-cost RDF processing facility reported to produce RDF at a net disposal cost of less than $10/ton MSW. RDF cofiring would also be beneficial to the utility in cases where it enables lost capacity to be recovered, e.g. in units limited by coal pulverizer capacity.

In spite of the recent improved RDF cofiring experience in utility boilers, the nontechnical issues and the lack of incentive to participate have shifted most utility and community interest toward refuse disposal in dedicated refuse-fired plants producing steam and/or electricity.

DEDICATED REFUSE FIRED FACILITIES

Projects involving utility purchase of steam or electricity from dedicated facilities include those at Hempstead, New York, Miami, Florida, Pinellas County, Florida, and Gallatin, Tennessee. Future projects include those under construction in Westchester County, New York and Baltimore, Maryland, and the planned conversion of the facility in Saugus, Massachusetts to electricity generation.

Except for the Gallatin plant, these plants use proven European waterwall incineration technology and burn unprocessed MSW. The Gallatin plant started up in 1982 and uses two rotary waterwall combustor boilers to dispose of 150 tons/day of refuse.

In order to avoid chloride corrosion attack on the steam generator tubes, steam temperatures and pressures are generally limited to 900 psig, and 850°F, in comparison to 2400 psi and 1000°F in a modern utility boiler.

Advantages of the dedicated facilities include:

- Boiler is designed to burn refuse which avoids O and M problems of retrofitted boiler.
- Risk to electric utility is minimized.
- Electricity is sold to utility at avoided cost.
- Cogeneration of steam and electricity is possible, leading to maximization of overall energy recovery and revenues from energy sales.
- In return for tax writeoffs, financing can be more easily obtained from equity investors for dedicated energy recovery projects, which reduces the bond financing required and ultimately the net waste disposal cost.

For example, Table 7 summarizes energy recovery, capital cost, and net waste disposal cost from a recently-completed evaluation of a proposed 800 ton/day refuse-fired cogeneration facility in Nashville, Tennessee

TABLE 7

Estimated Cost And Performance Of Proposed Refuse-Fired Cogeneration Facility (Ref 8)

MSW Capacity:	800 tons/day 262,800 tons/year at 90% capacity factor	
Steam Conditions:	600 psig, 600°F	
Number of Modules:	2 operating, I standby	
Total Capital Requirement (end 1982 $):	$100.784 million	
Total O&M (end 1982 $):	$1.61 million/yr.	
	No Steam Sales	Maximum Steam Sales
Steam Sales (lb/hr):	0	163,880
Net Electric Capacity (kW):	13,280	1320
Overall Energy Recovery (%):	15.7	65.5
Levelized Busbar Cost (mills/kWh, 1983-2012):	176	22
Breakeven Tipping Fee (end 1982 $/ton MSW):	34.20[b]	18.51a,b)

---

a) Steam Price: $6.64/1000 lb 275 psi steam
b) Electricity Price: 3.5 ¢/kWh

(8). Two cases are compared--operation with zero steam sales and operation with maximum steam sales. For the assumptions made in the evaluation, a shift from zero to maximum steam sales increases overall thermal energy recovery from 15.7 to 65.5 percent and reduces the net waste disposal cost from $34 to $18.5 per ton MSW.

EPRI PROGRAM

EPRI's program on municipal solid waste (MSW) utilization is conducted in the Fluidized Combustion and Alternate Fuels Program of the Coal Combustion Division. The overall objectives of the program are:

- Assess the impact of cofiring refuse-derived fuel (RDF) with coal or oil on power plant performance and reliability,
- Maintain an up-to-date technical and economic assessment of refuse-to-energy technology.

Table 8 lists published reports and completed and on-going projects from the program. Major activities have included technical, conceptual design, and economic assessments of refuse-to-energy technologies (RP261, RP1255, and RP2190; EPRI Reports 261-1, CS-2274, CS-2409 and CS-3377), field evaluation of boiler corrosion and field and laboratory evaluation of boiler slagging and fouling potential at Wisconsin Electric Power Company's Oak Creek Station (RP898-1; EPRI Report CS-1983, Vol. 1 and 2), evaluations of RDF preparation process flowsheets and the impact of screening on RDF quality (RP1180-6; Reports FP-1249 and CS-1802), and EPRI seminars on MSW utilization (1977, 1980, and 1982; EPRI Reports WS79-225 and CS-2723).

