EPA-650/2-74-073

August 1974

Environmental Protection Technology Series

ST. LOUIS/UNION ELECTRIC REFUSE FIRING DEMONSTRATION AIR POLLUTION TEST REPORT

Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

January 1975

We are pleased to enclose the St. Louis/Union Electric Refuse Firing Demonstration Air Pollution Test Report, which presents the results of air emission tests performed during October through December 1973 independently by Midwest Research Institute (MRI) and by the Union Electric Company (UE). The MRI tests are part of the U.S. Environmental Protection Agency's (EPA) comprehensive evaluation of the program conducted jointly by the City of St. Louis, UE, and EPA's Office of Solid Waste Management Programs and Office of Research and Development to demonstrate the use of prepared solid waste as a supplementary fuel in a coal-burning electric utility boiler. MRI used the EPA-approved testing method to measure particulate and gaseous emissions. UE employed the American Society of Mechanical Engineers testing method to measure particulates only, using a separate sampling program. The report provides data on both sets of tests.

Based on the MRI tests, it appears that gaseous emissions (sulfur oxides, nitrogen oxides, hydrogen chloride, and mercury vapor) are not significantly affected by combined firing of waste and coal.

Both MRI and UE tests found that particulate levels per cubic foot of exhaust gas at the inlet to the air pollution control device (the electrostatic precipitators) were not affected by combined firing; however, total inlet particulate levels did increase because of increases in the stack gas flowrate.

The MRI tests did not find an increase in particulate emissions when solid waste was combined with coal. However, the UE tests did find an increase in such emissions. We want to call to your attention, therefore, the fact that this report is not conclusive on this subject. There is evidence, furthermore, to indicate that neither set of tests provide an optimum representation of combined firing of solid waste and coal. It appears that the electrostatic precipitator was not properly conditioned prior to the tests and could have been tuned for better particulate collection performance.

The report recommends that further tests be conducted to complete the characterization of particulate emissions and to support the development of Federal and State air emission control standards. In response to this recommendation, a second series of tests, conducted independently by EPA and UE, were initiated in late 1974 and are expected to be completed by mid-1975.

--ARSEN J. DARNAY
Deputy Assistant Administrator
for Solid Waste Management Programs

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ST. LOUIS/UNION ELECTRIC REFUSE FIRING DEMONSTRATION AIR POLLUTION TEST REPORT

by

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Contract No. 68-02-1324
Task No. 11
ROAP No. 21AQQ010
Program Element No. 1AB013

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Prepared for

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U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

August 1974

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

ABSTRACT

The report gives results of tests performed to determine the effects of mixed-fuel firing on boiler emissions and electrostatic precipitator (ESP) performance, using shredded municipal wastes as a supplementary fuel in a 140 megawatt coal-fired utility boiler. Tests were performed at boiler loads of 75 to 140 megawatts when firing coal-only and when firing fuel mixtures which provided solid waste heat inputs to the boiler of 9 to 27%. Test measurements included: total particulate, particulate size distribution, O_2, CO_2, CO, NO, SO_2, SO_3, Cl^-, Hg_v, in situ fly ash resistivity, and ESP operating conditions. Firing mixed fuels caused no statistically significant changes in gaseous pollutant emissions. Particulate stack emissions increased, as a result of an ESP performance loss related to changes in ESP electrical operating conditions and gas flow volumes. However, excessive sparking rates on some mixed-fuel tests indicated that the ESP could have been tuned for better collection. ESP performance was significantly affected by the fuel mix (coal and waste). Additional tests will be required to establish the magnitude of performance losses which may result from mixed-fuel firings.

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ACKNOWLEDGEMENTS

This report was prepared for EPA/CSL under Contract No. 68-02-1324. The test programs discussed in this report was performed by Midwest Research Institute, Southern Research Institute, EPA and Union Electric personnel.

Dr. Larry J. Shannon, Head, Environmental Systems Section (MRI), Dr. F. I. Honea and Mr. M. P. Schrag were the principal MRI authors of this report. Other MRI personnel who contributed were Mr. Dave Bendersky, Mr. Emile Baladi and Ms. Christine Guenther.

Mr. James D. Kilgroe, Project Officer (EPA/CSL) planned and directed the tests and was a principal author of the report.

Dr. Grady B. Nichols, Head, Particulate Control Section, Southern Research Institute, coordinated SRI activity and authored a report which was incorporated into this document.

The cooperation and aid of Union Electric personnel is also acknowledged. Mr. Dave Klumb, Mr. K. R. Bledsoe, Mr. Jim Honeywell, Mr. Jake Wagner, and Mr. Harvey Morris were especially helpful. The cooperation of Union Electric's Betterment Engineering Office who provided information on Union Electric's test results reported herein is also gratefully acknowledged.

Approved for:

MIDWEST RESEARCH INSTITUTE

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31 August 1974

SUMMARY

This report presents the results of an initial series of air pollution tests conducted as part of the technical activities on the St. Louis Demonstration Program. These tests were designed to determine: (1) the effects of the combined firing of shredded refuse and coal on pollutants emitted from the boiler, (2) the operating characteristics and collection efficiency of the electrostatic precipitator (ESP), and (3) the efficiency of combustion of the solid waste fuel. Tests were conducted independently by Midwest Research Institute (MRI) and it subcontractor, Southern Research Institute (SRI), under EPA funding and direction, and by Union Electric Company.

The tests conducted by EPA/MRI and the tests conducted by Union Electric involved generally different test methods, data acquisition, data reduction, and analyses procedures. In some instances, the differences in these procedures have contributed to apparently conflicting interpretations of the results. Comparisons and contrasts of the separate sets of data and results, where made in this report, are done to provide substantiation of indicated trends and to illuminate possible problem areas in the future use of solid waste as fuel.

DESCRIPTION OF TESTS

Tests conducted by EPA/MRI included measurements of gaseous and particulate emissions and an evaluation of the performance of the electrostatic precipitator. The Union Electric tests were similar but did not include measurement of gaseous pollutant emissions. The EPA/MRI tests were conducted using EPA methods as guidelines. Modifications were made to the methods where operating problems necessitated some changes in sampling procedures. All tests performed by Union Electric were conducted in accordance with ASME Power Test Code 27.

The primary test variables in the EPA/MRI emission tests included the boiler load (120, 100, and 80 megawatts) and the percentage of solid waste heat input provided to the boiler (9, 18, 27%). All tests were run using low sulfur coal from Orient 6 mine in Illinois. The test sequences

employed by EPA/MRI were to a great extent dictated by "normal" solid waste processing plant operations and Union Electric operating procedures and by operating problems which arose during the 2-week test period.

Union Electric, also using Orient 6 coal, conducted two series of performance tests on the ESP over a 2-month period. One series, conducted in October 1973, evaluated ESP performance while coal only was fired in the boiler. The second series, conducted in November 1973, with the exception of one test involved evaluation of ESP performance under conditions of combined-firing of coal and refuse. Boiler loads of 75, 100 and 140 megawatts were employed by Union Electric. Prior to Union Electric's coal-only tests, the ESP was washed and adjusted and the unit was operated in a normal manner, firing only coal for 2 weeks. During the 2 weeks prior to the Union Electric combined-firing tests, 81 tons of refuse were fired.

As noted previously, EPA/MRI coal only and coal plus refuse tests were performed during a single 2-week test period. As a result some compromises were required--the most significant being the use of a short stabilization or conditioning time for the ESP between major changes in fuel mixtures. The difference in pre-test history of refuse firing prior to coal firing tests (hours compared to days) was a significant variation in the EPA/MRI and Union Electric procedures.

TEST RESULTS

The percentage of refuse burned (i.e., refuse burn-out) appears to be strongly dependent upon the percent of refuse fired at each boiler output level (see Figure 8, p. . While several factors may contribute to this behavior, the variations in fuel-mixing patterns in the furnace probably can account for most of the effects. Surprisingly, no correlation could be found between refuse moisture content and degree of burnout.

Measurements of stack gas composition indicated that no significant changes in gaseous pollutant levels occur when refuse is substituted for coal under the conditions tested by EPA/MRI.

Comparison of the particulate emission data from each of the tests conducted by EPA/MRI and Union Electric indicates close agreement of inlet grain loadings, but significant differences in the outlet grain loadings. Inlet grain loadings for both EPA/MRI and Union Electric tests generally fell within the normal data scatter at each of their respective boiler load conditions. There did not appear to be any significant trends in inlet grain loading resulting from either load changes or the substitution of refuse for coal as fuel. The mean inlet grain loading was approximately 1.95 grains/dscf over the boiler load range of 75 to 140 megawatts and refuse energy levels from 0 to 27%.

The outlet grain loading increased with increasing boiler load. The data scatter also increased with increasing boiler load. For given boiler load conditions on the EPA/MRI tests, the outlet particulate emissions did not appear to vary significantly with changes in fuel mixture. The mean outlet particulate loadings for the EPA/MRI tests were moderately higher than the Union Electric coal-only outlet loadings at comparable boiler loads. However, the mean Union Electric outlet grain loading for coal plus refuse was almost double the mean values of the Union Electric coal-only tests at comparable boiler loads. Union Electric outlet grain loadings for coal plus refuse were also significantly higher than the outlet grain loading for the EPA/MRI coal plus refuse firing tests.

No significant differences in ESP efficiency were noted in the EPA/MRI tests as a function of fuel mixture, but ESP efficiency declined with increased boiler load.* Contrary to the EPA/MRI data, efficiencies calculated from the Union Electric data showed a marked dependence on fuel mixture--a significantly lower efficiency resulting from combined firing. In addition, the trend to decreasing efficiency with increasing boiler load is more prevalent in the Union Electric data for the combined-firing case. A comparison of efficiencies is given below.

		Mean ESP Efficiencies	
Fuel	Boiler Load (megawatts)	EPA/MRI	Union Electric
Coal	75		98.8
Coal	80	97.2	
	100	97.2	98.3
	120	96.5	
	140		96.9
Coal and Refuse	75		97.7
	80	98.1	
	100	96.7	96.5
	120	96.5	
	140		93.8

$$* \quad \text{Efficiency} = \frac{\text{Inlet Grain Loading - Outlet Grain Loading}}{\text{Inlet Grain Loading}}$$

The differences in ESP efficiency between the MRI and Union Electric coal-only tests are probably the result of significant variations in the pre-test history of boiler fuels fired and their effect upon ESP performance.* With the exception of one coal-only test in November, all the Union Electric coal-only tests involved no changes in boiler fuels between tests. EPA/MRI test procedures were such that the coal-only tests were conducted between coal plus refuse firing tests and, furthermore, prior to all EPA/MRI tests the boiler had been operating in a combined-firing mode for several weeks. Thus, a very short stabilization time in the order of 12 to 16 hr was allowed in the EPA/MRI coal-only tests and the data obtained by EPA/MRI for the coal-only tests probably reflect precipitator performance on combined fuel rather than coal only.

The reason for the significant differences in particulate emission levels between EPA/MRI and the Union Electric mixed fuel tests are not entirely known. It is probable that these changes are due to differences in the ESP electrical control settings or the particulate sampling test methods used. ESP sparking rates for the Union Electric coal plus refuse tests were significantly higher than for the comparable EPA/MRI tests and it is postulated that the ESP electrical control setting used for the Union Electric tests provided a lower collection efficiency than those used for the EPA/MRI tests.

An analysis of the performance of the ESP with changes in pertinent effluent stream variables and ESP electrical parameters was conducted. This analysis indicated that, while part of the decrease in precipitator efficiency noted in the Union Electric coal plus refuse tests may be due to nonoptimum adjustment of the ESP for operation on coal plus refuse, the efficiency of the ESP does decrease when coal and refuse are fired in the boiler. Additional theoretical analysis using SRI models for ESP performance suggested that a major variable influencing precipitator performance is the gas flowrate. In that regard, gas flowrates at a given gross generation level appear to increase when refuse is substituted for coal as fuel to the boiler.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusions from the air pollution tests are (a) the EPA/MRI and Union Electric test results are broadly comparable considering the differences in test procedures, (b) the efficiency of the ESP decreases when coal and refuse are fired in the boiler, and (c) the degradation in ESP performance probably results from a combination of

* Minimum recommended stabilization time for an ESP is on the order of 3 to 5 days.

factors including increased gas flowrates resulting from changes in fuel composition and moisture content and changes in the electrical performance characteristics of the ESP.

Additional air pollution testing is recommended in order to complete the characterization of particulate emissions resulting from refuse firing. Since the previous tests conducted using modified EPA methods were probably only representative of combined-firing conditions, future tests should include determination of emission levels for coal-only firing conditions. A stabilization time for the ESP of 2 to 5 days should be allowed between coal and coal plus refuse firing tests.

INTRODUCTION

The use of shredded solid waste as a supplementary fuel in a pulverized coal-fired utility boiler is currently being demonstrated in a program funded by the City of St. Louis, the Union Electric Utility Company and the U.S. Environmental Protection Agency (EPA). European utility boilers have used solid waste as a supplementary fuel since about 1965. Heat recovery from the incineration of solid wastes has been widely practiced for a number of years. Both of these practices involve the combustion of the solid waste fuels upon grates. The fuel mix and the firing techniques (grate or suspension) and the subsequent combustion mechanisms and furnace-flow pattern influence the boiler emissions and operation of the emission control devices. Thus, the emissions from large boilers which suspension-fire shredded solid wastes and pulverized coal as fuels may be significantly different from grate fired boilers. The performance of control devices operating on the boilers may also vary significantly. Prior to the tests reported herein, no experimental emission data were available on mixed suspension-fired fuels.

The primary objectives of the tests discussed in this document were to characterize the emissions which result from the suspension firing of solid waste as a supplementary fuel in a pulverized coal utility boiler and to evaluate techniques for limiting or controlling these emissions. Two series of tests were conducted: (1) a sequence of tests conducted by Midwest Research Institute and its subcontractor, Southern Research Institute, under EPA funding and direction, and (2) a sequence of tests conducted by Union Electric. The tests conducted by EPA/MRI included measurements of gaseous and particulate emissions and an evaluation of the performance of the electrostatic precipitator used for particulate emission control. The Union Electric tests were similar, but did not include measurement of gaseous pollutant emissions.

The following sections of this report present a brief description of the St. Louis demonstration system, test plans and procedures, data reduction, analyses and interpretation of tests, and recommendations.

DESCRIPTION OF ST. LOUIS-UNION ELECTRIC DEMONSTRATION SYSTEM

The St. Louis-Union Electric System is the first demonstration plant in the U.S. to process raw municipal waste for use as a supplementary fuel in power plant boilers. In addition to producing a fuel, ferrous metals are recovered from the waste for use as a scrap charge in steel production.

Two separate facilities comprise the system--a processing plant operated by the City of St. Louis and two identical boilers (tangentially fired), which were modified to fire shredded refuse, at the Union Electric Company's Meramec Plant near St. Louis, Figure 1 presents a flow diagram of the processing plant. Raw solid waste is discharged from packer-type collection trucks onto the floor of the receiving building (Figure 1). Front-end loaders are used to push the solid waste to a receiving belt conveyor. This method of handling the waste was selected over the pit and crane method because it is more economical and enables the operator to remove unwanted materials. This method also permits greater and more uniform production rates. From the receiving conveyor, the raw solid waste is transferred to the hammermill.

The St. Louis processing plant utilizes single-stage shredding (milling) of the solid waste. In the shredder, 30 large metal hammers swing around a horizontal shaft, grinding the solid waste against an iron grate until the material is shredded into particles small enough to drop through the grate openings (2 in. by 3 in.). The design called for a nominal particle size of 1-1/2 in. Preliminary data show that over 90% by weight of the incoming waste is reduced to particles not greater than 1 in. in any dimension.

From the hammermill, the shredded waste is conveyed to the air classifier. The air classifier separates the heavier, mostly noncombustible particles from the lighter ones. The shredded waste is dropped into a vertical chute. A column of air blowing upward from the bottom of the chute catches the lighter materials, causing them to rise to the top.

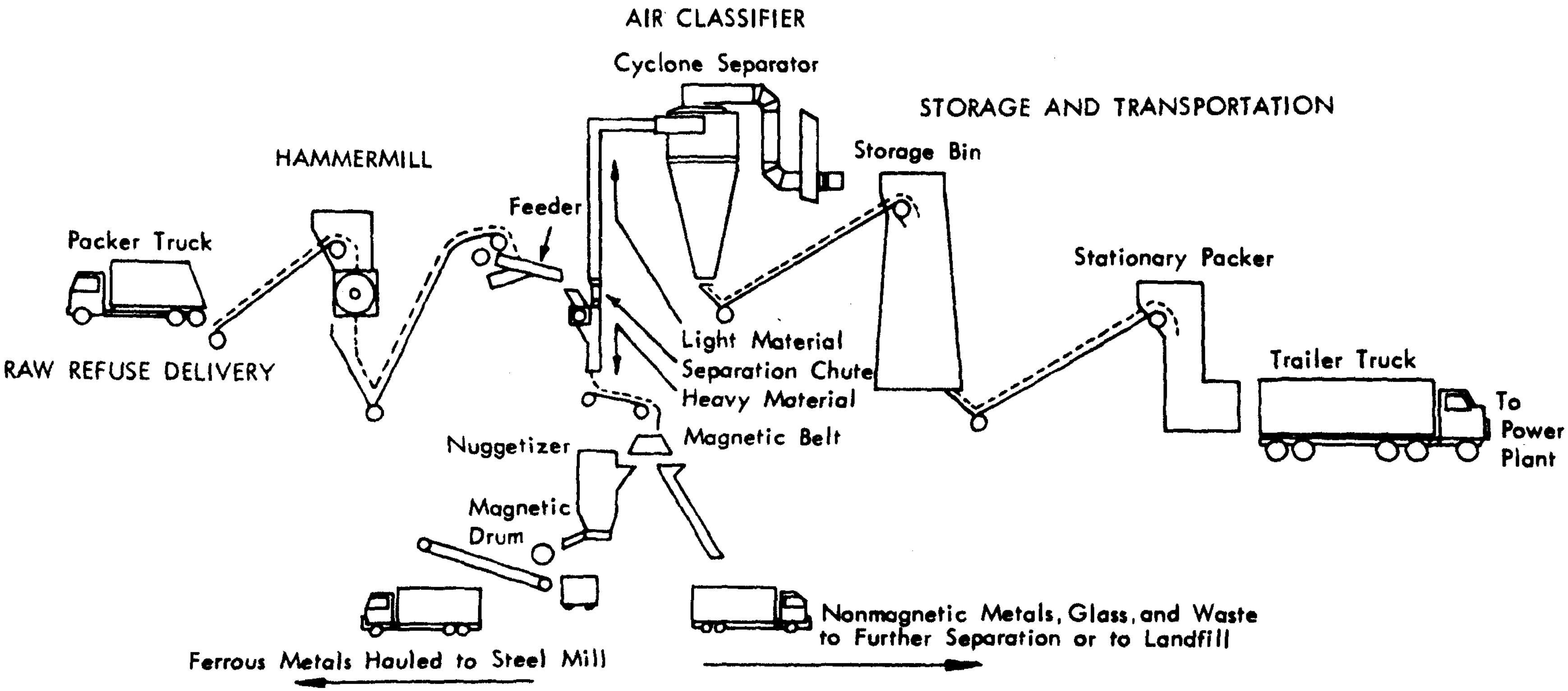


Figure 1. Flow diagram of processing plant.[5]

The heavier materials drop to the bottom. By varying the air velocity and the cross-sectional area of the chute, the percentage split between heavy and light fractions can be controlled. The light materials are carried pneumatically from the separation chute to the cyclone separator, where they are removed from the air stream and allowed to fall onto the conveyor leading to the storage bin.

The heavy material, which drops out of the bottom of the air classifier, is passed through a magnetic device which removes the ferrous metals. The ferrous metal is then sent through a "nuggetizer" which densifies the metal. The densified metal is passed through a second magnetic device as a final cleanup prior to shipment to the steel mill.

The refuse fuel is removed from the storage bin by an auger feed system and conveyed by belts into a stationary packer where the material is compressed and loaded into a transport truck for delivery to the power plant, located approximately 18 miles from the processing plant.

A schematic diagram of the facilities at Union Electric's Meramec Plant to receive, store, and burn the refuse fuel is shown in Figure 2. The refuse fuel is unloaded from the transport truck into a receiving bin from which it is conveyed through a pneumatic feeder to the surge bin. The surge bin is equipped with four drag-chain unloading conveyors, each of which feeds a pneumatic feeder. The pneumatic feeders convey the refuse fuel through four separate pipelines directly into four firing ports in the boiler. Sufficient velocity is imparted to the particles to carry them into the furnace high-temperature zones where the particle ignite and burn rapidly. To accommodate the refuse nozzles, one elevation of gas nozzles was removed and additional modifications were made to each firing corner to permit combined refuse and pulverized-coal firing. The refuse firing system is completely independent of the main combustion control system. The boiler operator can only initiate or stop refuse firing; he does not have control of the refuse firing rate. The firing rate can only be adjusted by manually changing the feeder valve and drag-chain speeds at the refuse surge bins control center.

Two identical boilers at Union Electric Company's Meramec Plant have been modified to burn the shredded refuse (Figure 3). Each unit has a nominal rating of 925,000 lb of steam per hour burning Illinois coal at the rate of 56 tons/hr. The firing of 56 tons of coal per hour is equivalent to about 1,200 million Btu/hr. Each unit supplies a turbine-generator with a nominal rating of 125 megawatts. Each unit is tangentially fired with 16 pulverized coal nozzles (four per corner), with provisicn for full load on natural gas. The furnace is 28 ft deep, 38 ft wide, and approximately 100 ft high.

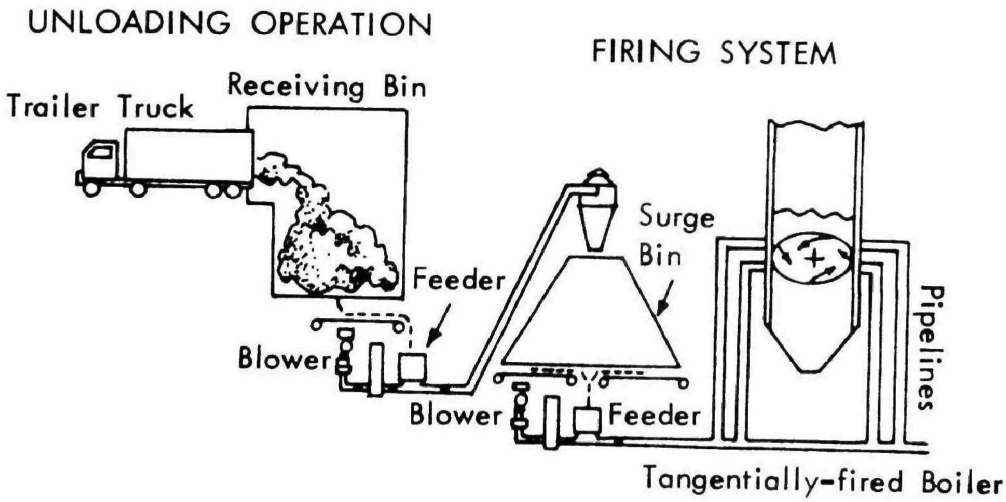


Figure 2. Schematic diagram of Union Electric facilities to receive, store and burn refuse.[5/]

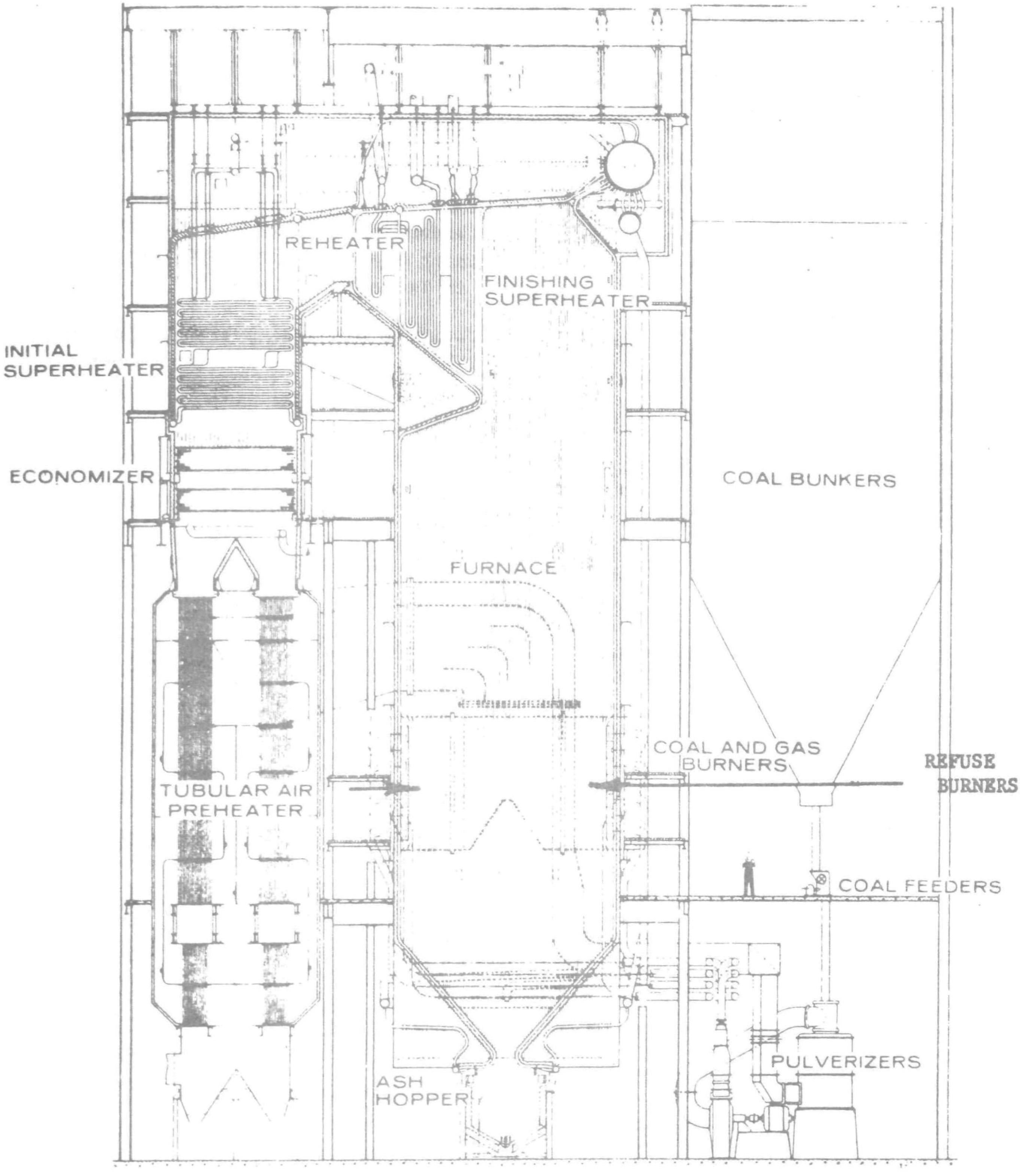


Figure 3. View of boiler at Union Electric's Meramec Plant.

Particulate matter formed during the combustion process is carried out of the boiler by hot gases. Before leaving the 250-ft boiler stack, the gases pass through an electrostatic precipitator which is designed to collect approximately 97% of the total particulate matter (i.e., coal-fly ash). The electrostatic precipitator is actually two units in parallel with a common inlet duct and separate outlet ducts. The flow from the individual outlet ducts is directed to a single exhaust stack. The pertinent specifications for the electrostatic precipitator are given in Table 1.

No modifications were made to the bottom-ash-handling systems. Bottom ash is hydraulically transferred (i.e., sluiced) from the ash hopper to an ash holding pond.

Table 1. CHARACTERISTICS OF ELECTROSTATIC PRECIPITATOR

Plate Area--55,700 ft^2

Plate to Plate Spacing

(a) Inlet--8-3/4 in.
(b) Outlet--10 in.

Corona Wire Diameter--0.109 in.

Specific Collection Area--135 ft^2/1,000 cfm

Migration Velocity--15 cm/sec

Current Density--18 n-amps/cm^2

Electrical Sets--four in all; two side by side and two in direction of flow.

Design Efficiency--97.5%, burning coal at approximately 125 megawatts and 411,500 acfm into the precipitator.

TEST PLANS AND PROCEDURES

The tests conducted by MRI for EPA and those conducted by Union Electric were based on testing plans and procedures developed by each organization. Details of the individual test plans are presented next.

