



470
8-3-81
④

②

Dr. 2895

DOE/ET/10484-T2

Sp. - 135
Bins - 30169
NTIS - 25
Rec. - 470

MASTER!

A MULTI-STAGE DESULFURIZING FLUID-BED COMBUSTOR FOR
COAL-FIRED HOT GAS GENERATOR SYSTEMS

Topical Report 3

Task 6. Modifications to Materials Handling Equipment

Task 7. Testing

By
Charles Lowell

April 1981

Work Performed Under Contract No. AC21-78ET10484

Wormser Engineering, Inc.
Middleton, Massachusetts



U. S. DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A05
Microfiche A01

Report #DE 10484/T3

"A Multi-Stage Desulfurizing Fluid-Bed Combustor

For Coal-Fired Hot Gas Generator Systems" *

Topical Report #3

Task 6. Modifications To Materials Handling Equipment

Task 7. Testing

Prepared By: Charles Lowell, Project Engineer

Approved By: William F. Dawson, Program Manager

April, 1981

Work Performed Under Contract #DE-AC21-78MC-10484

(Formerly Contract #ET-78-C-01-2859)

*** U.S. Patent #4051791**



WORMSER ENGINEERING, INC.
212 S. Main St., Middleton, Massachusetts 01949

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

mjt

Abstract

This report covers the modification of Materials Handling Equipment, Testing and Program Management of Tasks 6, 7 and 8 of Phase 2. The Cohogg system contains a pyrolyzer for partial gasification of the coal through sub-stoichiometric combustion, a char burner which burns the char (generated in the pyrolyzer) in excess air, and an afterburner where the pyrolyzer gases and the char burner gases mix to produce a high temperature ($\sim 3000^{\circ}\text{F}$) environmentally clean flame capable of replacing an oil or gas burner.

The system has operated successfully and demonstrated the capability of producing an environmentally clean high temperature flame. Operation with 15% excess air overall demonstrated a 3200°F capability while sulfur retention was in excess of 90%. After more than 100 hours of operation the system shows itself to have flexibility in coal type, sorbent type, and operating temperatures while maintaining a clean high temperature flame and meeting or exceeding current pollution restrictions.

Table of Contents

	<u>Page #</u>
List of Tables and Figures	iv
1.0 Introduction	1
1.1 Background	1
1.2 Emissions	7
1.3 COHOGG[®] Applications	8
2.0 Phase 2. Contract Workscope	10
2.1 Task 6. Modifications to Materials Handling Equipment	10
2.2 Task 7. Testing	10
2.3 Task 8. Program Management	11
3.0 Summary of Phase 2 Results To Date	11
3.1 Task 6. Results	11
3.2 Summary List of Task 7. Results To Date	25
3.3 Task 7. Testing	26
4.0 Conclusion	67
References	72

List of Tables and Figures

<u>Tables</u>	<u>Page No.</u>
1. USM Prediction Equations	28
2. Coal Types for Test Program	29
3. Sorbent Types	49
4. Resource Engineering, Inc. Lab. results (1600°F Temperature Test Run)	54
5. Resource Engineering, Inc. Lab. results (1700°F Temperature Test Run)	55
6. Resource Engineering, Inc. Lab. results (1800°F Temperature Test Run)	56
7. Resource Engineering, Inc. Lab. results (1900°F Temperature Test Run)	57
8. Resource Engineering, Inc. Lab. results (24 Hour Run)	68
 <u>Figures</u>	
1. COHOGG® Schematic (Diagram)	2
2. COHOGG® Flow Diagram	4
3. Increase in Volatile Matter due to Pyrolysis Temperature	5
4. Effect of Heating Rate on Volatiles Yield	5
5. COHOGG® Flame Temperature vs. Volatiles Yield	6
6. Rotary Valve	12
7. Sorbent Recirculation Schematic	14
8. Coal Mechanical Level Gauge	16

9. Hammermill Crusher	17
10. Midwestern Industries Screen Separator	18
11. Flexifeeder	20
<u>Pyrolyzer Temperature Variation Tests</u>	
12. Devolatization versus Pyrolyzer Temperature	31
13. Percent Stoichiometric air versus temperature at $\frac{1}{2}$ million BTU/Hr.	32
14. Char Particle Size Distribution	33
<u>Pyrolyzer Coal Size Distribution Tests</u>	
15. Devolatization % Versus Screen Size	36
16. % Stoichiometric Air Versus Screen Size	37
17. Coal/Char Size Versus Screen Size	38
<u>Cyclone Efficiency</u>	
18. Cyclone Versus Screen Size	39
19. First Cyclone Char Size Distribution	41
20. 2nd Cyclone Char Size Distribution	42
21. Sensitivity of Overall Char Collection Efficiency to 2nd Cyclone Efficiency	43
<u>Pyrolyzer Turn Down Tests</u>	
22. Devolatization % Versus Coal Feed Rate	44
23. Char Particle Size Distribution Versus Coal Feed Rate	45
24. Cyclone Collection Versus Coal Feed Rate	46
<u>Pyrolyzer Sorbent Tests</u>	
25. Overall Desulfurization % Versus Ca/S Ratio For Four Sorbent Types	48
<u>Char Burner Temperature Tests</u>	
26. Batch Bed SO_2 Retention	51
27. NO_x Generation	52

24 Hour Run

28. SO₂ Retention and NO_x Generation 59

29. Afterburner Flame Temperature 61

30. Total Pressure Drop Across Char Burner Beds 64

31. Representative Strip Chart 65

Major System Components

32. First and Second Cyclone Design 23

33. Char Burner 69

34. Pyrolyzer 24

35. Afterburner 70

36. COHOGG[®] Schematic 71

Reference Graphs

37. Afterburner Temperature Thermocouple Radiation Error 62

38. Flame Temperatures vs. Excess Air 66

1.0 Introduction

1.1 Background

COHOGG is a Coal Hot Gas Generator designed to allow the replacement of an oil or gas burner with an environmentally acceptable coal burner. Fluid bed coal combustors cannot provide high enough temperatures for process burners or high temperature boilers because of the limiting temperatures for clinkering ($\sim 2000^{\circ}\text{F}$) and sulfur dioxide absorption ($\sim 1600^{\circ}\text{F}$). Wormser Engineering, Inc. is developing a unique line of coal FBC's known as Wormser Grates which have several notable advantages over the typical FBC. If a partially gasifying pyrolyzer is added to a Wormser Grate system, it is possible to generate a high temperature, environmentally clean flame and therefore substitute for a gas or oil burner. Figure 1 shows a diagrammatic representation of the COHOGG principle.

Coal is fed to a pyrolyzer with a low percentage of stoichiometric air which provides the heat of pyrolysis and partially gasifies the coal. The resultant gases are fed to an afterburner and the char is fed to a Wormser Grate, where it is burned with excess air to maintain the bed temperatures at the optima for combustion efficiency and SO_2 clean-up. The char burner combustion products with the excess air are fed to the afterburner where they burn the pyrolyzer gases to produce the $\sim 3000^{\circ}\text{F}$ flame.

The COHOGG system is highly efficient and low in cost. The high efficiency results from (a) no in-process gas clean-up requiring a large loss of sensible heat, and (b) high carbon utilization because only partial gasification occurs in the pyrolyzer and the upper bed in the Wormser Grate provides additional fines burn-up.

The capital cost is low since the reactor sizes are similar to other gasification systems but there is no need for sulfur clean-up, carbon burn-up or fines recycling systems downstream. Installed equipment cost may be reduced by half for these reasons.

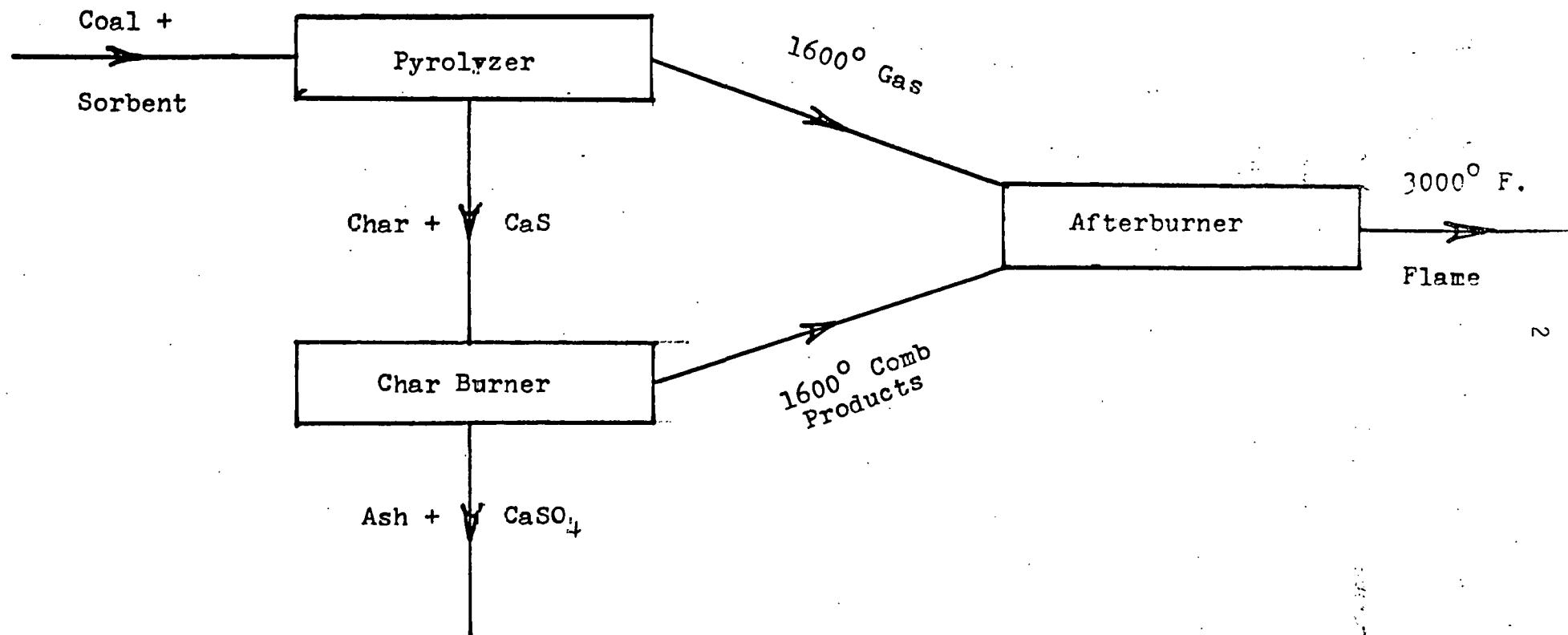


Figure 1. COHOGG[®] Schematic.

A flow diagram of a COHOGG installation is shown in Figure 2. The afterburner shown may not be required in retrofit cases where the existing boiler combustion volume can act as the combustion chamber. In a new installation, savings in boiler volume may be available if the combustion space is absorbed in the COHOGG system. (The high combustion constituent gas temperatures will provide high rates of reaction and reduced volume requirements in any case.)

Operational advantages of COHOGG are the ability to use a wide range of high sulfur bituminous coals and its low maintenance requirements. These result from the long residence time at temperature in the pyrolyzer which minimizes the formation of tars. This minimizes deposition in the ducting which would otherwise require frequent shutdown for cleaning.

The high temperature capability of the system stems from the high fraction of devolatilization achieved in the pyrolyzer. The pyrolyzer design is that used successfully in the U.S. Bureau of Mines' pyrolysis investigation (Ref. 1 and 2). The percentage of volatiles achieved is larger than that measured from proximate analysis and is due to the high temperature and the heating rate. Figure 3 shows the range of results from the USBM tests while Figure 4 shows the effect of heat rate on the percentage of volatiles achieved (Ref. 3).

Figure 5 shows the theoretical flame temperature achievable in COHOGG if the char burner combustion products are at 1600°F. The 57 percent devolatilization shown necessary to reach 3000°F seems quite achievable according to the USBM results shown on Figure 3.

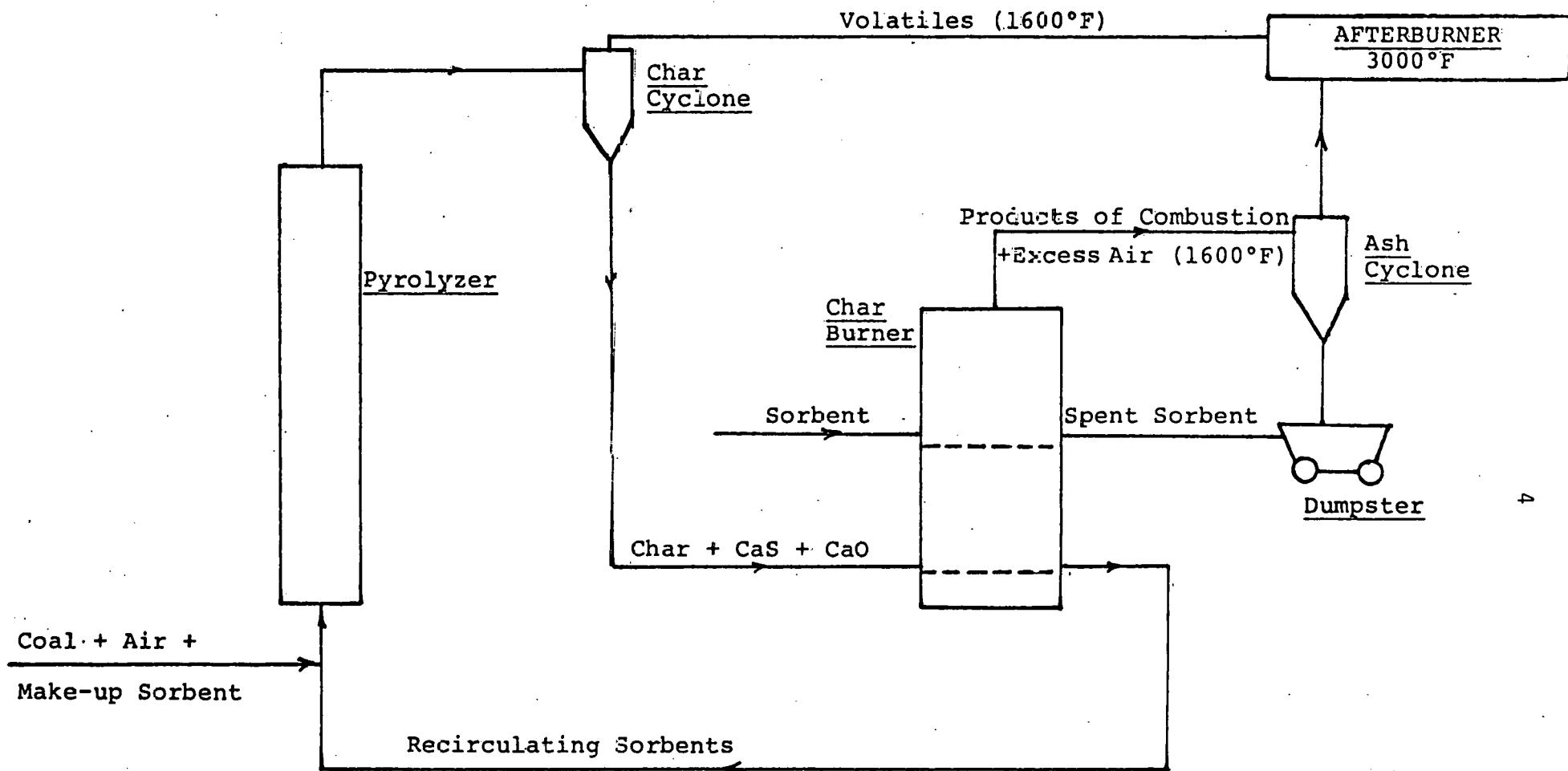


Figure 2. COHOGG[®] Flow Diagram.

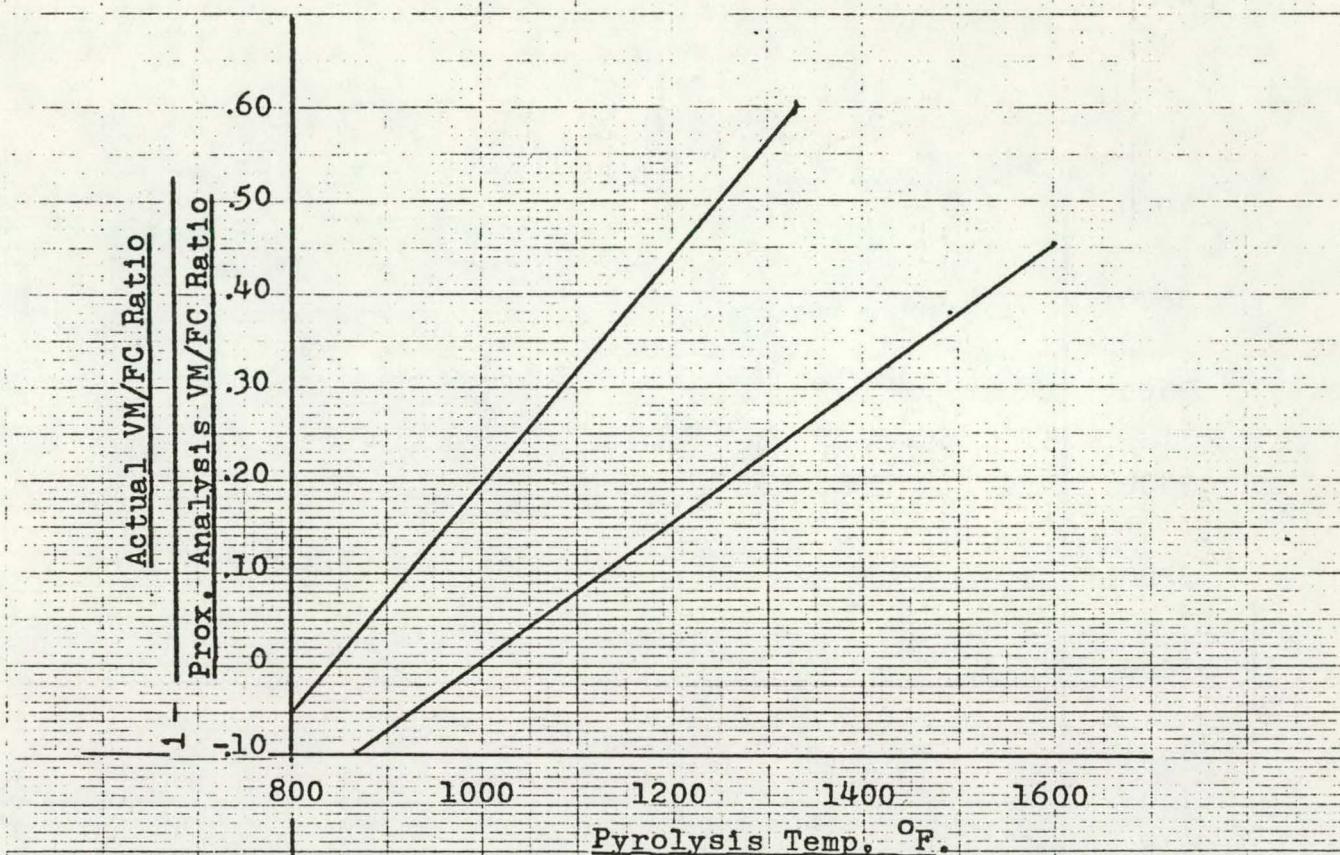


Figure 3. Increase in VM Due to Pyrolysis Temp.