CONCLUSIONS

- Typical utility role is as customer for refuse energy.
- Major operating problems with RDF cofiring have been largely overcome by utilities.
- Nontechnical issues have shifted most utility interest away from RDF cofiring.
- Higher revenues are possible from the sale of electricity and coegenerated steam than RDF.
- Trend is toward refuse-fired cogeneration plants.

TABLE 8

EPRI Program - Municipal Solid Waste As A Utility Fuel

Projects	Contractor	Reports
o "Fuels From Municipal Refuse For Utilities: Technical Assessment"	Bechtel	261-1 (1975, RP261-1)
o "Annotated Bibliography on Supplemental Firing of Municipal Solid Waste in Electric Utility Boilers"	Battelle	FP-678 (1977)
o "Cofiring of RDF and Coal at Oak Creek"	Combustion Engineering	CS-1983, Vol. 1 (1981, RP898-1) Vol. 2 (1982)
o "Impact of Screening on RDF Quality"	Cal Recovery Systems	FP-1249 (1979, RP1180-6) CS-1802 (1981)
o "Evaluation of Energy Recovery From Municipal Solid Waste in Oil-Fired Power Plants"	Stone & Webster Mgmt. Consultants	CS-2274 (1982, RP1255-90)
o "Technology Assessment: Municipal Solid Waste As A Utility Fuel"	EBASCO Services	CS-2409 (1982, RP1255-3)
o "Guidelines for Cofiring RDF in Utility Boilers"	Midwest Research Inst.	1985 (RP1861)[a]
o "Feasibility and Design of Proposed Nashville Refuse-Fired Cogeneration Facility	Nashville Electric Service	CS-3377 (1984, RP2190-1)
o "Design and Operation of Sumner County Refuse-Fired Cogeneration Facility"	TVA	1984 (RP2190-2)
Seminars		
o "Utilization of Refuse Derived Fuels by Electric Utilities	San Diego, CA November, 1977	
o "Municipal Solid Waste as a Utility Fuel"	Ft. Lauderdale, FL, January,	Proceedings WS79-225 1980(1980)
o "Municipal Solid Waste as a Utility Fuel"	Miami Beach, FL May, 1982	Proceedings CS-2723 (1982)

---

[a] Data analysis completed during 1983 under Argonne National Laboratory sponsorship.

REFERENCES

1. Fiscus, D. E.., H. D. Ege, R. D. Petersen, J. C. Glaub, G. M. Savage, A. W. Joensen, "Study of Existing RDF Cofiring Experience - Phase I, Volume I Final Report", Contract No. 31-109-38-6832, Argonne National Laboratory, Argonne, IL., October 1983.

2. "Study of Existing RDS Cofiring Experience - Phase I, Volume II, Appendixes", Contract No. 31-109-38-6832, Argonne National Laboratory, Argonne, IL., October 1983.

3. "Study of Existing RDF Cofiring Experience - Phase II, Volume III Final Report", Contract No. 31-109-38-6832, Argonne National Laboratory, October 1983.

4. Fiscus, D. E., R. D. Petersen, J. C. Glaub, A. W. Joensen, C. V. Pearson and C. R. McGowin. "RDF Cofiring in the Electric Utility Industry," ASME Solid Waste Processing Conference, Nashville, TN., June 10, 1983.

5. Fiscus, D. E., et al. "Electric Utility Operating Problems in Cofiring RDF," Joint Power Generation Conference, Indianapolis, Indiana (September 26, 1983).

6. "Megawatts from Waste," EPRI Journal, Vol. 8, No. 1, pp. 20-25 (January/February 1983).

7. "Technical Assessment: Municipal Solid Waste as a Utility Fuel", EPRI CS-2409, May 1982.

8. "Feasibility and Design of the Proposed Nashville Refuse-Fired Cogeneration Facility," EPRI CS-3377 (January 1984).

OGDEN MARTIN SYSTEMS
OF LAKE, INC.

40 LANE ROAD
P.O. BOX 2615
FAIRFIELD, NEW JERSEY 07007-2615
(201) 882-9000

AN OGDEN PROJECTS COMPANY

VIA CERTIFIED MAIL

December 21, 1990

Mr. Alan Zahm
State of Florida
Department of Environmental Regulation
3319 McGuire Boulevard
Suite 232
Orlando, FL 32803-3767

Reference: Lake County Resource Recovery Facility
Okahumpka, Florida
LK0673L, Project C-1025

Subject: Reference Permit AC 35-115379
PSD-FL-113

Dear Mr. Zahm:

In keeping with Specific Condition 7.a of the above referenced permit, I am writing to notify your office of the schedule of compliance testing for air emissions. Environmental compliance tests are scheduled to take place from January 14 - 18, 1990 at the Lake County Facility.