GENERAL EPA/MRI TEST PLAN

Table 2 presents a summary of nominal test conditions planned for the EPA/MRI emission tests. The primary test variables included the boiler load (120, 100, and 80 megawatts) and the percentage of solid waste energy provided to the boiler (0, 9, 18, and 27%). All tests were run using low sulfur coal from Orient 6 mine in Illinois. The maximum boiler load was determined by the maximum sustainable rate of refuse firing (20 tons/hr) and an expected nominal solid waste higher heating value of 5,500 Btu/lb. Operations at the city solid waste processing plant were conducted as needed to provide the refuse quantities required to satisfy the test plan.

Figure 4 presents a schematic representation of the "boiler load" versus "percentage of refuse heat input" test matrix. The majority of tests were conducted at 80 megawatts and 100 megawatts for which a wide range of refuse heat inputs to the boiler were attainable--the maximum sustainable heat input from refuse at 120 megawatts is less than 15%. There were only two transport trucks available to haul in solid waste from the city processing plant and the solid waste could be supplied only at a rate less than the maximum firing rate which is about 20 ton/hr. Hence, the maximum firing rates were established by the initial solid waste supply at the firing site (a full surge silo, receiving building and a full truck standing by), the maximum delivery rate and the time needed to complete an emission test (4 to 5 hr) before the solid waste supply at the firing site was depleted.

A second rationale for testing predominately at reduced loads was the fact that the lower gas flowrates would provide experimental data which could be used to define the precipitator design and operating parameters needed to achieve high collection efficiencies.

Table 2. TEST PLAN FOR MRI/EPA EMISSION TESTS

Test No.	Date 1973	Boiler Load (megawatts)	Refuse Heat Input (%)	Nominal Refuse Rate (tons/hr)	Refuse Load (megawatts)
0	12/4	120	9	9.0	10.8
1	12/5	100	9	8.0	9.0
2	12/5	100	9	8.0	9.0
3	12/6	100	0	0.0	0.0
4	12/9	80	18	12.8	14.4
5	12/9	80	18	12.8	14.4
6	12/10	80	0	0.0	0.0
7	12/10	80	27	19.0	21.6
8	12/11	120	9	9.3	10.8
9	12/12	120	0	0.0	0.0
10	12/12	120	18	18.8	21.6
11	12/13	100	9	8.0	9.0
12	12/13	100	18	15.8	18.0
13	12/14	80	9	6.5	7.2

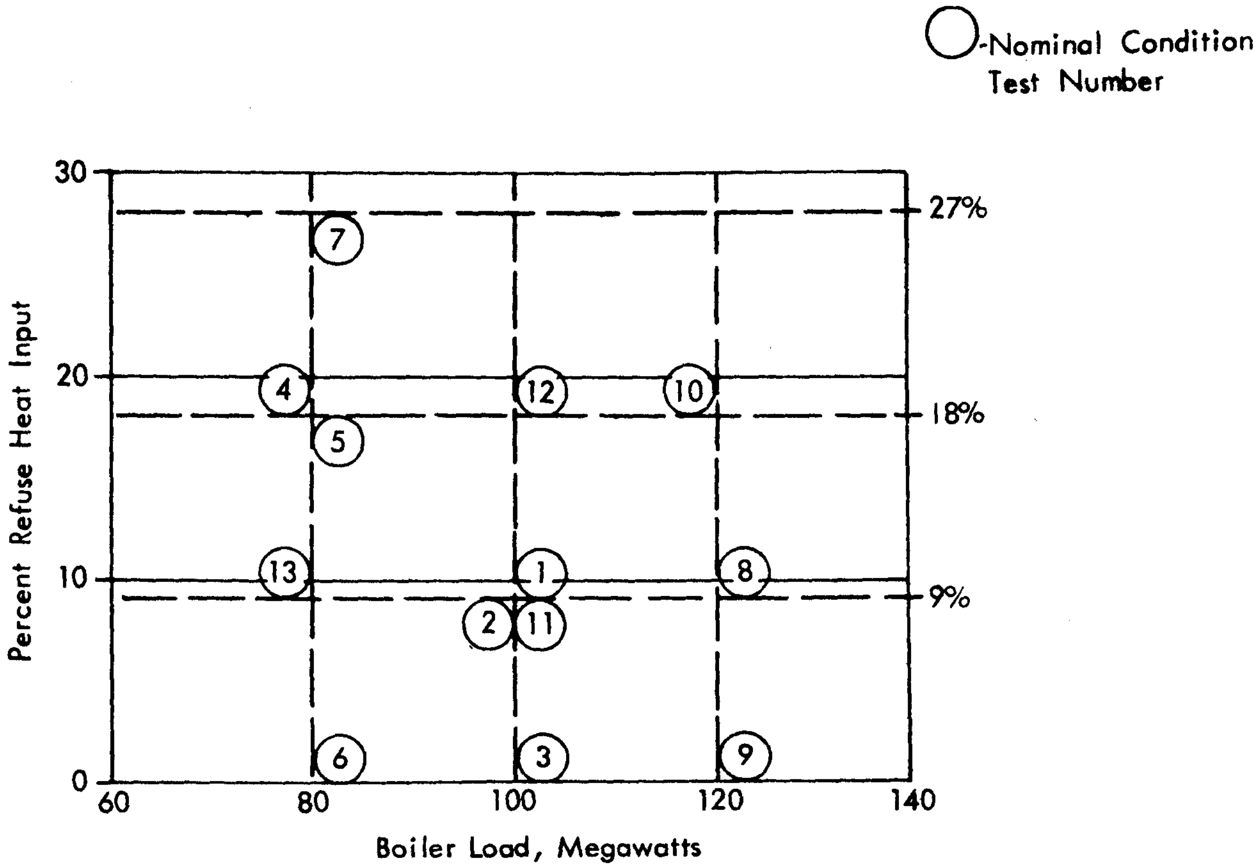


Figure 4. Test matrix for EPA/MRI plan.

Actual EPA/MRI Test Sequences and Procedures

The test sequences and test procedures were to a great extent dictated by "normal" solid waste processing plant and utility operating procedures and by operating problems which arose during the 2-week test period. It was realized that the electrostatic precipitator (ESP) performance is to a degree determined by the fly-ash coatings on the discharge and collection electrodes and that it may require a number of days of operation on a given fuel to stabilize or condition the ESP at a nominal collection level. However, the normal operating mode at St. Louis-Union Electric is to fire solid waste only during one or two shifts per day, 5 days/week--solid waste is neither collected nor processed during the weekend and there is not sufficient storage capacity to allow continuous weekend firing, even considering that enough solid waste could potentially be processed. Thus, the tests as conducted would give stack emissions which were representative of the cyclic mode of operation at St. Louis, but which would not perhaps be representative of emissions under conditions of continuous refuse firing at constant loads. Because of the importance of previous fuel-firing history on ESP operation, Tests 1 and 2 were conducted during the same day at the same boiler load and refuse firing conditions to obtain data at duplicate test conditions and to evaluate the short-term effects of conditioning on ESP collection efficiency. In the morning tests, refuse firing was initiated approximately 1 hr before the start of the emission tests. Emission testing on Test 2 was started in the afternoon after refuse had been continuously fired for approximately 5 hr. This procedure was repeated for Tests 4 and 5 at different load and refuse firing conditions.

Coal base line tests (no refuse firing) were conducted in the mornings after firing coal all night. The first base line test (Test 3) was being conducted expeditously when the refuse processing plant had to shut down operations because of the breakdown of a receiving conveyor system. A second base line test was scheduled for Monday morning (12/10) of the second week of tests when the ESP would have been subjected to coal firing only for the entire weekend. However, the boiler blew a steam tube and in order to regain lost test time refuse was processed and stored on Friday (12/7) and fired on Sunday (12/9). The second base line test was conducted as planned on Monday (12/10) and the last on Wednesday (12/12) during the middle of the test week. In both of these cases refuse had been fired the previous day.

The general procedure following receipt and firing of the solid waste at the power plant is given in Table 3. This procedure was followed to enable determination of the percentage of refuse heat input to the boiler. All refuse received for a given test was fired (the weight of refuse in each truck was recorded) and the incremental boiler electrical loads generated by refuse firing were determined.

EPA/MRI Measurement, Sampling and Analysis Methods

The operating procedures, measurements performed, and samples collected during the test period were designed to characterize the boiler fuel input (coal and refuse), the boiler performance, the electrostatic precipitator performance, and the furnace and stack emissions.

Coal and refuse samples were collected and analyzed to characterize the properties of the fuel consumed during each test (Tables 6 through 9 summarize the data on fuel properties). The refuse sampling and analysis procedures were those established and used throughout the first year of the St. Louis-Union Electric Demonstration Program. Refuse samples from the EPA/MRI emission tests were subjected to proximate, ultimate and ash analyses. Coal samples were obtained from each of the coal hoppers just upstream of the four pulverizers. These samples were taken every 2 hr during each test. Composites of samples from each test were subjected to proximate, ash and ultimate analyses.

Primary voltages, primary currents and spark rates were recorded from meters on each of the four ESP electrical sets. Secondary voltages were measured on three of the sets by use of voltage dividers installed between the precipitator leads and ground, which measures the electric potential between the corona wires and plates. Secondary currents were read on the rectifier set secondary ammeters. Secondary voltages and currents on the fourth electrical set were not measured because only three suitable voltage dividers were available. In-situ fly ash resistivity was measured using a point-to-plane instrument. No attempt was made to optimize the electrical performance of the ESP sections for each test condition except for the adjustment of the voltage levels to prohibit excessive sparking.

The methods used for emission measurement sampling and analysis are presented in Table 4. Figures 5 and 6 show the actual sampling ports and traverse points. Problems which required some change in sampling procedures were encountered in some of the test runs.

Table 3. EPA/MRI EMISSION TEST PROCEDURE

Approx. Time	Step No.	Activity
6:00 AM	1	Start transferring refuse stored from previous day from city receiving building to surge silo.
6:30 AM	2	Set boiler to appropriate test load.
7:00 AM	3	First refuse truck arrives and unloads. Immediately transfer refuse to surge silo.
7:30 AM	4	Second truck arrives and unloads. Do not start transfer of refuse to surge silo until after refuse firing has started.
7:45 AM	5	After second truck has unloaded start refuse firing using following steps.
		(a) Set coal mill feed controls on manual at test load (TL).
		(b) Start firing refuse, adjusting refuse feed rate to pick-up desired boiler load from refuse heat input (TL + ΔL). Modulate load manually to keep turbine throttle pressure constant.
		(c) After desired level of boiler heat input has been achieved by adjustment of the refuse firing rate, go back to original boiler test load (TL) and return boiler to automatic control.
8:15 AM	6	EPA control room data recorder records start-up events and starts tabulating boiler operating conditions.
8:30 AM	7	Start emission test measurements.
12:30 PM	8	Complete emission measurements.
1:00 PM	9	Perform following test, recording boiler load, turbine throttle pressure and other pertinent data.
		(a) Go to manual control.
		(b) Stop refuse firing and record drop in load (adjust load as necessary to maintain turbine throttle pressure).

Table 3. (Concluded)

Approx. Time	Step No.	Activity
1:00 PM (cont'd)	9	(c) Record boiler operating conditions after throttle pressure has stabilized at the equilibrium value recorded just prior to the cessation of refuse firing. (d) With the boiler control on manual restart refuse firing. (e) Adjust the refuse firing rate to achieve the required refuse heat input to boiler. (f) After the desired refuse heat rate has been achieved return boiler to automatic and allow boiler to stabilize.
2:00 PM	10	Start emission measurements for afternoon test run.
6:00 PM	11	Complete tests. Continue to fire refuse until all but refuse from last trailer truck load of day has been depleted. Refuse from this last trailer load is to be stored in the receiving building overnight and transferred to the surge bin at 6:00 AM the next day. (Step 1).

Table 4. METHODS OF SAMPLING AND ANALYSIS USED BY MRI

Sample Type	Sampling Method	Sample (or data) Collected by[a]	Analysis Method: Method	Analysis Method: By[a]	Purpose of Test
Mass particulate	Adapted Method 5[f]	MRI	Gravimetric	MRI	Concentration of particulate
Particulate size distribution	Andersen (outlet)	MRI	Gravimetric	MRI	Physical characterization--particle size distribution
Particulate size distribution	Brink (inlet)	MRI	Gravimetric	MRI	Physical characterization--particle size distribution
O_2, NO, CO, CO_2, and SO_2	Instrumental	EPA	Infrared, paramagnetic coulometric chemiluminescence	MRI	Amount of gases in the flow
Hg_v	Modified Method 5[b]	MRI	Atomic absorption	MRI	Amount of Hg_v in the flow
	EPA[c]	MRI	Atomic absorption	MRI	Amount of Hg_v in the flow
Cl^-	Modified Method 5[b]	MRI	Coulometric[e]	MRI	Amount of Cl^- in the flow
SO_3	Controlled[d] condensation	MRI	Barium perchlorate	MRI	Amount of SO_3 in the flow
Coal	Composite	MRI	Proximate and ultimate	MRI	
Fly-Ash	Grab	MRI	---	---	Fly-Ash element analysis
Velocity	With Method 5	MRI	Data handling	MRI	Profile and flow rate of stack gas
Temperature	With Method 5 thermocouple	MRI	Data handling	MRI	Temperature profile of stack gas
Fly-Ash	In situ resistivity probe	SRI	Calculation	EPA	Fly-Ash resistivity

a/ EPA = Environmental Protection Agency
MRI = Midwest Research Institute
SRI = Southern Research Institute

b/ First impinger water was replaced with 0.5 N nitric acid and second impinger water replaced with 0.5 N KOH. One-third of each impinger liquid used for mass determination, one-third analyzed for Hg by AA and one-third analyzed for Cl^- by coulometric titration.

c/ EPA method for the collection and analysis of Hg supplied by Robert Statnich, Control Systems Laboratory.

d/ Driscoll, J. N., and A. W. Berger, "Improved Chemical Methods for Sampling and Analyses of Gaseous Pollutants from the Combustion of Fossil Fuels," Final Report for Contract CPA 22-69-95, Walden Research Corporation.

e/ EPA Method 8.

f/ EPA Method 5 was used as the basis for testing. Adaptations and modifications were necessary because of field conditions.

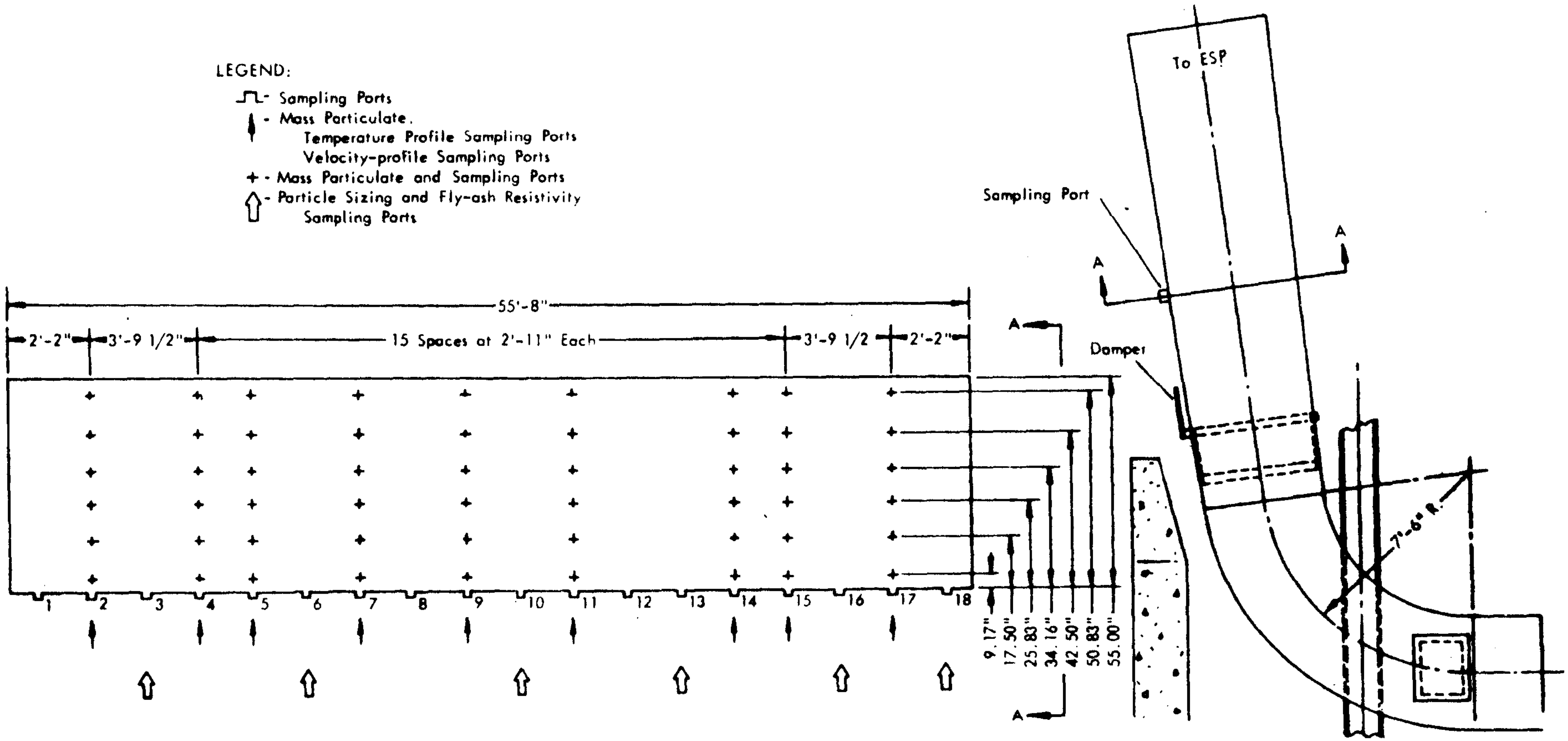


Figure 5. EPA/MRI sampling location at input to the ESP.

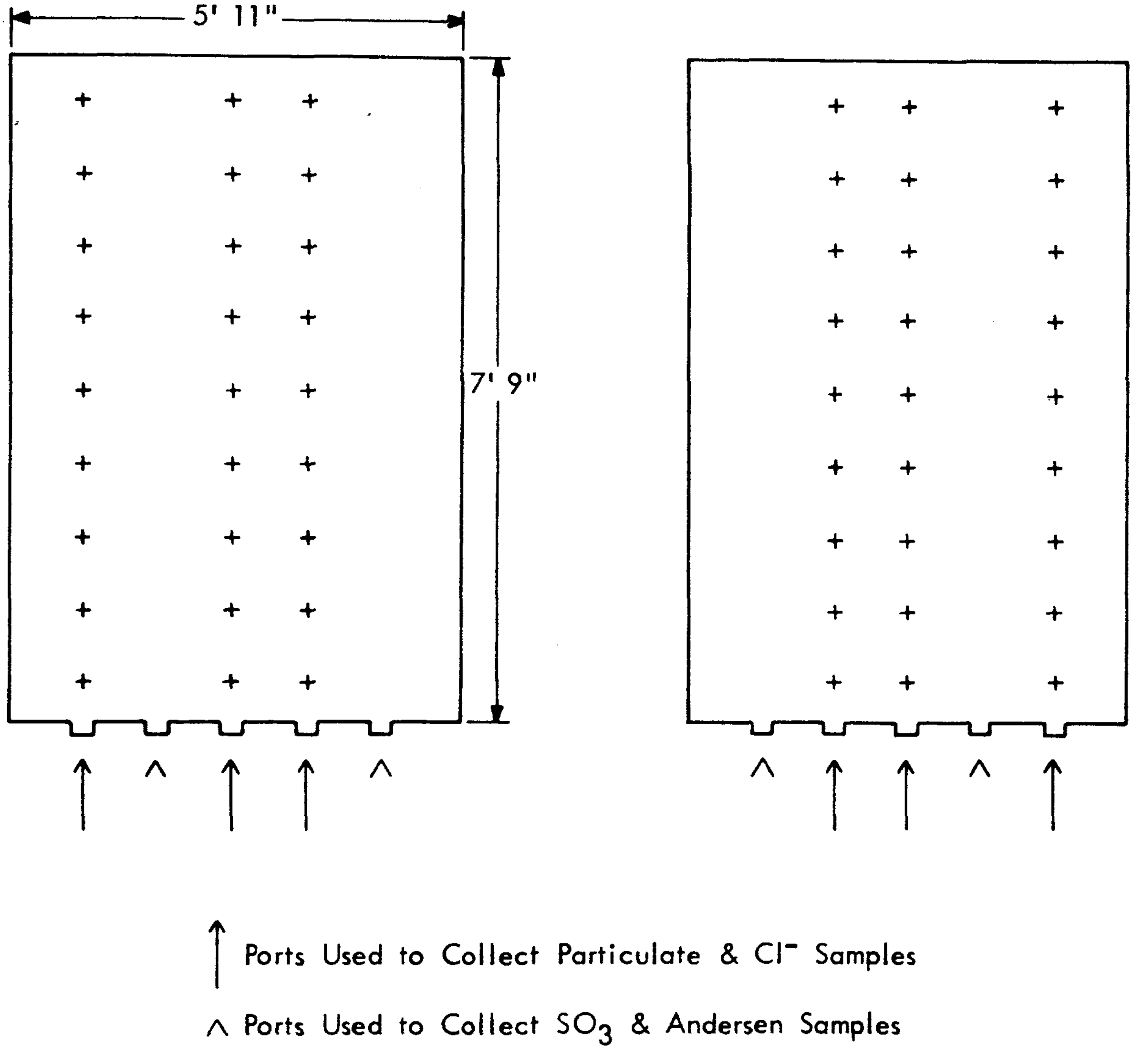


Figure 6. MRI/EPA sampling location at outlets to the ESP

Specific problems and modifications to procedures in each test are enumerated in Table 5. Total particulate measurements were made at the ESP inlet and outlet using the EPA mass train. The two outlet ducts were sampled sequentially during the time period when samples were being collected on the inlet duct. Particle size distributions were measured using a Brink cascade impactor on the inlet and an Andersen cascade impactor on the outlet.

Gaseous emission measurements for O_2, CO, CO_2, NO and SO_2 were made using continuous monitoring instruments mounted in an EPA instrumentation van. Gas samples for the instruments were drawn through a stationary sampling line mounted in the flow duct downstream of the induction fan on the west ducting to the stack. Prior to start of the test program, sample probe traverses were made to insure that there was no gas composition stratification within the duct. A calibration of each of the instruments was made before and after each test run using bottled calibration gases.

Mercury was sampled employing two methods. The first method used a sampling train containing five midget impingers. The first impinger contained sodium bicarbonate solution to remove interferences. The second and third impingers contained acidic potassium permanganate to collect mercury vapor. The fourth impinger was dry and the fifth impinger contained silica gel. Sampling was conducted following standard gas sampling procedures.

The second mercury sampling method consisted of the impingers attached to the RAC particulate sampling train. The first impinger was filled with 0.5 N HNO_3 instead of water to collect the mercury and the second impinger was filled with 0.5 N KOH instead of water to collect chloride ions.

One-third aliquots of the first and second impingers were analyzed for mercury following standard atomic absorption spectroscopy procedures. Chloride analysis was conducted on one-third aliquots of the contents of the first and second impingers from the RAC train described above. The analytical procedures followed the procedure described by J. J. Lingane.[3] The chloride ion concentration was determined by adding the required reagents and analyzing using a Buchler-Coltove Chloridometer. The technique consists of the coulometric generation of silver reagent and the amperometric detection of the end point.

Sulfur trioxide was collected using the controlled condensation method described in an EPA report prepared by Walden Research Corporation.[4] The gas stream is cooled to the condensation temperature of sulfuric acid and the resulting acid mist is collected on a glass frit. The collected sample is recovered in distilled water and analyzed for sulfate ion following the analytical procedure described in EPA Method 8.

Table 5. MODIFICATIONS TO TEST OR SAMPLING PROCEDURES RESULTING FROM OPERATING PROBLEMS

Test No. 0: The sampling probe used on the inlet was stainless steel for this test only. Sampling for Hg_V by the EPA provided method, was not accomplished because of impinger boiling over. The boiling over occurred because of the relatively high flow recommended in the method (2,000 cc/min for 30 min).

Test No. 1: All the sampling probes used in this test and thereafter were glass. The flowrate through the impingers in the Hg_V apparatus was dropped to about 500 cc/min for 60 min to stop the impingers from boiling over.

Tests Nos. 2 and 3: Two complete tests were accomplished without any problem. However, after Test No. 3 was accomplished, a rupture in the boiler forced the plant to shut the boiler down for repair. Test No. 4 was delayed 2 days by the repair activity.

Tests Nos. 4 and 5: A slowdown in refuse delivery after Test No. 4 delayed the start of Test No. 5 about 1 hr.

Tests Nos. 6, 7, and 8: No major difficulties encountered in Tests Nos. 6 and 7. However, some problems in firing of the refuse caused Test No. 8 to start 2 hr late.

Tests Nos. 9 and 10: A 3-hr delay of the start of Test No. 10 was caused by problems with refuse delivery. The fly-ash probe built by MITRE could not be used because of obstruction encountered above the first four hoppers.

Tests Nos. 11, 12, and 13: No major problems were encountered in these tests.

Plans had been initially made to collect boiler residue samples to evaluate the percentage of refuse burn-out (energy recovery) and the amount of residue generated under the various test conditions. The test procedure was to have involved: bulldozing a depression in the ash sluicing area, filling the depression with the sluiced boiler residue and taking appropriate core samples. However, the high water level of the adjacent Meramec River at the time of the tests prevented adequate runoff of the sluicing water causing the area where the sampling was to have been conducted to become partially submerged. As a result, residue sampling was not conducted.

UNION ELECTRIC TEST PLANS

Union Electric conducted two series of performance tests to determine the effect of refuse firing on the performance of the electrostatic precipitator and on particulate emissions.[6,7] All tests were conducted in accordance with ASME Power Test Code 27. Figure 7 illustrates the sample point locations available at the inlet and outlet of the precipitators.

The first series of tests were performed on 16-19 October 1973. These tests were run at steady load conditions at three different load points firing only low sulfur Orient 6 coal. Tests 6 and 7, Tests 1, 2, and 3, and Tests 4 and 5 were run at 140, 100 and 75 megawatts, respectively. Prior to testing, the precipitator was inspected. Any grounded sections were cleared for full operation of the precipitator. The unit was operated in a normal manner, and was conditioned by firing only low sulfur coal for 2 weeks prior to testing. Prior to that time the precipitator was washed to remove any residual fly ash which was not from combustion of Orient 6 coal. On 15 October 1973, each rectifier set was checked and adjusted for optimum control settings. These control settings were used for all of the coal-only firing tests.

The unit was brought to test load an hour before testing each day to allow conditions to stabilize. Prior to particulate sampling, precipitator inlet and outlet velocity traverses and an outlet oxygen traverse were made. Four inlet and four outlet particulate sampling meter stations were used. The dust samples were collected in 5 micron alundum thimbles on the outlet. Difficulty in obtaining 5 micron thimbles necessitated the use of 20 micron alundum thimbles on the inlet. Sampling time for the precipitator tests was 1-1/2 hr. The inlet and both outlets were sampled concurrently.