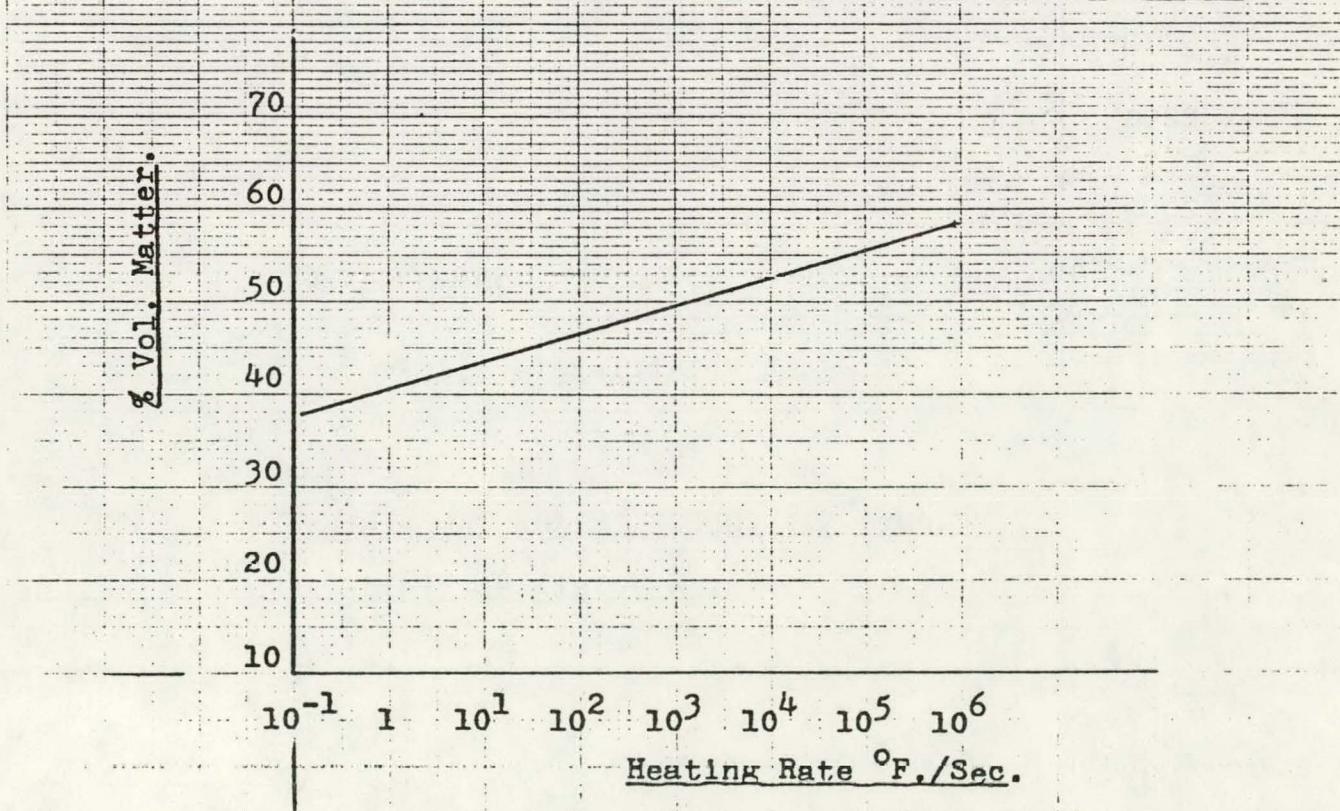


Figure 4. Effect of Heating Rate on Volatiles Yield.

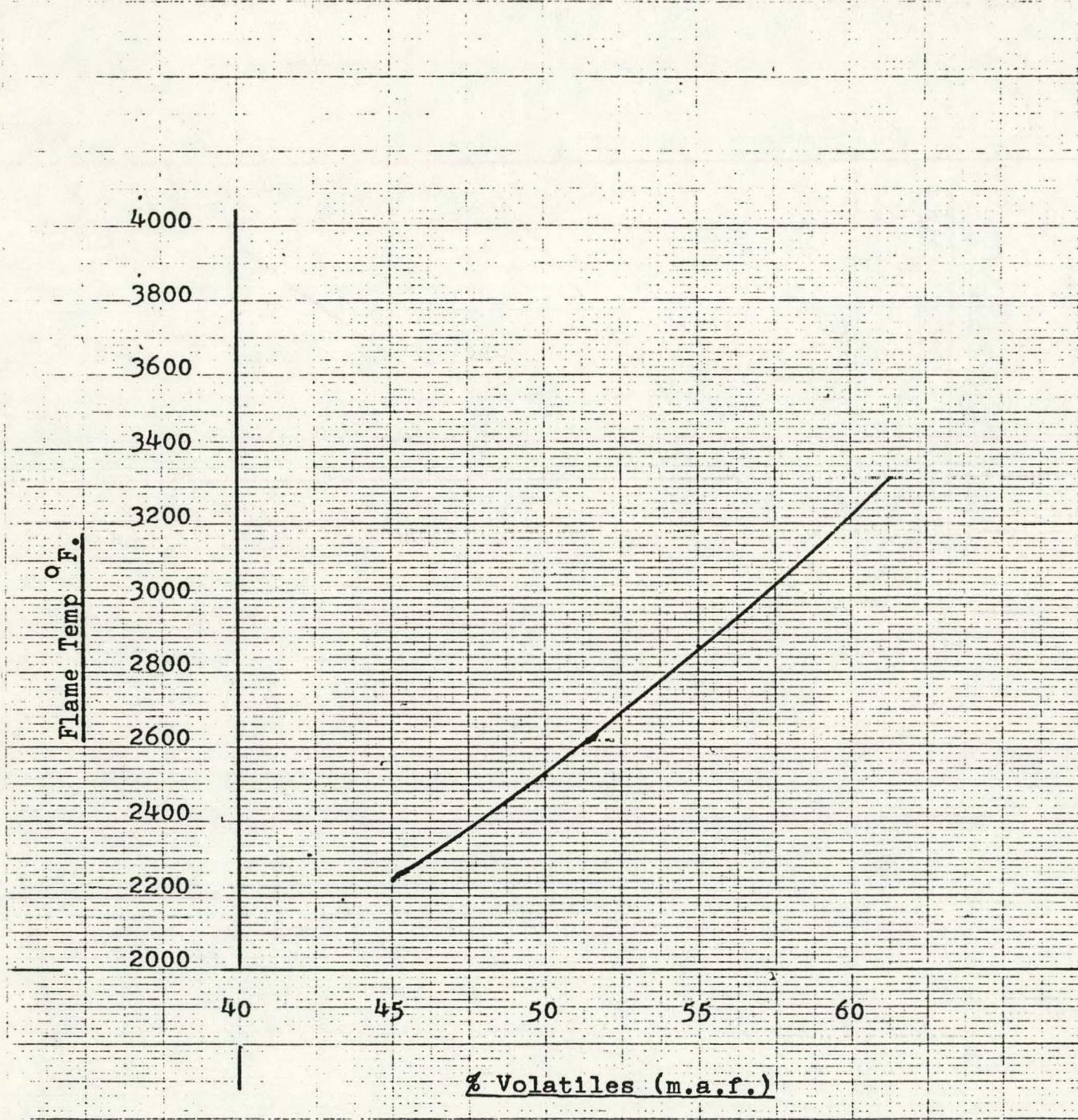
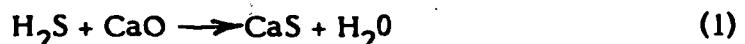


Figure 5. COHOGG R Flame Temperature
Vs. % Volatiles Yield

1.2 Emissions



Figure 2 shows coal and limestone being pneumatically transported to the pyrolyzer. The limestone is calcined in the pyrolyzer and the resulting lime reacts with the hydrogen sulfide in the volatiles as follows:



The sorbent is transported to the char burner bottom bed where it is oxidized back to lime and sulfur dioxide:



The sulfur dioxide is then scrubbed by the upper bed in the char burner to produce an inert mixture of predominantly CaSO_4 :



Some CaO may still be present.

A major advantage of the Wormser Grate in the COHOGG system is that separate beds allow each to be operated at the optimum temperature for its particular chemistry. Secondary air can be injected between the two beds to provide this control. Wormser Grate experience indicated that SO_2 scrubbing efficiencies in the upper bed will be in the 90 percents.

NO_x

The sub-stoichiometric operation of the pyrolyzer releases the fuel nitrogen in molecular form so that fuel NO_x generation should be zero. In direct coal combustion processes, fuel N₂ forms the majority of the NO_x formed because of the very high local temperatures occurring during the particle burning history. The amount formed depends upon the excess air ratio to a certain extent (Ref. 4). The thermal NO_x formed subsequently will be low due to the low temperatures in the char burner and, even at the higher temperature in the afterburner, will be low due to the short time at temperature before cooling in the boiler tube passes or the process for which heat is being provided. Staged combustion in pulverized coal systems has already demonstrated this principle.

Particulates

Particulate control may be achieved through conventional high efficiency cyclones since the particle sizes will be relatively large. In some applications, however, it is likely that a conventional collector downstream of the boiler or process will be required.

1.3 COHOGG Applications

No other high temperature direct coal fired combustion system has the self cleaning, efficiency and cost advantages of COHOGG so that it becomes the system most capable of replacing direct fired processes using oil or gas.

Process heat (as opposed to process steam) uses some 40% of the energy consumed by industry, of which the primary users are petroleum refining (1.1 mbd of gas and oil in 1974), primary metals (.55 mbd), chemicals (.4 mbd) and stone, clay, and glass (.4 mbd). In identifying the impediments in the conversion of these applications to coal, low-BTU gasifiers have in most cases been deemed technically suitable, with the only constraint being economics. (In some cases, flame temperature of low-BTU gasifiers was a constraint).

COHOGG appears to overcome all of the technical limits of direct-fired coal systems (product contamination, fouling, combustion volume restrictions), as well as the low-temperature constraint of low-BTU gasifiers. What remains to be seen is whether the economic benefits of COHOGG (vs gasifiers, due to the elimination of the scrubber) are sufficient to significantly increase the use of coal in the process industries. (Ref. 5).

COHOGG application to the utility field is not as near term as the industrial sector, although it does allow convenient conversion of existing gas or oil installations. It will be useful in combined cycle systems where it can provide high turbine inlet temperatures but there are other technical problems of hot gas clean-up and gas turbine corrosion which need to be solved before COHOGG can be most useful in this area.

Space heating uses about half of the heat used in direct heat generation so the potential savings through the use of COHOGG are large. However, the smaller unit sizes required in this field will require development beyond the scope required for the areas above and the potential savings are not in the near term.

2.0 Phase 2 Contract Workscope

The Phase 2 objective was to convert the bench model from a fully manual system to one capable of continuous operation. Also, the objective was to install the sorbent recycling system and to continue the sorbent-variety testing initiated in Phase 1. The work was to provide the basis for selecting the direction of future R & D work. The workscope as proposed was subsequently modified and is summarized below.

2.1. Task 6. Modifications to Materials Handling Equipment

To improve operation of the system tested in Phase 1, the design, fabrication and installation will be completed on:

- air lock devices on the coal and sorbent hoppers to allow manual filling during operation
- a sorbent return system from the char burner bottom bed to the pyrolyzer feed line
- direct-reading mechanical level detectors in the coal, char and sorbent hoppers

2.2 Task 7. Testing

This task shall include tests for:

- calibration of the materials handling system modifications from Task 1
- sorbent utilization
- variation in pyrolyzer sorbent-type
- endurance testing with an initial goal of 100 hours operation

2.3 Task 8. Program Management

This task includes the management and administrative functions of the program, including report preparation, budgeting, scheduling and program direction.

3.0 Summary of Phase 2 Results to Date

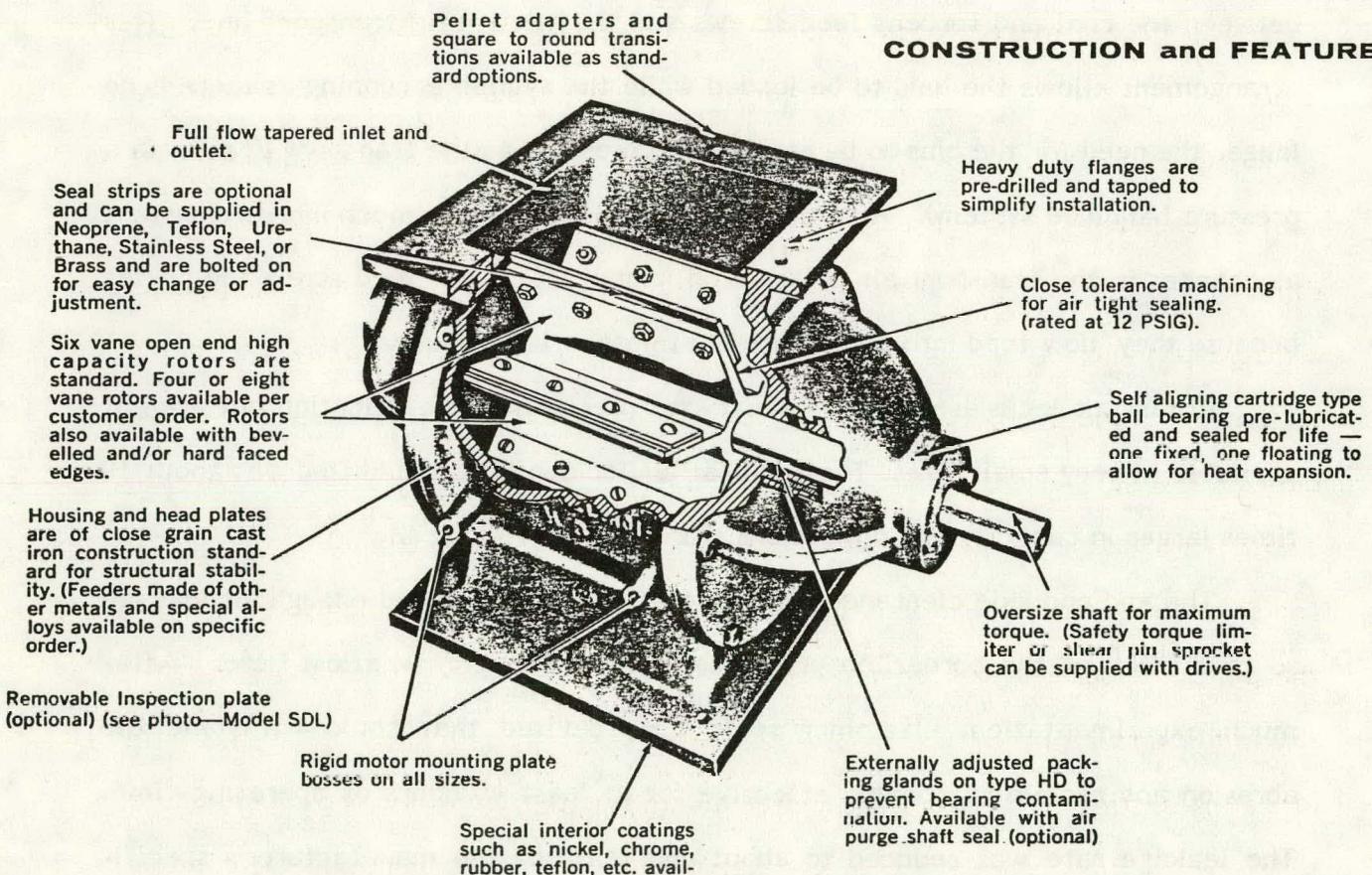
3.1 Task 6. Modifications to Materials Handling Equipment

3.1.1 Rotary Air Lock

A William W. Meyer Company "4 x 4" rotary air lock (Figure 6) was installed between the coal and sorbent feed screws and the pneumatic transport line. This arrangement allows the bins to be loaded while the system is running as there is no longer the need for the bins to be at the same pressure as the transport line (as in a pressure balanced system). Also the feed rates have become much more consistent as changes in the transport air pressure no longer affect the feed screw feed rates because they now feed into a chamber at atmospheric pressure.

Rotary air locks are used in industry for precisely this application but are not available in very small sizes. The smallest air lock that we could find was about 10 times larger in capacity and dimensions than what we required.

The end and side clearances of the rotating blades allowed enough air leakage so that much of the borderline pyrolyzer blower capacity was lost here. After much experimentation, elastomer seals were devised that could withstand the abrasion and remain reasonably effective for at least 40 hours of operating time. The leakage rate was reduced to about one tenth of the manufacturer's specifications. On a scaled up Cohogg system, the same rotary valve leakage rate would

MEYER ROTARY AIR LOCKFIGURE 6.**CONSTRUCTION and FEATURES**

be a much smaller percentage of the transport air blower capacity and would not be an issue.