Additionally please find attached a copy of our Source Test Plan for the air emissions testing. Note that this plan includes the certification of the continuous emissions monitoring (CEM) system during such testing.

Please feel free to call me at (201) 882-7246 if you need further information or have any comments or questions.

Very truly yours,

L Peter Young

L. Peter Young
Project Manager

cc: C. Fancy, FDER (w/att.)
C. Phillips, FDER
D. Findell, Lake County (w/att,)
J. Treshler, OMS
D. Lehman, OMS
pf 5.1 Air Permit

pja/1241

SOURCE TEST PLAN

Source Information

Type Unit:	Municipal Solid Waste-to-Energy Facility
Facility:	Ogden Martin Systems of Lake, Inc. 3830 Rogers Industrial Park P. O. Box 189 Opahumka, FL 34762
Purpose of Test:	Demonstration of Compliance with Florida Department of Environmental Regulation, Permit No. AC 35-115379
Person(s) to Contact:	Mr. George Ball-Lloveria, Facility Manager (904) 365-1611
	Mr. John Klett, Executive Vice President-Facility Operations (201) 882-7158

Testing Firm Information

Company:	Contractor to be selected
Person(s) to Contact:	Mr. G. J. Aldina Director, Environmental Testing (201) 882-4136
	Mr. Todd B. Westersund Senior Environmental Engineer (201) 882-4144

Testing Information

Procedure:	Testing two (2) municipal solid waste-fired boilers for various air pollutant emissions. Performance Specification Testing (PST) of the Continuous Emission Monitoring System (CEMS).
Proposed Test Dates:	January 14 through 16, 1990

Prepared by: T. B. Westersund

December 13, 1990
OPI Report No. 308

TABLE OF CONTENTS

1.0 INTRODUCTION

A contractor for Ogden Martin Systems of Lake, Inc., will test the following air pollutant emissions from the Lake County Resource Recovery Facility for determination of compliance with Florida Department of Environmental Regulation, Permit No. AC 35-115379, Specific Condition 4. To determine compliance with Specific Condition 5, Performance Specification Testing (PST) will be performed on the Continuous Emission Monitoring System (CEMS).

Pollutant	Reference Sampling Method
Particulate Matter (PM)	U.S. EPA Method 5
Sulfur Dioxide (SO_2)$^{(1)}$	U.S. EPA Method 6C
Oxides of Nitrogen (NO_x)	U.S. EPA Method 7E
Carbon Monoxide (CO)	U.S. EPA Method 10
Volatile Organic Compounds (VOC)	U.S. EPA Method 25A (dry)
Lead, Mercury (Pb, Hg)	U.S. EPA Method 12/101A
Fluorides (F)	U.S. EPA Method 13B
Beryllium (Be)	U.S. EPA Method 104
Visible Emissions (VE)	U.S. EPA Method 9
Hydrogen Chloride (HCl)$^{(1)}$	U.S. EPA Proposed Method 26

$^{(1)}$$SO_2$ and HCl will be sampled at the inlet and outlet of the air pollution control equipment.

2.0 SCHEDULE OF ACTIVITIES

2.0 SCHEDULE OF ACTIVITIES

Day	Unit	Parameter	Reference Method	Replicates	Approx. Sampling Volume (ft^3)	Approx. Sampling Time (min)
1	---	Setup				
2	1	PM/Pb, Hg, Be	EPA 5,12/101A,104	1,2,3	60	120
	1	Fluorides	EPA 13B	1,2,3	60	120
	1	VE	EPA 9	1,2,3	---	60
	2	SO_2,(1)NO_x,CO,VOC	EPA 6C,7E,10,25A	1,2,3	15	60
	2	SO_2,CO(PST)	EPA 6C,10	4-9	15	30
	2	HCl(1)	EPA Proposed 26	1,2,3	30	60
3	2	PM/Pb, Hg, Be	EPA 5,12/101A,104	1,2,3	60	120
	2	Fluorides	EPA 13B	1,2,3	60	120
	2	VE	EPA 9	1,2,3	---	60
	1	SO_2,(1)NO_x,CO,VOC	EPA 6C,7E,10,25A	1,2,3	15	60
	1	SO_2,CO(PST)	EPA 6C,10	4-9	15	30
	1	HCl(1)	EPA Proposed 26	1,2,3	30	60

---

(1)SO_2 and HCl will be sampled at the inlet and outlet of the air pollution control equipment.