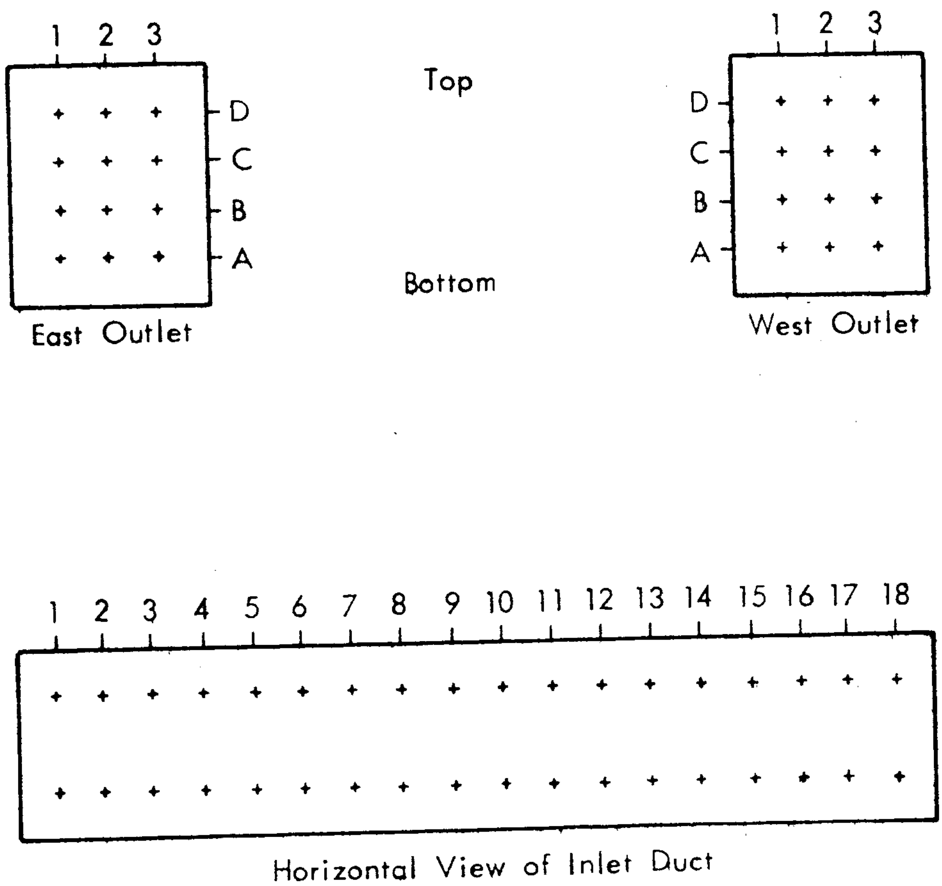


Figure 7. Union Electric sample traverse points on ESP inlet and outlet.

A second series of tests was conducted on 26-30 November 1973. Tests were run at steady load conditions at three different load points firing low sulfur Orient 6 coal and refuse. Tests 1-T, 2-T, 3-T, and 9-T, Tests 4-T and 5-T, and Tests 6-T and 7-T were run at 140, 100, and 75 megawatts, respectively, with refuse firing; Test 8 was run at 140 megawatts with coal-firing only. Tests 8 and 9-T were run on the same day so that coal firing and refuse firing test results could be compared.

The precipitator was not inspected prior to the Union Electric refuse firing tests since it had been inspected around the end of September prior to the coal firing precipitator tests. However, on 26 November 1973, the precipitor rectifier sets were checked with voltage dividers and adjusted for refuse firing conditions. These settings were used for all refuse firing tests. During the 2 weeks prior to testing with refuse, 81 tons of refuse were fired. Before starting the emission tests, the unit was brought to test load and refuse was burned for an hour each day to allow ESP and boiler conditions to stabilize. Prior to particulate sampling, precipitator inlet and outlet velocity traverses and an outlet oxygen traverse were made. As with the coal-firing tests, four inlet and four outlet particulate sampling meter stations were used. Dust samples were collected in 20-micron and 5-micron alundum thimbles on the inlet and outlet, respectively. Sampling times for the precipitator tests were 1-1/2 hr. Sampling at the inlet and both outlets were conducted concurrently.

DATA REDUCTION PROCEDURES

Data reduction procedures utilized by MRI and Union Electric were generally different. Details of procedures used by MRI are presented followed by the Union Electric procedures.

MRI DATA REDUCTION PROCEDURES

The data collected in the field were returned to MRI and transferred to the appropriate coding form (see Figures A-1 to A-3, Appendix A). Laboratory analysis data were recorded in bound notebooks and copies of these data were made available for further data reduction.

Separate computer programs were used in the reduction of the following data:

1. Particulate loading

2. Andersen particle size

3. Brink particle size

4. SO_x

These programs are written in FORTRAN IV language.

All coded data were keypunched and verified in MRI's computer center. The computer programs were checked for special run requirements and the programs and data were run on MRI's remote-branch processing DATA 100 terminal on-line to United Computing Systems, Inc., hardware.

The following sections describe the data reduction programs in more detail.

Particulate Data

The particulate or "STACK" data reduction program reads the keypunched particulate data and outputs the following tables:

1. Particulate data and calculated values: raw data including a temperature profile and calculated results for a velocity profile.

2. Example particulate calculations: a summary of the equations used in the program, as determined from Method 5 of the Federal Register, and conversion equations to metric units.

3. Particulate emission data (also in metric units): a table of average values and calculated values used in and calculated from the basic equations given in the example calculations.

4. Summary of results (also in metric units): a summary of the major calculated results: volume of dry gas sampled, percent moisture, average stack temperature, flowrates, percent isokinetic, percent excess air, and the particulate data (partial and total catch) for weight, loading and emission rate.

Example calculations for the inlet data on Test 0 (Run 0-I) are shown in Table A-2, Appendix A. Table A-3, Appendix A, presents a summary of results for all tests conducted by MRI. Particulate loadings have not been corrected for deviation from isokinetic sampling. The range of values for percent isokinetic is within ± 5%, except for the outlet on Test 1 and correction is not necessary. The particulate loadings given in Table A-3 have not been adjusted to 50% excess air. Calculated values should not be interpreted as having more than three-digit accuracy.

Andersen Particle Size Data

The Andersen program inputs the following data for each run:

1. Date of run

2. Particle density (assumed unit density)

3. Sampling rate (cubic feet per minute)

4. Net and tare weights for each stage

The program calculates cumulative weight percentages for each stage from the data in (4) above. The program also uses an MRI derived computerized form of the Ranz and Wong[1/] impactor equation to determine jet velocity (centimeters per second) and particle cutoff diamter (microns) for each stage.

The above results are plotted on log-probability graph paper to determine cumulative weight percentages less (or greater) than any given size. Assuming a log-normal distribution, the most probable particle diamter will equal the particle size on the graph at 50% cumulative weight.

Brink Particle Size Data

The Brink data reduction is handled similar to the Andersen data.

Cumulative weight percentages are determined for each stage from the Brink analytical data, including the cyclone catch. (These results are given in Table A-4, Appendix A.)

The data were plotted against the standard particle cutoff diameters of 7.5 µm for the cyclone and 2.5, 1.5, 1.0, 0.5, and 0.25 µm, respectively, for each stage, based on a particle density of 2.27 g/cc.

SO_3 Data

The SO_3 program reduces the sampling and analysis data for each run.

The tables output from this program are:

SO_3 Raw Data - A listing of input data not printed on the summary tables. These data include: initial and final dry test meter readings, barometric pressure and meter vacuum.

Example SO_3 Calculations - A summary of the basic equations (from Method 8 of the Federal Register) including calculations for the volume of dry gas sampled (in cubic feet) and concentration (in pounds per dry standard cubic feet and parts per million).

SO_3 Data - A summary of sampling and analysis data and calculated results using the equations listed in the example calculations.

Example calculations for the inlet on Test 0 (Run 0-I) are given in Table A-5, Appendix A. Values are given in pounds per dry standard cubic feet and parts per million as SO_3.

UNION ELECTRIC PROCEDURES

Although specific details of the data reduction procedures utilized by Union Electric were not obtained, notebooks containing summary sheets of combustion calculations, coal analysis, refuse analysis, refuse feed rate calculations, thimble weight sheets, efficiency calculations, and test data were provided by Union Electric. Information contained in the notebooks was reviewed and a series of tables were prepared to summarize the principal results of the Union Electric test program.

Union Electric calculated gas flowrates using a computer combustion program. Inputs to the program included boiler performance conditions, excess oxygen, fuel composition and a fuel Btu value. However, because refuse ultimate analyses were not available when the Union Electric report was prepared they used the same fuel composition for all runs--coal and coal plus refuse. The fuel Btu value was adjusted according to the percentage of refuse heat input and the refuse and coal heating values. Gas flowrates calculated by the above procedure are at best estimates. A more extensive discussion of Union Electric test results and procedures is presented in a later section.

ANALYSES AND DISCUSSION OF TESTS

An analysis and discussion of the test data obtained by EPA/MRI and Union Electric is presented in this section. In addition to the tests to determine the influence of refuse firing on emissions from the boiler, samples of the coal and refuse were collected by both organizations for subsequent analyses. The results of the analyses of coal and refuse samples are presented first, followed by a discussion of the emission tests. A summary of fuel composition and heat values for the EPA/MRI tests are given in Table 6.

COAL ANALYSES

Coal samples corresponding to the coal fired in individual emission tests were obtained by MRI and Union Electric. Samples collected by MRI were returned to Kansas City and then sent to Industrial Testing Laboratory (Kansas City, Missouri) for analyses. Union Electric performed their own analyses using ASTM test procedures.

Table 7 presents a summary of the coal analyses. Complete data are presented in Tables B-1 and B-2 in Appendix B. Significant differences exist in the moisture content and heating values of the as received coal. Samples obtained by EPA/MRI show substantially lower moisture content and higher heating values. Since the EPA/MRI coal samples were not transported or stored under controlled conditions and some time elapsed before they were sent out for analyses, it is likely that the EPA/MRI data do not represent the actual as received coal samples.

One potentially important factor is noted about the Union Electric coal data. During the October tests when coal-only was fired, the average as received coal heat content was 11,975 Btu/lb. During November when all but one test was conducted with refuse firing, the average coal heating value was 11,510 Btu/lb. This represents an average loss in coal heating value of approximately 4% because of higher coal moisture content.

Table 6. FUEL COMPOSITION AND HEAT VALUES

Nominal Load (megawatts)	% Refuse Fired	Refuse Firing Rate Avg (lb/hr)	Fuel Composition (%) As Received: Coal Moisture	Coal Ash	Coal Carbon	Coal Sulfur	Refuse[b] Moisture	Refuse Ash	Refuse Sulfur	Total Sulfur In Fuel	Heating Values (Btu/lb): Coal Wet[a]	Coal Dry	Refuse Wet	Refuse Dry
80	0	0	6.35	6.70	71.19	1.35				1.35	12,628	13,484		
80	9	18,860	6.02	7.56	70.62	1.59	23.2	18.5	0.17	1.45	12,526	13,328	5,247	6,827
80	18	37,300	6.51	6.55	70.84	1.56	39.0	12.1	0.12	1.28	12,594	13,471	4,503	7,400
80	18	37,300	6.48	7.87	69.88	1.61	49.0	12.9	0.09	1.32	12,384	13,242	3,591	7,009
80	27	43,000	6.27	6.76	70.36	1.47	37.8	13.3	0.10	1.08	12,594	13,436	4,542	7,048
100	0	0	6.49	6.54	71.16	1.33				1.33	12,639	13,416		
100	9	22,240	6.17	7.57	70.51	1.73	22.3	15.7	0.12	1.57	12,513	13,336	5,531	7,117
100	9	31,650	6.37	7.06	70.81	1.50	34.5	14.9	0.14	1.37	12,589	13,445	4,838	7,387
100	9	31,650	5.96	6.86	71.19	1.46	34.4	13.7	0.09	1.32	12,617	13,417	4,815	7,322
100	18	31,400	6.28	8.33	68.70	2.80	23.6	17.9	0.11	2.32	12,392	13,222	5,315	6,952
120	0	0	6.60	7.13	70.54	1.25				1.25	12,526	13,411		
120	9	32,210	6.62	6.26	71.85	1.36	22.2	17.5	0.16	1.23	12,676	13,575	5,557	7,142
120	9	36,875	6.38	6.50	70.99	1.38					12,603	13,462		
120	18	30,800	6.28	6.78	71.53	1.52	20.0	17.1	0.11	1.25	12,641	13,488	5,809	7,262
Average			6.34	7.03	70.73	1.56	30.6	15.4	0.12		12,566	13,410	4,975	7,147
Maximum			6.62	8.33	71.85	2.80	66.3	19.7	0.26		12,676	13,575	6,466	8,013
Minimum			5.96	6.26	68.70	1.25	14.3	7.6	0.08		12,384	13,222	2,293	6,603

a/ Data suspect because of improper sample storage technique.
b/ Mean value from samples taken during EPA/MRI emission tests. Indicated maxima and minima for refuse are extreme values from raw data (Table B-4).

Table 7. SUMMARY OF COAL PROXIMATE ANALYSES

	As Received						Dry Basis				
	% Moisture	% Ash	% F.C.	% Volatile	Btu/lb	% S	% Ash	% F.C.	% Volatile	Btu/lb	% S
Union Electric October Tests											
Average	10.8	7.0	48.6	33.6	11,989	1.36	7.9	54.5	37.7	13,435	1.53
Maximum	12.0	7.6	50.5	38.9	12,078	1.49	8.4	56.2	43.8	13,539	1.68
Minimum	9.9	6.1	43.8	31.9	11,772	1.22	6.9	49.3	36.1	13,350	1.37
Union Electric November Tests											
Average	13.9	6.3	48.1	31.7	11,510	1.28	7.4	55.8	36.8	13,363	1.48
Maximum	14.6	7.5	49.1	34.6	11,811	1.36	8.8	56.7	39.5	13,516	1.56
Minimum	12.4	5.7	46.9	30.1	11,289	1.22	6.8	53.5	35.2	13,199	1.41
EPA/MRI Tests [a/]											
Average	6.34	7.03	52.28	34.34	12,565	1.57	7.51	55.83	36.67	13,417	1.67
Maximum	6.62	8.33	53.48	36.92	12,676	2.80	8.89	57.13	39.39	13,575	2.99
Minimum	5.96	6.26	48.47	33.01	12,384	1.25	6.70	51.72	35.34	13,222	1.34

a/ As received EPA/MRI moisture data suspect because improper sample storage technique.

REFUSE ANALYSES

The proximate analysis and heating values for the refuse utilized in the EPA/MRI and Union Electric tests are summarized in Table 8. Tabular data of refuse and ash analyses from samples taken during the Union Electric and EPA/MRI test periods are presented in Tables B-4 to B-7 in Appendix B. The moisture content and the heating value of the refuse varied over a wide range during the first few days of the EPA/MRI test period, but were more uniform during the latter part of the test period. Moisture and Btu contents during the Union Electric tests did not exhibit such extreme variations.

Table 9 summarizes the results of ultimate analyses of selected refuse samples. These samples were collected during the Union Electric tests in November. It should be noted that these analyses are for the light fraction of the milled and air classified refuse.

COMBUSTION EFFICIENCY OF REFUSE

A precise determination of the combustion efficiency of refuse is not possible due to the indirect methods used in measuring the refuse flowrates and the energy input from refuse. In addition as previously noted there was no information obtained regarding the quantity and heating value of the bottom ash generated from refuse firing.

The above data gaps preclude calculation of a proper energy balance. However, utilization of nominal or average values for refuse flowrate, refuse energy input and heating value for the respective test periods does allow calculation of an apparent refuse combustion efficiency.

The apparent combustion efficiency of the refuse (i.e., refuse burn-out) was estimated from the equation

$$\eta_r = \frac{\text{(Generator Output) (Unit Heat Rate)}}{H_r m_r} \left(\frac{\text{\% Refuse Energy}}{100} \right) . \quad (1)$$

Table 8. SUMMARY OF REFUSE PROXIMATE ANALYSES, MILLED AND AIR CLASSIFIED

	Moisture		Dry Weight Basis					Received Moisture Basis				
	Total (%)	Sample (%)	S (%)	Cl (%)	Ash (%)	As Dry (Btu/lb)	NaCl (%)	S (%)	Cl (%)	Ash (%)	As Received (Btu/lb)	NaCl (%)
Union Electric Tests												
Average	35.3	0.89	0.19	0.52	24.3	7,394.4	0.42	0.12	0.33	15.7	4,768.5	0.27
Maximum	43.2	1.47	0.23	0.76	33.1	13,002.0	0.49	0.16	0.58	20.2	7,593.0	0.39
Minimum	16.7	0.41	0.13	0.35	19.4	6,817.0	0.33	0.07	0.22	12.3	4,040.0	0.21
EPA/MRI Tests												
Average	29.9	1.46	0.16	0.57	21.3	7,261.5	0.39	0.12	0.41	14.9	4,975.0	0.27
Maximum	66.3	2.62	0.33	1.14	27.3	8,013.0	0.46	0.26	0.95	19.7	6,466.0	0.35
Minimum	14.3	0.46	0.12	0.33	15.0	6,603.0	0.33	0.08	0.15	7.6	2,293.0	0.11

Table 9. SUMMARY OF ULTIMATE ANALYSES OF SELECTED REFUSE SAMPLES[a/]
(Weight Percent)

	As Received						Dry Basis					
	C	H[b/]	N	S	Ash	O (by difference)[b/]	C	H[b/]	N	S	Ash	O (by difference)[b/]
Average	39.2	5.9	0.72	0.24	22.3	31.7	40.5	5.7	0.75	0.25	23.1	29.7
Maximum	41.0	6.2	0.82	0.29	28.9	35.4	42.3	6.1	0.84	0.30	29.8	33.4
Minimum	37.2	5.5	0.63	0.21	18.8	26.0	38.4	5.3	0.65	0.22	19.5	24.0

a/ Samples taken during U.E. refuse firing tests in November. Complete data is given in Appendix B.
b/ Includes hydrogen and oxygen contained in moisture of "As Received" refuse.

Equation (1) was derived as follows

$$H_T = \eta_r H_r m_r + \eta_c H_c m_c \tag{2}$$

$$\eta_r = \frac{H_T}{H_r m_r}\left[1 - \frac{\eta_c H_c m_c}{H_T}\right] \tag{3}$$

$$\eta_r = \frac{H_T}{H_r m_r}\left[\frac{\text{\% Refuse Energy}}{100}\right] . \tag{4}$$

Equation (4) can be written in the form of Eq. (1) by use of generator output and unit heat rate, i.e.,

$$\eta_r = \frac{\text{(Generator Output) (Unit Heat Rate)}}{H_r m_r}\left[\frac{\text{\% Refuse Energy}}{100}\right].$$

In the preceding equations

H_T = total heat release, Btu per hour

H_r = average heating value of refuse, Btu per pound

H_c = average heating value of coal, Btu per pound

η_c = apparent combustion efficiency of coal

η_r = apparent combustion efficiency of refuse

m_r = mass of refuse to boiler, pound per hour

m_c = mass of coal to boiler, pound per hour

The unit heat rates as a function of gross generation are given in Figure A-4, Appendix A and the generator output is assumed to be the measured value.

Figure 8 presents the results of the estimates, indicating variations in refuse combustion efficiency from 60 to 95%. For comparison, Union Electric reported that combustion efficiency of refuse, during their tests, varied from 56 to 79%.[9/]

As shown in Figure 8, the percentage of refuse burned appears to be strongly dependent upon the percent of refuse fired at each power output level. While several factors may contribute to the behavior noted in Figure 8, the variations in fuel-mixing patterns in the furnace probably can account for most of the effects. Surprisingly, no correlation could be found between refuse moisture content and degree of burn-out.

STACK GAS COMPOSITION

Reduced test data on stack gas composition are presented in Tables 10 and 11. Table 10 presents the data in terms of actual system flowrates, while Table 11 presents the data corrected to 50% excess air. There is considerable scatter in the data and no meaningful trends are evident. It was concluded that no significant changes in gaseous pollution levels occur when refuse and coal are fired together in the boiler.

Figure 9 presents the SO_x emission rate as a function of percent refuse energy. The average values for coal-only firing and coal-refuse firing are also illustrated. No meaningful trends are evident, although the coal plus refuse tests appear to exhibit slightly higher (10%) average SO_x emissions. This apparent increase is probably not an effect of refuse firing since the refuse analyses indicate a uniformly low sulfur content (average 0.12%). It should be noted that the average sulfur content of the coal fired during the coal plus refuse tests was significantly higher than the average sulfur content of the coal fired during the coal-only tests, 1.63% versus 1.31%, respectively.

The EPA New Source Performance Standard for sulfur oxide from coal-fired boilers, 1.2 lb/million Btu, is also shown on Figure 9 for comparison. While this standard is not directly applicable to this plant, and may not be applicable to a new facility utilizing refuse as fuel, compliance with this requirement could involve the need for stack gas control equipment, if similar sulfur-content coal were co-fired with refuse.

Figure 10 presents the NO_x emission rate as a function of percent refuse energy. The average values for coal-only firing and coal plus refuse firing as indicated are not significantly different, nor are any trends apparent. The EPA New Source Performance Standard is indicated for reference and comparison. Although the standard is not directly applicable the NO_x emissions are generally less than those required by the NO_x standard.

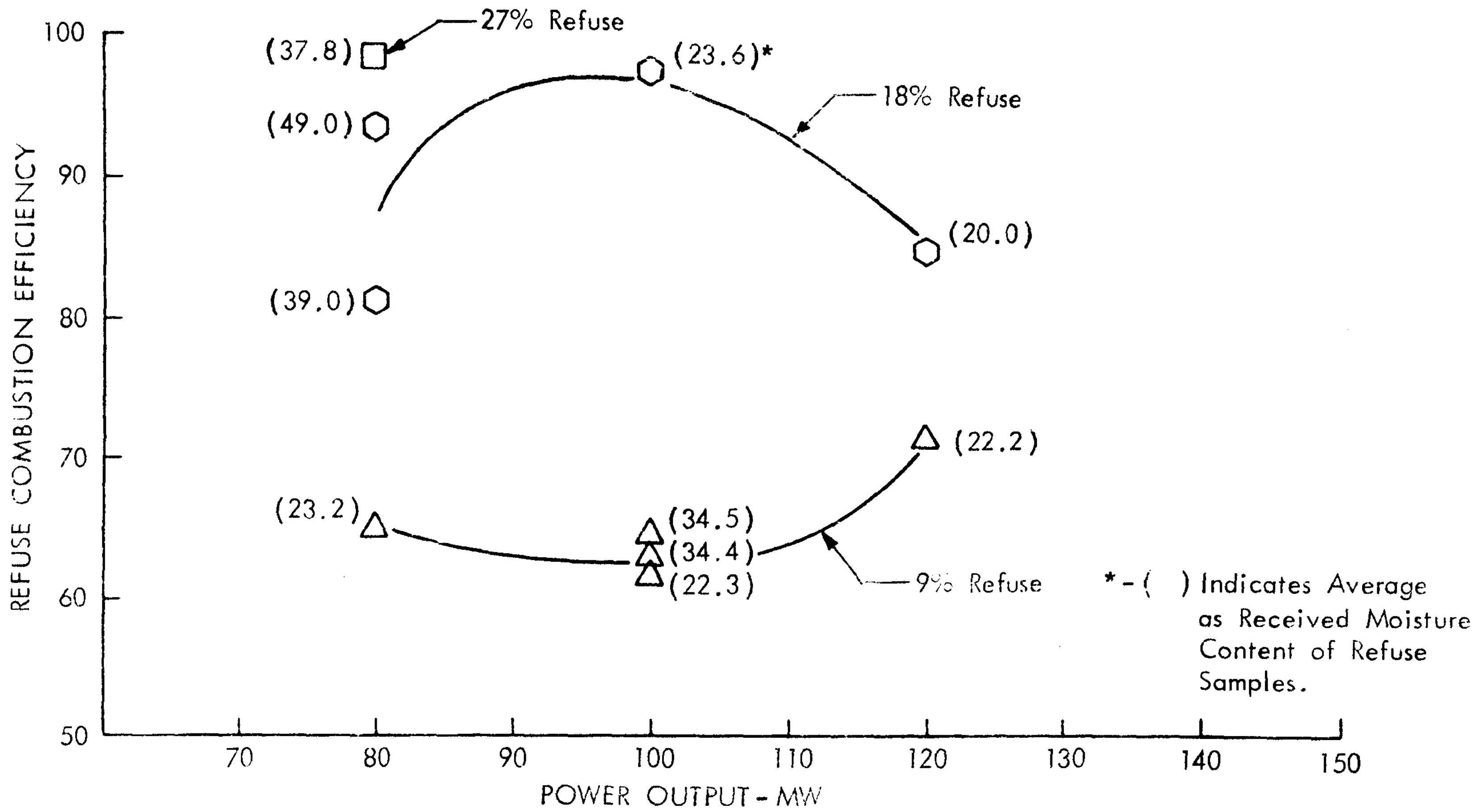


Figure 8. Apparent combustion efficiency of refuse.

Table 10. SUMMARY OF STACK GAS COMPOSITION DATA

Test No.	Nominal Load (megawatts)	Percent Refuse (heat input)	Percent Excess Air	Total Gas (acfm)	Flowrate (dscfm)	Gas Composition Dry Gas (volume) CO (ppm)	CO_2 (%)	O_2 (%)	N_2 (%)	SO_2 (ppm)	SO_3 (ppm)	NO (ppm)	Cl (mg/m^3)	Hg (µg/m^3)	(% moisture volume)
6	80	0	47	391,340	253,[illegible]52	62	13.6	6.7	79.7	900	4.1	255	290	0.017	6.2
13	80	9	40	401,084	250,[illegible]96	80	15.0	6.0	79.0	1,070	4.8	263	293	0.008	7.8
4	80	18	51	390,287	233,[illegible]58	85	14.5	7.0	78.5	900	22.2	400	416	0.019	8.8
5	80	18	40	442,128	265,[illegible]02	65	14.5	6.0	79.5	a/	0.0	340	401	0.014	9.4
7	80	27	36	398,035	243,[illegible]71	62	14.7	5.6	79.7	887	34.5	295	470	0.011	8.2
3	100	0	46	490,604	309,[illegible]98	75	13.6	6.6	79.8	800	0.0	360	377	0.007	7.3
1	100	9	40	526,735	317,[illegible]34	75	14.5	6.0	79.5	1,060	23.5	250	413	0.018	9.3
2	100	9	35	487,482	291,028	75	14.5	5.5	80.0	1,000	0.0	240	467	0.021	10.0
11	100	9	40	488,205	293,517	63	15.2	5.9	78.9	1,230	0.0	267	355	0.029	8.0
12	100	18	39	483,260	285,348	68	13.3	6.0	80.7	1,590	1.0	234	322	0.013	8.5
9	120	0	37	563,698	347,[illegible]6	42	14.6	5.7	79.7	1,130	24.0	278	339	0.014	6.9
0	120	9	45	622,148	358,1[illegible]1	62	14.5	6.5	79.0	900	0.0	220	408	0.012	8.5
8	120	9	37	674,652	413,1[illegible]8	62	13.5	5.8	80.7	1,000	0.0	347	458	0.007	8.0
10	120	18	34	573,193	346,5[illegible]4	60	15.6	5.3	79.1	1,030	0.0	275	421	0.019	8.4
Average						67	14.4	6.0	79.6	1,040	8.16	289	388	0.019	8.2
Maximum						85	15.6	7.0	80.7	1,590	34.5	400	470	0.029	10.0
Minimum						42	13.3	5.5	78.5	800	0.0	220	290	0.007	6.2

a/ Data not available because of instrument malfunction.

Table 11. STACK GAS COMPOSITION CORRECTED TO 50% EXCESS AIR

Test No.	Nominal Load (megawatts)	% Refuse (heat input)	Gas Composition: Dry Gas (volume) N_2 (%)	O_2 (%)	CO_2 (%)	CO (ppm)	SO_2 (ppm)	NO (ppm)	SO_3 (ppm)	Cl (mg/m^3)	Hg ($\mu g/m^3$)	H_2O (% moisture volume)
6	80	0	79.7	7.0	13.3	61	882	250	4.0	284	0.017	6.1
13	80	9	79.0	7.0	14.0	75	999	246	4.5	274	0.007	7.3
4	80	18	78.5	6.9	14.6	86	906	403	22.3	419	0.019	8.9
5	80	18	79.5	7.0	13.5	61	a/	317	0.0	374	0.013	8.8
7	80	27	79.6	7.0	13.4	56	804	267	31.3	426	0.010	7.5
3	100	0	79.8	7.0	13.2	73	779	350	0.0	367	0.007	7.1
1	100	9	79.5	7.0	13.5	70	989	233	21.9	385	0.017	8.7
2	100	9	79.9	7.1	13.0	67	899	216	0.0	420	0.019	9.1
11	100	9	78.9	6.9	14.2	59	1,149	249	0.0	332	0.027	7.5
12	100	18	80.6	7.1	12.3	63	1,471	217	0.9	298	0.012	7.9
9	120	0	79.6	7.0	13.4	38	1,031	254	22.1	309	0.013	6.3
0	120	9	79.0	7.0	14.0	60	870	213	0.0	394	0.012	8.2
8	120	9	80.5	7.1	12.4	57	912	316	0.0	418	0.006	7.3
10	120	18	79.1	7.0	13.9	54	920	246	0.0	376	0.017	7.6
Average			79.5	7.0	13.5	63	970	270	7.6	363	0.014	7.7
Maximum			80.6	7.1	14.6	86	1,471	403	31.3	426	0.027	9.1
Minimum			78.5	6.9	12.3	38	779	213	0.0	274	0.006	6.1

a/ Data not available because of instrument malfunction.