A simple valved airlock arrangement was installed on the char burner sorbent feed transport line. A rotary air lock was deemed not necessary as the sorbent hopper needs infrequent filling and feeds well when sealed. By closing two valves, the sorbent feeder can be isolated from the transport air pressure during the few minutes it takes to fill the hopper.

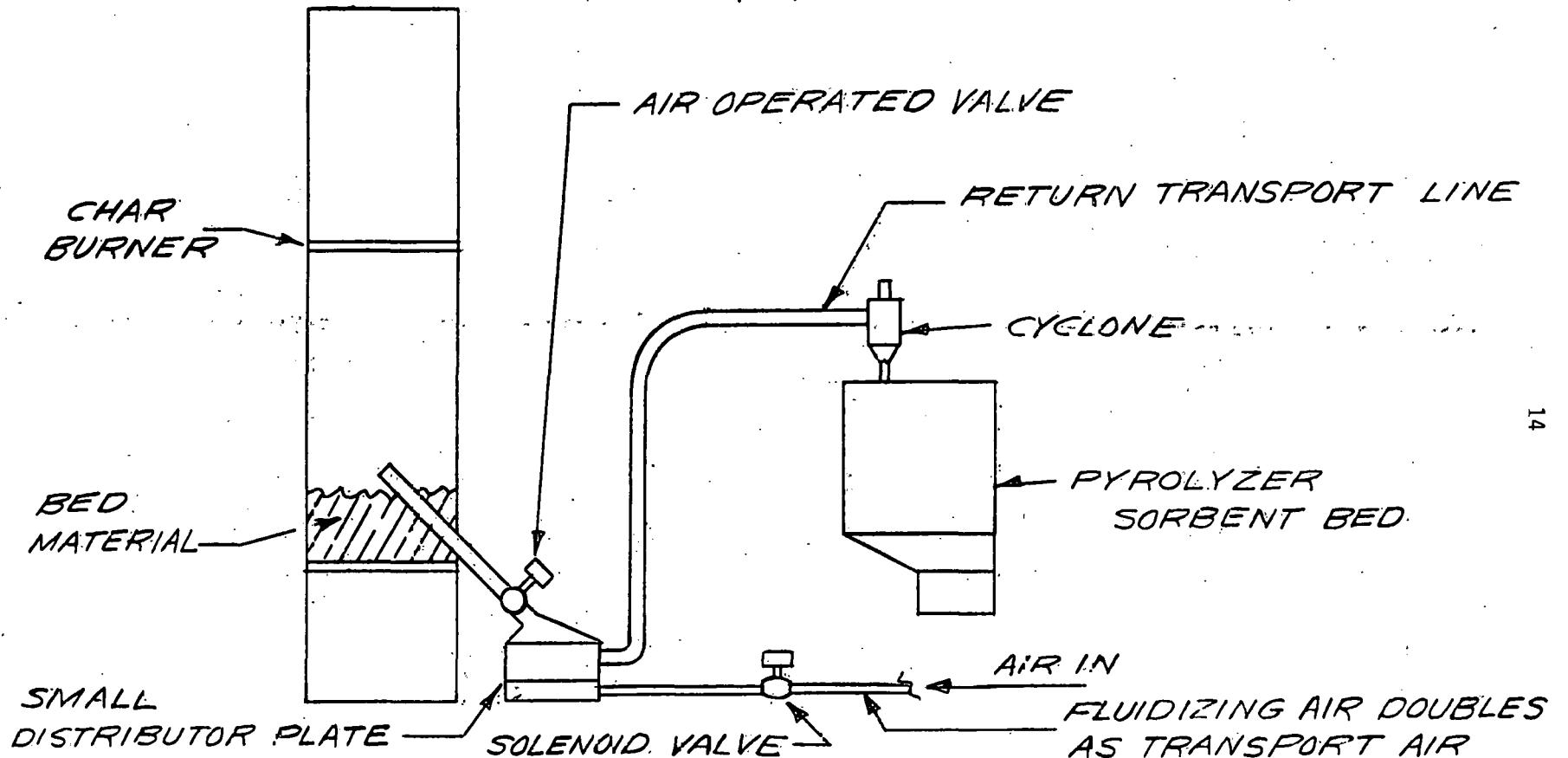
3.1.2. Sorbent Return System

A sorbent return system (Figure 7) was installed between the char burner combustion bed and the pyrolyzer sorbent hopper. It works as follows:

Bed material fills a 1 1/2" standpipe that enters the combustion bed just above the distributor plate and extends above the bed material at a 45° angle. Fluidizing action causes bed material to fall into the open upper end of the pipe at a rate dependent on the bed height. A KTM Company high temperature ball valve at the lower-end of the pipe and outside the char burner, periodically opens and closes allowing the accumulated bed material to enter a small collection pot. In conjunction with the valve closing, fluidizing air enters the bottom of the pot and forces the solids out a one inch pipe, transporting them to a small cyclone above the pyrolyzer sorbent hopper where the solids drop into the hopper and are again fed to the pyrolyzer.

For testing purposes, the solids collected in the pot were transported to a separate container to be weighed and sampled before being manually returned to the pyrolyzer sorbent hopper during the char burner testing and also the 24 hour run.

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: FRACTIONS DECIMALS ANGLES \pm XX \pm \pm XXX \pm			JOB NO.		WORMSER ENGINEERING, INC. 212 S. Main St., Middleton, Massachusetts 01949 (617) 777-3060		
			APPROVALS	DATE			
			DRAWN R.P.	4-24-81			
MATERIAL			CHECKED		SORBENT RECIRCULATION SYSTEM SCHEMATIC		
FINISH			FIGURE 7.		SIZE	CODE IDENT NO.	DRAWING NO.
USED ON					A		
APPLICATION			DO NOT SCALE DRAWING		SCALE		SHEET OF

3.1.3 Mechanical Coal Level Gauge

A Monitor CM 4 mechanical level gauge shown in Figure 8 (weight on a string type) was installed in the coal hopper. The readout is located on the control panel with a timer that checks the level at regular intervals. The level gauge is accurate and repeatable allowing for easy computation of coal feed rates and convenient coal level measurements at the start and end of runs.

Two capacitance type Endress and Hauser level gauges purchased in Phase 1 were installed on the pyrolyzer and char burner sorbent hoppers. They have not stayed calibrated (as was the problem when they were mounted on smaller vessels in Phase 1) and so are not suited to our needs. Although it would be convenient to have accurate level gauges here, the low usage rate and ease of filling of the sorbent hoppers makes use of the level gauges as a low alarm only, sufficient for our purposes.

3.1.4 Hammermill Crusher

A Holmes Brothers Laboratory Hammermill crusher (Figure 9) was purchased and has greatly sped up handling of the coal. We can now crush a barrel of coal once instead of twice, and do it in five minutes instead of the $\frac{1}{2}$ hour it took with the old jaw crusher. It will also crush limestone if the need arises.

3.1.5 Screener

A Midwestern Industries three stage screener (Figure 10) was purchased to size coal and sorbents for size distribution testing. This was a big improvement over manually shaking a single screen over a barrel and, needless to say, was much faster.

Monitor CM4 Mechanical Level Gauge

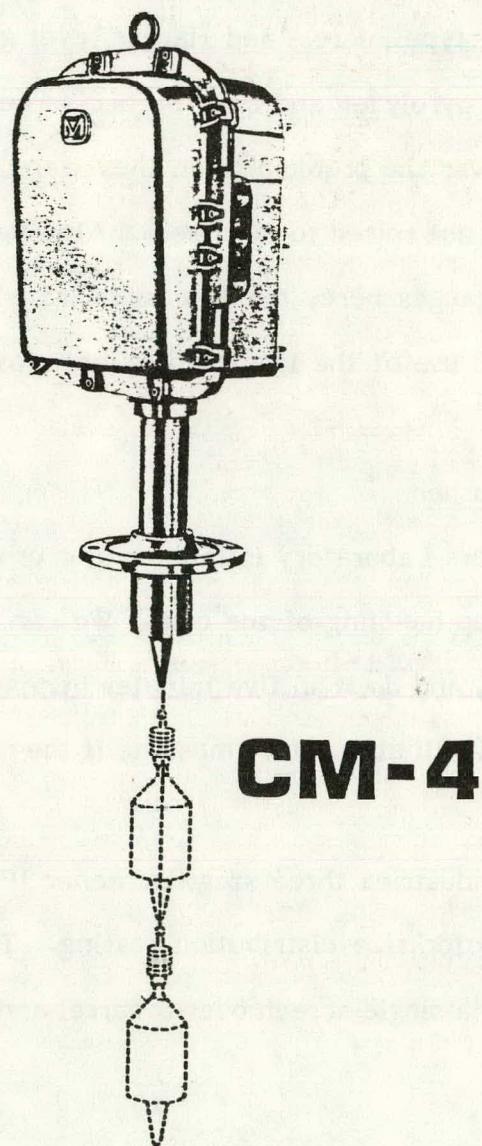
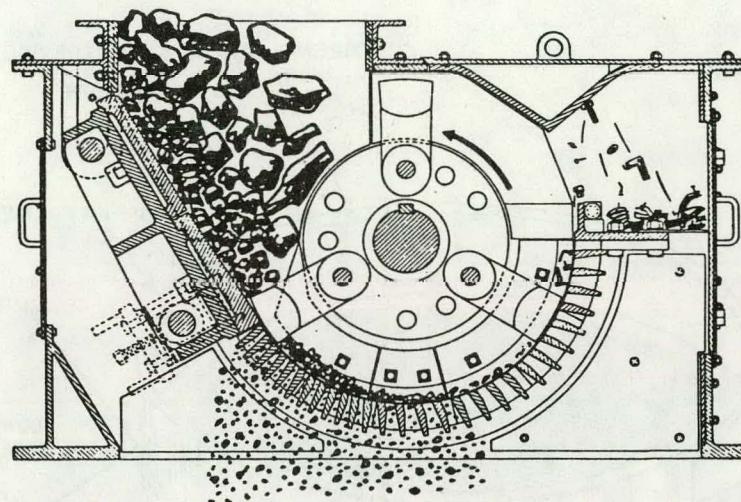


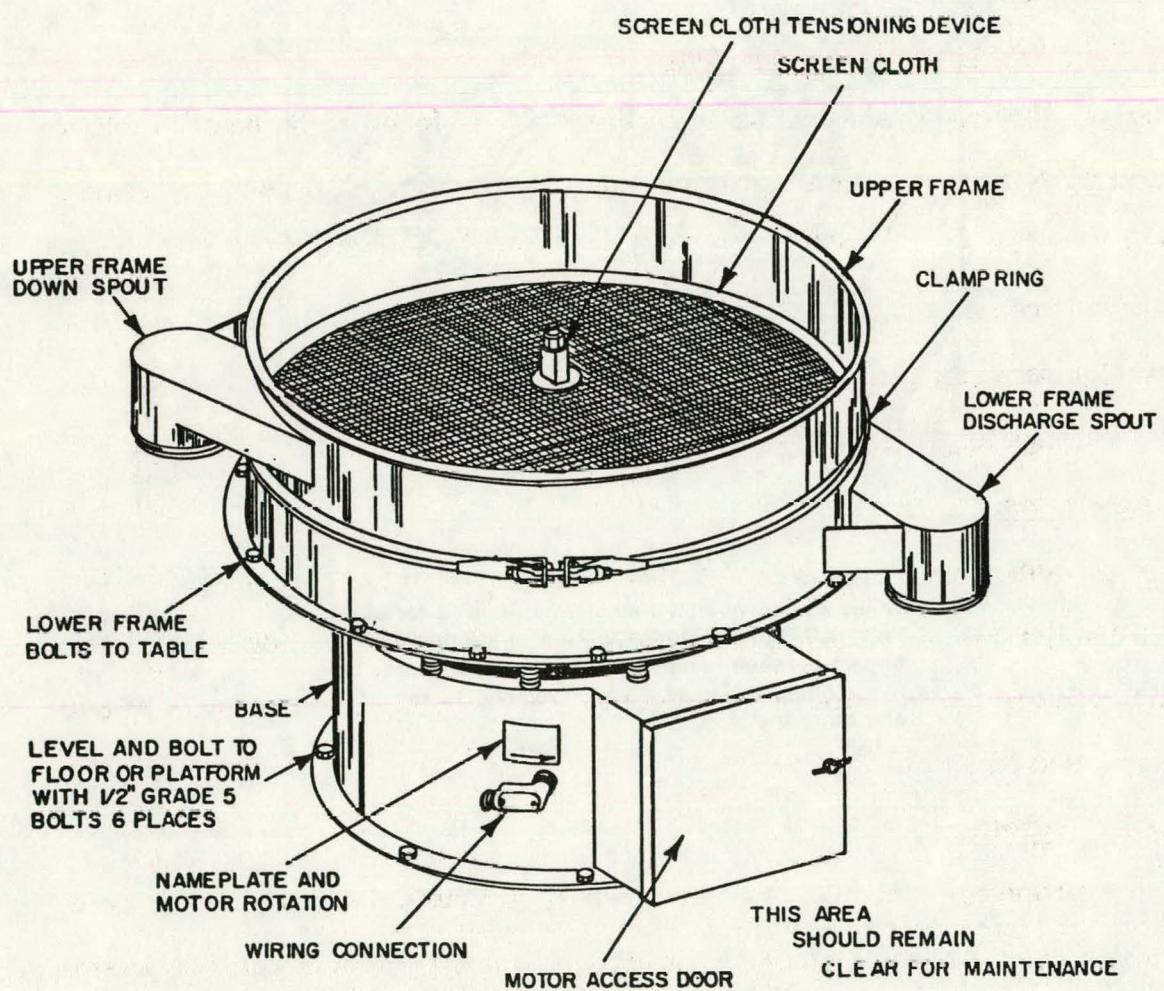
Figure 8.



When a nonreversible hammermill is used for attrition reduction, material is broken down first by impact between hammers and material and then by a scrubbing action of material against screen bars and other material.

Hammermill Crusher

Figure 9.

Midwestern Industries Screen Separator

01480

Figure 10.

3.1.6 Flexifeeder

An Automatic Industrial Machinery, Inc., Flexifeeder (Figure 11) was installed to load coal from the ground level to the top of the coal hopper. Now coal can easily be loaded during a run and an automatic level gauge shuts off the feeder when the coal hopper is full. This has put behind us the bucket brigade and ladder routine of Phase 1.

Other system modifications included:

3.1.7 Thermolectron Gas Analyzer

The gas chromatograph purchased in Phase 2 was found to be nearly useless for measuring NO_x levels. We were able to replace this with a company owned Thermolectron Emissions analyzer for the duration of Phase 2. This system has the ability to measure SO_2 and NO_x simultaneously and continuously. A Lynn Products Company oxygen analyzer was purchased to allow us to correct the indicated readings for excess air.

3.1.8 Blower

A redundant blower was added to the char burner feed system so that the pyrolyzer and the char burner could be operated independently. A side benefit was the ability to keep the char transport line clear when cooling the char burner beds after completion of a run.

3.1.9 Controller

A proportioning controller and electrically actuated butterfly valve were added to the char burner combustion air line. This system maintains a preset temperature in the char burner combustion bed. This task had previously been a full time job for one person. The controller tends to over react to changes in temperature in the bed producing moderate swings in combustion air flow. There

The basic system for low-cost conveying: the Round Spiral.

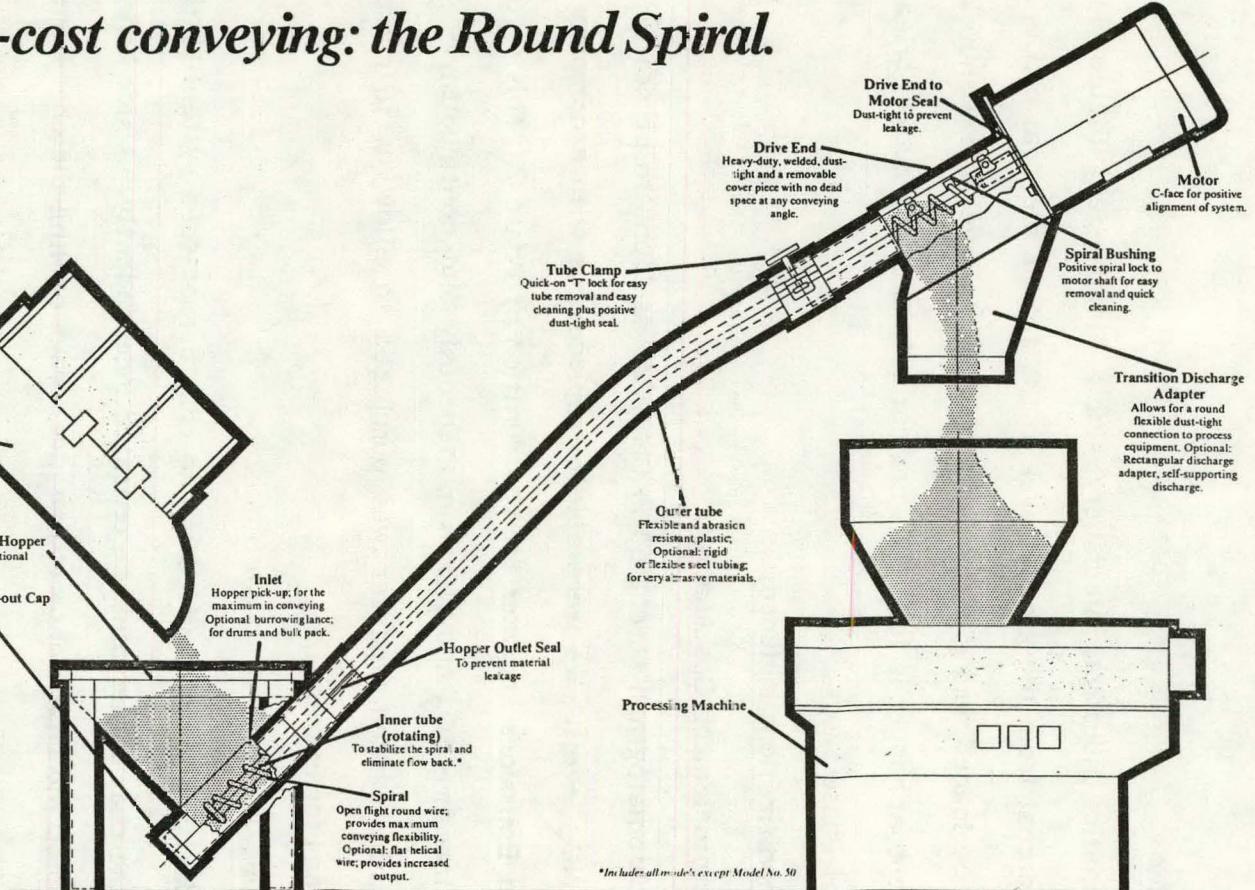
The Round Spiral System is the all-purpose conveyor for a wide range of materials. It is faster than belt, screw or bucket systems; gentler than vacuum or pneumatic conveyors. And it is completely sealed and fabricated to meet OSHA and USDA requirements.