3.0 QUALITY ASSURANCE/QUALITY CONTROL

3.0 QUALITY ASSURANCE/QUALITY CONTROL

A quality assurance/quality control program will include the use of designated sampling and analytical equipment according to the U.S. EPA referenced methods and calibration gases traceable to the National Institute of Standards and Technology (NIST), formerly NBS.

Inert sample containers, field data forms, from the U.S. EPA Quality Assurance Handbook for Air Pollution Measurement Systems, Volume III, Stationary Source Specific Methods, EPA-600/4-77-027b, and chain of custody forms will be used to promote quality assurance.

4.0 SOURCE TEST INFORMATION

FACT SHEET ... **OGDEN PROJECTS, INC.**

OGDEN MARTIN SYSTEMS, INC.
OGDEN ENVIRONMENTAL SERVICES, INC.

LAKE COUNTY RESOURCE RECOVERY FACILITY
(Interim Operation)

GENERAL

Owner/Operator:	Ogden Martin Systems of Lake, Inc. 3830 Rogers Industrial Park P.O. Box 189 Okahumpka, FL 34762 (904) 365-6595
Client:	Lake County, Fla.
Construction Date:	November 1988
Contracted Commercial Operations Date:	March 1991
Guaranteed Construction Price:	$60 million
Financed Costs:	$70 million tax exempt revenue bonds/$9 million taxable revenue bonds/$10 million company equity

TECHNICAL INFORMATION

Site:	15 acres in Lake County, Fla.
Waste-to-Energy System:	Two, 264 tons per day waterwall furnaces with Martin reverse-reciprocating grates and ash handling system
Waste Type:	Municipal, residential and commerical solid waste
Rated Refuse Burning Capacity:	528 tons per day
Guaranteed Throughput:	163,000 tons per year
Guaranteed Waste Delivery:	130,000 tons per year
Boiler Design:	865 psig/830°F superheater outlet conditions
Air Pollution Control Equipment:	Dry flue gas scrubbers and fabric filter baghouses
Energy Generation at Rated Capacity:	14.5 MW
Sold To:	Florida Power Corporation

-###-

0790

4.2 SAMPLING AREA DESCRIPTION

The sampling points for the performance of the test program are at the sampling platform, 80 feet above the grade on the main stack (sampling ports are at an elevation of 85 feet). There are three flues, each with an inside diameter of 5 feet, 3 inches. Each flue has two sampling ports, 90 degrees apart and 6 inches in diameter. These sampling ports are located greater than 8 diameters after a disturbance and greater than 8 diameters before the stack outlet (see drawings on following pages for details).

Estimated typical flue gas conditions at both flues are as follows:

Temperature: 270°F
Moisture Content: 16%
Flue Gas Flow: 52,000 SCFM @ 68°F
Flue Gas Velocity: 55 ft/sec

5.0 OPERATIONAL PARAMETERS

5.0 OPERATIONAL PARAMETERS

During the air pollutant emissions testing, plant process data will be monitored and collected by OMS personnel to ensure representative operation of the facility. Steam flow rate will be documented to ensure representative heat input at design conditions.

Florida Department of Environmental Regulation

Twin Towers Office Bldg. ● 2600 Blair Stone Road ● Tallahassee, Florida 32399-2400

Bob Martinez, Governor
Dale Twachtmann, Secretary
John Shearer, Assistant Secretary

October 5, 1989

Mr. Joe Aldina
Ogden Martin Systems, Inc.
40 Lane Road
Fairfield, New Jersey 07007-2615

Dear Mr. Aldina:

Re: Lake County Waste-to-Energy Facility
AC 35-115379, PSD-FL-113

This letter is in response to your request for a clarification of the permit condition concerning CEM requirements and the possibility for a time share CEM system.

Specific Condition No. 5 of the above mentioned permit requires a CEM for each unit for each pollutant specified. For example, for two units you need two opacity CEMs. Therefore, in accordance with the permit conditions, a time share system would not be acceptable.

If you need any further clarification, please call Pradeep Raval at (904)488-1344 or write to me at the above address.

Sincerely,

C. H. Fancy, P.E.
Bureau of Air Regulation

CHF/PR/t

cc: C. Collins, C District
W. Aronson, EPA
C. Shaver, NPS
P. Raval
B. Andrews
G. Pennington

● **SENDER:** Complete items 1 and 2 when additional services are desired, and complete items 3 and 4.
Put your address in the "RETURN TO" Space on the reverse side. Failure to do this will prevent this card from being returned to you. The return receipt fee will provide you the name of the person delivered to and the date of delivery. For additional fees the following services are available. Consult postmaster for fees and check box(es) for additional service(s) requested.