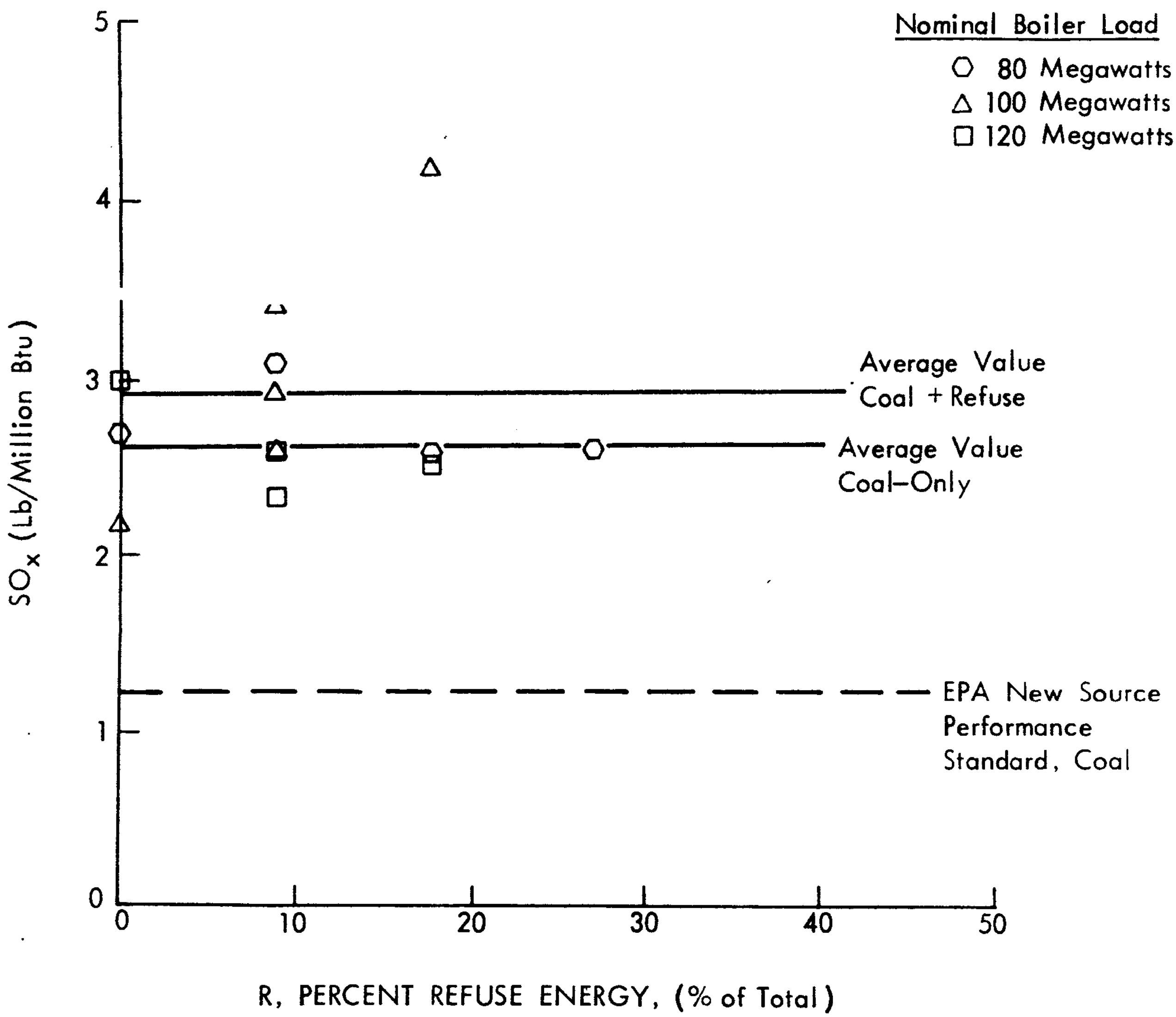


Figure 9. Sulfur oxide emissions as a function of percent refuse energy.

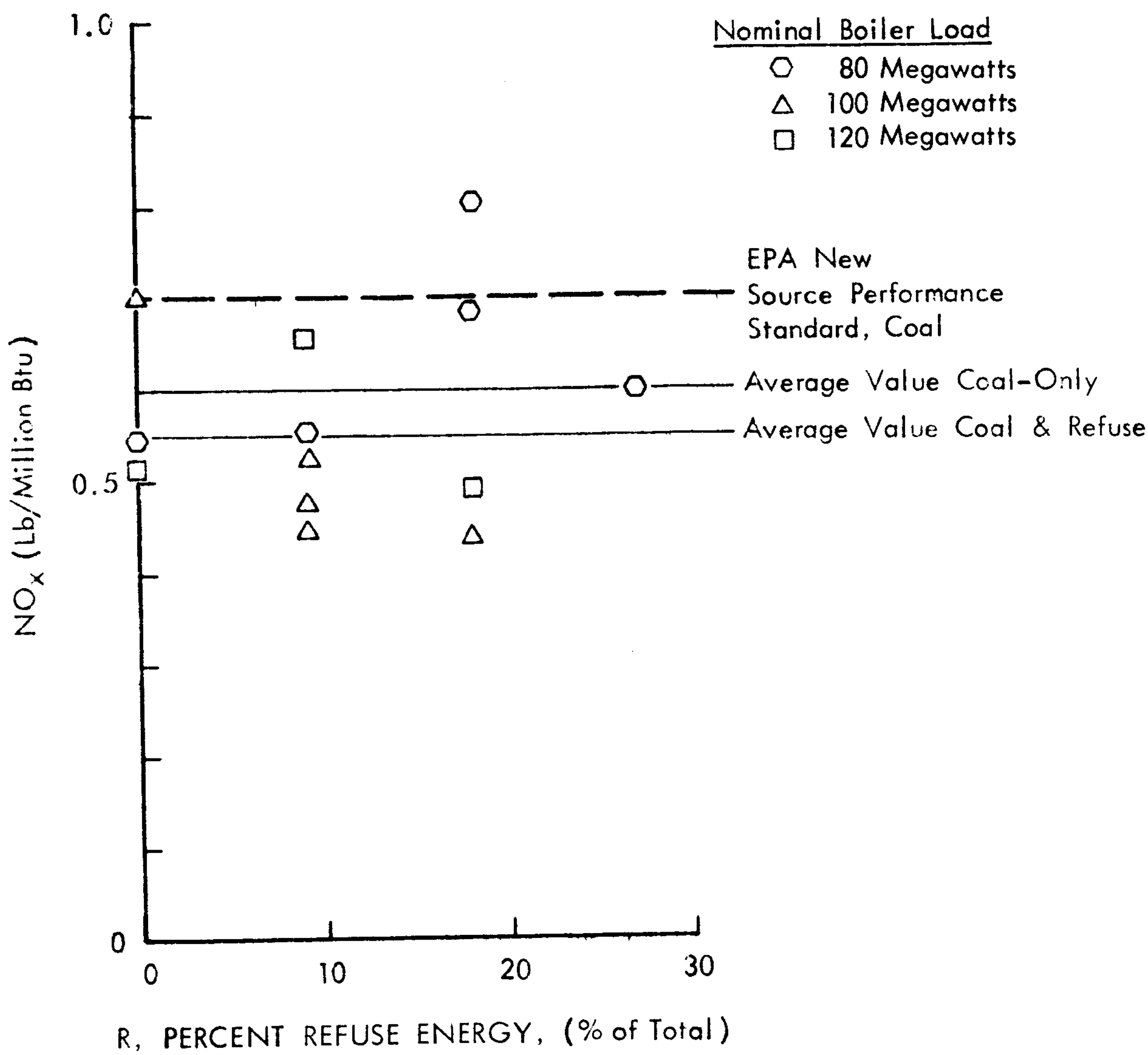


Figure 10. NO_x emissions as a function of percent refuse energy.

PARTICULATE EMISSIONS

Tables 12 and 13 present the particulate emission data from each of the tests conducted by EPA/MRI and Union Electric. Table 14 presents a summary of the mean and mean deviation of these data as differentiated by boiler load, coal, or coal plus refuse test conditions. Graphical comparisons of the mean values for inlet and outlet grain loadings for the EPA/MRI tests and the Union Electric tests are shown in Figures 11 and 12, respectively. Figure 13 is a presentation of mean particulate emission data for both test series, EPA/MRI and Union Electric.

EPA/MRI Particulate Loading Data

Inspection of Table 12, Figure 11 and the corresponding values in Table 14 indicates that the inlet loadings generally fall within the normal data scatter at each of their respective load conditions. The data scatter (mean deviation) increases with increasing load. There does not appear to be any significant effect due to refuse being fired.

Although the EPA/MRI coal-only tests appear to exhibit an increasing inlet particulate loading with increasing power level, this apparent trend is suspect. There was only one test conducted at each load on the EPA/MRI coal-only tests. The inlet loading for the test at 80 megawatts was abnormally low and the increased inlet loadings at 100 megawatts and 120 megawatts are both within the normal data scatter. Because of the abnormally low point at 80 megawatts the EPA/MRI inlet data may only fortuitously show this increasing trend. Figure 13, the plot of all mean inlet grain loading data, shows no trend and supports the conclusion that the EPA/MRI data point at 80 megawatts is probably not representative.

The outlet grain loading data show a trend of increased grain loading (Figures 11 and 13) with increased load. The data scatter also increases with increased boiler load. For given boiler load conditions on the EPA/MRI tests, the outlet particulate emissions did not appear to vary significantly whether coal or coal plus refuse was fired.

Union Electric Particulate Loading Data

Inlet grain loadings for the Union Electric tests (Table 13, Figure 12) also generally fall within the normal data scatter at each of their respective conditions. The data scatter increases with increasing power level. No significant trends for inlet grain loading are observed with either increasing power level or fuel combinations.

Table 12. SUMMARY OF PARTICULATE GRAIN LOADINGS--EPA/MRI TESTS

Boiler Load (megawatts)	Refuse Heat Input Percent	Date (1973)	Percent Excess Air	Grain Loading (grain/scfd)[a/]			
				Inlet to Precipitator		Outlet of Precipitator	
				Actual	Corrected to 50% Excess Air	Actual	Corrected to 50% Excess Air
80	0	12/10	47	1.56	1.53	0.043	0.042
80	9	12/14	40	1.86	1.75	0.041	0.038
80	18	12/9	51	1.97	1.98	0.024	0.024
80	18	12/9	40	1.90	1.78	0.03	0.028
80	27	12/10	36	2.08	1.91	0.03	0.029
100	0	12/6	46	1.80	1.75	0.05	0.049
100	9	12/5	40	1.95	1.83	0.056	0.053
100	9	12/5	35	1.84	1.67	0.074	0.068
100	9	12/13	40	1.82	1.70	0.05	0.046
100	18	12/13	39	2.05	1.91	0.064	0.059
120	0	12/12	37	1.92	1.77	0.07	0.062
120	9	12/4	45	2.09	1.96	0.09	0.085
120	9	12/11	37	1.80	1.66	0.044	0.04
120	18	12/12	34	1.61	1.45	0.06	0.056

a/ 70°F, 29.92 in. Hg.

Table 13. SUMMARY OF PARTICULATE GRAIN LOADINGS--UNION ELECTRIC TESTS[a]

Boiler Load (megawatts)	Percent Refuse	Test No.	Date (1973)	Grain Loading (grain/scfd) Inlet to Precipitator	Outlet of Precipitator
75	0	4	10/18	1.91	0.025
75	0	5	10/18	1.96	0.02
75	13.2	6T	11/29	2.08	0.045
75	14.7	7T	11/29	1.89	0.045
101	0	1	10/16	2.35	0.036
100	0	2	10/17	1.93	0.029
100	0	3	10/17	2.04	0.04
100	14.8	5T	11/28	2.13	0.076
100	15	4T	11/28	2.07	0.07
139	0	6	10/19	1.81	0.047
140	0	7	10/19	2.07	0.05
140	0	8	11/30	1.96	0.084
140	10	1T	11/26	1.67	0.07
140	10	2T	11/27	1.77	0.12
140	10	3T	11/27	2.11	0.14
140	11.4	9T	11/30	2.09	0.12

a/ Union Electric data were reported according to ASME standard conditions (32°F and 29.92 in. Hg). Values in this table have been converted to 70°F, 29.92 in. Hg for purposes of more direct comparison with EPA/MRI values.

Table 14. PARTICULATE EMISSION DATA, MEAN AND MEAN DEVIATION

	Inlet (grain/dscf)		Outlet (grain/dscf)	
	Mean	Deviation	Mean	Deviation
EPA/MRI Tests, Coal				
80 megawatts	1.56	[a]	0.043	[a]
100 megawatts	1.80	[a]	0.050	[a]
120 megawatts	1.92	[a]	0.067	[a]
EPA/MRI Tests, Coal plus Refuse				
80 megawatts	1.95	0.072	0.037	0.0074
100 megawatts	1.91	0.085	0.062	0.0098
120 megawatts	1.83[b]	0.172[b]	0.065	0.0163
	1.94[c]	0.146[c]		
Union Electric Tests, Coal				
75 megawatts	1.94	0.025	0.023	0.0025
100 megawatts	2.11	0.163	0.035	0.004
	1.99	0.055		
140 megawatts	1.95	0.068	0.060	0.0157
Union Electric Tests, Coal plus Refuse				
75 megawatts	1.99	0.095	0.045	0
100 megawatts	2.10	0.003	0.073	0.003
140 megawatts	1.91	0.190	0.113	0.0151
			0.127	0.009

a/ Only one test.
b/ Value for all data points.
c/ Value without extreme data point.

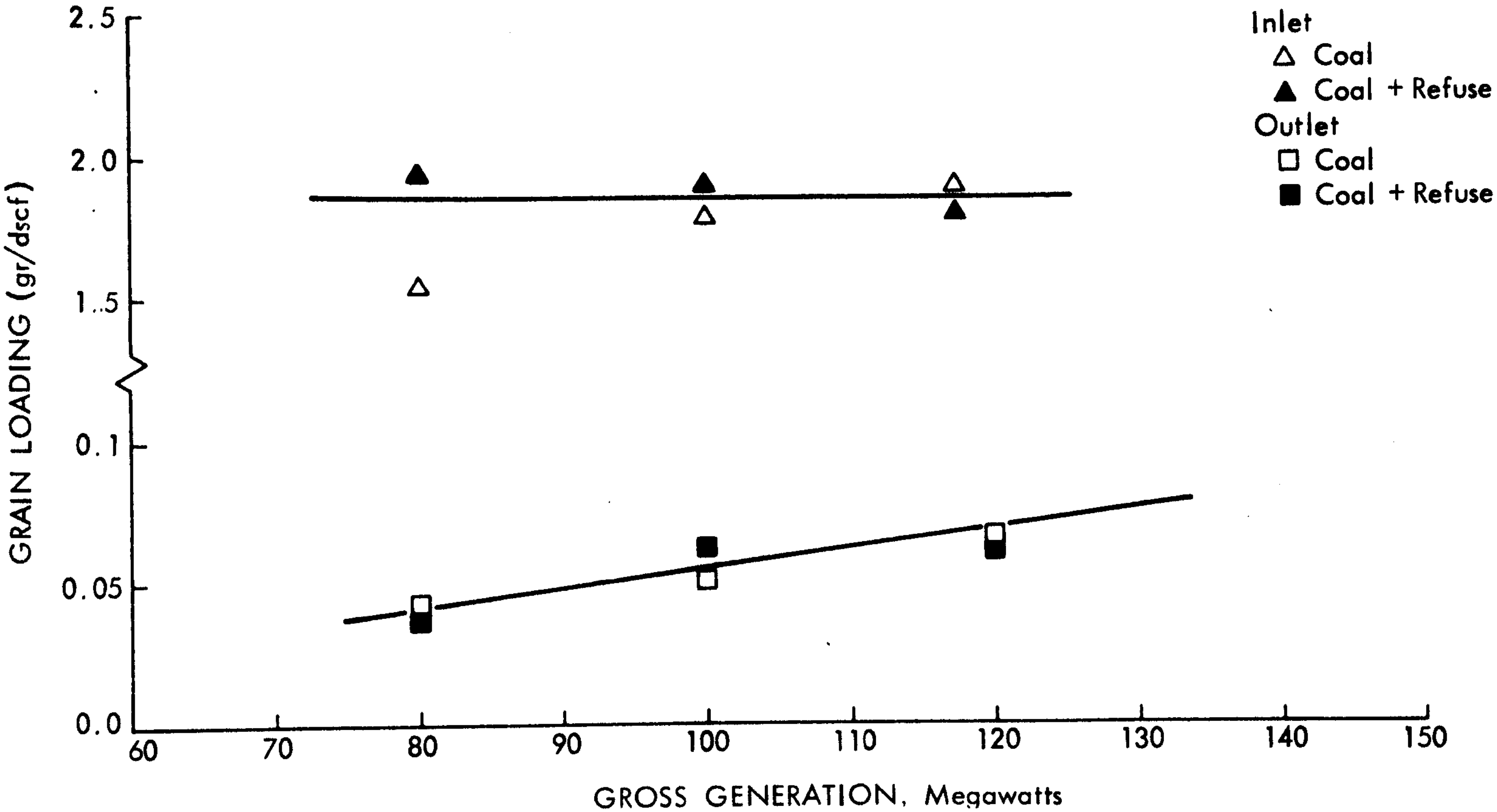


Figure 11. Comparison of inlet and outlet grain loadings for coal only and coal plus refuse firing-EPA/MRI mean value data.

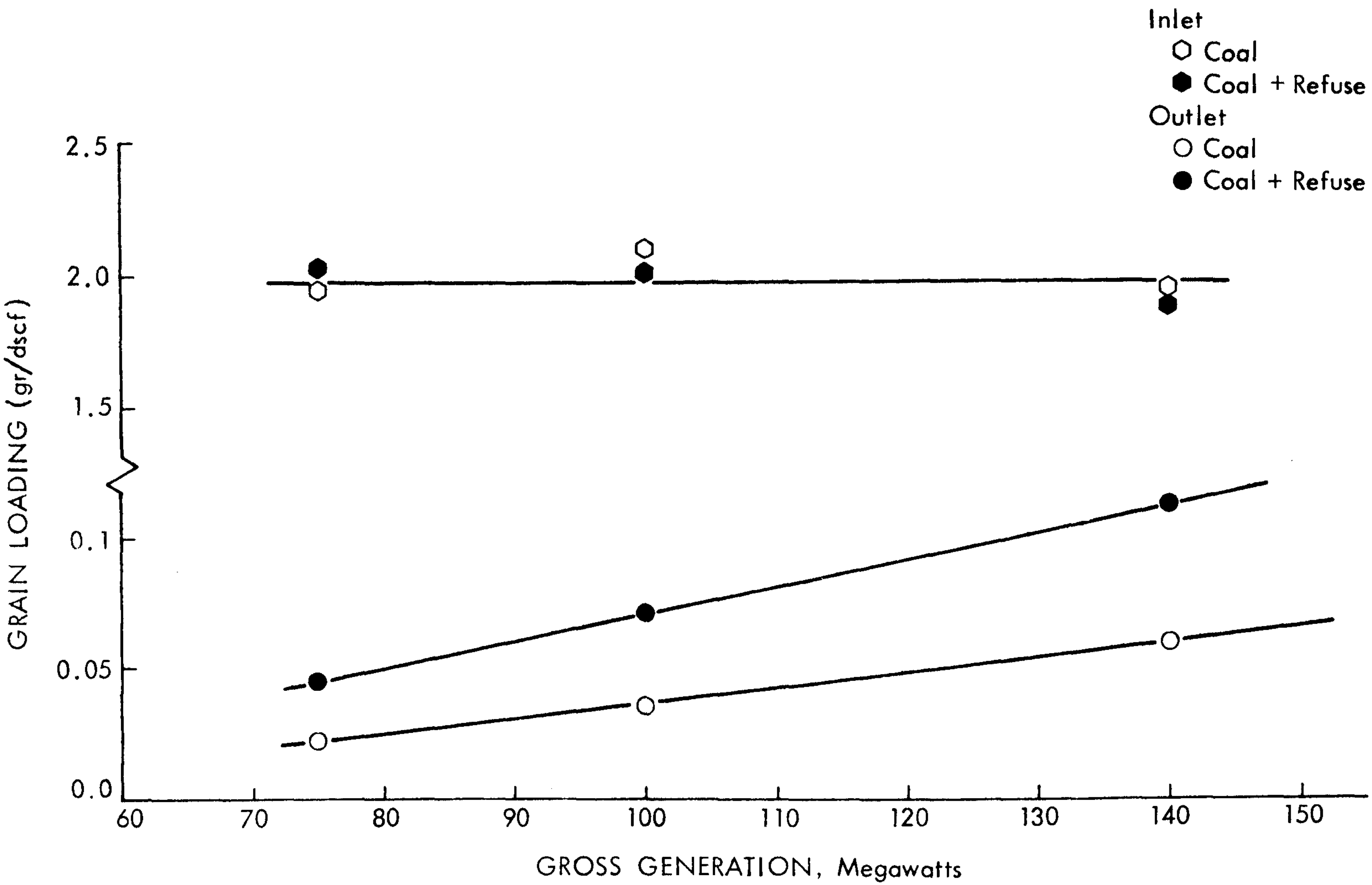


Figure 12. Comparison of inlet and outlet grain loading for coal only and coal plus refuse firing-Union Electric mean value data.

The outlet grain loading data (Figure 12) show a definite trend of increased grain loading with increased power level. More significantly, perhaps, is the indicated difference between coal-only and coal plus refuse outlet loadings. Outlet grain loading for mixed fuel tests were approximately double those for coal-only tests at the same loads. This fact will be discussed in more detail later.

Interpretation of Emission Data

Figure 13 presents both EPA/MRI and Union Electric electrostatic precipitator inlet and outlet loadings for the various combinations of boiler loads and fuel firings. Inlet grain loadings are essentially constant for all conditions in both test series.

The mean EPA/MRI outlet particulate loadings were only moderately higher than the Union Electric coal-only outlet loadings at comparable boiler loads. However, the mean Union Electric outlet loading for coal plus refuse is almost double the mean values of the coal-only tests at comparable boiler loads. Examination of the Union Electric data at 140 megawatts suggests a possible explanation for the apparent difference in data. As shown in Table 13, one of the Union Electric coal-only tests at 140 megawatts was conducted about 1 month after the original Union Electric coal-only tests. Outlet grain loading for that test is more nearly equivalent to that for the combined coal plus refuse tests than to the previous coal-only tests. The Union Electric test procedures for their last coal-only test were quite similar to the EPA/MRI procedures whereas the Union Electric original coal tests involved a 2-week stabilization period. During the 2-week stabilization period, only coal was fired in the boiler. In this regard, it is very interesting to note that the Union Electric coal-only test of 11/30 at 140 megawatts correlates very closely with the EPA/MRI coal-only data at lower gross generation rates. Thus, the differences between the coal-only outlet grain loadings reported by EPA/MRI and Union Electric may be due principally to differences in the pre-test history of fuel firing used to establish the base-line particulate emissions. This point will be discussed in more detail in the next section on electrostatic precipitator performance.

Figure 14 presents a correlation of uncontrolled particulate emissions (pounds per 10^6/Btu) as a function of percent refuse energy. The apparent trend of a slight increase in uncontrolled particulate emissions with increasing percent of refuse energy is probably mainly a result of data scatter.* Additional testing will be required to clarify this point.

* As shown in Figure 14, with the exception of one test at 100 megawatts and 18% refuse energy, all data points are within a $\pm$ 10% variation of the mean curve.

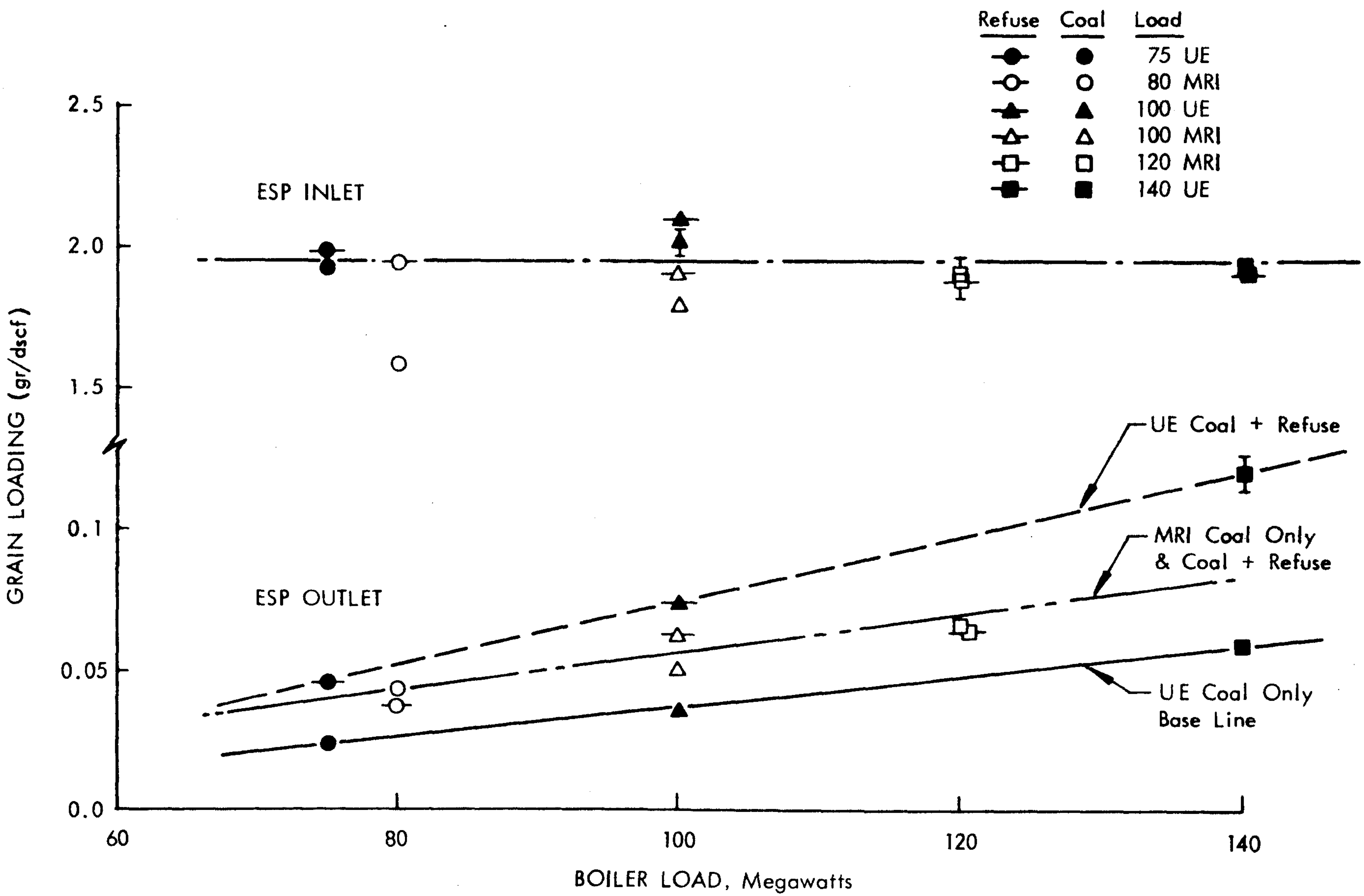


Figure 13. Mean particulate emission data.