The table below gives the Round Spiral's conveying capacity for all models.

Model No.	Optimum Tube Size (diameter)	Motor Rating (H.P.)	Maximum Unit Length** (in feet)	Minimum Radius of Tube Bend (in feet)	Maximum Particle Size (in inches)	Conveying Capacity (cu ft/hr)
50	1 1/2"	1	20	3	1/8	10
100	2"	1 1/2	30	4	1/4	25
200	2 1/2"	2	30	5	3/8	50
300	3"	3	30	10	3/8	100
400	4"	5-7 1/2	40-60	25	1	250

*Rate calculated on free-flowing material at 40 lb/cu. ft. Testing is recommended for verification.

**Longer systems available by connecting multiple units in series.



*Includes all models except Model No. 50

THE FLEXIFEEDER SYSTEM

Automatic Industrial Machines, Inc.

FIGURE 11.

were no discernible undesirable effects from these swings but a desensitized control mode should be investigated in future work.

3.1.10 Alarm

All of the important readouts were rewired so that if any exceeded setpoint, an alarm bell would ring.

3.1.11 Preheat burner

A larger preheat burner that was more dependable and easier to light was installed in the pyrolyzer. This burner was installed, like the one it replaced, above the cone section of the pyrolyzer (figure 34) as there simply wasn't room to install a burner at the cone entrance. The preheat time could be further reduced if the preheat burner were firing into the bottom of the cone and this could be a useful future modification. The current arrangement was quite satisfactory for the testing program of Phase 2.

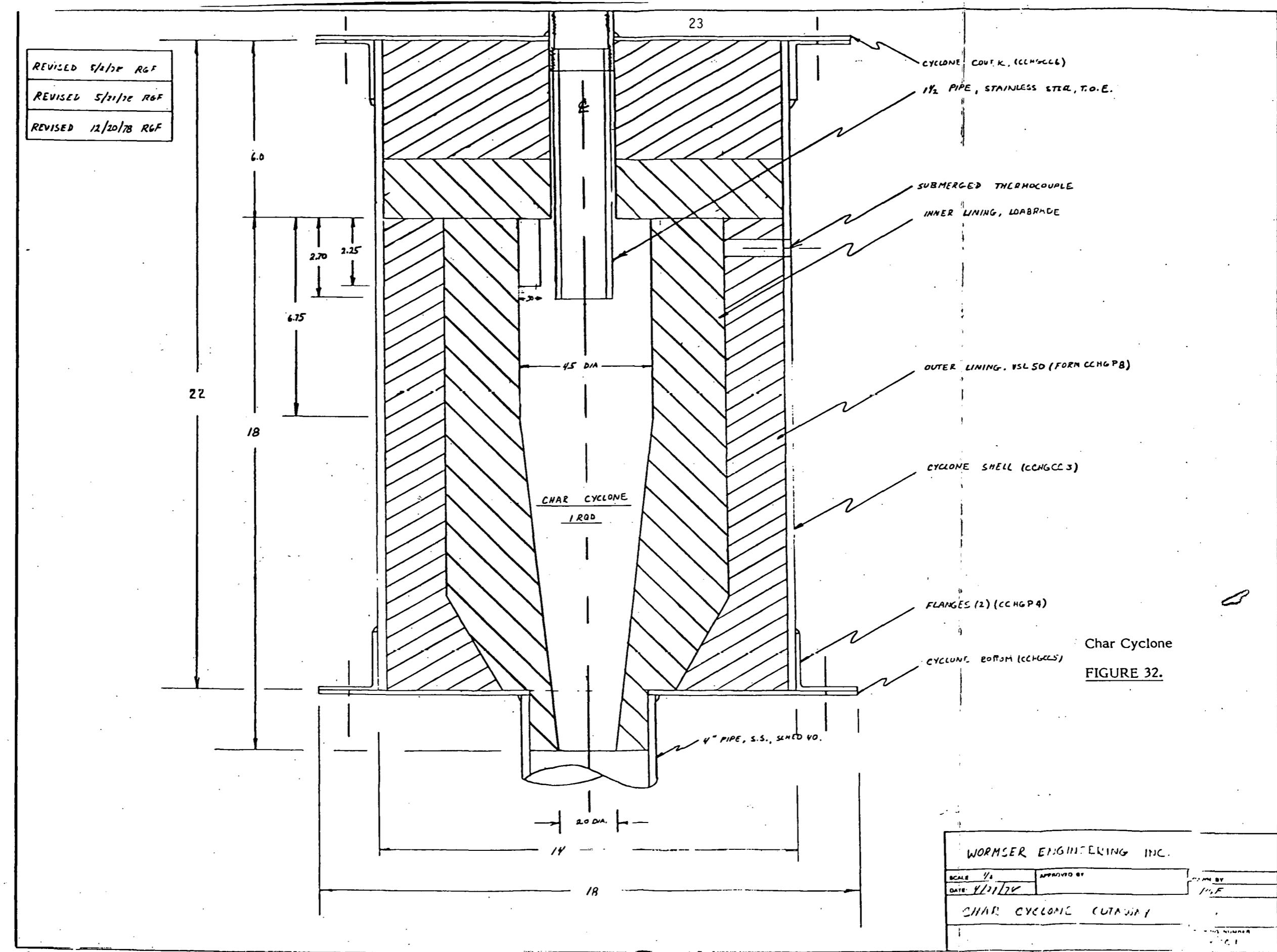
3.1.12 Char Drum

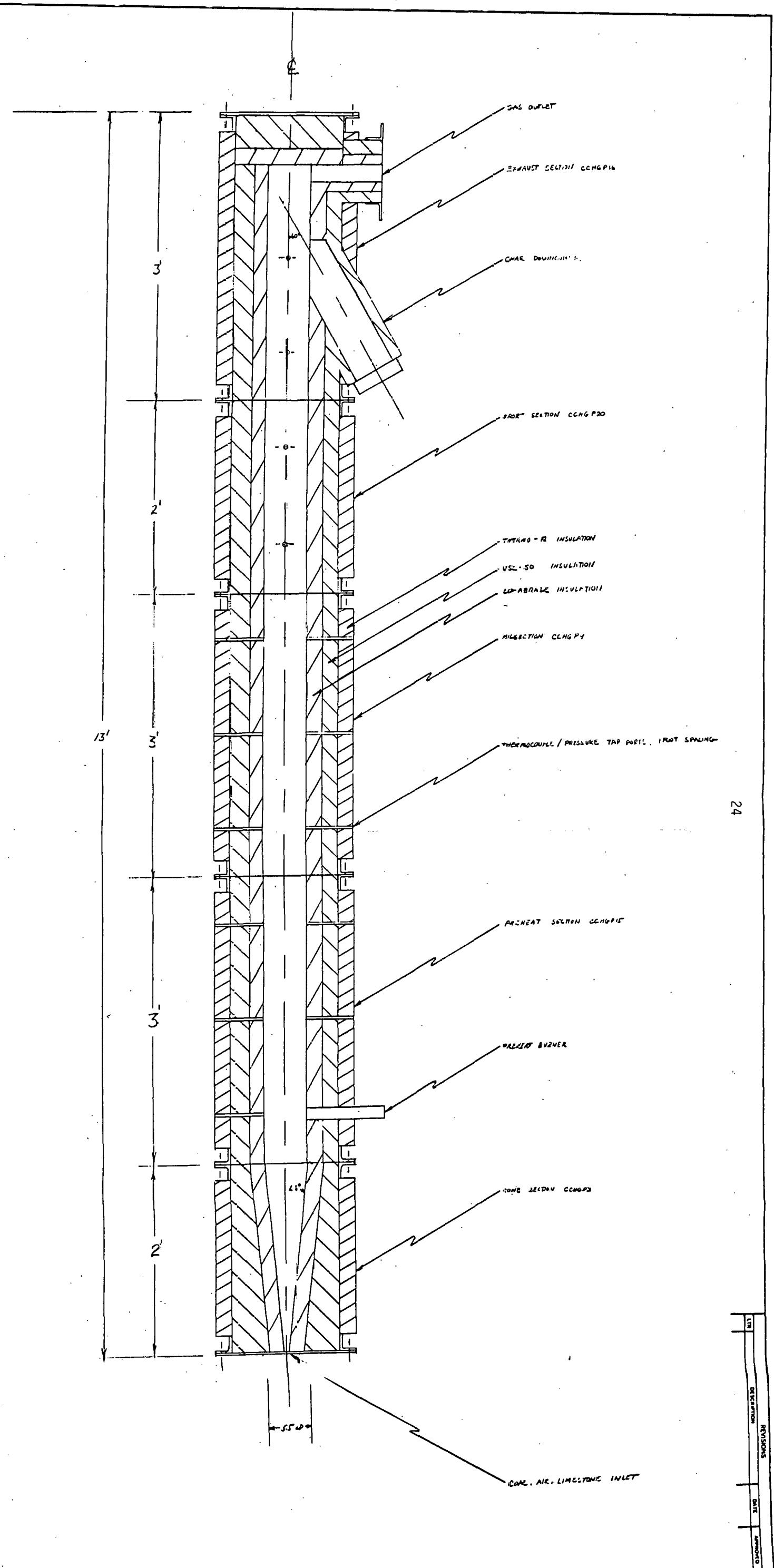
A 55 gallon drum was sealed and flanged so that it could be connected to the char downcomer when the pyrolyzer was being tested by itself for devolitization of various types of coal at various temperatures.

3.1.13 Additional Char Cyclone

A second char cyclone was constructed and installed downstream of the first. It was constructed to be internally identical to the first (Figure 32). However, unlike the first, it has smoother internal surfaces of stainless steel which are externally insulated, whereas the first has cast surfaces of hard refractory. As the first one is more heavily loaded with solids than the second, and also rougher internally than the second, it is likely that the efficiency of the second is greater. We have assumed that they both have the same collection efficiency, allowing us to make a conservative estimate of the overall collection efficiency of the two in series.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK





COHOGG Pyrolyzer Cutaway

WORMS IN INSECTICIDE	
100 ml.	100 g.
0.0001	0.0001
0.001	0.001
0.01	0.01
0.1	0.1
1.0	1.0
10.0	10.0
100.0	100.0
1000.0	1000.0

3.2 Summary List of Task 7. Results To Date

<u>Item Description</u>	<u>Contract Goals</u>	<u>Cohogg Test Results</u>
SO ₂ System retention	Minimum of 70%	95% with Ca/S of 2.5
NO _x generation	Max. of 300 ppm at char burner exit	550 ppm (total NO _x) average at afterburner exit for 24 hour run (*1)
CaS conversion efficiency	minimum of 98%	98% + (*2)
Cyclone efficiency	minimum of 95%	98% with two cyclones
Carbon utilization efficiency	minimum of 90%	98% on 1800° F char burner temperature test
Range of FSI coals with which system can operate	none	Full range; FSI of 1-8.5
Turndown Ratio	none	5.5:1

(*1) 550 ppm NO_x (.66 lb/million BTU) is the overall system NO_x level measured at the afterburner exhaust. The bench model Cohogg layout was not arranged to allow NO_x measurement at the char burner exit.

(*2) Results from the char burner temperature tests indicate that CaS in the lower bed was well under 1% at the end of the runs. The 24 hour run should show similar results.

3.3 Task 7: Testing

3.3.1 Calibration of Materials Handling System Modifications

Coal and sorbent feeders were calibrated at many different feed rates to generate a calibration curve for each feed mechanism after installation of the rotary air locks. There was a significant improvement in the repeatability of the feed rates resulting from the isolation of the screw feeders from the fluctuations of the transport air pressure, against which they had been feeding originally.

3.3.2 Pyrolyzer Modeling

A clear Lexan model duplicating the internal shape of the pyrolyzer was made to simulate cold operation of the pyrolyzer including the solids and air transport systems. Answers were needed to two questions: how does the limestone behave in the cone section during preheating of the pyrolyzer, and how much vertical mixing occurs during typical operation of the pyrolyzer when it contains its steady state inventory of solids?

The preheat burner enters the pyrolyzer about 6 inches above the cone exit (See figure 34). The startup procedure is as follows: the preheat burner is lit and, after the preheat section of the pyrolyzer reaches about 1400°F and the exit duct reaches about 700°F (about 3/4 hour), limestone feed is initiated. From observing the lexan model, and from experience during subsequent preheatings, it became apparent how to vary the transport air flow rate as the solids inventory of the pyrolyzer cone section increases. The aim is to cause the tumbling of the limestone in the cone section to both reach the preheat burner and also the bottom of the cone, thereby transferring the heat down to the cone. When the cone section reaches about 1100°F , coal feed is initiated and the run is officially started.

With the pyrolyzer at its steady state compliment of solids for various superficial velocities, it was found that vertical mixing was much less than we had anticipated. The solids moved in slugs of from two inches to two feet in height and any given particle might move as much as six inches to a foot in height as these slugs passed it by. However, relative motion between particles was slight. Only in the cone section was there vertical mixing. It seems, therefore, that a particle entering the pyrolyzer at the bottom during typical operating conditions gradually moves upward in a predictable stepwise motion after passing through the cone.

3.3.3 Pyrolyzer temperature variation tests

The pyrolyzer was operated on Illinois #6 coal (for properties see Table 2) over a range of temperatures to study the effect of pyrolyzer operating temperatures on devolatilization. A similar coal feed rate was used for all seven runs. The various operating temperatures were achieved by varying the combustion/transport air flow from one run to the next. Other operating conditions were held constant.

The devolatilization testing versus temperature curves of figure 12 shows four lines. The top curve is the moisture/ash free devolatilization measured by weight loss. The project goal is 57% devolatilization at not more than 15% stoichiometric air. Note that over the temperature range of 1400⁰F to 1600⁰F devolatilization well exceeds this value. The second curve shows devolatilization measured as the weight loss from the as fed coal to the resulting char. This curve includes the moisture and ash content of the coal and the ash content of the char. The third curve shows devolatilization less the percent combusted by the pyrolyzer combustion/transport air. This curve compares reasonably well with the lower curve generated by the USBM prediction equations for these test conditions. The USBM prediction equations are shown in Table 1.

- Prediction equations for entrained-bed carbonization of coals¹

TABLE I.

Equations ²	s^3	DF ⁴	Correlation coefficients	
			R_b^5	R_c^6
(1) Devolatilization of coal, pct, as carbonized: $D = 15.6 + 0.26(V_1) + 4.1(T/100)$ $- 0.048(K/100)^3 + 0.12(L/10)^4 \dots \dots \dots$	4.52	59	0.937	0.328
(2) Volatile matter in char, pct, mf basis: $V_2 = 3.67(V_1) - 4.1(V_1/10)^2 - 1.47(M)$ $+ 0.068(M)^2 - 8.8(T/100)$ $+ 0.26(T/100)^2 + 0.9(K/100) \dots \dots \dots$	2.33	34	0.964	0.425
(3) Carbonization temperature, ° F: $T = 1,672 + 2.2(V_1/10)^3 - 36.6(V_2)$ $+ 0.704(V_2)^2 - 144.8(R) + 15.46(R)^2$ $- 0.43(R)^3 \dots \dots \dots$	39.7	57	0.976	0.334
(4) Air-to-coal ratio, scf/lb of as-carbonized coal: $R = 12.6 + 0.006(M)^2 + 0.0022(T/100)^3$ $- 0.58(V_2) + 0.41(V_2/10)^3 \dots \dots \dots$	0.912	59	0.957	0.328
(5) Yield of char, pct of feed coal: $Y = 0.1035(V_1)^2 - 1.92(V_1/10)^3 - 0.6(M)$ $- 3.3(T/100) + 10.47(L) - 0.515(L)^2$ $+ 7.56(L/10)^3 \dots \dots \dots$	4.69	34	0.983	0.425

¹These equations are considered to be "most likely to be useful." Additional "satisfactory" equations, of major usefulness in special circumstances, appear in table A-3.

²Units and definitions:

D = Devolatilization of coal, percent reduction of volatile matter in coal feed.

V_1 = Volatile matter content of coal, percent, as-fed basis.

M = Moisture content of coal, percent, as-fed basis.

T = Temperature of carbonization, ° F.

K = Coal feed rate, pounds per hour of as-fed coal.

L = Reactor length, feet

V_2 = Volatile matter content of char, percent, moisture-free basis.

R = Air-to-coal ratio, standard cubic feet per pound, as-fed basis.

Y = Yield of char, percent of coal, as-fed basis.

³Estimated standard deviation.

⁴Residual degrees of freedom used to determine correlation coefficients.

⁵Multiple correlation coefficient.

⁶Critical correlation coefficient at the 99-pct confidence level.

Comparisons between the calculated (equations in table 3) and experimental data for the same parameters, using carbonization tests not included in the computation of the equations, are shown in table 4.

TABLE I.