1. ☐ Show to whom delivered, date, and addressee's address. *(Extra charge)*
2. ☐ Restricted Delivery *(Extra charge)*

3. Article Addressed to:

Mr. Joe Aldina
Ogden Martin Systems, Inc.
40 Lane Road
Fairfield, New Jersey 07007-2615

4. Article Number
P 938 762 711

Type of Service:
☐ Registered
☒ Certified
☐ Express Mail
☐ Insured
☐ COD
☐ Return Receipt for Merchandise

Always obtain signature of addressee or agent and DATE DELIVERED.

5. Signature — Address
X

6. Signature — Agent
X

7. Date of Delivery

8. Addressee's Address *(ONLY if requested and fee paid)*

PS Form 3811, Mar. 1988 ★ U.S.G.P.O. 1988-212-865 **DOMESTIC RETURN RECEIPT**

P 938 762 711

RECEIPT FOR CERTIFIED MAIL

NO INSURANCE COVERAGE PROVIDED
NOT FOR INTERNATIONAL MAIL
(See Reverse)

Sent to
Mr. Joe Aldina, Odgen Martin Systems

Street and No.
40 Lane Road

P.O., State and ZIP Code
Fiarfield, NJ 10770-2615

Postage	$
Certified Fee	
Special Delivery Fee	
Restricted Delivery Fee	
Return Receipt showing to whom and Date Delivered	
Return Receipt showing to whom, Date, and Address of Delivery	
TOTAL Postage and Fees	$

Postmark or Date

Permit: AC 35-115379
PSD-FL-113
Mailed: 10-6-89

PS Form 3800, June 1985

Florida Department of Environmental Regulation

Twin Towers Office Bldg. ● 2600 Blair Stone Road ● Tallahassee, Florida 32399-2400

Bob Martinez, Governor
Dale Twachtmann, Secretary
John Shearer, Assistant Secretary

FAX TRANSMITTAL LETTER

TO:

NAME: JOE ALDINA

AGENCY: OGDEN MARTIN

TELEPHONE: (fax) 201 882 8989

NUMBER OF PAGES (INCLUDING COVER SHEET) 2

FROM:

NAME: P. RAVAL

AGENCY: DER

IF ANY OF THE PAGES ARE NOT CLEARLY RECEIVED, PLEASE CALL IMMEDIATELY. PHONE NO. 904 488 1344

SENDERS NAME: P. RAVAL

DATE: 10-5-89

COMMENTS:

OGDEN MARTIN
SYSTEMS, INC.

AN OGDEN COMPANY

40 LANE ROAD
CN 2615
FAIRFIELD, NEW JERSEY 07007-2615

BRIAN BAHOR
MANAGER - ENVIRONMENTAL TECHNOLOGY
(201) 882-72

November 22, 1988

NOV 1988
CENTRAL FLORIDA DISTRICT

Mr. Tom Sawicki
State of Florida
Department of Environmental Regulation
Central Florida District
3319 Maguire Boulevard
Suite 232
Orlando, FL 32803-3767

Subject: Lake County Resource Recovery Facility
Permit No. SC35-117519

Dear Mr. Sawicki:

A letter dated October 12, 1987 was issued by Mr. Alexander of your department to the prior owners of the referenced permit NRG/Recovery Group, Inc. This letter, which is now part of the referenced permit, requires that a certified copy of the land ownership deed is submitted to your department prior to construction commencement.

The enclosed copy of the certified deed is submitted in accordance with this requirement.

The project schedule is at a point where surface based construction is scheduled to commence during the week of November 27, 1988. Surface construction includes clearing and grubbing and mobilization of work crews including trailer placement.

I believe that this submission satisfies the requirement of the referenced permit condition. If any questions exist, please do not hesitate to contact me direct or the Project Manager, Mr. Peter Young at (201) 882-7246.

Very truly yours,

OGDEN MARTIN SYSTEMS, INC.

Brian Bahor

Brian Bahor, Manager
Environmental Technology

BB:sh/395
Encl.