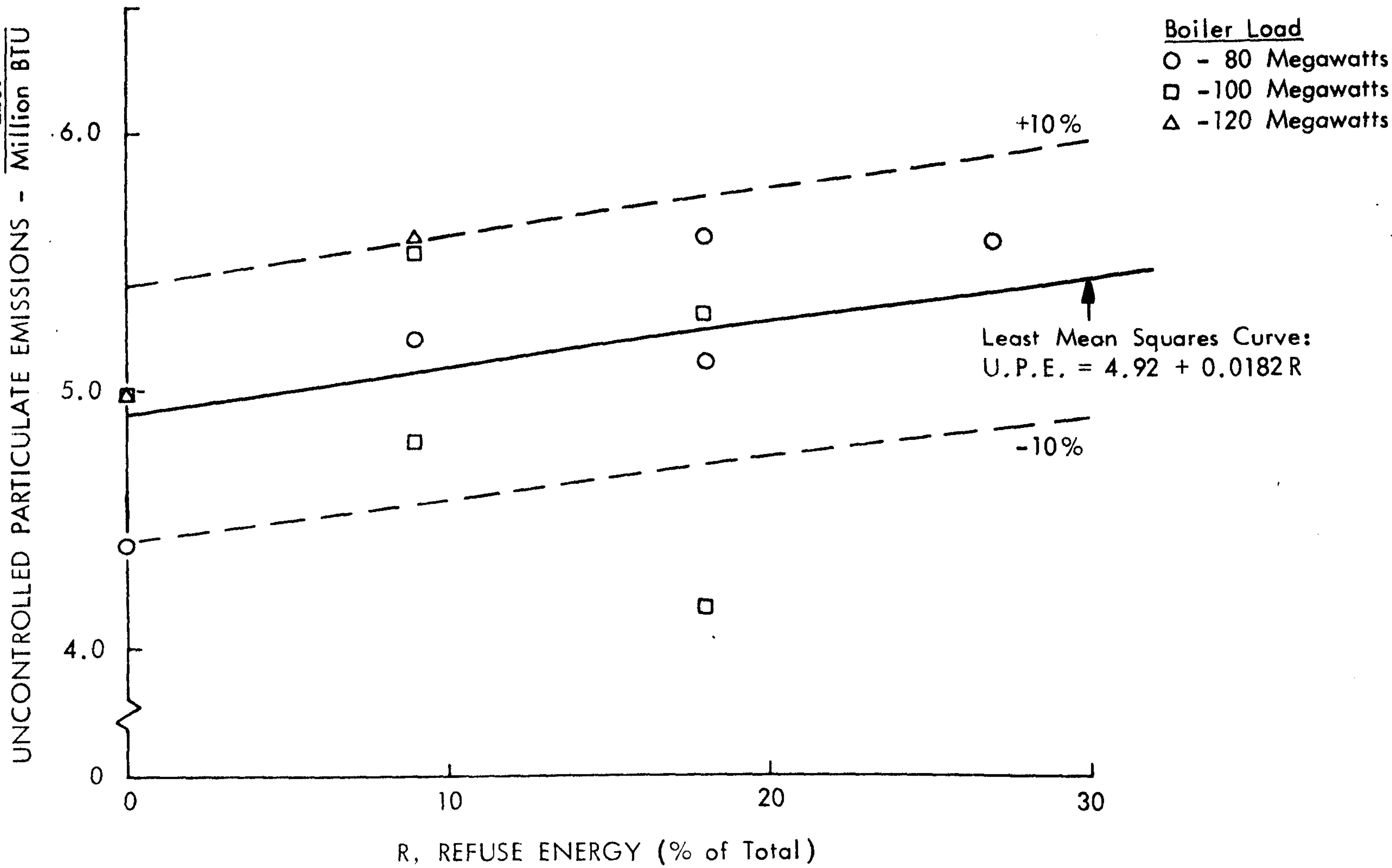


Figure 14. Uncontrolled particulate emission rate as a function of percent refuse energy.

Particle size distributions of the particulates at the inlet to the precipitator (EPA/MRI) tests are given in Figures 15, 16, and 17. Data were not available for the test condition of 9% refuse energy and 80 megawatts. Because of the significant amount of data scatter at the duplicate test conditions, there does not appear to be any valid discernible trends.

Electrical Measurements

During the EPA/MRI and Union Electric tests, primary voltages, primary currents and sparking rates were recorded for each of the four ESP electrical sets. In addition secondary voltages and currents were recorded during each of the EPA/MRI emission tests and special ESP voltage versus current tests were run after the completion of some of the EPA/MRI emission tests. Figure 18 presents typical data for secondary voltage.

Electrical measurements made during the EPA/MRI and Union Electric tests are presented in detail in Tables C-1 and C-2 in Appendix C. Summaries of this data are presented in Tables 15, 16, and 17. These measurements indicate that firing of refuse results in increased sparking rates and reduced ESP voltage and current (power) levels. During the EPA/MRI test series, the firing of refuse resulted in average losses in ESP power ranging from 13.2 to 18.4%. Corresponding changes in average sparking rates varied from 2 sparks/min to 68 sparks/min. There was no apparent trend in sparking rate change or power loss with boiler load or the percent of refuse fired. The Union Electric data indicated average ESP power losses which ranged from 4.1 to 16.1% when firing refuse. Average sparking rate increases ranged from 201 sparks/min to 339 sparks/min. While the Union Electric sparking rate data did not show any trends with load, the average power loss increased montonically with load.

It is generally accepted that optimum or maximum precipitator collection efficiencies are obtained at peak time average voltage (power) levels.[8/] While peak average voltages may occur in the neighborhood of 100 sparks/min, sparking rates in the range of 200 to 300 sparks/min generally correspond to less than maximum power input and would be indicative of less than nonoptimum performance. The rather high sparking rates recorded during the Union Electric combined firing tests suggest that the precipitator was not operating at optimum conditions during those tests.

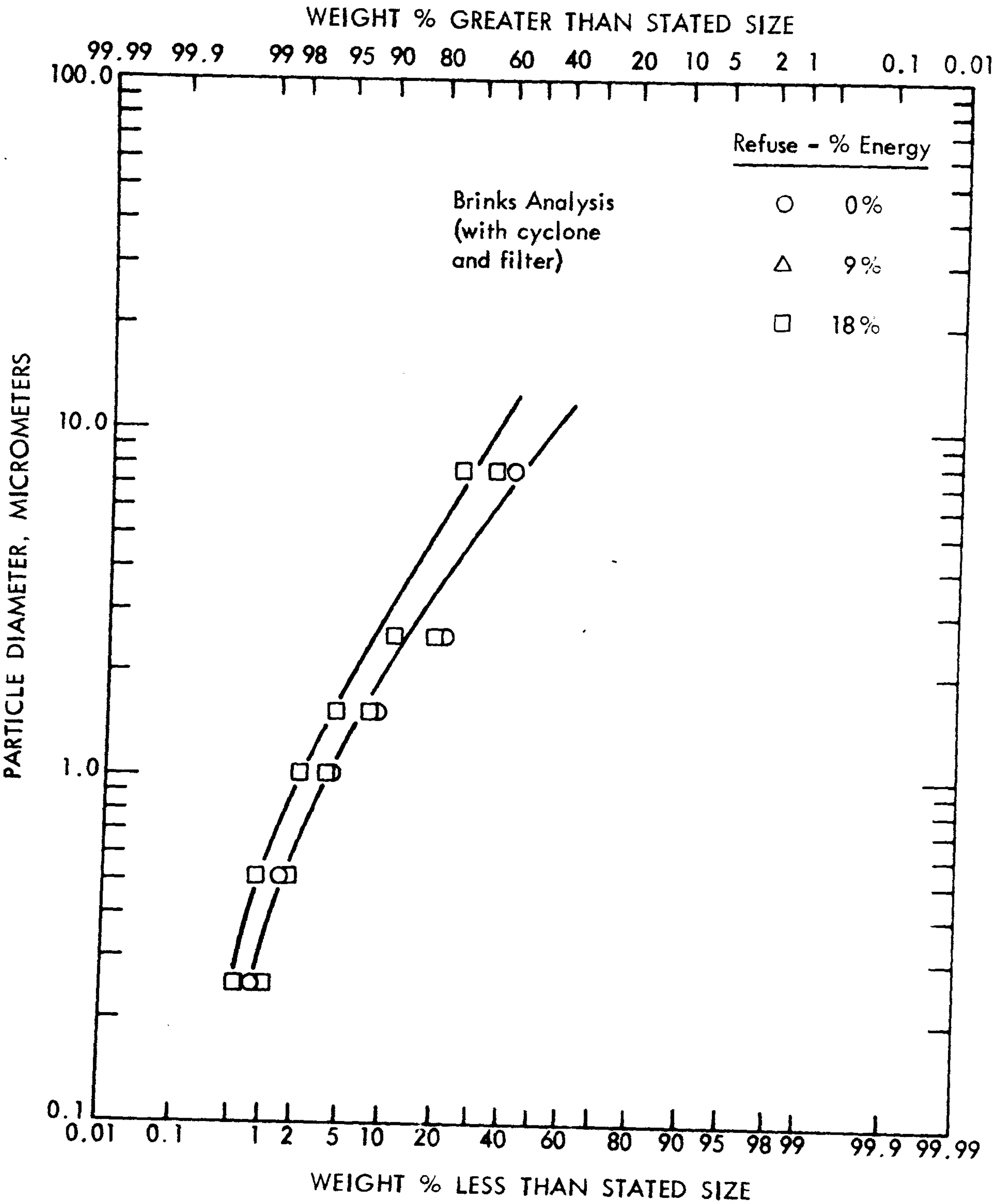


Figure 15. Particle size distribution at ESP inlet, power output = 80 megawatts.

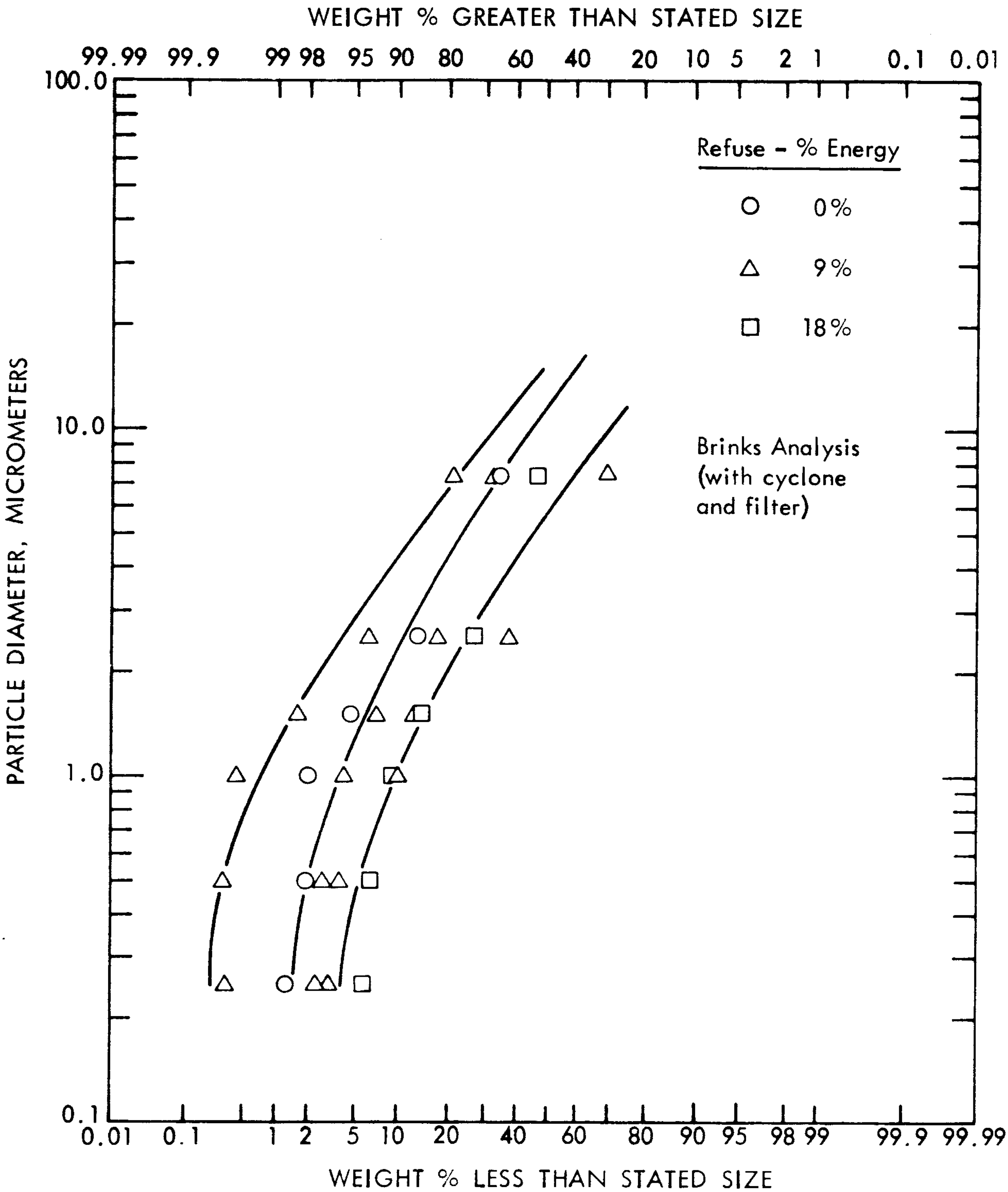


Figure 16. Particle size distribution at ESP inlet, power output = 100 megawatts.

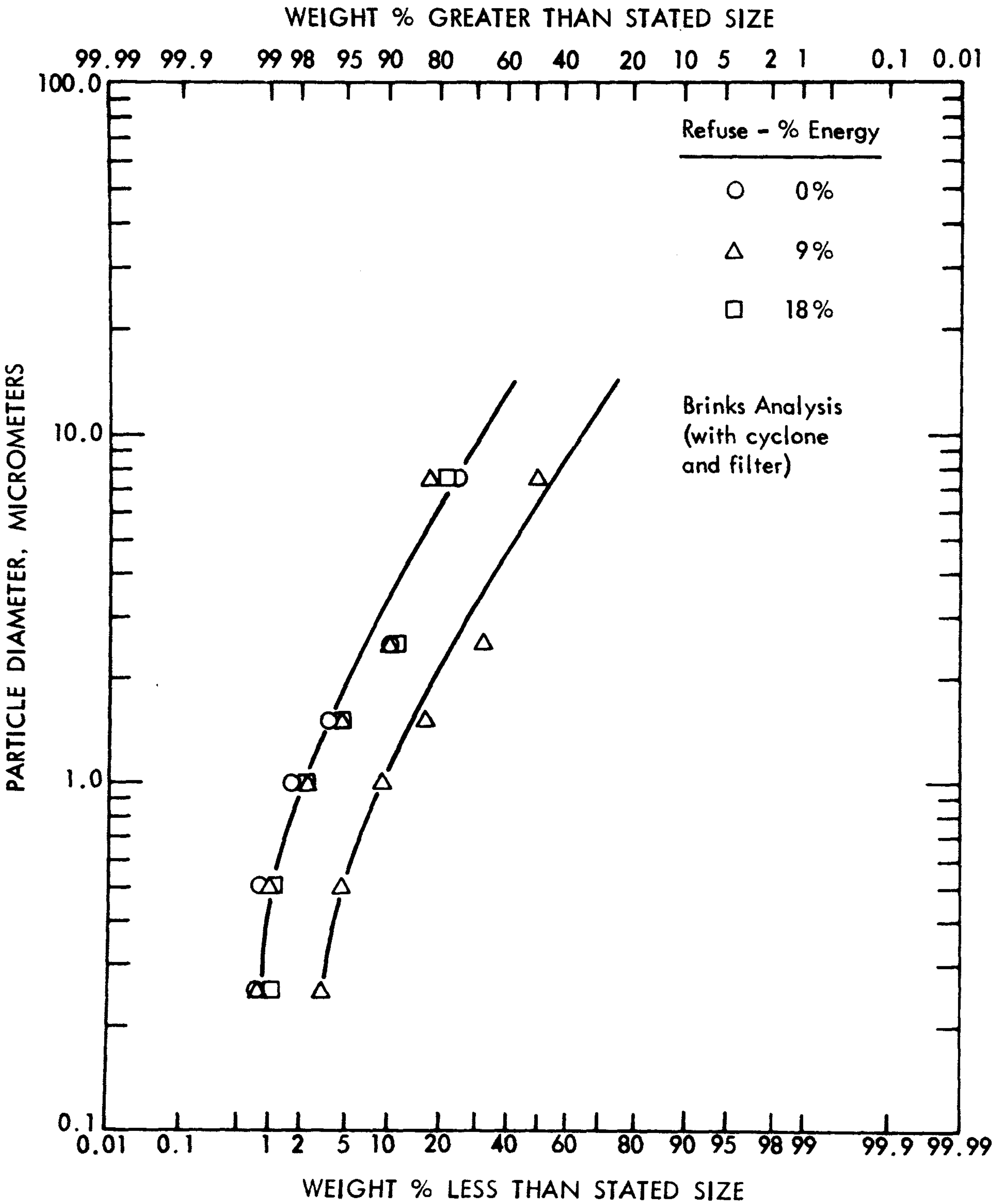


Figure 17. Particle size distribution at ESP inlet,
power output = 120 megawatts.

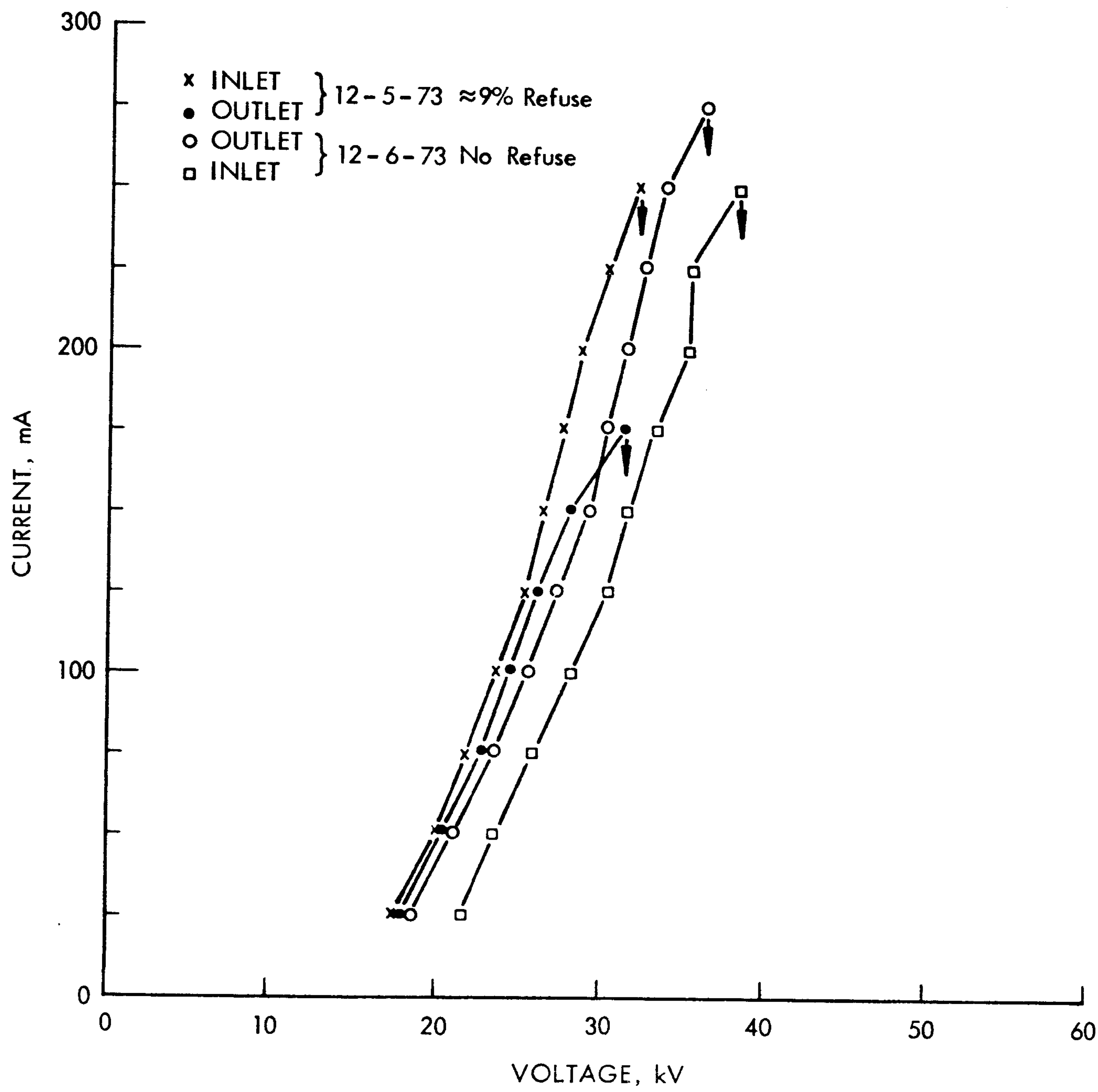


Figure 18. Secondary voltage versus current curves with 9% refuse firing and coal only at a generation rate of 100 megawatts.

Table 15. AVERAGE PRECIPITATOR ELECTRICAL PERFORMANCE MEASUREMENTS[a]
(EPA/MRI Tests)

Gross Generation (megawatts)	Refuse Heat Input (percent)	Test No.	Primary Voltage (volts)	Primary Current (amps)	Primary Power (kw)	Secondary Voltage (kv)	Secondary Current (m-amps)	Secondary Power (kw)	Sparking Rate (sparks/min) Average	Sparking Rate (sparks/min) Minimum	Sparking Rate (sparks/min) Maximum
80	0	6	295	42	12.3	36	265[b]	9.5[b]	88	50	120
80	9	13	266	41	10.9	25	263	6.6	84	10	150
80	18	4	266	41	10.9	32	259[b]	8.2[b]	61	0	180
80	18	5	268	39	10.4	33	248[b]	8.2[b]	122	30	420
80	27	7	265	40	10.6	31	256	7.9	90	10	170
100	0	3	295	43	12.8	37	280[b]	10.4[b]	14	0	5
100	9	1	261	39	10.2	32	253	8.0	115	70	185
100	9	2	263	39	10.2	33	248	8.1	114	50	200
100	9	11	263	41	10.7	27	254	6.8	70	5	190
100	18	12	255	42	10.7	25	265[b]	6.6[b]	32	0	145
120	0	9	290	42	12.2	33	268[b]	8.7[b]	13	0	30
120	9	8	271	40	10.9	30	251	7.6	109	5	300
120	18	10	258	39	10.0	27	246	6.6	108	25	340

a/ Average value for all four ESP electrical sets computed from data in Table C-1, Appendix C.
b/ One or more readings above 300 m-amp meter limit - averages based on low side by undetermined value.

Table 16. AVERAGE PRECIPITATOR ELECTRICAL PERFORMANCE MEASUREMENTS[a/]
(Union Electric Tests)

Gross Generation (megawatts)	Refuse Heat Input (%)	Test No.	Primary Voltage (volts)	Primary Current (amps)	Primary Power (kw)	Sparking Rate (sparks/min) Average	Sparking Rate (sparks/min) Minimum	Sparking Rate (sparks/min) Maximum
75	0	4	304	45	13.7	19	3	33
75	0	5	306	45	13.9	9	0	23
75	13.2	6T	288	45	12.9	163	77	257
75	14.7	7T	293	46	13.5	268	105	330
101	0	1	315	46	14.3	23	0	59
100	0	2	312	46	14.2	11	0	30
100	0	3	313	45	14.2	15	0	30
100	14.8	5T	287	47	13.4	304	110	450
100	15	4T	275	45	12.5	405	270	460
139	0	6	318	45	14.4	12	1	21
140	0	7	312	45	14	26	11	38
140	0	8	299	45	13.4	147	40	300
140	10	1T	273	45	12.2	255	35	363
140	10	2T	269	44	11.9	286	100	450
140	10	3T	273	44	12.1	333	138	500
140	11.4	9T	272	39	10.6	309	220	450

a/ Average value for all ESP electrical sets computed from data in Table C-2, Appendix C. Secondary voltage and current not reported.

Table 17. COMPARISON OF COAL AND COAL PLUS REFUSE ESP ELECTRICAL MEASUREMENTS

Gross Generation (megawatts)	Fuel	Average Primary Measurements Voltage (volts)	Current (amps)	Power (kw)	Average Change in Power (%)	Sparking Average (sparks/min)
MRI/EPA Tests						
80	Coal only	295	42	12.3	0	88
	Coal plus refuse[a/]	266	40	10.7	-13.2	90
100	Coal only	295	43	12.8	0	14
	Coal plus refuse[a/]	261	40	10.5	-18.4	74
120	Coal only	290	42	12.2	0	13
	Coal plus refuse[a/]	264	39	10.4	-14.9	81
Union Electric Tests						
75	Coal only	305	45	13.8	0	14
	Coal plus refuse	290	45	13.2	-4.1	215
100	Coal only	313	46	14.3	0	16
	Coal plus refuse	281	46	12.9	-9.8	355
140	Coal only	310	45	13.9	0	62
	Coal plus refuse	272	43	11.7	-16.1	296

a/ Average for all coal and refuse tests.

PERFORMANCE OF ELECTROSTATIC PRECIPITATOR

Determination of the performance of the electrostatic precipitator under conditions of combined firing with coal and refuse was a key goal of the test program.

Southern Research Institute (SRI) personnel assisted in the test program with EPA/MRI to evaluate the collection efficiency of the electrostatic precipitator while burning refuse in conjunction with fossil fuels in the boiler. SRI provided measurements of the particulate resistivity and the electrical conditions in the precipitator during portions of this test program. In addition, SRI provided analytical assistance, utilizing its computer models, in evaluating the precipitator performance.

The following subsections present the results of the measurements of the particulate resistivity and precipitator electrical conditions and a discussion of the performance of the electrostatic precipitator.

Particulate Resistivity

Measurements of particulate resistivity were made by SRI using a point-to-plane instrument. No significant variation in resistivity was detected with changing fuels as shown in Figure 19.

Efficiency of Electrostatic Precipitator

The efficiency of the electrostatic precipitator was calculated from the following equation:

$$\text{Efficiency } \% = \frac{\text{Inlet Grain Loading - Outlet Grain Loading}}{\text{Inlet Grain Loading}} \times 100$$

Figure 20 presents a comparison of electrostatic precipitator efficiencies obtained using the mean values of inlet and outlet grain loading given in Table 14 and Union Electric's coal-only test in November. No significant differences in ESP efficiency were noted in the EPA/MRI tests as a function of fuel mixtures, but ESP efficiency declined with increasing boiler load.