COAL TYPES FOR
TEST PROGRAM BASED
ON R.E.I. STUDY

SEAM	RANK	STATE	% MOISTURE	% ASH	VOLATILE MATTER	FIXED CARBON	% SULFUR	BTU	ASH SOFTENING TEMP	F.S.I.	GRINDABILITY	AGGLOMERATE	RUN
RES. ENG HIGH (90% U.S. COALS)	—	—	31.7	18.85	44.8/45.9	4.42	14,760	2860	8	102	—	—	29
RES. ENG LOW (90% U.S. COALS)	—	—	1.3	7.72	7.09/84.6	.54	10,812	1985	1	44	—	—	
POCAHONTAS	L.V.B.	W. VA.	3.1	13	14.8/69.1	.57	13,763	2860	8.5	102	✓	✓	
"SHOE"	M.V.B	W. VA.	6.83	10.15	23.8/60	.64	12,745	2075	6		✓	✓	
ELKHORN #3	H.V.A.B.	Ken-tucky	8.5	4.9	37.9/58.2	.60	14,500	2650	3	44	✓	✓	
ILL #6	Sub.Bit. A	Ill.	4.2	11.61	37.9/57.8	4	11,268	2185	1			✓	
RANGE TESTED	L.V.B.	—	8.5	13	37.9	4	14,500	2860	8	102	—	—	
	Sub.A.	—	3.1	4.9	14.8	.57	11,268	2075	1	44	—	—	

TABLE 2.

As would be expected, the trend was for greater devolatilization at higher operating temperatures (Figure 12) with an apparent exception at around 1300°F. Devolatilization at 1300°F to 1325°F did not follow the expected curve and two extra runs were done at these temperatures in an effort to determine why. The low operating temperatures of the cyclone (600°F) during these low temperature runs makes it likely that condensation occurred on the walls of the char cyclone (there was only one in operation at this time) causing some char to be lost to the afterburner resulting in the optimistic devolatilization figures. Direct observation of the volatiles condensed on the cyclone walls was not deemed practical as this would entail major disassembly of the system and require a great deal of time. However, it has been found that during preheating prior to a typical run, any previously condensed material is removed from the entire system, allowing the cyclone to perform normally during subsequent runs at higher temperatures. It seems unlikely that there would ever be motivation to operate the pyrolyzer at 1300°F, but even if there were, this condensation is likely a peculiarity of our bench model, with its high surface to volume ratio contributing to the low cyclone temperature, and is not relevant to a scaled up system.

The percentage stoichiometric air versus temperature curve (figure 13) shows a higher percentage being required for higher temperatures. The project goal was not to exceed 15%; however, additional air is required in the bench model to overcome excessive heat losses through the vessel walls at the higher operating temperatures caused by the large surface-to-volume ratio in this small scale system.

The char-particle size distribution versus temperature curve (figure 14) shows no discernible trend in particle size while varying temperature in this range.

Figure 12.

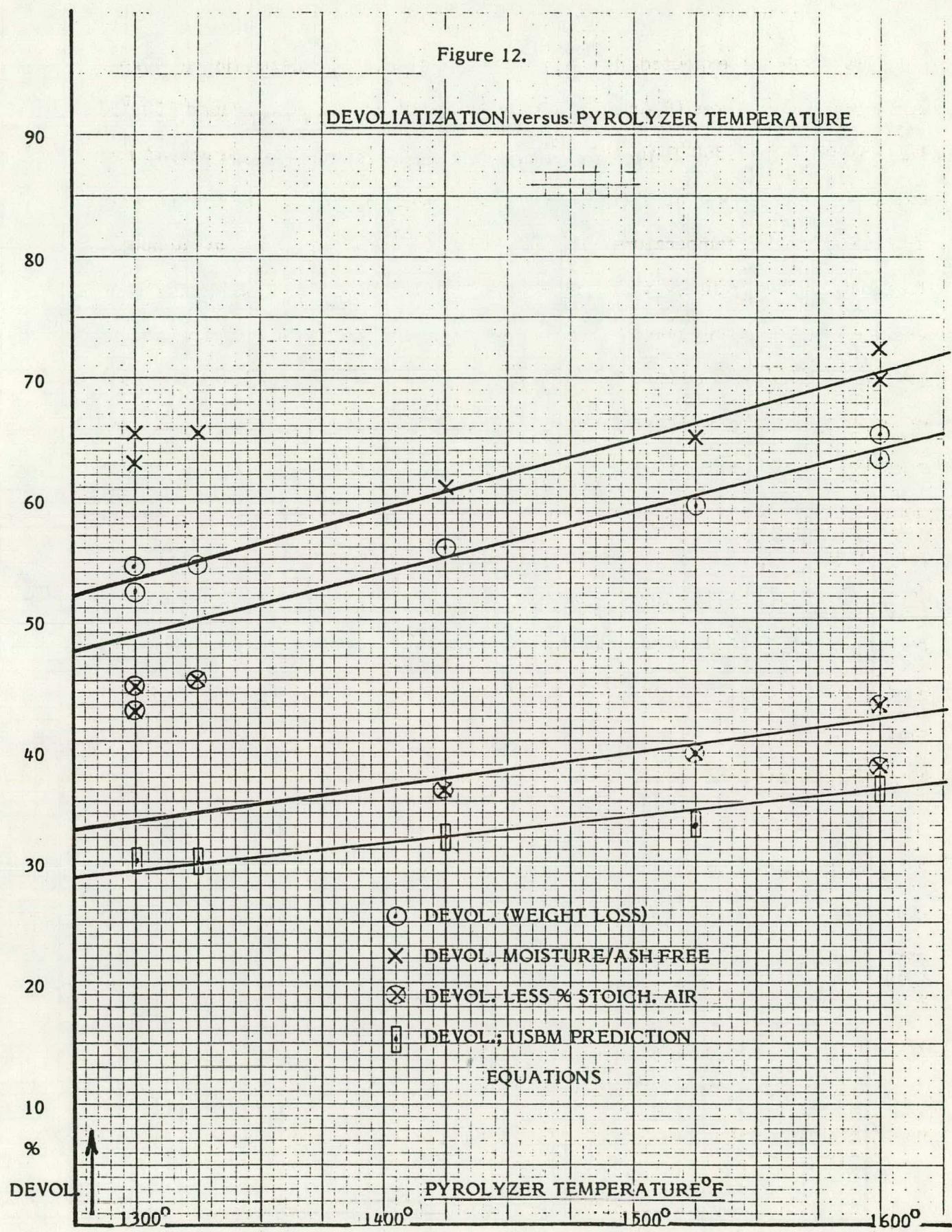
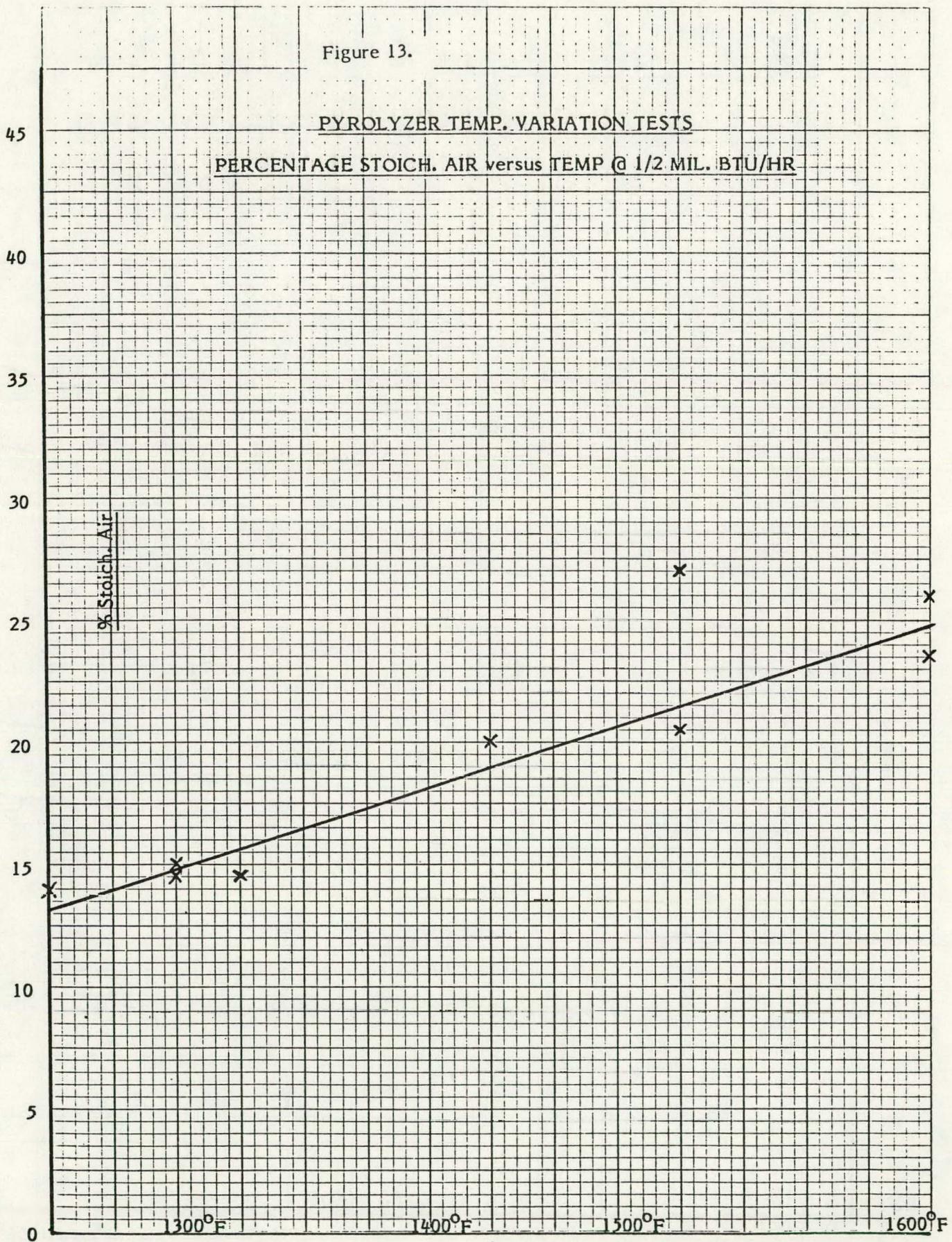
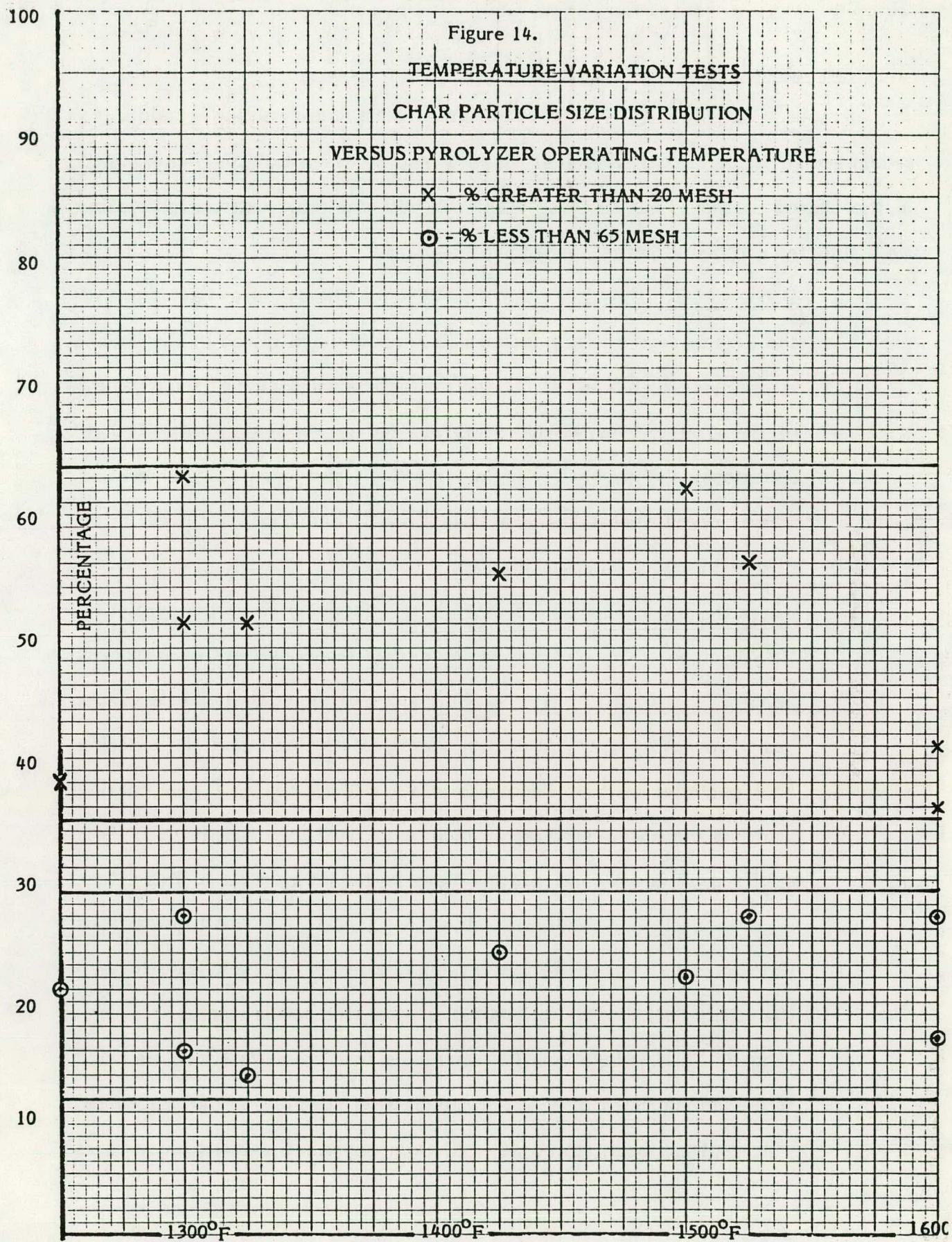


Figure 13.

PYROLYZER TEMP. VARIATION TESTS

PERCENTAGE STOICH. AIR versus TEMP @ 1/2 MIL. BTU/HR





3.3.4 Coal Types Tests

Resource Engineering, Inc. of Lexington, Massachusetts was retained to recommend a series of coal types that would be representative of coal being mined in the United States. Four of these (Table 2), with the most extreme properties were selected and tested in the Cohogg pyrolyzer.

- Pochahontas. This coal from West Virginia stands out as having one of the highest free swelling indexes (8.5) of any coal mined in the U.S.A. It also has a high % ash (13%) and the highest ash softening temperature of the group. When Pochahontas was fed into a small starter bed of limestone, the pyrolyzer agglomerated. However, no agglomeration was observed when this coal was fed into a column of char (the United States Bureau of Mines technique).
The apparent explanation is that as coal particles enter the pyrolyzer, they become sticky on being heated; their tendency towards stickiness being a function of the free swelling index of the coal. If the pyrolyzer has an inventory of dry particles, these particles will coat the entering coal particles as they become sticky on being heated. This coating protects them from sticking to each other until they pass through their sticky stage and become coating material for later arrivals. This effect is particularly important with high F.S.I. coals. The small quantity of limestone that was used for starting purposes was not adequate to keep the sticky Pochahontas coal particles separated during startup.
- "Shoe." This medium volatile bituminous coal from West Virginia has a free swelling index of 6 which required no special startup procedure. This coal has been stored at USM Company for the last twenty years

and represented a very low ash fusion point(2075°F) coal as well as being locally available.

- Elkhorn. This high volatile coal has a very high BTU value (14,500 BTU/lb). It also has the highest moisture content (8.5%) and the lowest ash content (4.9%) of any of the coals tested.
- Illinois #6. This high volatile coal (37.9% and very similar in this respect to Elkhorn), had the highest sulfur content (4%), and the lowest free swelling index (1) of any of the coal tested. This coal was used for much of the testing for Phase 2 and also for the 24 hour run.

3.3.5 Coal Size Distribution

The pyrolyzer was run with four different coal size distributions between $1/4''$ x $1/8''$ to $3/8''$ x 0 (as crushed) while other conditions remained constant. The devolatilization versus coal size chart (figure 15) shows no discernible trend in devolatilization for the size distributions studied. The percentage stoichiometric air versus screen size (figure 16) shows larger coal particles requiring more air to maintain the same operating temperature. The coal size distribution versus char particle size (figure 17) distribution curve shows char becoming smaller as coal feedstock becomes smaller (as expected).

3.3.6 Cyclone Efficiency

The bar graph showing efficiency for one cyclone and two cyclones in series versus coal screen size (figure 18) shows efficiency improving, if anything, as coal feed size gets smaller. Note the contract objective of 95% has been well exceeded by use of two cyclones. The chart was constructed assuming the efficiency of the two cyclones is the same. It is likely, however, that the second cyclone, having smoother inside surfaces, has a higher efficiency than the first. Figure 19 & 20

Figure 15.
PYROLYZER COAL SIZE DIST. TESTS

DEVOLITIZATION % VERSUS SCREEN SIZE
(WEIGHT LOSS)

60

50

40

30

% DEVOLATIZATION

1/4 x 1/8

1/4 x 20

1/4 x 0

3/8 x 0

CO
SI

Figure 16.