DEPARTMENT OF ENVIRONMENTAL REGULATION

ROUTING AND TRANSMITTAL SLIP

ACTION NO

ACTION DUE DATE

1. TO: (NAME, OFFICE, LOCATION)
~~Clair Fancy~~ — Initial — Date 11/22/88
2. ~~Air Resources Mgmt, Permitting~~ — Initial — Date
3. ~~Air Section~~ — Initial — Date
4. Patty – For permit file — Initial — Date

REMARKS:

RECEIVED
NOV 28 1988
DER BAQM

INFORMATION

- ☐ Review & Return
- ☐ Review & File
- ☐ Initial & Forward
- ☐

DISPOSITION

- ☐ Review & Respond
- ☐ Prepare Response
- ☐ For My Signature
- ☐ For Your Signature
- ☐ Let's Discuss
- ☐ Set Up Meeting
- ☐ Investigate & Report
- ☐ Initial & Forward
- ☐ Distribute
- ☐ Concurrence
- ☐ For Processing
- ☐ Initial & Return

FROM: A. T. Sawicki, P.E.

DATE

PHONE

OGDEN MARTIN SYSTEMS, INC.

AN OGDEN COMPANY

POST OFFICE BOX 0709
BRANDON, FL 34299-0709

JOSEPH R. TRESHLER
GENERAL MANAGER
MARKETING AND OPERATIONS
SOUTHEASTERN UNITED STATES
(813) 684-5688

RECEIVED
NOV 22 1988
Office of the Secretary

November 18, 1988

Mr. Dale Twachtmann
Secretary
Department of Environmental Regulation
State of Florida
2600 Blair Road
Tallahassee, FL 32399-2400

Dear Dale,

I thought you might appreciate one of the groundbreaking mementos from the ceremonies held on November 15, 1988 for the Lake County Waste to Energy Facility.

Groundbreaking ceremonies provide a good point of reflection for members of a project team. For some members it symbolizes the completion of long, exacting specifications, permitting, financing, and contract development efforts. For other members it is the start of the adventure to construct and then operate the facility.

We at Ogden Martin Systems, Inc., sincerely appreciate the prompt and professional attention we received in completing the permitting requirements for this project. We look forward to continuing this relationship with your staff through the construction phase and into the ongoing operational phase of this facility.

Once again, thank you for your continued support in the development of resource recovery options for Florida Communities.

Best regards,

J. R. Treshler

JRT/k
cc: G. Mills
P. Young
B. Stone

RECEIVED
NOV 22 1988
DER - BAQM

Patty -
for
file

OGDEN MARTIN SYSTEMS, INC.

AN OGDEN COMPANY

40 LANE ROAD
CN 2615
FAIRFIELD, NEW JERSEY 07007-2615
(201) 882-9000

RECEIVED
NOV 14 1988
DER - BAQM

Clair,

Thanks again for the cooperation you extended when requested to respond under such a tight schedule. Your responsiveness helped the project to succeed. Hope you can attend the ceremonies.

Simon Gabor

WARRANTY DEED
FROM INDIVIDUAL TO CORPORATION

RAMCO FORM 34

This Warranty Deed *Made the* 9th *day of* November *A. D. 19* 88 *by*
F. BROWNE GREGG, as Trustee
hereinafter called the grantor, to
NRG/RECOVERY GROUP, INC.
a corporation existing under the laws of the State of FLORIDA *, with its permanent postoffice address at* 40 LANE ROAD, FAIRFIELD NEW JERSEY *,*
hereinafter called the grantee:

(Wherever used herein the terms "grantor" and "grantee" include all the parties to this instrument and the heirs, legal representatives and assigns of individuals, and the successors and assigns of corporations)

Witnesseth: *That the grantor, for and in consideration of the sum of $* 10.00 *and other valuable considerations, receipt whereof is hereby acknowledged, hereby grants, bargains, sells, aliens, remises, releases, conveys and confirms unto the grantee, all that certain land situate in* LAKE *County, Florida, viz:*

AS PER SCHEDULE "A" ATTACHED HERETO AND BY REFERENCE MADE A PART HEREOF.

THE PROPERTY BEING CONVEYED HEREIN DOES NOT CONSTITUTE ANY PART OF THE HOMESTEAD OF GRANTOR.

Together *with all the tenements, hereditaments and appurtenances thereto belonging or in anywise appertaining.*

To Have and to Hold, *the same in fee simple forever.*

And *the grantor hereby covenants with said grantee that the grantor is lawfully seized of said land in fee simple; that the grantor has good right and lawful authority to sell and convey said land; that the grantor hereby fully warrants the title to said land and will defend the same against the lawful claims of all persons whomsoever; and that said land is free of all encumbrances, except taxes accruing subsequent to December 31, 19*87.