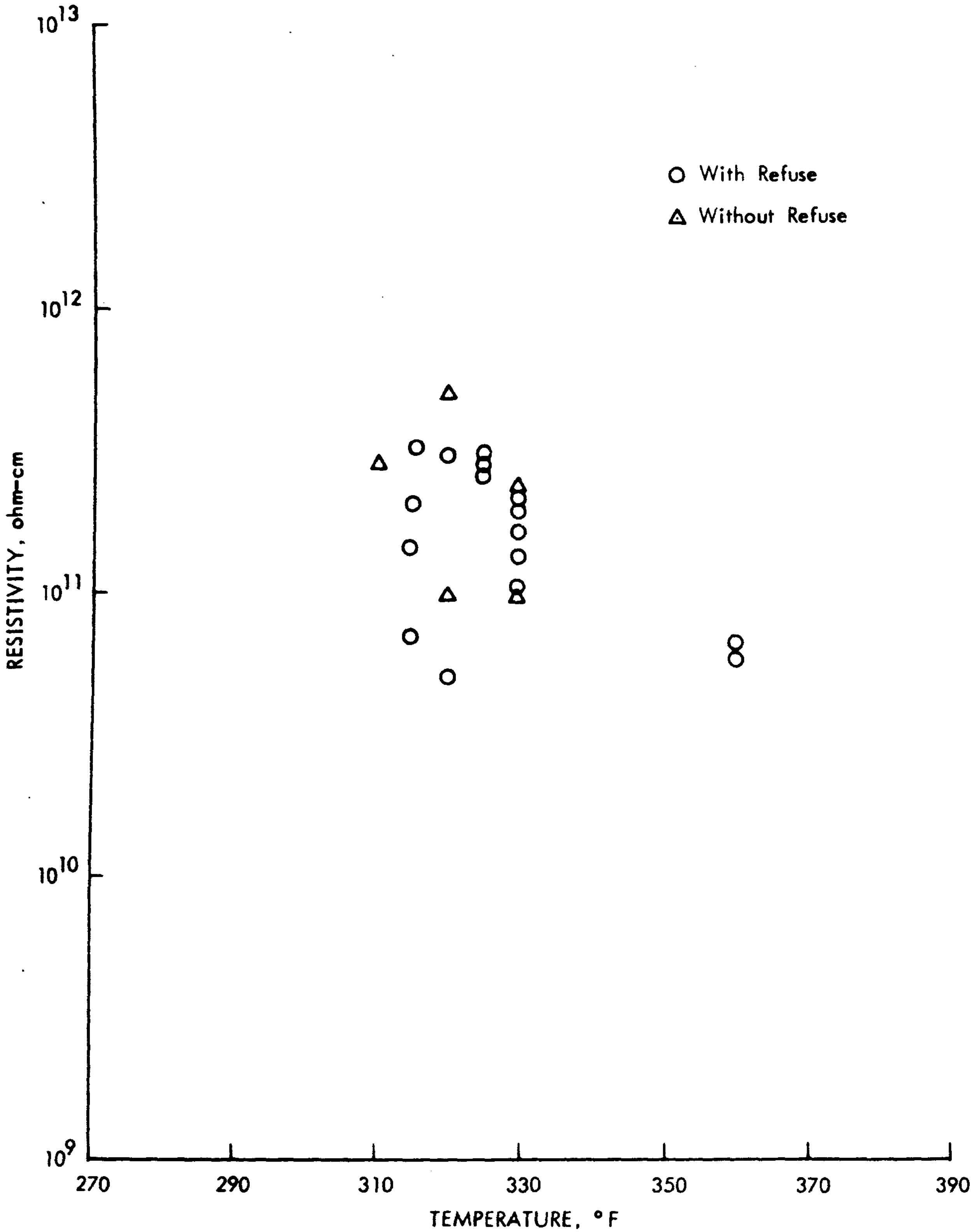
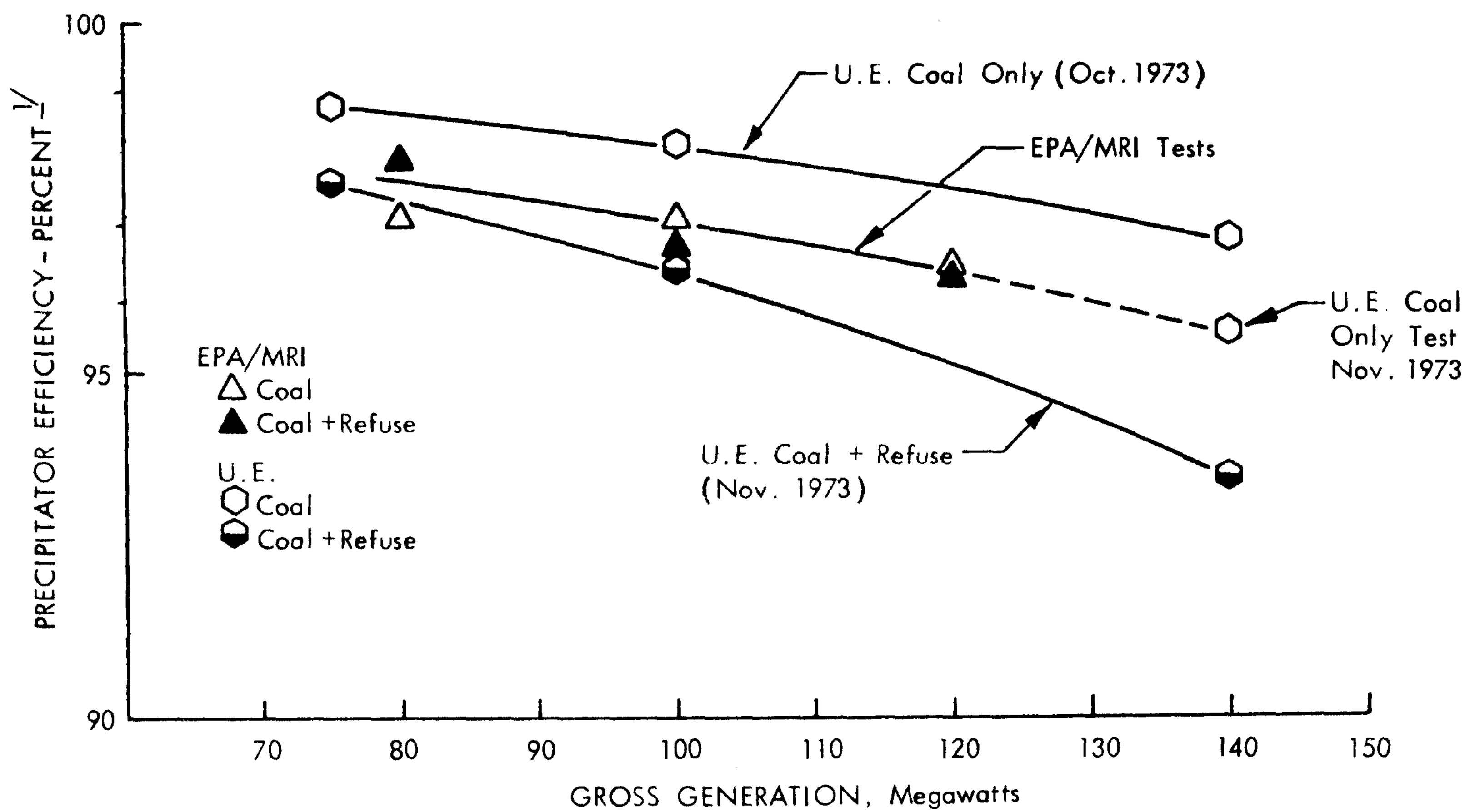


Figure 19. Resistivity versus temperature with and without refuse firing at the Meramec Power Station, December 1973.



1/ Calculation using mean values for inlet and outlet grain loading, Table XIV.

Figure 20. Variation of ESP efficiency with changes in fuel and boiler load.

Efficiencies calculated from the Union Electric data show a marked dependence on fuel mixture--a significantly lower efficiency resulting from combined firing. In addition, the trend to decreasing efficiency with increasing boiler load is more prevalent for the combined-firing case.

The differences in efficiency between the EPA/MRI and Union Electric coal-only tests may be primarily the result of the pre-test history of refuse firing. With the exception of one test in November 1973, all of the Union Electric data for coal-only firing were obtained in October 1973. The Union Electric November test, conducted at a power level of 140 megawatts, indicates a precipitator efficiency substantially lower than the earlier Union Electric coal-only test at 140 megawatts. Possible explanations for this difference are that: a coal-only base-line shift unrelated to the firing of refuse occurred between the time of the October tests and the test in November; the collection efficiency of the precipitator was shifted because of refuse particles in the residual dust layer on the ESP electrodes; or the November test result was in error. Analysis of the available information and data does not yield conclusive proof as to which of these alternatives are correct, but further analysis permits the postulation of a logical answer.

As noted in the section describing test procedures, prior to the Union Electric tests in October 1973, the precipitator was checked and adjusted and the unit was operated in a normal manner firing only low sulfur coal for 2 weeks. Sufficient time for stabilization of the precipitator was allowed by this procedure, and the data obtained should represent actual conditions resulting from coal-only firing. EPA/MRI test procedures were such that the coal-only tests were conducted between coal plus refuse firing tests, and, furthermore, prior to all EPA/MRI tests the boiler had been operating in a combined-firing mode for several weeks. Thus, a very short stabilization time was allowed in the EPA/MRI coal-only tests and there was s significant pre-test history of previous refuse firing. The data obtained by EPA/MRI for the coal-only tests probably reflect precipitator performance on combined fuel rather than coal only. The Union Electric coal-only test conducted in November 1973, was conducted on the same day as a coal plus refuse test, and in addition, during the 2 weeks prior to testing, 81 tons of refuse were fired in the boiler. That test procedure parallels the test procedure used by EPA/MRI, and as shown in Figure 20, the data point at 140 megawatts forms a logical extension to the EPA/MRI data. Therefore, it seems likely that the difference in the EPA/MRI and Union Electric data for coal-only firing can be largely attributed to the differences in precipitator conditioning procedures.

Part of the decrease in precipitator efficiency noted in the Union Electric coal plus refuse tests may in part be due to nonoptimum adjustment of the ESP for operation on coal plus refuse. However, it is unlikely that the decrease can be entirely associated with improper adjustment of the precipitator and one must conclude that the Union Electric data do indicate that the efficiency of the precipitator decreases when coal and refuse are fired in the boiler. Possible explanations for the observed decrease in precipitator efficiency with refuse firing are discussed next.

The performance of an electrostatic precipitator depends upon a variety of particulate and carrier gas properties such as inlet grain loading, particle size distribution, particulate resistivity, gas flowrate, gas temperature, and moisture content of gas stream. Since no significant changes were noted in inlet grain loading, particulate resistivity or gas temperature, changes in precipitator performance cannot be attributed to variations in those parameters. Inlet size distribution data do not show any consistent trends with the type of fuels fired and one cannot conclude that changes in the particle size distribution are a primary cause of the ESP performance loss when firing refuse.

The addition of fuel with an elevated moisture content (i.e., refuse) results in a change in the gas composition at the precipitator inlet. The average moisture in the gas stream during the EPA/MRI coal-only tests was 6.8% by volume, while the average during refuse firing was in excess of 8%. Additional moisture in the gas stream can produce changes in the electrical conditions of the precipitator resulting in changes in efficiency.

Specific changes which occurred in the electrical conditions of the precipitator are evidenced by shifts in the voltage versus current data and the spark rate (see Tables 15, 16, and 17). Secondary voltage decreased and sparking rates increased with refuse firing. Both of these changes generally result in lower ion densities and decreased particle charging which in turn causes a decrease in precipitator collection efficiency.

One of the apparent changes that occurred with refuse firing in the Union Electric tests was an increase in gas flowrate through the precipitator. Union Electric estimations based on changes in fuel heating values (fuel composition was assumed to remain constant), indicated a 10 to 17% increase in gas flow in the November 1973 tests (coal plus refuse) in comparison to the October tests (coal-only). Their November velocity traverses showed a 1 to 7% increase over the October tests while a 5% increase was noted when comparing the one coal-only test in November to a coal plus refuse test conducted the same day. Nonideal flow measuring conditions, inaccuracies inherent in field measurement techniques and the effect of excess air on gas volumes preclude firm judgments regarding magnitude of gas flowrate increases during the Union Electric refuse firing tests.

The EPA/MRI data which were calculated from velocity profiles show only a slight increase in gas flowrate at a given power output when refuse is substituted for coal fed to the boiler. However, most of the EPA/MRI test data indicate flowrates into the precipitator considerably in excess of the design flowrate* and an increase in flowrate with increase in gross generation.

Theoretical gas flowrates were calculated by assuming complete combustion of coal and refuse to CO_2, H_2O, SO_2, etc., with 50% excess air. Table 18 and Figure 21 summarize the results of the calculations. At a given power output, theoretical flowrates increase with increasing percent refuse fired and increasing moisture content in the refuse. Theoretical flowrates are in excess of design flowrates for the ESP when coal or coal and refuse are fired at power outputs exceeding 120 megawatts.*

Calculated gas flowrates are considerable lower than those measured in the EPA/MRI test program (Figure 21). Errors in the field measurements, air leakage into the system, incorrect heating values for coal and refuse, incorrect boiler efficiency data, inefficient combustion, or errors in estimated coal and refuse firing rates may contribute to the discrepancy.

The electrical conditions and particle size distributions that were determined from the EPA/MRI field tests, together with the electrostatic precipitator design data, were utilized as an input to the Southern Research Institute precipitator systems model. The model was used to predict the collection efficiency as a function of volume flowrate for the Meramec Station. These results are plotted together with the measured performance data in Figure 22. The gross generation rates corresponding to the inlet volume flowrates are also shown in Figure 22. The computer predicted performance parallels both the EPA/MRI and Union Electric measured performance for the conditions representative of coal plus refuse firing (see Figure 20).

---

* According to Union Electric, the electrostatic precipitator was originally designed for 97.5% efficiency burning coal at approximately 125 megawatts and 411,500 acfm into the precipitator.

Table 18. THEORETICAL GAS FLOWRATE AT 310°F and 1 ATM

Power Output (megawatts)	Fuel Moisture (% wt. wet)		Exhaust Volume Flowrates (cfm)			
	Coal	Refuse	Coal	10% R	20% R	30% R
60	10	10	206,978	211,707	--	--
	10	30	206,978	213,379	219,191	225,248
	10	50	206,978	215,124	--	--
80	10	10	272,067	278,295	284,731	291,014
	10	30	272,067	280,493	288,130	296,093
	10	50	272,067	282,787	293,690	304,483
100	10	10	337,136	344,848	352,828	360,613
	10	30	337,136	347,572	357,039	366,906
	10	50	337,136	350,414	363,929	377,303
120	10	10	405,016	414,285	423,866	433,222
	10	30	405,016	417,557	428,925	440,782
	10	50	405,016	420,972	437,203	453,273
140	10	10	476,519	--	--	509,704
	10	30	476,519	491,281	504,652	518,600
	10	50	476,519	--	--	533,295

Basis for calculation:

(a) Ideal combustion to CO_2, H_2O, SO_2.

(b) 50% Excess air.

(c) Average properties for coal and refuse were used in the combustion calculations.

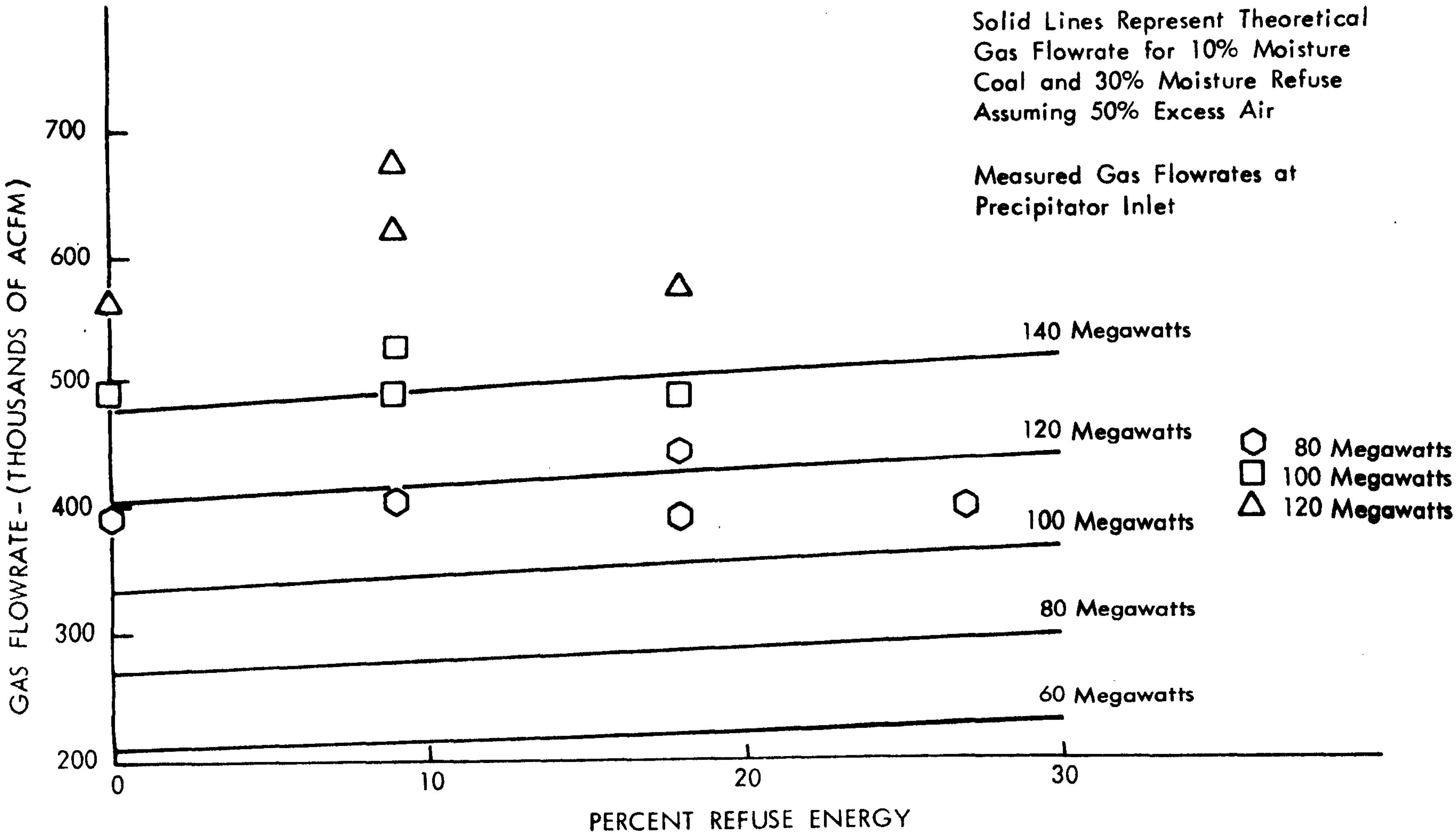
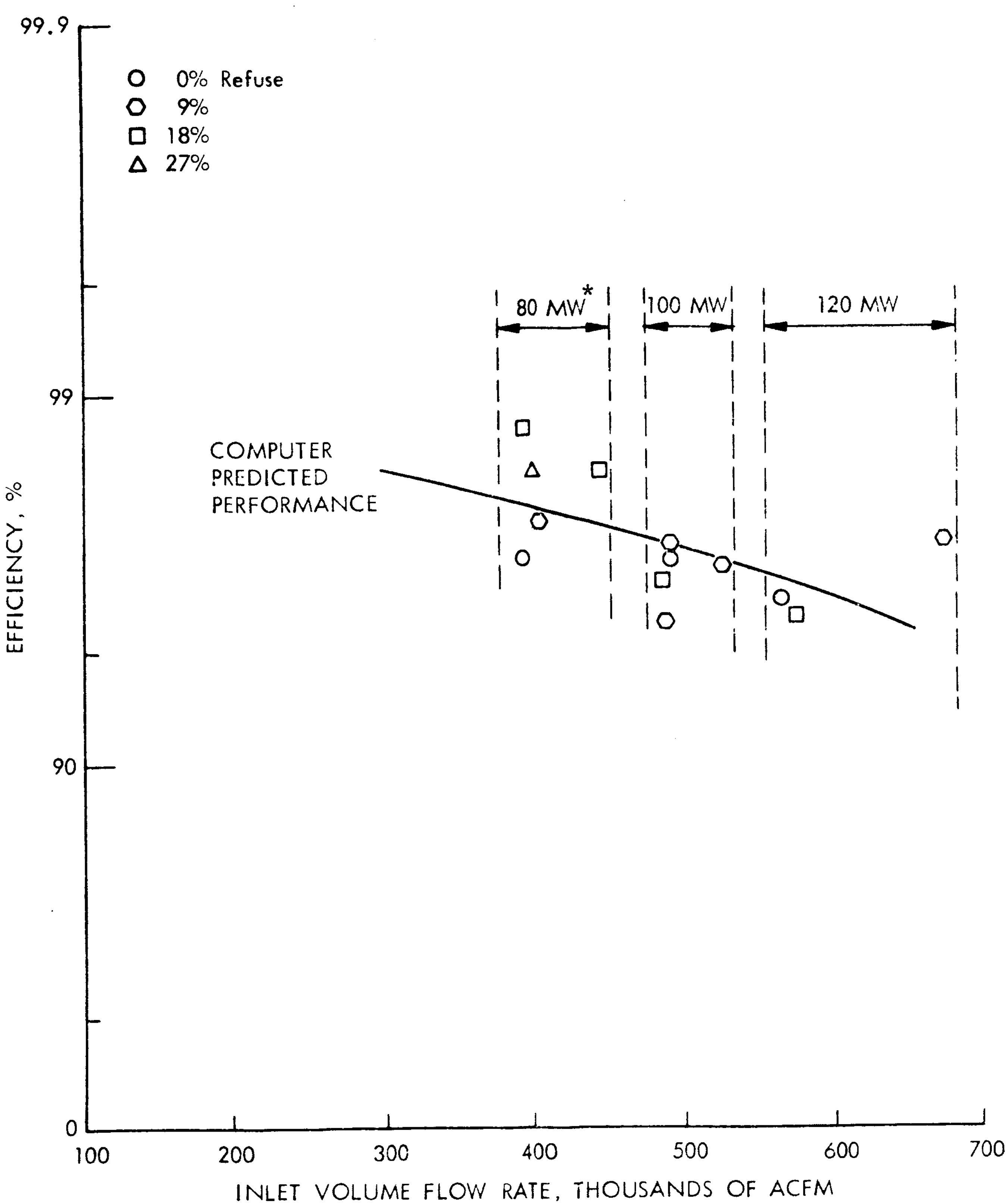


Figure 21. Comparison of theoretical and measured gas flowrates.



* MW = megawatts.

Figure 22. Efficiency versus volume flowrate for the Meramec Power Station with varying feed rates for refuse.

From the preceding discussion, it appears that the major variable influencing precipitator performance is the electrical operating conditions (peak power and sparking rate) and gas flowrates. Gas flowrates, at a given gross generation level, appear to increase when refuse is substituted for coal as fuel to the boiler. The exact mechanisms which caused the change in electrical operating conditions are currently unknown.

In order to achieve emission levels with combined firing comparable to those for the coal-only tests reported by Union Electric, the following steps should be considered:

1. Fine tune the electrostatic precipitator to operate at optimum level with combined firing; or

2. Reduce the boiler load when firing coal and refuse; or

3. Reduce the moisture content of the refuse by drying it prior to combustion; or

4. A combination of the above.

CONCLUSIONS

The conclusions derived from the air pollution test program are grouped into three distinct categories: (1) conclusions on test procedures; (2) conclusions on emission levels and precipitator performance; and (3) conclusions on refuse combustion efficiency. Each category is discussed separately.

TEST PROCEDURES

The primary observation for the EPA/MRI test program is that insufficient stabilization time for the ESP was allowed for the coal-only tests. The minimum stabilization time required for a modification to a precipitator has been estimated to be on the order of 3 to 5 days. Because of the insufficient stabilization time, all the test data obtained in the EPA/MRI coal-only tests are probably representative of coal plus refuse firing conditions.

The test procedure for the original series of coal-only tests conducted by Union Electric allowed sufficient stabilization time and the results are considered to be indicative of coal-only firing conditions. However, it is possible that there was a shift in ESP collection efficiency, after the October coal-only tests, which was not related to the firing of refuse.

Continuous firing of refuse (24 hr/day) may result in ESP performance losses greater than indicated by the EPA/MRI or Union Electric tests. While it is believed that further performance degradation with continuous firing will not be significant, the influence of continuous firing can only be determined by further tests.

EMISSION LEVELS AND PRECIPITATOR PERFORMANCE

1. No significant changes in gaseous pollution levels occur when refuse and coal are fired together under the conditions tested.

2. Mass concentrations (i.e., grain loading) of particulates at the inlet to the electrostatic precipitator were in the same range for all tests conducted by EPA/MRI and Union Electric.

3. The inlet grain loading is not dependent upon fuel composition or gross power generation over the ranges involved in the test program.

4. The increase in outlet grain loading is more significant as the gross generation rate increases.

5. There is an apparent decrease in ESP efficiency when coal and refuse are fired in the boiler. The performance change probably results from a combination of factors which include:

a. Increased gas flowrates resulting from fuel compositional changes and moisture content.

b. Changes in ESP electrical performance characteristics.

6. The increase in emissions may be significantly moderated by optimizing the ESP electrical operation and rapping cycles for combined firing and by control of the refuse moisture content. This postulation will require verification by further testing.

REFUSE COMBUSTION EFFICIENCY

The following are tentative conclusions and should be verified by sampling and analysis of the boiler residue:

1. Refuse combustion efficiencies range from approximately 60 to 95%.

2. Increased refuse firing rates show increased combustion efficiencies.

RECOMMENDATIONS

Additional air pollution testing is recommended in order to complete the characterization of particulate emissions resulting from refuse firing. Since the previous tests conducted using modified EPA methods were probably only representative of combined firing conditions, future tests should include determination of emission levels for coal-only firing conditions. We recommend that much greater stabilization times for the ESP be allowed between major changes in firing conditions in any future test program. We also recommend a more complete study of emissions at gross generation rates exceeding 120 megawatts.

To facilitate the determination of combustion efficiencies and other system parameters, we also recommend that any future test program give attention to precise measurement of data needed to provide boiler mass and energy balances.

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APPENDIX A

DATA FORMS, SAMPLE CALCULATIONS, AND SUMMARY OF RESULTS

This appendix contains examples of data forms, sample calculations and summaries of results of calculations. Specific items presented in this appendix are delineated in the following table.

Table A-1. CONTENTS OF APPENDIX A

Figure No.	Description
A-1	Source Testing Program Format (Sampling Data Reduction)
A-2	Brink/Andersen Particle Size Coding Form
A-3	Gas Program Format (SO_x, NO_x, CO Gases)
A-4	Power Curve for Meramec Plant
Table No.	**Description**
A-2	Example of Particulate Calculations
A-3	Summary of Results of Particulate Calculations
A-4	Brink Particle Size Data (with Cyclone and Filter)
A-5	Example of SO_3 Calculations

FIGURE A-1

MRI

SOURCE TESTING PROGRAM FORMAT

(SAMPLING DATA REDUCTION)

Project No ______________________

Recorded By ______________________

Date ______________________

Page _____ of _____

1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80
1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890

Run No.	Date	Atmos Temp (°F)	Atmos Press (in.Hg)	Stack Vacuum (in.H_2O)	Moisture (ml)	Partic. Weight Partial (mg)	Partic. Weight Total (mg)	Stack Area (ft^2)	Initial Dry Test Meter (ft^3)	% O_2 (Dry)	CO_2 (Dry)	No. of Points
	— —											

% CO (Dry)	CO (ppm)	Pitot Tube Coefficient

	Port	Point	Sample Time (Min)	Dry Test Meter Final Reading (ft^3)	Pitot Reading (in.H_2O)	Orifice Pressure (in.H_2O)	Meter Temp - In (Left) (°F)	Meter Temp - Out (Right) (°F)	Train Vacuum (in. Hg)	Stack Temp (°F)	Sample Gas Temp (°F)(- if silica gel)	Probe Tip Diameter (in.)
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												

MRI-F1 (1/73)

Figure A-1. Source testing program format (sampling data reduction).

FIGURE A-2

JOB Andersen Coding Form

BY

DATE

MRI

PAGE ___ OF ___

NOTES

FIELD IDENTIFICATION

1-10		11-20	21-30	31-40	41-50
Run No.	Date	Rate thru Impactor (cfm)	Density of Particle (Assume = 1)	Imp. Efficiency (≈ .14 at 50%)	Filter Weight (gm)
		.	.	.	.

	Sample (Plate + Pan)	Sample (Pan)	Tare (Plate + Pan)	Tare (Pan)
0				
1				
2				
3				
4				
5				
6				
7				
8				

99

Figure A-2. Brinks/Andersen coding form.

FIGURE A-3

MRI

GAS PROGRAM FORMAT
(SO_2, SO_3, NO_x, CO GASES)

Project No ____________________

Recorded By ____________________

Date ____________________

Page ____ of ____

1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80
1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0	1 2 3 4 5 6 7 8 9 0

SO_2

A	B	C	D	E	F	G	H
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .
	– –			.	.	.	. .

A - Run Number
B - Date of Run
C - Port Number
D - Point Number
E - Init. Dry Test Meter Reading (ft^3)
F - Final Dry Test Meter Reading (ft^3)
G - Avg. Dry Gas Meter Temp (°F)
H - Barometer Pressure (in. Hg)
I - Meter Vacuum (in. Hg)

J	K	L	M	N	O
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.
	.	.	.	.	.

J - Sample Number
K - Vol. of Titrant for Sample (ml)
L - Vol. of Titrant for Blank (ml)
M - Normality of Titrant (g-eq/l)
N - Total Solution Volume (ml)
O - Vol. of Sample Aliquot Titrated (ml)

99

Figure A-3. Gas program format (SO_2, SO_3, NO_x, CO gases).