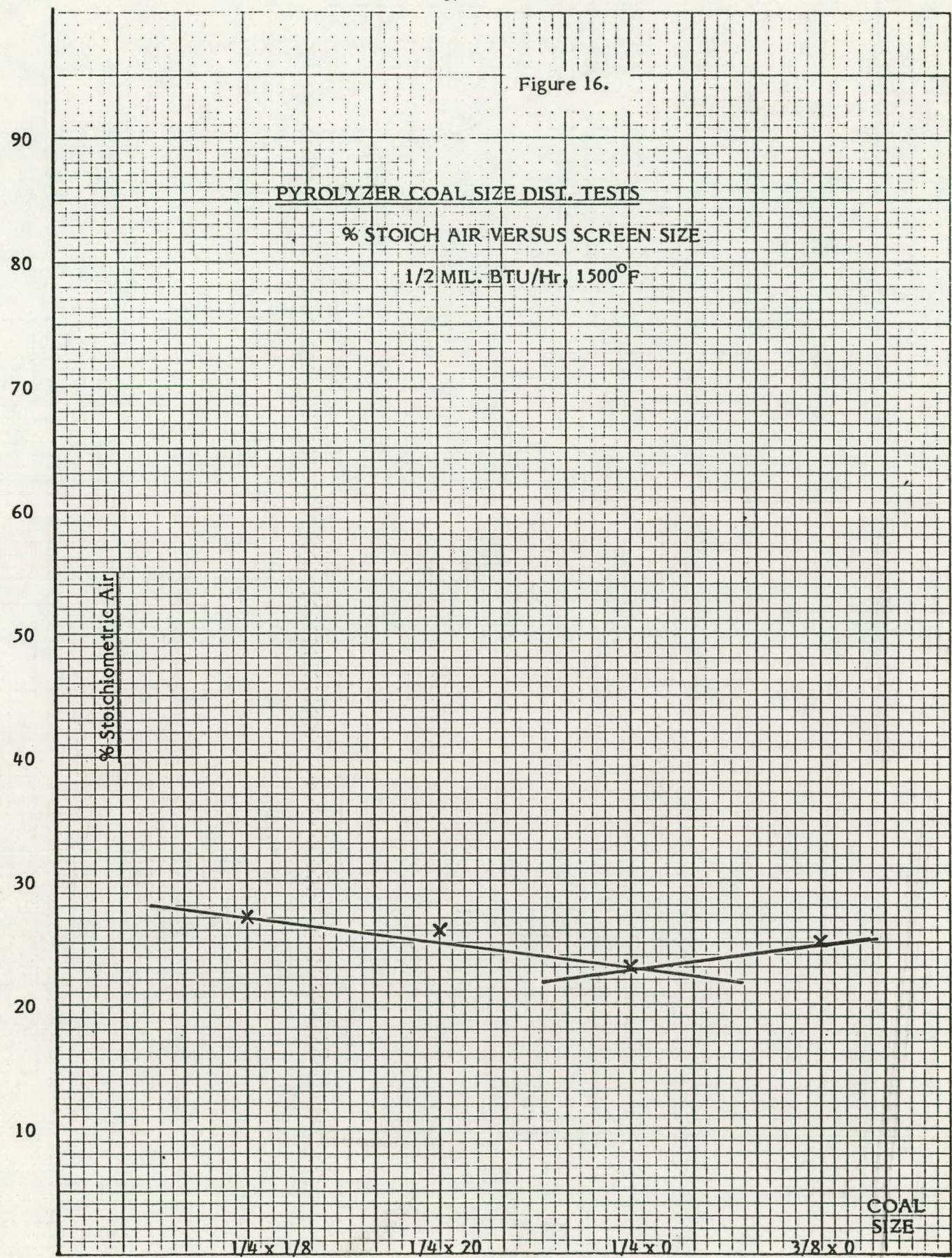


Figure 17.

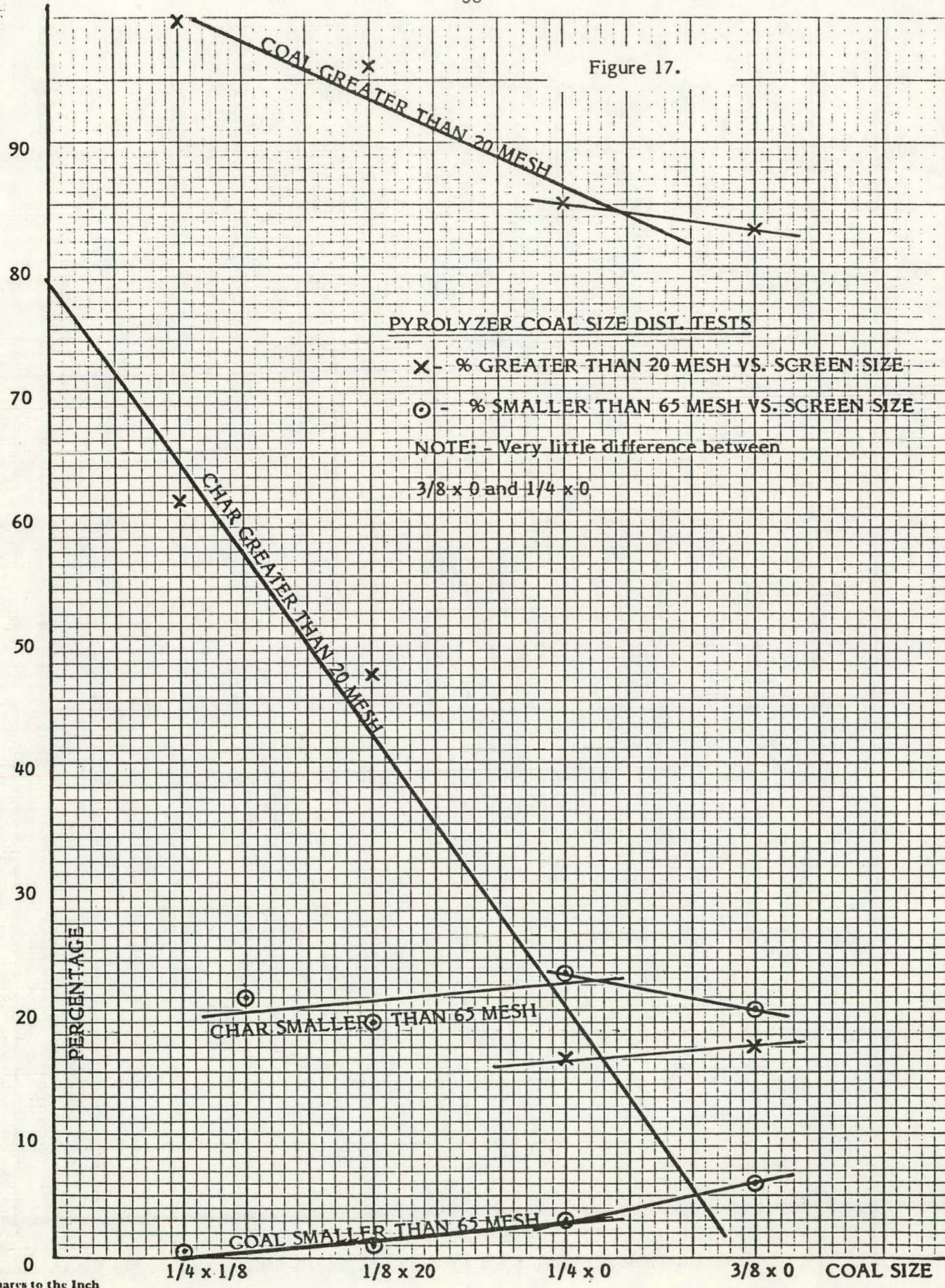
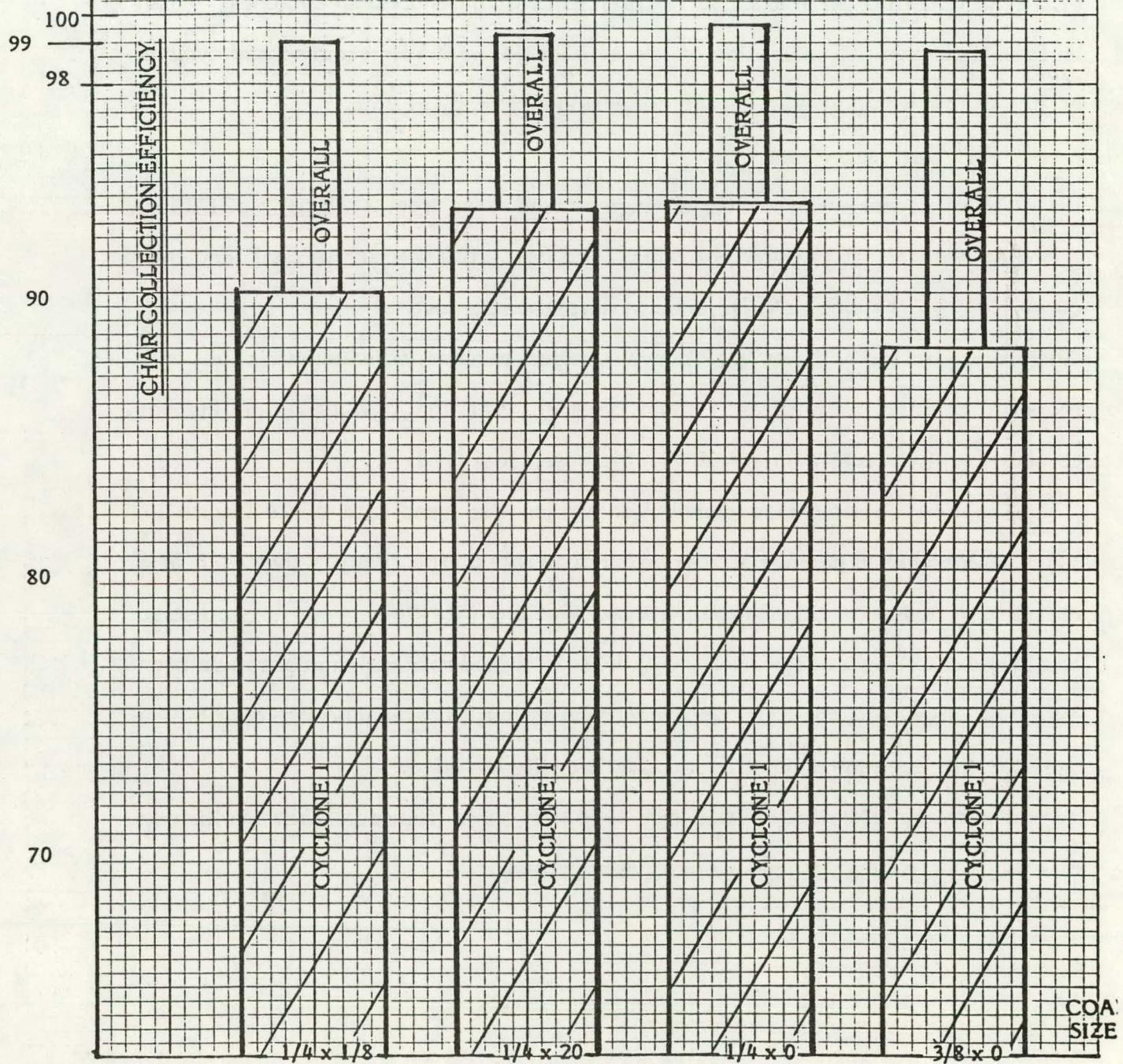


Figure 18.

PYROLYZER COAL SIZE DIST. TESTS

CYCLONE VS. SCREEN SIZE



show the size distributions of the char collected in the two cyclones. In Phase 1 the stack cooling spray water was collected in an attempt to measure the weight of the entrained char. The amount was insignificant. A similar attempt in Phase 2 gave the same result. Consequently, while it is not possible to attach a concrete number to the char collection efficiency without a closure on mass balance, the objective of 95% appears to have been easily met. Figure 21 shows the sensitivity of overall collection efficiency to the efficiency of the individual cyclones. It can be seen that even a combination of low efficiencies of the first and second cyclone of 80% & 75% would give an overall collection efficiency of 95%.

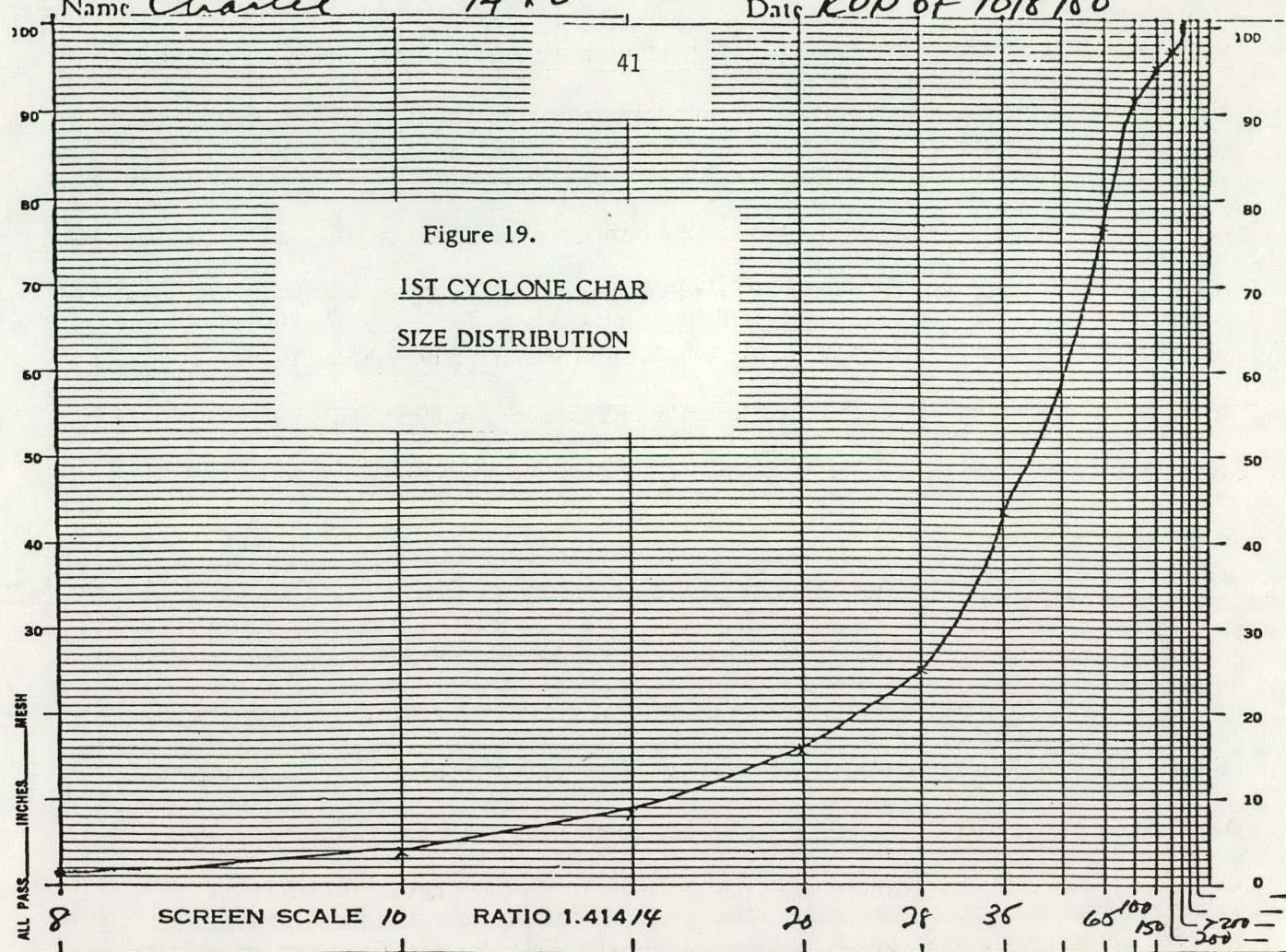
3.3.7 Turn Down Test

The pyrolyzer was run over a range of feed rates from 24 lb/hr to 131 lb/hr, giving an operational turndown of 5.5:1. The devolatization versus coal feed rate curve (figure 22) shows no difference in devolatization over the feed range tested. When one considers, however, that a smaller percent stoichiometric air was required at high feed rates, it can be seen that the devolatization (net of combustion air) actually improved with increased coal feed rate.

The char particle size distribution versus coal feed rate curve (figure 23) shows an increase in particle size at higher feed rates. This likely is the result of a decrease in residence time in the pyrolyzer - at any rate, there does not appear to be a trend of char size degradation with increased feed rate which might have been expected. However, the Tyler Screen method we use to determine size distribution does not do a good job on char as the char is easily abraided.

The cyclone efficiency versus coal feed rate curve (figure 24) shows collection efficiency increasing with gas velocity as expected.