In Witness Whereof, *the said grantor has hereunto set* his *hand and seal the day and year first above written.*

Signed, sealed and delivered in our presence:

Susan E. Strickland

F. Browne Gregg
F. Browne Gregg, as Trustee (L.S.)

(L.S.)

STATE OF FLORIDA,
COUNTY OF LAKE

I HEREBY CERTIFY that on this day, before me, an officer duly authorized in the State aforesaid and in the County aforesaid to take acknowledgments, personally appeared
F. BROWNE GREGG, as Trustee,

to me known to be the person described in and who executed the foregoing instrument and he acknowledged before me that he executed the same.

WITNESS my hand and official seal in the County and State last aforesaid this 9th day of November, A. D. 19 88.

Florence E. Staneff
NOTARY PUBLIC - My Commission
Expires: 9-10-91

This Instrument prepared by:
Address

PARCEL NO. 1:
That part of the Southeast 1/4 of the Southeast 1/4 of Section 15 and that part of the Northeast 1/4 of the Northeast 1/4 of Section 22, Township 20 South, Range 24 East, in Lake County, Florida, and that part of Lot 8 in Roadside Subdivision, in Lake County, Florida, according to the plat thereof recorded in Plat Book 9, page 62, Public Records of Lake County, Florida, all bounded and described as follows: From the Southeast corner of said Section 15, run South 89 degrees 56'10" West along the South line of said Section 15 a distance of 25 feet to the West line of the right of way of County District Road No. 2-3110 and the point of beginning of this description. From said point of beginning run North 0 degrees 03'15" East along the Westerly line of said right of way 378.63 feet to the South line of the right of way of Jim Rogers Industrial Park Road; thence South 89 degrees 56'10" West along the South line of said right of way 435 feet; thence South 0 degrees 03'15" West 1002.63 feet to the South line of the North 624 feet of the Northeast 1/4 of said Section 22; thence North 89 degrees 56'10" East parallel with the North line of said Northeast 1/4 a distance of 436.69 feet to the West line of the right of way of County District Road No. 2-3110; thence North 0 degrees 06'03" West along the West line of said right of way 624 feet to the point of beginning.

PARCEL NO. 2:
That part of the Southeast 1/4 of the Southeast 1/4 of Section 15, and that part of the Northeast 1/4 of the Northeast 1/4 of Section 22, Township 20 South, Range 24 East, in Lake County, Florida, and that part of Lot 8 in Roadside Subdivision, in Lake County, Florida, according to the plat thereof recorded in Plat Book 9, Page 62, Public Records of Lake County, Florida, all bounded and described as follows: From the Southeast corner of said Section 15, run South 89 degrees 56'10" West along the South line of said Section 15 a distance of 25 feet to the West line of the right of way of County District Road No. 2-3110; thence North 0 degrees 03'15" East along the West line of said right of way 378.63 feet to the South line of the right of way of Jim Rogers Industrial Park Road; thence South 89 degrees 56'10" West along the South line of said right of way 435 feet to the point of beginning of this description. From said point of beginning continue South 89 degrees 56'10" West along the South line of said right of way 218 feet; thence South 0 degrees 03'15" West 1002.63 feet to the South line of the North 624 feet of the Northeast 1/4 of said Section 22; thence North 89 degrees 56'10" East parallel with the North line of said Northeast 1/4 a distance of 218 feet; thence North 0 degrees 03'15" East 1002.63 feet to the point of beginning.

PARCEL NO. 3:
That part of Sections 15 and 22, Township 20 South, Range 24 East, Lake County, Florida, described as follows: Commencing at the Southeast corner of said Section 15 (N.E. corner of Section 22), run South 89 degrees 56'10" West along the South line of said Section 15 a distance of 25.0 feet to the West right of way of County Road Dist. 2-3110; thence North 0 degrees 03'15" East along said right of way 378.63 feet to the South right of way of a road; thence South 89 degrees 56'10" West along said right of way 653.0 feet to the Point of Beginning, from said Point of Beginning, continue South 89 degrees 56'10" West along said South line 200.00 feet; thence South 0 degrees 03'15" West 1002.63 feet to the South line of the North 624 feet of the Northeast 1/4 of aforesaid Section 22; thence North 89 degrees 56'10" East parallel with the North line of said Northeast 1/4 a distance of 200.00 feet; thence North 0 degrees 03'15" East 1002.63 feet to the Point of Beginning.