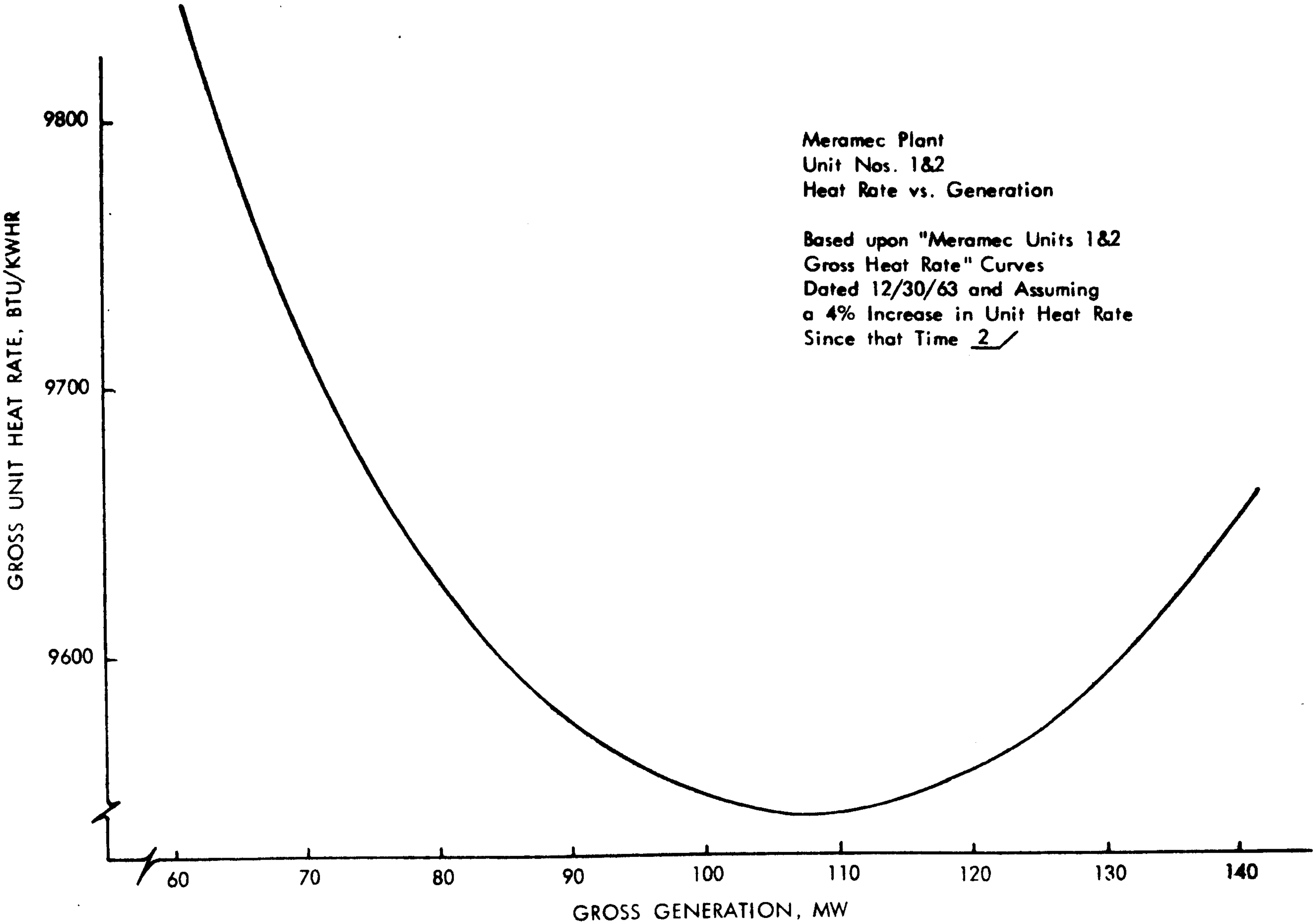

Figure A-4. Efficiency curve for Meramec boiler.[2/]

Table A-2. EXAMPLE OF PARTICULATE CALCULATIONS

1. VOLUME OF DRY GAS SAMPLED AT STANDARD CONDITIONS

```
                17.71*VM*(PB + PM/13.6)
VMSTD  =   ---------------------------
                     TM+460.

           17.71* 58.60*(29.12+ 1.076/13.6)
       =   ---------------------------------   =    57.19 DSCF
                     70.0+460.

VMSTM  =   VMSTD*0.028317=   57.19*0.028317=        1.62 DNM3
```

2. VOLUME OF WATER VAPOR AT STANDARD CONDITIONS

```
VWV    =   0.0474*VW   = 0.0474* 130.0          =    6.16 SCF

VWM    =   VWV*0.028317 =  6.162*0.028317       =    .1745 NM3
```

3. PERCENT MOISTURE IN STACK GAS

```
            100.*VWV        100.*  6.16
PMOS   =   -----------  =  -------------   =    9.7 PERCENT
           VMSTD+VWV       57.19+  6.16
```

4. MOLE FRACTION OF DRY STACK GAS

```
           100.-PMOS        100.-    9.7
MD     =   -----------  =  --------------   =    .903
              100.             100.
```

5. AVERAGE MOLECULAR WEIGHT OF DRY STACK GAS

```
MWD    =   (PCO2 * 44/100) + (PO2 * 32/100)
              +(PN2+PCO * 28/100)

       =   (14.5 * 44/100) + ( 6.5 * 32/100)
              +(79.0 * 28/100)
                                              =    30.58
```

6. MOLECULAR WEIGHT OF STACK GAS

```
MW     =   MWD*MD + 18*(1-MD)

       =    30.6* .903 + 18*(1- .903)         =    29.36
```

7. STACK GAS VELOCITY AT STACK CONDITIONS

```
VS    =  4360*AVG SQRT(DPS*(TS+460))*
              SQRT(1/(PS*MW))

      =  4360*   17.761
             *SQRT(1/(28.38*    29.36))       =       2683 FPM

VSM   =  VS*0.3048  =     2683*0.3048        =        818 METERS/MIN
```

8. STACK GAS VOLUMETRIC FLOW AT STANDARD CONDITIONS, DRY BASIS

```
            0.123*VS*AS*MD*PS
QS     =    -----------------
                 TS+460

            0.123*  2683* 33399* .903*28.38
       =    -------------------------------
                 328.6 +460
                                              =    358111 DSCFM

QSM    =  QS*0.028317 =  358111*0.028317     =      10141 NM3/MIN
```

9. STACK GAS VOLUMETRIC FLOW AT STACK CONDITIONS

```
            QS * (TS+460)
QA     =    ---------------
            17.71 * PS * MD

             358111*( 328.6+460)
       =    --------------------              =     622148 ACFM
            17.71*28.38* .903

QAM    =  QA*0.028317 =  622148*0.028317     =      17617 NM3/MIN
```

10. PERCENT ISOKINETIC

```
            1032*(TS+460)*VMSTD
PERI   =    -------------------
            VS*TT*PS*MD*(DN*DN)

            1032*( 328.6+460)*    57.19
       =    ---------------------------       =     100.3 PERCENT
             2683* 108.0*28.38* .903* .250
                                    * .250
```

11. PARTICULATE LOADING -- PROBE, CYCLONE, AND FILTER
(AT STANDARD CONDITIONS)

```
CAN   = 0.0154 * (MF/VMSTD)
      = 0.0154*(7757.95/   57.19)           = 2.08914 GR/DSCF
CANM  = CAN*2288.34 =  2.08914*2288.34      = 4780.67 MG/NM3
```

12. PARTICULATE LOADING -- TOTAL
(AT STANDARD CONDITIONS)

```
CAO   = 0.0154 * (MT/VMSTD)
      = 0.0154*(7757.95/   57.19)           = 2.08914 GR/DSCF
CAOM  = CAO*2288.34 =  2.08914*2288.34      = 4780.67 MG/NM3
```

13. PARTICULATE LOADING -- PROBE, CYCLONE, AND FILTER
(AT STACK CONDITIONS)

```
        17.71*CAN*PS*MD
CAT   = ----------------
            TS+460

        17.71* 2.0891*28.38* .903
      = -----------------------------       = 1.20252 GR/ACF
              328.6+460

CATM  = CAT*2288.34 =  1.20252*2288.34      = 2751.78 MG/M3
```

14. PARTICULATE LOADING -- TOTAL
(AT STACK CONDITIONS)

```
        17.71*CAO*PS*MD
CAU   = ----------------
            TS+460

        17.71* 2.0891*28.38* .903
      = -----------------------------       = 1.20252 GR/ACF
              328.6+460

CAUM  = CAU*2288.34 =  1.20252*2288.34      = 2751.78 MG/M3
```

Table A-2. (Concluded)

15. PARTICULATE EMISSION RATE
-- PROBE, CYCLONE, AND FILTER

```
CAW    =  0.00857*CAN*QS

       =  0.00857*   2.0891*   358111                 =   6411.61 LB/HR

CAWM   =  CAW*0.45359 = 6411.61*0.45359               =   2908.24 KG/HR
```

16. PARTICULATE EMISSION RATE
-- TOTAL

```
CAX    =  0.00857*CAO*QS

       =  0.00857*   2.0891*   358111                 =   6411.61 LB/HR

CAXM   =  CAX*0.45359 = 6411.61*0.45359               =   2908.24 KG/HR
```

17. PERCENT EXCESS AIR AT SAMPLING POINT

```
         100. *  (PO2-0.5*PCO)
EA    =  ----------------------
         0.264*PN2-PO2+0.5*PCO

         100. *( 6.5-0.5* 0.0)
      =  -------------------------          =      45.3 PERCENT
         0.264*79.0- 6.5+0.5* 0.0
```

Table A-3. SUMMARY OF RESULTS OF PARTICULATE CALCULATIONS

NAME	DESCRIPTION	UNITS	0-I	0-0	1-I	1-0
	DATE OF RUN		12-04-73	12-04-73	12-05-73	12-05-73
VMSTD	VOL DRY GAS-STD COND	DSCF	57.19	63.43	74.34	87.37
PMOS	PERCENT MOISTURE BY VOL		9.7	8.5	9.0	9.3
TS	AVG STACK TEMPERATURE	DEG.F	328.6	330.8	315.9	307.8
QS	STK FLOWRATE, DRY,STD CN	DSCFM	358111	300215	317534	258310
QA	ACTUAL STACK FLOWRATE	ACFM	622148	503597	526735	418929
PERI	PERCENT ISOKINETIC		100.3	80.0	98.0	99.5
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	7757.95	372.15	9394.79	317.75
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	2.08914	.09035	1.94620	.05601
CAT	PART. LOAD-PTL.STK CN	GR/ACF	1.20252	.05386	1.17323	.03454
CAW	PARTIC EMIS-PARTIAL	LB/HR	6411.61	232.46	5296.12	123.99
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	7757.95	372.15	9394.79	317.75
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	2.08914	.09035	1.94620	.05601
CAU	PART. LOAD-TTL.STK CN	GR/ACF	1.20252	.05386	1.17323	.03454
CAX	PARTIC EMIS-TOTAL	LB/HR	6411.61	232.46	5296.12	123.99
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-3. (Continued)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	2-I	2-0	3-I	3-0
	DATE OF RUN		12-05-73	12-05-73	12-06-73	12-06-73
VMSTD	VOL DRY GAS-STD COND	DSCF	70.38	89.75	72.29	91.31
PMOS	PERCENT MOISTURE BY VOL		10.6	10.0	7.5	7.3
TS	AVG STACK TEMPERATURE	DEG.F	313.9	314.1	308.5	314.2
QS	STK FLOWRATE, DRY,STD CN	DSCFM	291028	254086	309898	265332
QA	ACTUAL STACK FLOWRATE	ACFM	487482	416519	490604	415847
PERI	PERCENT ISOKINETIC		101.3	104.0	97.7	101.3
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	8401.59	433.67	8429.84	299.31
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	1.83826	.07441	1.79571	.05048
CAT	PART. LOAD-PTL,STK CN	GR/ACF	1.09744	.04539	1.13429	.03221
CAW	PARTIC EMIS-PARTIAL	LB/HR	4584.82	162.04	4769.09	114.79
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	8401.59	433.67	8429.84	299.31
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	1.83826	.07441	1.79571	.05048
CAU	PART. LOAD-TTL,STK CN	GR/ACF	1.09744	.04539	1.13429	.03221
CAX	PARTIC EMIS-TOTAL	LB/HR	4584.82	162.04	4769.09	114.79
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-3. (Continued)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	4-I	4-0	5-I	5-0
	DATE OF RUN		12-09-73	12-09-73	12-09-73	12-09-7
VMSTD	VOL DRY GAS-STD COND	DSCF	55.87	75.56	61.72	78.[illegible]
PMOS	PERCENT MOISTURE BY VOL		10.9	8.8	10.1	9.
TS	AVG STACK TEMPERATURE	DEG.F	317.4	318.5	319.7	31[illegible].
QS	STK FLOWRATE, DRY,STD CN	DSCFM	233758	220407	265602	21[illegible]57
QA	ACTUAL STACK FLOWRATE	ACFM	390287	355823	442128	3564[illegible]
PERI	PERCENT ISOKINETIC		100.1	100.9	97.3	1[illegible].

PARTICULATES -- PARTIAL CATCH

NAME	DESCRIPTION	UNITS	4-I	4-0	5-I	5-0
MF	PARTICULATE WT-PARTIAL	MG	7153.18	115.72	7609.58	154.4
CAN	PART. LOAD-PTL.STD CN	GR/DSCF	1.97162	.02358	1.89880	.0301
CAT	PART. LOAD-PTL.STK CN	GR/ACF	1.18088	.01461	1.14068	.0185
CAW	PARTIC EMIS-PARTIAL	LB/HR	3949.75	44.55	4322.07	56.7

PARTICULATES -- TOTAL CATCH

NAME	DESCRIPTION	UNITS	4-I	4-0	5-I	5-0
MT	PARTICULATE WT-TOTAL	MG	7153.18	115.72	7609.58	154.4
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	1.97162	.02358	1.89880	.0301
CAU	PART. LOAD-TTL,STK CN	GR/ACF	1.18088	.01461	1.14068	.0185
CAX	PARTIC EMIS-TOTAL	LB/HR	3949.75	44.55	4322.07	56.7
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.

Table A-3. (Continued)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	6-I	6-0	7-I	7-0
	DATE OF RUN		12-10-73	12-10-73	12-10-73	12-10-73
VMSTD	VOL DRY GAS-STD COND	DSCF	60.89	81.06	61.23	79.73
PMOS	PERCENT MOISTURE BY VOL		6.1	6.2	10.8	8.2
TS	AVG STACK TEMPERATURE	DEG.F	301.7	301.5	306.4	304.7
QS	STK FLOWRATE, DRY,STD CN	DSCFM	253452	233036	243571	221718
QA	ACTUAL STACK FLOWRATE	ACFM	391340	356779	398035	348072
PERI	PERCENT ISOKINETIC		100.6	102.4	105.3	105.8
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	6159.55	225.06	8271.39	166.40
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	1.55794	.04276	2.08025	.03214
CAT	PART. LOAD-PTL,STK CN	GR/ACF	1.00900	.02793	1.27298	.02047
CAW	PARTIC EMIS-PARTIAL	LB/HR	3383.98	85.39	4342.32	61.07
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	6159.55	225.06	8271.39	166.40
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	1.55794	.04276	2.08025	.03214
CAU	PART. LOAD-TTL,STK CN	GR/ACF	1.00900	.02793	1.27298	.02047
CAX	PARTIC EMIS-TOTAL	LB/HR	3383.98	85.39	4342.32	61.07
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-3. (Continued)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	8-I	8-0	9-I	9-0
	DATE OF RUN		12-11-73	12-10-73	12-12-73	12-11-73
VMSTD	VOL DRY GAS-STD COND	DSCF	92.44	103.16	80.30	97.10
PMOS	PERCENT MOISTURE BY VOL		9.0	8.0	7.7	5.9
TS	AVG STACK TEMPERATURE	DEG.F	310.8	312.4	307.7	304.1
QS	STK FLOW RATE, DRY,STD CN	DSCFM	413128	306680	347396	300854
QA	ACTUAL STACK FLOWRATE	ACFM	674652	486713	563698	471351
PERI	PERCENT ISOKINETIC		95.5	99.0	96.8	95.0
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	10788.10	292.50	10018.03	421.55
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	1.79731	.04367	1.92138	.06686
CAT	PART. LOAD-PTL,STK CN	GR/ACF	1.10059	.02751	1.18411	.04267
CAW	PARTIC EMIS-PARTIAL	LB/HR	6363.38	114.76	5720.29	172.38
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	10788.10	292.50	10018.03	421.55
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	1.79731	.04367	1.92138	.06686
CAU	PART. LOAD-TTL,STK CN	GR/ACF	1.10059	.02751	1.18411	.04267
CAX	PARTIC EMIS-TOTAL	LB/HR	6363.38	114.76	5720.29	172.38
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-3. (Continued)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	10-I	10-O	11-I	11-O
	DATE OF RUN		12-12-73	12-12-73	12-13-73	12-13-73
VMSTD	VOL DRY GAS-STD COND	DSCF	80.62	97.19	69.13	90.78
PMOS	PERCENT MOISTURE BY VOL		9.3	8.4	8.9	8.0
TS	AVG STACK TEMPERATURE	DEG.F	302.8	306.1	312.4	317.7
QS	STK FLOWRATE, DRY,STD CN	DSCFM	346574	290553	293517	269623
QA	ACTUAL STACK FLOWRATE	ACFM	573193	467969	488205	440078
PERI	PERCENT ISOKINETIC		97.4	98.4	98.6	99.1
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	8405.07	391.29	8164.17	286.96
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	1.60549	.06200	1.81865	.04868
CAT	PART. LOAD-PTL,STK CN	GR/ACF	.97074	.03850	1.09340	.02982
CAW	PARTIC EMIS-PARTIAL	LB/HR	4768.53	154.39	4574.70	112.48
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	8405.07	391.29	8164.17	286.96
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	1.60549	.06200	1.81865	.04868
CAU	PART. LOAD-TTL,STK CN	GR/ACF	.97074	.03850	1.09340	.02982
CAX	PARTIC EMIS-TOTAL	LB/HR	4768.53	154.39	4574.70	112.48
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-3. (Concluded)

SUMMARY OF RESULTS

NAME	DESCRIPTION	UNITS	12-I	12-O	13-I	13-O
	DATE OF RUN		12-13-73	12-13-73	12-14-73	12-14-73
VMSTD	VOL DRY GAS-STD COND	DSCF	68.29	86.52	59.37	77.52
PMOS	PERCENT MOISTURE BY VOL		10.0	8.5	7.9	7.8
TS	AVG STACK TEMPERATURE	DEG.F	317.7	317.8	306.8	305.6
QS	STK FLOWRATE, DRY,STD CN	DSCFM	265348	254223	250196	226506
QA	ACTUAL STACK FLOWRATE	ACFM	483260	417248	401084	358696
PERI	PERCENT ISOKINETIC		100.2	100.2	99.4	100.7
PARTICULATES -- PARTIAL CATCH						
MF	PARTICULATE WT-PARTIAL	MG	9092.44	357.83	7173.39	204.87
CAN	PART. LOAD-PTL,STD CN	GR/DSCF	2.05042	.06369	1.86056	.04070
CAT	PART. LOAD-PTL.STK CN	GR/ACF	1.21070	.03881	1.16062	.02570
CAW	PARTIC EMIS-PARTIAL	LB/HR	5014.18	138.76	3989.37	79.00
PARTICULATES -- TOTAL CATCH						
MT	PARTICULATE WT-TOTAL	MG	9092.44	357.83	7173.39	204.87
CAO	PART. LOAD-TTL,STD CN	GR/DSCF	2.05042	.06369	1.86056	.04070
CAU	PART. LOAD-TTL,STK CN	GR/ACF	1.21070	.03881	1.16062	.02570
CAX	PARTIC EMIS-TOTAL	LB/HR	5014.18	138.76	3989.37	79.00
IC	PERC IMPINGER CATCH		0.0	0.0	0.0	0.0

Table A-4. BRINK PARTICLE SIZE DATA (WITH CYCLONE AND FILTER)

Stage	Run 0 Wt. %	Run 0 Cum. Wt. %	Run 1 Wt. %	Run 1 Cum. Wt. %	Run 2 Wt. %	Run 2 Cum. Wt. %	Run 3 Wt. %	Run 3 Cum. Wt. %	Run 4 Wt. %	Run 4 Cum. Wt. %	Run 5 Wt. %	Run 5 Cum. Wt. %	Run 6 Wt. %	Run 6 Cum. Wt. %
Cyclone	49.4	49.4	78.6	78.6	30.5	30.5	65.4	65.4	74.7	74.7	63.0	63.0	57.8	57.8
1	18.6	68.0	15.1	93.7	32.4	62.9	20.8	86.2	14.4	89.1	17.8	80.8	20.9	78.7
2	15.5	83.5	4.6	98.3	24.2	87.1	9.0	95.2	6.8	95.9	12.1	92.9	13.1	91.8
3	7.5	91.0	1.3	99.6	3.2	90.3	2.8	98.0	2.1	98.0	3.6	96.5	4.2	96.0
4	4.6	95.6	0.1	99.7	6.1	96.4	0.0	98.0	1.2	99.2	1.8	98.3	2.6	98.6
5	1.3	96.9	0.0	99.7	0.6	97.0	0.7	98.7	0.3	99.5	0.7	99.0	0.6	99.2
Filter	3.1	100.0	0.3	100.0	3.0	100.0	1.3	100.0	0.5	100.0	1.0	100.0	0.8	100.0

Stage	Run 7		Run 8		Run 9		Run 10		Run 11		Run 12		Run 13
Cyclone	9.9	9.9	80.5	80.5	74.1	74.1	78.5	78.5	67.9	67.9	53.8	53.8	
1	10.0	19.9	8.9	89.4	15.5	89.6	10.2	88.7	14.7	82.6	19.4	73.2	
2	6.4	26.3	5.9	95.4	6.8	96.4	6.7	95.4	10.1	92.7	13.3	86.5	b/
3	1.8	28.1	2.4	97.7	1.8	98.2	2.2	97.6	3.3	96.0	4.5	91.0	
4	1.2	29.3	1.3	99.0	1.0	99.2	0.8	98.4	1.5	97.5	2.4	93.4	
5	0.3	29.6	0.2	99.2	0.0	99.2	0.0	98.4	0.1	97.6	0.7	94.1	
Filter	70.4*	100.0	0.8	100.0	0.8	100.0	1.6	100.0	2.4	100.0	5.9	100.0	

a/ Filter not dry.
b/ No data available.

Table A-5. EXAMPLE OF SO_3 CALCULATIONS

1. VOLUME OF DRY GAS SAMPLE THROUGH THE DRY GAS METER (AT STANDARD CONDITIONS)

```
                530        PM
VMSTD =  VM * ------ * ------
                TM       29.92

                   VM *  PM
      =  17.71 * -----------
                     TM

                   .162* 27.75
      =  17.71 * ----------------          =     .1531 CU.FT.
                     519.00
```

2. CONCENTRATION OF SULFUR TRIOXIDE AT STANDARD CONDITIONS

```
                            (VT-VTB)*N*(VSOLN/VA)
CSO3   =   0.0000882 *  --------------------
                                VMSTD

                        (    1.00-     .51)* .00190
                                *( 170.0/  10.0)
       =   0.0000882 *  --------------------------
                                     .1531

                                             = .00000912 LB/DSCF

          387.*(CSO3*1000000.0)    387*   9.12
CPPM  =  ----------------------- = ----------- =        44.1 PPM
                  80.0               80.0
```

APPENDIX B

COAL ANALYSES AND REFUSE ANALYSES

Table B-1. COAL ANALYSES

	As Received						Dry Basis					
Test	% Moisture	% S	% Ash	% F.C.	% Volatile	Btu/lb	% S	% Ash	% F.C.	% Volatile	Btu/lb	Power MW
0	6.38	1.38	6.50	53.48	33.64	12,603	1.47	6.94	57.13	35.93	13,462	120
1	6.37	1.50	7.06	52.05	34.52	12,589	1.60	7.54	55.59	36.87	13.445	100
2	5.96	1.46	6.86	53.45	33.73	12,617	1.55	7.29	56.84	35.87	13,417	100
3(co)[a/]	6.49	1.33	6.54	52.29	34.68	12,639	1.42	6.99	55.92	37.09	13,516	100
4	6.51	1.56	6.55	52.57	34.37	12,594	1.67	7.01	56.23	36.76	13,471	80
5	6.48	1.61	7.87	51.85	33.80	12,384	1.72	8.42	55.44	36.14	13,242	80
6(co)	6.35	1.35	6.70	52.96	33.99	12,628	1.44	7.15	56.56	36.29	13,484	80
7	6.27	1.47	6.76	52.76	34.21	12,594	1.57	7.21	56.29	36.50	13,436	80
8	6.62	1.36	6.26	52.91	34.21	12,676	1.46	6.70	56.66	36.64	13,575	120
9(co)	6.60	1.25	7.13	53.26	33.01	12,526	1.34	7.63	57.03	35.34	13,411	120
10	6.28	1.52	6.78	52.23	34.71	12,641	1.62	7.23	55.73	37.04	13,488	120
11	6.17	1.73	7.57	51.55	34.71	12,513	1.84	8.07	54.94	36.99	13,336	100
12	6.28	2.80	8.33	48.47	36.92	12,392	2.99	8.89	51.72	39.39	13,222	100
13	6.02	1.59	7.56	52.14	34.28	12,526	1.69	8.04	55.48	36.48	13,328	80

a/ (co) = Coal only.