Cumulative Direct Diagram of Screen Analysis on Sample of CHAR HOPPER
Name Charlie 1/4 x 0 Date RUN OF 10/18/80



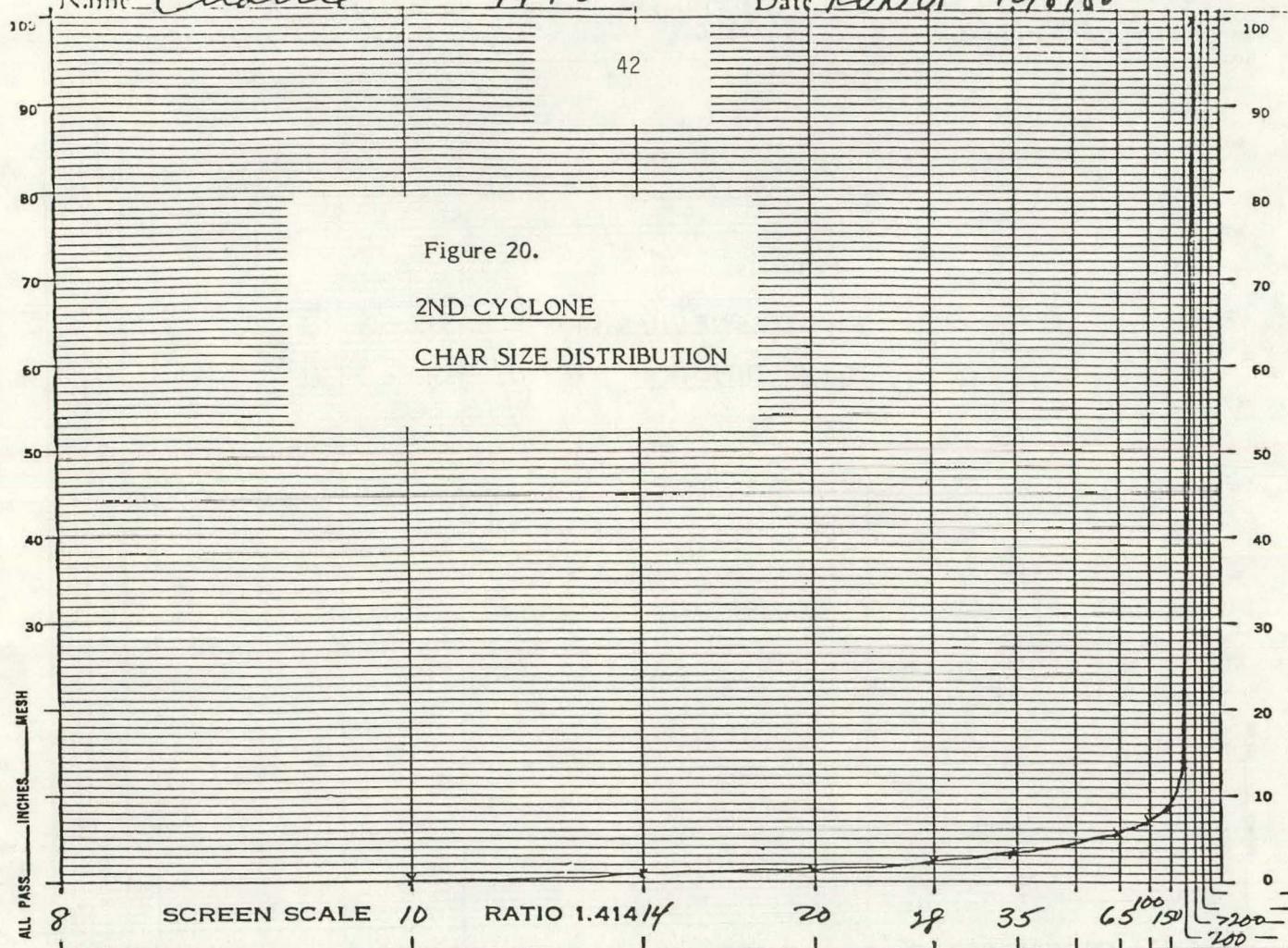
SCREEN SCALE RATIO 1.414												
Openings	Tyler Mesh	U. S. No.	Sample Weights	Per Cent	Per Cent Cumulative Weights	Sample Weights	Per Cent	Per Cent Cumulative Weights	Sample Weights	Per Cent	Per Cent Cumulative Weights	
Inches	Milli-meters											
1.050	26.67											
.742	18.85											
.525	13.33											
.371	9.423											
.263	6.680	3										
.185	4.699	4										
.131	3.327	6										
.093	2.362	8										
.065	1.651	10										
.046	1.168	14										
.0328	.833	20										
.0232	.589	28										
.0164	.417	35										
.0116	.295	48										
.0082	.208	65										
.0058	.147	100										
.0041	.104	150										
.0029	.074	200										
Pass	.074	>200										
			Totals.	32.4								

THE TYLER SCREEN AND SCREEN SCALE

Cumulative Direct Diagram of Screen Analysis on Sample of CHAR 2ND CYCLONEName Charlie

4440

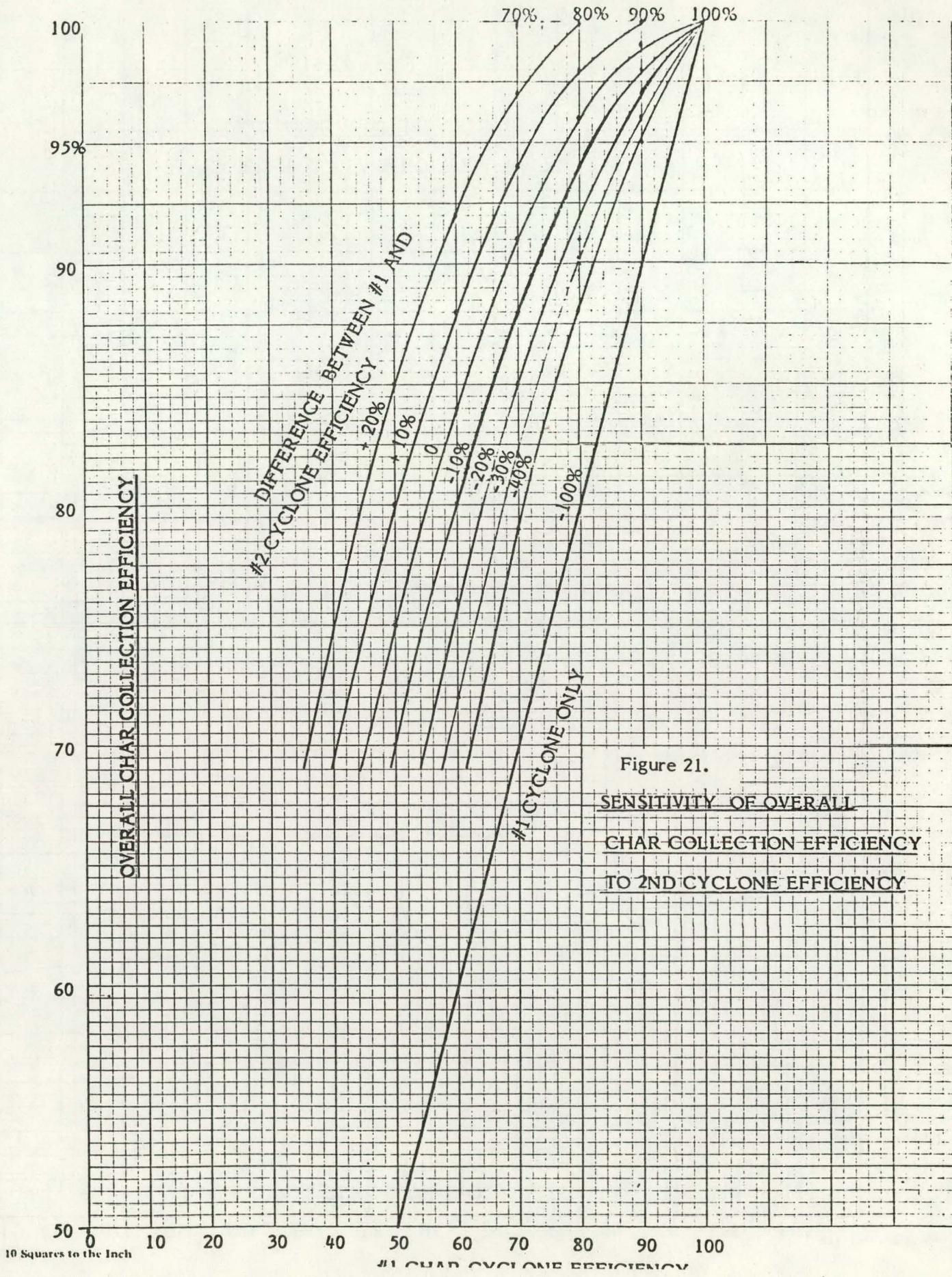
Date RUN OP 10/18/78



SCREEN SCALE RATIO 1.414												
Openings		Tyler Mesh	U. S. No.	Sample Weights	Per Cent	Per Cent Cumulative Weights	Sample Weights	Per Cent	Per Cent Cumulative Weights	Sample Weights	Per Cent	Per Cent Cumulative Weights
Inches	Milli-meters											
1.050	26.67											
.742	18.85											
.525	13.33											
.371	9.423											
.263	6.680	3										
.185	4.699	4	4									
.131	3.327	6	6									
.093	2.362	8	8									
.065	1.651	10	12	.1	.4	.4						
.046	1.168	14	16	.1	.4	.8						
.0328	.833	20	20	.2	.7	1.5						
.0232	.589	28	30	.3	1.1	2.6						
.0164	.417	35	40	.3	1.1	3.7						
.0116	.295	48	50									
.0082	.208	65	70	.5	1.9	5.6						
.0058	.147	100	100	.4	1.5	7.1						
.0041	.104	150	140	.4	1.5	8.6						
.0029	.074	200	200	1.3	4.8	13.4						
Pass	.0029	.074	200	> 200	23.2	86.0	99.4					
				Totals,	27.0							

3MM ON FINER

W. S. TYLER, INCORPORATED, MENTOR, OHIO, 44060 U. S. A.



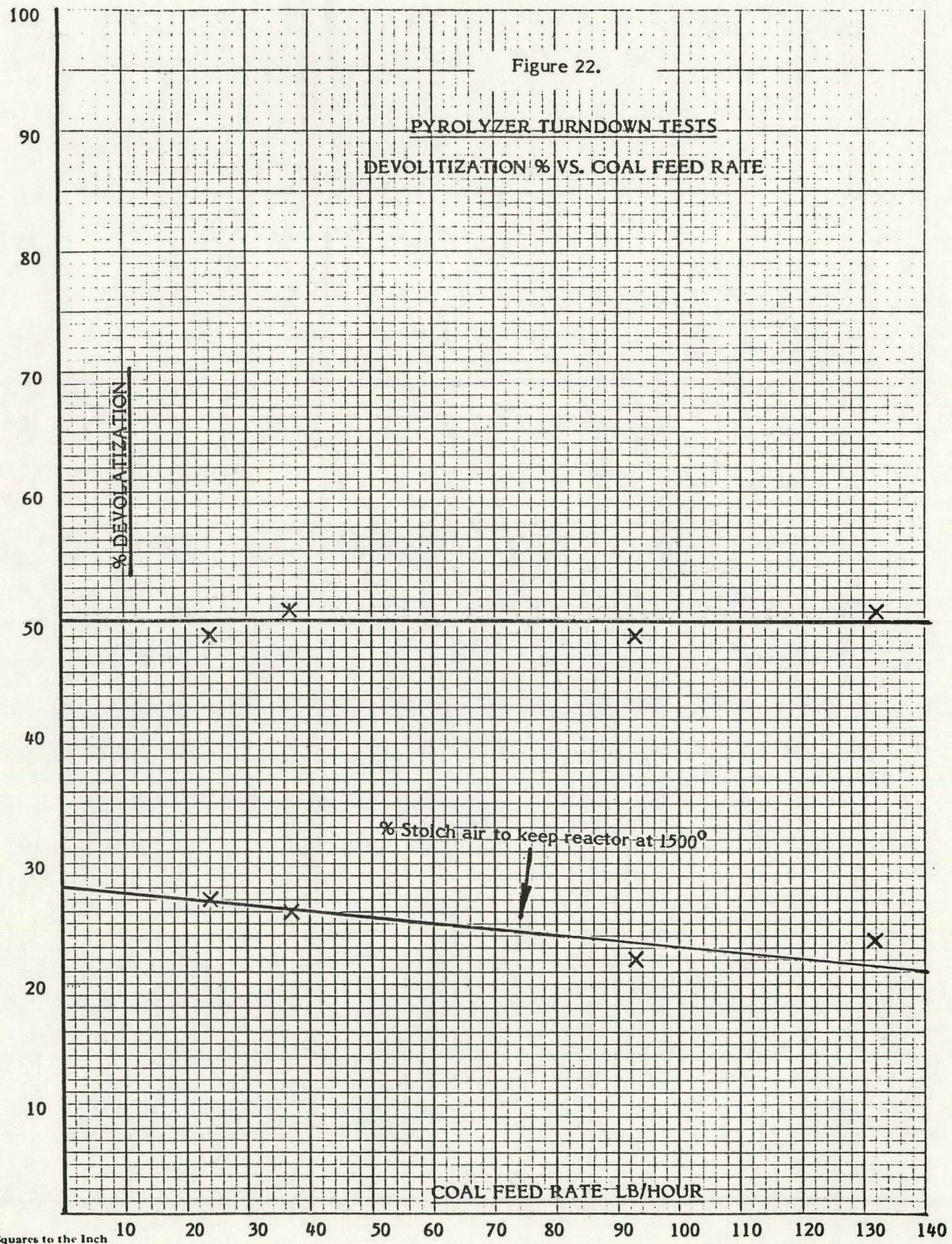


Figure 23.

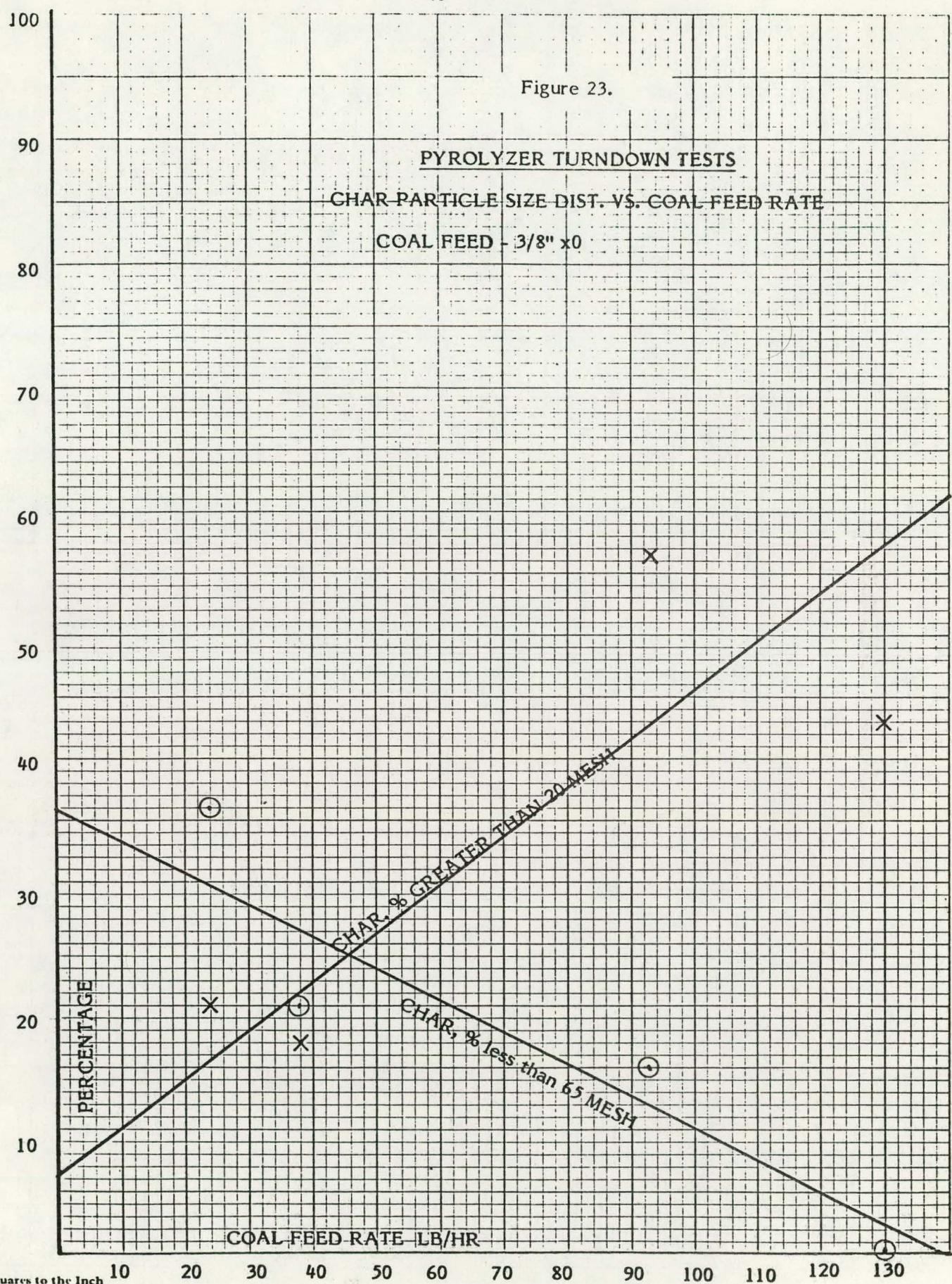
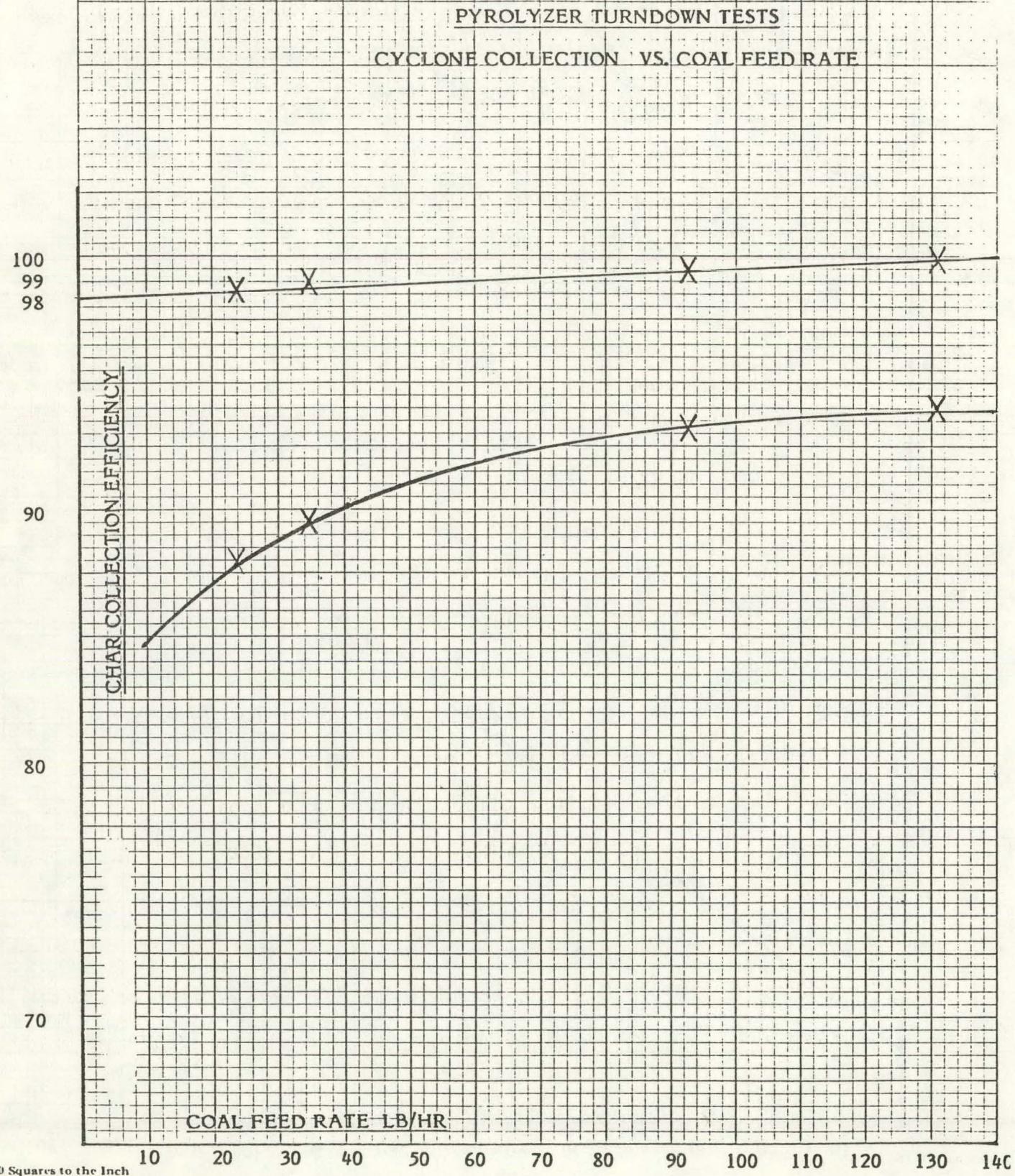


Figure 24.