THE ABOVE THREE PARCELS ARE DESCRIBED IN WHOLE AS FOLLOWS:
That part of Sections 15 and 22, Township 20 South, Range 24 East, Lake County, Florida, described as follows: Commencing at the Southeast corner of said Section 15 (N.E. corner of Section 22), run South 89 degrees 56'10" West along the South line of said Section 15 a distance of 25.0 feet to the West right of way of County Road Dist. 2-3110 and the Point of Beginning of this description; thence North 0 degrees 03'15" East along said right of way 378.63 feet to the South right of way of a road; thence South 89 degrees 56'10" West along said right of way 853.0 feet; thence South 0 degrees 03'15" West 1002.63 feet, more or less, to the South line of the North 624.0 feet of the Northeast 1/4 of aforesaid Section 22; thence North 89 degrees 56'10" East parallel with the North line of said Northeast 1/4 a distance of 854.69 feet to the aforesaid West right of way of County Road Dist. 2-3110; thence North 0 degrees 06'03" West along said West right of way 624.00 feet to the Point of Begininng.

Florida Department of Environmental Regulation

Twin Towers Office Bldg. ● 2600 Blair Stone Road ● Tallahassee, Florida 32399-2400

Bob Martinez, Governor   Dale Twachtmann, Secretary   John Shearer, Assistant Secretary

November 7, 1988

Mr. Brian Bahor
Ogden Martin Systems
40 Lane Road
Fairfield, New Jersey 07007-2615

Dear Mr. Bahor:

RE: Lake County Waste-to-Energy Facility
Permit Nos. AC 35-115379, PSD-FL-113

The Department has received the drawings submitted by you (C0101, M0044, M0045) dated November 3, 1988. The submittal of the drawings does not require any additional air regulatory review because the above referenced permit is not affected. The drawings will be added to update your file. Please submit the final drawings when available.

Sincerely,

C. H. Fancy, P.E.
Deputy Chief
Bureau of Air Quality
Management

CHF/pa

Fed. Exp
11-3-88
Fairfield, NJ

file copy

OGDEN MARTIN SYSTEMS, INC.

AN OGDEN COMPANY

40 LANE ROAD
CN 2615
FAIRFIELD, NEW JERSEY 07007-2615

BRIAN BAHOR
MANAGER - ENVIRONMENTAL TECHNOLOGY
(201) 882-7236

November 3, 1988

RECEIVED
NOV 4 1988
DER BAQM

Mr. Clair H. Fancy, P.E.
Deputy Chief
Bureau of Air Quality Management
State of Florida
Department of Environmental Regulations
2000 Blair Stone Road
Tallahassee, FL 32399-2400

Subject: Lake County Waste-to-Energy Facility
Reference Permit Nos. AC 35-115379 & PSD-FL-113

Dear Mr. Fancy:

I greatly appreciate the time and assistance you have given us relevant to permit questions pertaining to the above project. As our local Florida counsel expressed in our conference call today, there is a concern that the general conditions to DER permits require that construction of the project be done in accordance with approved drawings or exhibits which were submitted by NRG/Recovery Group at the time application for the permits was made. Since Ogden Martin Systems of Lake, Inc. (OMSL) intends to construct the project in a different manner than originally contemplated by NRG/Recovery Group, it could be in technical violation of the permits unless its drawings were approved. Accordingly, we herewith submit the drawings which, although not complete at this state, do represent the general parameters by which OMSL will construct the facility.

Two sets of current drawings are submitted for your review with each set consisting of three drawings (C0101, M0044 and M0045). Please note that these drawings are not final, however, OMSL will submit final drawings upon their availability. A specific correction that should be noted on Drawing No. M0044-Rev. B is the correct stack height of 199 feet (elevation 303).

We would greatly appreciate the Florida Department of Environmental Regulation substituting these drawings as the "approved drawings and exhibits," pursuant to the General Conditions of the above-referenced permits and supplying us with a written acknowledgement of this fact.

In order to facilitate your response, please use our Federal Express Account Number which is #1163-6430-1 or one of our telecopy numbers, either 201/882-8239 or 201/882-8207. A special account number is not available for the telecopy number, however, OMSL will pay for the phone bill which occurs by the use of these numbers. For your convenience a prepared Federal Express form is enclosed.

Thank you again for your assistance and cooperation.

Sincerely,

OGDEN MARTIN SYSTEMS OF LAKE, INC.

Brian Bahor

Brian Bahor, Manager
Environmental Technology

BB:sh/378a
Encls.

VIA FEDERAL EXPRESS

copied: Pradeep Raval