Table B-2. COAL ANALYSES

(UNION ELECTRIC)

	As Received						Dry Basis					
Test	% Moisture	% S	% Ash	% F.C.	% Volatile	Btu/lb	% S	% Ash	% F.C.	% Volatile	Btu/lb	Power MW
1T	14.5	1.25	6.93	48.5	30.1	11,289	1.46	8.1	56.7	35.2	13,203	140
2T	13.9	1.22	5.94	48.6	31.6	11,602	1.41	6.9	56.4	36.7	13,475	140
9T	12.4	1.36	6.1	46.9	34.6	11,811	1.56	7.0	53.5	39.5	13,483	140
8	12.7	1.26	6.7	49.1	31.5	11,617	1.44	7.7	56.2	36.1	13,307	140
6	11.1	1.36	6.1	43.8	38.9	11,960	1.53	6.9	49.3	43.8	13,454	140
7	10.8	1.25	7.1	49.3	32.7	11,967	1.40	8.0	55.3	36.7	13,417	140
4T	13.6	1.25	6.1	48.1	32.1	11,479	1.45	7.1	55.7	37.2	13,286	100
5T	14.6	1.24	5.7	48.2	31.5	11,543	1.45	6.7	56.4	36.9	13,516	100
1	12.0	1.48	7.0	49.0	31.9	11,772	1.68	8.0	55.7	36.3	13,377	100
2	9.9	1.49	7.0	50.5	32.5	12,057	1.65	7.8	56.1	36.1	13,381	100
3	10.7	1.36	6.7	50.2	32.4	12,078	1.52	7.5	56.2	36.3	13,526	100
6T	14.4	1.25	7.5	47.3	30.7	11,298	1.46	8.8	55.3	35.9	13,199	75
7T	14.5	1.33	6.2	48.2	31.1	11,440	1.55	7.2	56.4	36.4	13,380	75
4	10.0	1.39	7.6	48.1	34.5	12,015	1.54	8.4	53.4	38.3	13,350	75
5	10.8	1.22	7.5	49.5	32.2	12,076	1.37	8.4	55.5	36.1	13,539	75
3T	14.2	1.34	5.83	47.97	32.0	11,514	1.56	6.8	55.9	37.3	13,420	140

Table B-3. ULTIMATE COAL ANALYSES (MRI TESTS)

Sample No.	As Received Carbon	As Received Hydrogen	As Received Nitrogen	As Received Sulfur	As Received Ash	As Received Oxygen	Dry Basis Carbon	Dry Basis Hydrogen	Dry Basis Nitrogen	Dry Basis Sulfur	Dry Basis Ash	Dry Basis Oxygen
0	70.99	5.84	1.40	1.38	6.50	13.89	75.83	5.48	1.50	1.47	6.94	8.78
1	70.81	5.65	1.33	1.50	7.06	13.65	75.63	5.28	1.42	1.60	7.54	8.53
2	71.19	5.53	1.38	1.46	6.86	13.58	75.70	5.18	1.47	1.55	7.29	[illegible].81
3	71.16	5.53	1.26	1.33	6.54	14.18	76.10	5.14	1.35	1.42	6.99	9.00
4	70.84	5.65	1.41	1.56	6.55	13.99	75.77	5.27	1.51	1.67	7.01	8.77
5	69.88	5.46	1.56	1.61	7.87	13.62	74.72	5.07	1.67	1.72	8.42	8.40
6	71.19	5.62	1.33	1.35	6.70	13.81	76.02	5.25	1.42	1.44	7.15	8.72
7	70.36	5.51	1.32	1.47	6.76	14.58	75.07	5.13	1.41	1.57	7.21	9.61
8	71.85	5.73	1.33	1.36	6.26	13.47	76.94	5.35	1.42	1.46	6.70	8.13
9	70.54	5.61	1.43	1.25	7.13	14.04	75.52	5.2[illegible]	1.53	1.34	7.63	8.76
10	71.53	5.71	1.27	1.52	6.78	13.19	76.32	5.35	1.36	1.62	7.23	8.12
11	70.51	5.51	1.39	1.73	7.57	13.29	75.15	5.14	1.48	1.84	8.07	8.32
12	68.70	5.19	1.09	2.80	8.33	13.89	73.30	4.79	1.16	2.99	8.89	8.87
13	70.62	5.53	1.23	1.59	7.56	13.47	75.14	5.17	1.31	1.69	8.04	8.65

TABLE B-4. PROXIMATE ANALYSIS AND HEATING VALUES OF MILLED REFUSE
(MRI TEST PERIOD)

Sample			Weight	Moisture		Dry Weight Basis					Received Moisture Basis				
Month	Day	Hr	(lb)	Total (%)	Sample (%)	S (%)	Cl (%)	Ash (%)	As Dry (Btu/lb)	NaCl (%)	S (%)	Cl (%)	Ash (%)	As Received (Btu/lb)	NaCl (%)
12	5	9	45.1	34.5	0.46	0.21	0.50	22.8	7387.0	0.46	0.14	0.33	14.9	4838.0	0.30
12	9	15	29.8	66.3	0.62	0.23	0.43	27.3	6804.0	0.34	0.08	0.15	9.2	2293.0	0.11
12	9	16	20.7	39.5	0.98	0.15	0.52	26.0	7253.0	0.39	0.09	0.31	15.7	4388.0	0.24
12	9	13	32.4	41.3	1.25	0.19	0.47	23.6	6969.0	0.34	0.11	0.27	13.9	4091.0	0.20
12	9	11	18.0	49.1	0.63	0.17	0.41	15.0	7548.0	0.33	0.09	0.21	7.6	3842.0	0.17
12	9	7	26.4	28.8	0.62	0.19	0.53	23.3	7251.0	0.39	0.14	0.38	16.6	5163.0	0.28
12	7	8	22.4	39.0	0.60	0.15	0.33	19.4	7141.0	0.37	0.09	0.20	11.8	4356.0	0.22
12	7	9	29.0	28.7	1.21	0.13	0.35	22.1	7503.0	0.40	0.09	0.25	15.5	5274.0	0.28
12	10	13	32.1	25.2	0.72	0.16	0.77	26.1	6722.0	0.38	0.12	0.57	19.5	5028.0	0.28
12	10	8	14.1	52.0	0.93	0.19	0.37	22.7	7320.0	0.35	0.09	0.18	10.9	3514.0	0.17
12	10	14	9.3	44.0	1.58	0.14	0.81	19.2	7638.0	0.44	0.08	0.46	10.8	4277.0	0.25
12	10	9	12.0	29.9	1.78	0.17	0.44	17.3	7631.0	0.40	0.12	0.31	12.1	5349.0	0.28
12	11	11	29.5	21.3	1.65	0.17	0.53	25.0	6952.0	0.38	0.14	0.42	19.7	5471.0	0.30
12	11	9	23.6	22.0	2.62	0.17	0.48	22.3	6603.0	0.41	0.14	0.38	17.4	5150.0	0.32
12	11	12	24.2	23.2	1.37	0.33	0.47	22.3	7547.0	0.40	0.26	0.36	17.1	5796.0	0.30
12	11	13	17.8	22.2	1.84	0.13	0.72	20.5	7466.0	0.41	0.10	0.56	15.9	5809.0	0.32
12	12	13	18.8	19.1	2.32	0.12	0.66	21.3	6982.0	0.43	0.10	0.53	17.2	5648.0	0.35
12	12	15	12.8	14.3	2.13	0.13	1.10	21.5	7545.0	0.38	0.11	0.95	18.4	6466.0	0.33
12	12	9	18.9	21.0	1.56	0.14	0.47	18.9	6974.0	0.40	0.11	0.37	15.0	5509.0	0.31
12	12	12	24.5	25.6	1.77	0.15	0.53	23.8	7546.0	0.40	0.11	0.39	17.7	5614.0	0.30
12	13	12	17.6	22.0	1.56	0.15	0.73	21.3	7177.0	0.37	0.12	0.57	16.6	5598.0	0.29
12	13	9	17.1	20.8	2.11	0.14	0.68	24.3	7018.0	0.42	0.11	0.54	19.2	5558.0	0.33
12	13	11	21.5	22.8	1.78	0.15	1.14	16.3	7491.0	0.36	0.12	0.88	12.6	5783.0	0.28
12	13	7	20.9	23.5	1.69	0.15	0.53	19.0	6780.0	0.37	0.12	0.40	14.5	5186.0	0.28
12	13	8	22.5	21.9	2.21	0.12	0.48	17.9	8013.0	0.37	0.10	0.38	14.0	6258.0	0.29
12	13	10	18.0	20.1	1.86	0.12	0.39	16.2	7539.0	0.37	0.10	0.31	13.0	6024.0	0.30

TABLE B-5. ANALYSIS OF MILLED REFUSE ASH
(MRI TEST PERIOD)

Sample			Ash Weight	Analyses 1													
Month	Day	Hr	(gm)	P_2O_5 (%)	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	SnO_2 (%)	CuO (%)	ZnO (%)	PbO (%)
12	5	9	4.13	1.68	49.9	10.40	0.97	5.45	14.83	1.65	2.06	1.81	8.67	0.040	0.16	0.25	0.12
12	9	15	5.72	1.46	51.3	6.10	0.72	8.15	13.80	1.63	1.19	1.43	9.03	0.070	0.20	0.32	0.18
12	9	16	2.73	1.23	50.7	18.30	1.14	12.04	12.41	1.56	1.37	1.77	9.64	0.040	0.23	0.52	0.20
12	9	13	3.99	1.57	48.8	10.30	0.97	5.42	14.65	1.11	1.77	1.83	10.45	0.050	0.09	0.29	0.16
12	9	11	1.78	1.41	53.9	11.00	1.24	5.72	14.09	1.26	2.48	1.75	8.52	0.050	0.44	0.40	0.16
12	9	7	4.13	1.90	48.3	17.60	0.95	6.90	13.64	1.71	1.49	1.28	7.93	0.060	0.81	0.50	0.26
12	7	8	3.20	1.67	49.3	13.10	1.06	4.54	15.81	2.06	1.19	1.60	7.84	0.040	0.10	0.32	0.19
12	7	9	5.76	1.69	49.3	15.30	0.78	5.39	14.46	1.61	1.08	1.92	12.24	0.040	0.14	0.30	0.14
12	10	13	7.01	1.22	52.0	8.10	0.70	13.34	12.45	1.56	0.78	1.48	13.98	0.070	0.24	0.33	0.25
12	10	8	4.76	1.48	50.0	14.90	1.42	6.91	13.55	1.61	1.21	1.64	5.32	0.060	0.29	0.62	0.16
12	10	14	2.92	1.48	52.7	12.30	1.17	5.04	12.91	1.05	1.43	1.67	14.18	0.060	0.38	0.50	0.20
12	10	9	2.58	1.96	49.4	13.90	1.16	4.25	14.52	1.41	1.91	2.01	9.07	0.040	0.17	0.33	0.25
12	11	11	4.90	1.20	51.9	15.40	0.82	3.11	13.57	0.65	1.20	1.39	15.51	0.040	0.23	0.32	0.17
12	11	9	5.58	1.30	41.1	13.10	1.13	15.87	11.32	1.53	1.42	1.50	7.05	0.060	0.63	1.24	0.21
12	11	12	4.46	1.51	46.7	14.60	1.04	8.58	13.75	1.16	2.00	1.66	9.08	0.080	0.09	0.37	0.21
12	11	13	2.86	1.27	47.6	16.80	1.07	9.21	12.53	1.30	1.63	1.57	6.90	0.050	0.61	0.36	0.16
12	12	13	3.62	1.32	54.4	10.30	0.86	9.38	12.45	1.02	1.35	1.69	10.18	0.050	0.13	0.29	0.16
12	12	15	3.28	1.20	48.7	16.60	1.04	6.50	12.83	1.20	1.56	1.74	17.92	0.050	0.22	0.51	0.19
12	12	9	4.99	1.35	50.8	11.20	1.09	6.11	13.43	1.65	1.43	1.87	6.95	0.060	0.22	0.46	0.17
12	12	12	4.46	1.34	46.2	13.20	0.81	9.70	12.38	1.26	1.14	1.68	9.58	0.060	0.20	0.29	0.16
12	13	12	4.93	1.31	51.4	14.90	1.19	4.22	13.43	1.79	1.27	1.46	7.04	0.050	0.16	0.30	0.20
12	13	9	3.25	1.34	48.7	16.10	1.06	6.25	11.97	1.59	1.28	1.56	6.90	0.040	0.31	0.31	0.26
12	13	11	4.33	1.30	47.5	19.90	1.29	5.13	15.29	1.74	1.98	1.65	15.35	0.030	0.12	0.41	0.26
12	13	7	4.28	1.38	48.7	14.70	0.92	15.88	10.91	2.30	1.52	1.48	13.38	0.090	0.10	0.30	0.32
12	13	8	2.03	1.48	39.9	26.90	1.36	6.20	12.81	1.35	1.37	1.72	11.67	0.050	1.23	0.61	0.26
12	13	10	3.87	1.48	49.7	15.60	0.86	12.09	12.63	1.56	1.43	1.77	10.08	0.040	0.12	1.11	0.15

TABLE B-6. PROXIMATE ANALYSIS AND HEATING VALUES OF MILLED REFUSE (UNION ELECTRIC TEST PERIOD)

Sample			Weight	Analyses 1											
				Moisture		Dry Weight Basis					Received Moisture Basis				
Month	Day	Hr	(lb)	Total (%)	Sample (%)	S (%)	Cl (%)	Ash (%)	As Dry (Btu/lb)	NaCl (%)	S (%)	Cl (%)	Ash (%)	As Received (Btu/lb)	NaCl (%)
11	23	9	27.2	28.3	1.31	0.20	0.46	25.2	7012.0	0.43	0.15	0.33	18.1	5028.0	0.31
11	27	9	19.7	43.2	0.77	0.13	0.50	26.4	7136.0	0.46	0.07	0.26	15.0	4053.0	0.26
11	26	10	38.9	16.7	1.24	0.19	0.47	22.9	7174.0	0.46	0.16	0.39	19.1	5976.0	0.39
11	27	13	38.4	41.3	1.07	0.16	0.70	22.6	7687.0	0.40	0.09	0.41	13.3	4512.0	0.23
11	26	11	44.2	28.9	1.27	0.13	0.49	24.7	7188.0	0.44	0.09	0.35	17.6	5111.0	0.31
11	26	8	29.3	41.6	0.60	0.19	0.60	33.1	13002.0	0.49	0.11	0.35	19.3	7593.0	0.29
11	26	16	34.9	27.8	0.85	0.18	0.48	24.5	7082.0	0.41	0.13	0.35	17.7	5113.0	0.30
11	27	14	29.2	26.9	0.93	0.16	0.42	19.9	7261.0	0.39	0.12	0.31	14.5	5307.0	0.29
11	27	15	32.6	24.1	0.43	0.20	0.76	20.4	7433.0	0.40	0.15	0.58	15.5	5642.0	0.30
11	26	13	33.1	29.2	1.06	0.18	0.54	28.5	6824.0	0.46	0.13	0.38	20.2	4832.0	0.33
11	27	11	36.5	39.3	0.44	0.17	0.37	26.1	6826.0	0.46	0.10	0.23	15.9	4143.0	0.28
11	26	6	38.5	36.0	0.60	0.19	0.62	24.0	7157.0	0.44	0.12	0.40	15.4	4580.0	0.28
11	30	15	35.0	34.1	1.02	0.15	0.55	27.3	7169.0	0.42	0.10	0.36	18.0	4724.0	0.27
11	30	14	37.9	31.8	0.69	0.23	0.67	27.2	7171.0	0.39	0.16	0.46	18.5	4891.0	0.27
11	30	8	32.6	30.7	1.41	0.18	0.48	20.5	7425.0	0.40	0.13	0.33	14.2	5145.0	0.28
11	29	15	32.3	40.1	0.94	0.16	0.43	24.6	7134.0	0.36	0.10	0.26	14.8	4273.0	0.22
11	27	11	30.5	41.4	0.41	0.18	0.70	22.5	7669.0	0.40	0.11	0.41	13.2	4494.0	0.23
11	28	11	38.9	41.4	0.70	0.20	0.48	26.3	6957.0	0.44	0.12	0.28	15.4	4077.0	0.26
11	28	13	34.9	39.1	0.83	0.18	0.46	24.3	7344.0	0.42	0.11	0.28	14.8	4472.0	0.26
11	28	8	43.6	37.0	0.49	0.18	0.35	25.6	6817.0	0.41	0.11	0.22	16.1	4295.0	0.26
11	28	14	33.6	39.7	0.70	0.22	0.64	21.9	7145.0	0.37	0.13	0.39	13.2	4308.0	0.22
11	27	15	64.4	41.9	1.02	0.22	0.47	26.8	6953.0	0.48	0.13	0.28	15.6	4040.0	0.28
11	29	12	38.5	39.0	0.68	0.20	0.40	21.3	7269.0	0.34	0.12	0.25	13.0	4434.0	0.21
11	29	13	31.5	36.7	1.37	0.18	0.43	19.4	7535.0	0.33	0.12	0.27	12.3	4770.0	0.21
11	29	8	43.8	40.5	1.08	0.17	0.62	24.2	7209.0	0.45	0.10	0.37	14.4	4289.0	0.27
11	29	11	29.4	32.9	0.75	0.22	0.43	21.3	7254.0	0.38	0.15	0.29	14.3	4868.0	0.26
11	29	15	34.9	39.5	0.67	0.20	0.51	22.5	7139.0	0.41	0.12	0.31	13.6	4319.0	0.25
11	29	9	53.3	40.2	1.47	0.20	0.44	25.4	7071.0	0.41	0.12	0.26	15.2	4228.0	0.25

Table B-7. ANALYSIS OF MILLED REFUSE ASH
(UNION ELECTRIC TEST PERIOD)

Sample			Ash	Analyses 1													
Month	Day	Hr	Weight (gm)	P_2O_5 (%)	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	SnO_2 (%)	CuO (%)	ZnO (%)	PbO (%)
11	23	9	4.14	1.34	53.4	6.70	0.84	9.92	12.65	1.75	1.72	2.30	6.23	0.020	0.14	0.33	0.19
11	27	9	5.88	1.84	48.5	8.20	0.66	9.45	11.24	1.71	1.60	2.06	16.30	0.050	0.19	0.38	0.20
11	26	10	3.66	1.66	49.2	7.70	0.56	6.42	12.41	1.60	1.47	1.95	6.39	0.050	0.23	0.28	0.20
11	27	13	4.51	1.94	50.1	11.20	0.99	7.11	13.11	1.73	1.35	2.11	4.91	0.060	0.79	0.35	0.23
11	26	11	5.17	1.57	44.1	9.30	0.79	11.58	12.78	1.95	1.48	2.17	4.34	0.050	0.42	0.81	0.22
11	26	8	8.80	1.40	49.0	7.70	0.68	13.89	11.24	1.52	1.87	1.52	5.22	0.050	0.57	0.39	0.18
11	26	16	4.57	1.82	50.6	9.20	0.81	6.47	13.20	1.85	1.47	2.14	5.00	0.060	0.19	0.23	0.18
11	27	14	3.34	1.81	48.6	8.30	0.71	8.18	14.14	1.83	1.67	2.52	16.50	0.070	0.23	0.29	0.20
11	27	15	3.20	1.65	49.0	10.90	0.21	8.22	12.98	1.81	2.11	2.68	5.87	0.060	0.28	0.42	0.16
11	26	13	5.85	1.65	48.6	9.00	0.68	8.62	12.65	1.70	1.61	1.79	5.32	0.040	0.37	0.36	0.22
11	27	11	5.55	1.96	53.1	9.80	0.69	6.14	14.98	1.83	1.15	2.02	8.70	0.060	0.16	0.35	0.24
11	26	6	5.54	1.64	48.6	8.20	0.74	11.13	13.98	1.76	1.38	1.87	8.21	0.040	0.22	0.45	0.14
11	30	15	4.85	1.47	46.7	6.80	0.73	7.55	13.82	1.07	1.37	1.77	10.17	0.040	0.23	0.39	0.29
11	30	14	4.30	1.60	51.5	9.60	0.85	15.32	13.24	1.56	1.78	1.52	7.33	0.040	0.29	0.59	0.28
11	30	8	3.68	1.96	52.3	10.10	1.04	5.04	15.40	1.61	1.66	2.15	9.69	0.050	0.23	0.42	0.26
11	29	15	4.56	1.57	49.1	9.50	0.79	5.04	14.48	1.71	1.58	1.98	8.36	0.040	0.17	0.94	0.18
11	27	11	3.30	1.63	49.5	10.80	0.82	9.14	11.79	1.74	1.42	1.98	4.34	0.060	0.66	0.51	0.18
11	28	11	4.76	1.45	51.4	10.80	0.70	10.45	13.31	1.39	1.24	1.92	10.60	0.060	0.21	0.31	0.21
11	28	13	3.89	1.56	49.5	8.30	0.98	12.77	14.01	1.77	1.49	1.91	6.18	0.070	0.56	0.49	0.29
11	28	8	4.30	1.52	50.9	9.40	0.69	7.47	13.98	1.77	1.29	1.76	8.45	0.050	0.30	0.31	0.28
11	28	14	2.98	1.94	50.8	9.30	0.84	7.53	15.02	1.82	1.32	1.96	8.03	0.050	0.19	0.36	0.19
11	27	15	5.46	1.66	48.7	9.00	0.63	7.83	13.89	0.74	1.39	1.97	10.77	0.040	0.15	0.35	0.13
11	29	12	3.58	1.69	51.6	10.10	0.81	12.89	13.36	1.84	1.32	1.98	9.92	0.080	0.31	0.40	0.25
11	29	13	2.93	1.75	47.4	12.30	0.89	7.98	14.15	1.90	1.10	2.17	7.61	0.040	0.29	0.44	0.18
11	29	8	4.00	1.84	50.8	9.80	0.81	5.55	14.18	1.73	1.25	1.92	8.64	0.040	0.22	0.35	0.21
11	29	11	3.19	1.75	48.7	8.30	0.99	3.76	15.43	1.66	1.81	2.07	8.26	0.040	0.25	0.36	0.62
11	29	15	3.08	1.72	51.6	10.60	0.88	12.35	13.68	1.77	1.72	1.89	7.29	0.050	0.27	0.40	0.23
11	29	9	4.32	1.82	48.3	9.30	0.64	4.95	15.29	1.83	1.73	2.00	8.55	0.050	0.33	0.59	0.21

Table B-8. ULTIMATE ANALYSIS OF REFUSE SAMPLES TAKEN DURING UNION ELECTRIC TESTS IN NOVEMBER 1973

	As Received (wt %)						Dry Basis (wt %)					
Sample No.	Carbon	Hydrogen	Nitrogen	Sulfur	Ash	Oxygen	Carbon	Hydrogen	Nitrogen	Sulfur	Ash	Oxygen
1	40.36	6.0	0.72	0.28	19.81	32.83	42.0	5.79	0.75	0.29	20.61	30.56
2	38.66	5.76	0.70	0.27	20.19	34.42	40.33	5.53	0.73	0.28	21.06	32.07
3	40.74	6.11	0.76	0.25	19.25	32.89	42.27	5.93	0.79	0.26	19.97	30.78
4	37.21	5.54	0.68	0.29	24.25	32.03	38.61	5.33	0.71	0.30	25.16	29.89
5	39.02	5.80	0.74	0.21	21.86	32.37	40.31	5.62	0.76	0.22	22.58	30.51
6	40.96	5.99	0.77	0.23	21.39	30.66	42.31	5.82	0.80	0.24	22.09	28.74
7	37.17	5.57	0.70	0.23	26.53	29.80	38.35	5.39	0.72	0.24	27.37	27.93
8	38.42	5.82	0.72	0.24	22.15	32.65	39.74	5.64	0.74	0.25	22.91	30.72
9	40.02	5.96	0.82	0.23	22.98	29.99	41.21	5.81	0.84	0.24	23.66	28.24
10	39.16	5.83	0.63	0.21	19.12	35.05	40.43	5.66	0.65	0.22	19.74	33.30
11	39.76	5.97	0.69	0.27	20.12	33.19	41.19	5.79	0.71	0.28	20.84	31.19
12	37.45	5.55	0.70	0.23	21.76	34.31	38.78	5.35	0.72	0.24	22.53	32.38
13	38.38	5.73	0.78	0.24	28.90	25.97	39.58	5.56	0.80	0.25	29.81	24.00
14	40.15	6.00	0.74	0.23	22.21	30.67	41.35	5.85	0.76	0.24	22.88	28.92
15	40.78	6.23	0.72	0.23	20.65	31.39	42.21	6.06	0.75	0.24	21.37	29.37
16	39.96	6.03	0.76	0.24	22.74	30.27	41.27	5.86	0.78	0.25	23.49	28.35
17	39.29	5.86	0.70	0.24	24.18	29.73	40.63	5.68	0.72	0.25	25.01	27.71
18	38.92	5.96	0.71	0.21	24.60	29.60	40.19	5.79	0.73	0.72	25.40	27.67
19	39.01	5.79	0.75	0.26	18.77	35.42	40.52	5.58	0.78	0.27	19.50	33.35
20	38.29	5.64	0.70	0.27	24.69	30.41	39.49	5.47	0.72	0.28	25.47	28.57

APPENDIX C

ELECTRICAL MEASUREMENTS MADE ON ESP DURING EPA/MRI AND UNION ELECTRIC EMISSION TESTS

Table C-1. ESP TEST MEASUREMENTS (EPA/MRI)[a]

Load (megawatts)	Percent Refuse	Test No.	Date	Primary Voltage (volts) Set 1A	1B	1C	1D	Primary Current (amps) Set 1A	1B	1C	1D	Secondary Votage (kv) Set 1A	1B	1C	1D	Secondary Current (ma) Set 1A	1B	1C	1D	Spark Rate (sparks/Min) Set 1A	1B	1C	1D
80	0	6	12/10	290	303	287	302	39	45	67	46	39	38	(2)	32	227	283	248	>300[c]	103	53	107	90
80	9	13	12/14	267	280	245	272	41	44	37	43	34	35	--	10	245	270	243	292	60	17	117	143
80	18	4	12/9	261	284	233	288	40	42	37	45	33	36	--	26	235	262	241	294[c]	65	66	10	103
80	18	5	12/9	261	284	250	278	35	41	37	42	34	36	--	29	216	255	240	283[c]	96	94	150	151
80	27	7	12/10	268	291	230	272	39	41	38	41	34	35	--	24	244	253	245	281	88	95	18	161
100	0	3	12/10	304	288	299	290	44	45	41	45	40	36	--	37	265	275	279	>300[c]	9	0	34	13
100	9	1	12/5	258	278	253	253	41	40	39	38	32	33	--	30	247	253	249	265	80	103	92	183
100	9	2	12/5	260	278	256	259	41	38	40	36	33	34	--	32	241	231	267	251	75	111	81	188
100	9	11	12/13	265	277	240	270	43	43	37	39	32	34	--	14	257	265	240	255	20	45	53	160
100	18	12	12/13	258	268	229	268	43	44	37	44	30	32	--	13	258	268	240	295[c]	1	8	9	109
120	0	9	12/12	303	280	287	288	43	44	36	46	40	34	--	24	265	270	240	300[c]	17	0	17	17
120	9	8	12/11	274	288	255	266	43	42	38	38	34	37	--	21	258	256	243	249	28	79	155	174
120	18	10	12/12	260	275	238	259	40	40	36	39	32	34	--	15	244	252	235	253	51	95	131	150

a/ Average values per test for measurements recorded three to four times during the 4-hr test period--data probably not time average for entire tests.

b/ Measurement not recorded.

c/ One or more of recorded values above 300 ma meter limit, data biased on low side.

Table C-2. ESP TEST MEASUREMENTS (UNION ELECTRIC)[a/]

Load (megawatts)	Percent Refuse	Test No.	Date	Primary Voltage (volts) Set 1A	1B	1C	1D	Primary Current (amps) Set 1A	1B	1C	1D	Spark Rate (sparks/min) Set 1A	1B	1C	1D	Averages Voltage	Current	Spark Rate	Power x 10^3
75	0	4	10/18	310	302.5	305	300	47	46.5	42.5	43.75	27.5	2.5	32.5	15	304.4	44.9	19.4	13.67
75	0	5	10/18	312.5	300	310	300	48.75	46.5	43.25	43.25	15	0	22.5	0	305.6	45.4	9.4	13.87
75	13.2	6T	11/29	290	300	280	280	47	47.3	42.5	42	256.7	76.7	90	226.7	287.5	44.7	162.5	12.85
75	14.7	7T	11/29	300	-	280	300	46	46	43	49	330	186	105	450	293.3	46	267.8	13.49
101	0	1	10/16	330	309	315	304	48.5	47	43.5	43.5	32.5	0	59	0	314.5	45.6	22.9	14.34
100	0	2	10/17	315	310	320	305	48	47	43	44	30	0	15	0	311.9	45.5	11.2	14.19
100	0	3	10/17	320	310	317.5	305	48	47.5	43	43	30	0	30	0	313.1	45.4	15	14.21
100	14.8	5T	11/28	290	293.3	278.3	285	47.3	45	46	48	260	396.7	110	450	286.6	46.6	304.2	13.36
100	15	4T	11/28	276.7	288.3	270	266.7	47	48	44.7	41.7	431.7	460	270	460	275.4	45.4	405.4	12.50
139	0	6	10/19	327.5	317.5	317.5	310	48	46.5	43.25	43.5	21	1	17.5	7.5	318.1	45.3	11.8	14.41
140	0	7	10/19	320	311	312.5	305	47.5	46	43	43	37.5	11	32.5	23.5	312.1	44.9	26.1	14.01
140	0	8	11/30	320	300	300	277.5	42	48	b/	44	40	100	b/	300	299.4	44.7	146.7	13.38
140	10	1T	11/26	280	283.3	266.7	260	47	44	45	42.7	170	363.3	35	450	272.5	44.7	254.6	12.18
140	10	2T	11/27	280	276.7	263.3	256.7	47	45.3	43	42	227.5	366.7	100	450	269.2	44.3	286.0	11.92
140	10	3T	11/27	286.7	271.7	283.3	250	48	44.3	44.7	40.3	243.3	500	138.3	450	272.9	44.3	332.9	12.09
140	11.4	9T	11/30	275	275	270	270	22.7	46	44	43	220	330	235	450	272.5	38.9	308.8	10.60

a/ Average for values recorded at beginning, middle and end of test.
b/ Data not legible because of poor copy machine reproduction.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-073	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE St. Louis/Union Electric Refuse Firing Demonstration Air Pollution Test Report		5. REPORT DATE August 1974
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) L. J. Shannon, M. P. Schrag, F. I. Honea, and D. Bendersky		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Midwest Research Institute 425 Volker Boulevard Kansas City, Missouri 64110		10. PROGRAM ELEMENT NO. 1AB013; ROAP 21AQQ-010
		11. CONTRACT/GRANT NO. 68-02-1324 (Task 11)
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, N.C. 27711		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The report gives results of tests performed to determine the effects of mixed-fuel firing on boiler emissions and electrostatic precipitator (ESP) performance, using shredded municipal wastes as a supplementary fuel in a 140 megawatt coal-fired utility boiler. Tests were performed at boiler loads of 75 to 140 megawatts when firing coal-only and when firing fuel mixtures which provided solid waste heat inputs to the boiler of 9 to 27%. Test measurements included: total particulate, particulate size distribution, O_2, CO_2, CO, NO, SO_2, SO_3, Cl^-, Hg_v, in situ fly ash resistivity, and ESP operating conditions. Firing mixed fuels caused no statistically significant changes in gaseous pollutant emissions. Particulate stack emissions increased, as a result of an ESP performance loss related to changes in ESP electrical operating conditions and gas flow volumes. However, excessive sparking rates on some mixed-fuel tests indicated that the ESP could have been tuned for better collection. ESP performance was significantly affected by the fuel mix (coal and waste). Additional tests will be required to establish the magnitude of performance losses which may result from mixed-fuel firings.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Electrostatic Precipitators	Air Pollution Control	13B
Combustion	Boilers	Stationary Sources	21B
Refuse		Municipal Waste	13A
Wastes		Supplementary Fuel	
Coal		Mixed Fuel	21D
Electric Utilities		Particulates	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 116
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)