3.3.8 Pyrolyzer Sorbent Tests

The pyrolyzer was run with four sorbent types to determine relative desulfurization efficiencies. The sorbent types were Tymochtee dolomite, Carey dolomite, Grove limestone and Union Maine limestone. Desulfurization efficiencies of 95% were recorded with Tymochtee at a calcium/sulfur ratio of 2.5.

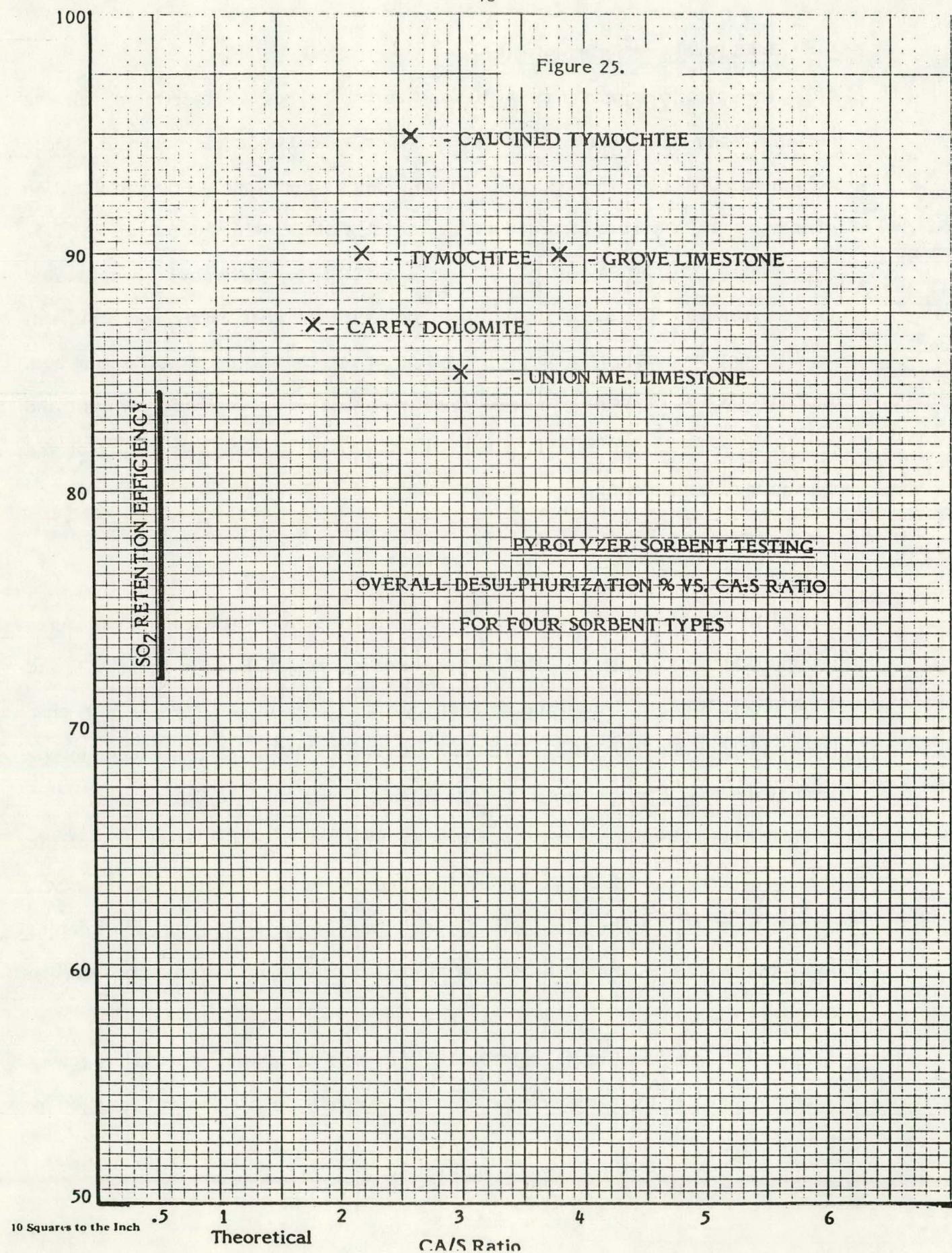
Figure 25 shows a plot of SO_2 retention with four different sorbents tested in the pyrolyzer. The actual system retention with the char burner operating will be different because of the scrubbing action of the char burner desulfurizing bed. Plotting the SO_2 retention versus Ca/S ratio calculated on coal sulfur content and pyrolyzer sorbent feed rate is a convenient way of showing the results of the pyrolyzer sorbent testing.

3.3.9 Char Burner Temperature Tests

The char burner combustion bed was operated at four different temperatures on four different occasions. The temperatures were 1600°F , 1700°F , 1800°F and 1900°F . Fresh raw Tymochtee dolomite sized (1/8" x 0) was used in both char burner beds at the start of each run and also fed to the pyrolyzer, except in the case of the 1800°F run, where 1/3 of the upper bed was calcined Tymochtee.

The purpose of these tests was to measure CaS conversion efficiency of the lower bed, carbon utilization of the char burner as a unit, as well as SO_2 retention and NO_x generation. With the exception of the 1800°F run, lab samples for these tests are not yet in, so trends in CaS conversion and unburned carbon cannot be shown.

Figure 26 shows the SO_2 retention efficiency and Figure 27 shows NO_x generation measured at the afterburner for each of the runs. The runs are identified by



COHOGG SORBENTS

TYPE FEED STOCK	CARBONATE RATIO	BULK DENSITY CARBONATE	OXIDE RATIO	THEO. BULK DENSITY OXIDE	SULFIDE RATIO	THE. BULK DENSITY SULFIDE	SULFATE RATIO	THEO. BULK DENSITY SULFATE	THEO. #5 SORBENT: #5 SULFUR 2X THEO	3X THEO	4X THEO	SIZE RANGE AS RUD	HARDNESS	ABRASION	PERCENTURE
UNION ME LIMESTONE (CARBONATES)	1	94.75	.578	54.77	.731	69.26	1.34	126.97	3.22	6.44	9.66	12.88			
CALCINED UNION (OXIDES)	1.73	94.75	1	54.77	1.27	69.56	2.35	128.71	1.80	3.6	5.4	7.2			
GRUVE LIMESTONE (CARBONATES)	1	93.75	.574	53.81	.724	67.68	1.34	125.63	3.28	6.56	9.84	13.2			
CALCINED GRUVE (OXIDES)	1.74	93.75	1	53.81	1.28	68.88	2.36	126.99	1.84	3.68	5.52	7.36			
CAREY DOLOMITE (CARBONATES)	1	82.75	.527	43.61	.614	50.81	1.959	79.36	5.78	11.56	17.34	23.12	6X16		
CALCINED CAREY (OXIDES)	1.89	82.75	1	43.61	1.16	50.59	1.77	77.19	3.24	6.48	9.72	12.96	—		
TYHOCHTEE DOLOMITE (CARBONATES)	1	80.75	.547	44.17	.625	50.47	1.963	77.76	6.03	12.06	18.09	24.12			
CALCINED TYHOCHTEE (OXIDES)	1.83	80.75	1	44.17	1.15	50.74	1.74	76.9	3.34	6.68	10.02	13.36			

TABLE 3.

their combustion bed temperature and as indicated in Figure 26 the upper bed was operated at different temperatures for each run. The Ca/S ratio for each run is in parenthesis and is the ratio of the total sorbent in both the char burner beds and that fed to the pyrolyzer (no sorbent was added to either bed during a run), compared to the sulfur content of the coal fed to the pyrolyzer. Table 3 shows the various ratios of sorbent to sulfur for a Ca/S ratio of one for various sorbents. As far as the char burner was concerned, these tests were batch tests of the beds so that SO_2 retention deteriorates with time as expected.

Each curve of Figure 26 represents the five hours of system operation after coal feed was initiated to the pyrolyzer. The curves are marked with an L and a U; the L indicates the time at which the lower bed attained the intended temperature, and the U indicates the time at which the upper bed reached its intended temperature. The automatic controller maintained the combustion bed at its run temperature, and a secondary air supply entering below the upper bed cooled the upper bed if necessary to maintain it at the intended temperature. During the 1600°F run, the upper bed was at 1400°F for some part of the run (2½ hours) and then rose to 1500°F for the latter part. Two U's indicate these two points.

There tended to be some upper bed temperature fluctuations of 25° or so up and down from the intended temperature. What with the runs being relatively short and there being some differences in the character of each run, it is difficult to draw many conclusions from these curves. However, there seems to be a trend toward better SO_2 retention at low upper bed temperatures for the Tymochtee. The 1700°F run consistently had the lowest upper bed temperatures by a small margin and had the best SO_2 retention overall. The Ca/S ratio of the 1600°F run of 4.5 and the 1700°F run of very nearly the same upper bed temperature seems to

CHAR BURNER TEMPERATURE TESTS BATCH BED SO₂ RETENTION

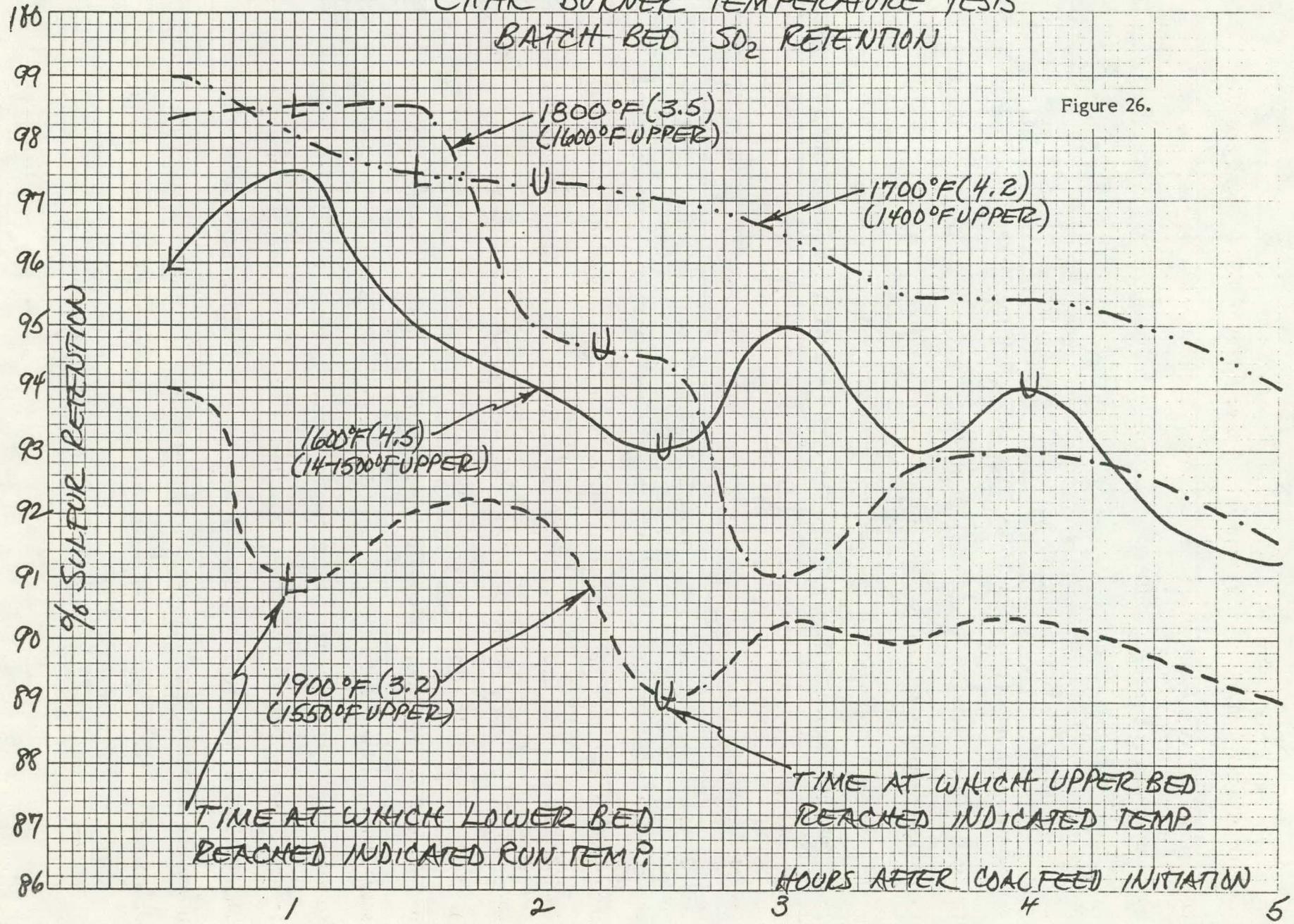
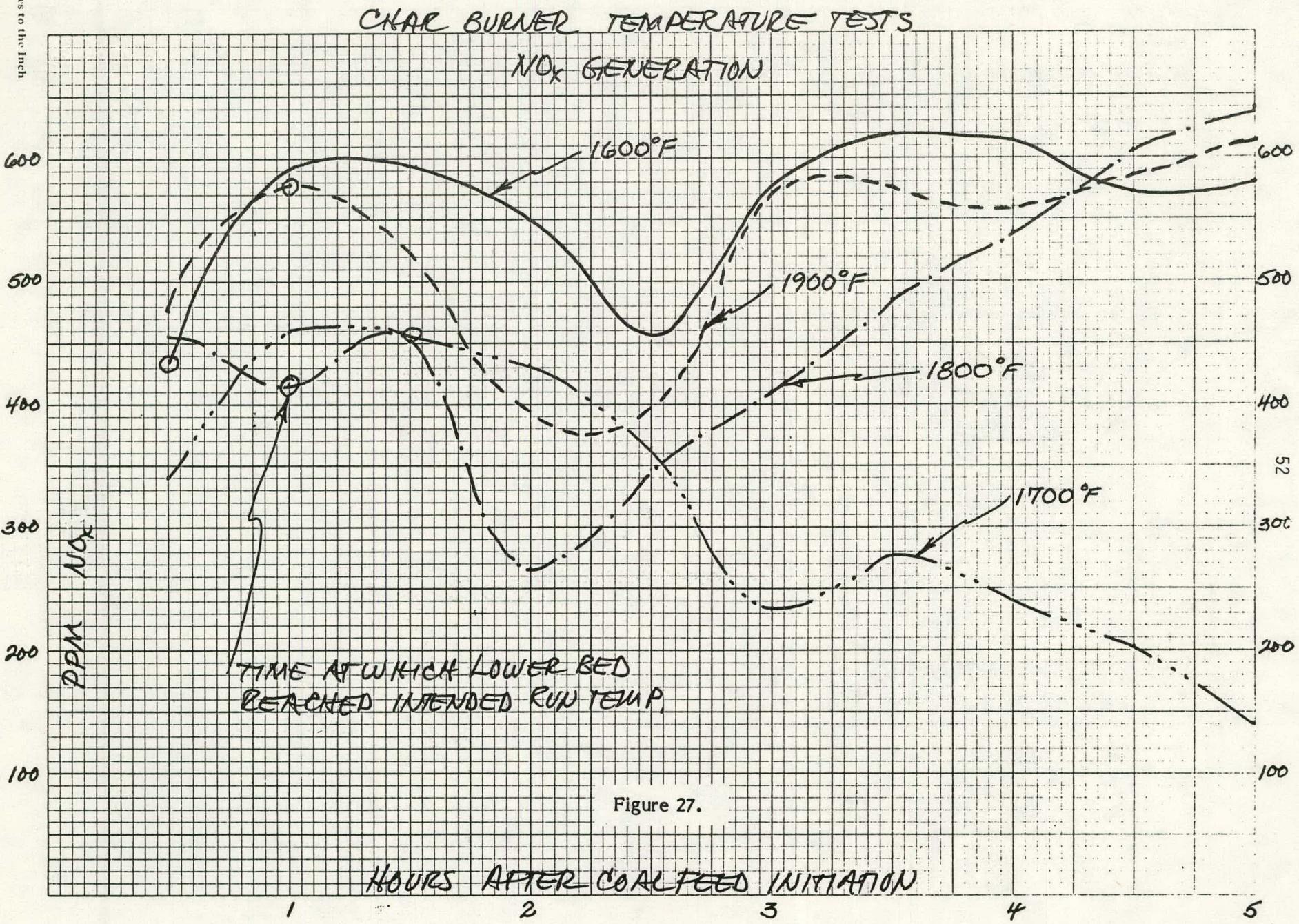


Figure 26.



follow the same rate of deterioration in SO_2 retention, but at a lower % SO_2 retention throughout. Why these two curves are not more nearly the same is not clear. The 1800°F run had the benefit of 1/3 of its upper bed being calcined before the start of the run which may explain the good SO_2 retention at its start.

There seems to be little correlation between other variables such as the effect of lower bed temperature on SO_2 retention or NO_x generation (Figure 27). Three of the four curves of Figure 27 show the NO_x generation to be remarkably similar over the temperature range. The vacuum pump associated with the NO_x analyzer began to fail during the 1700°F run which caused the calibration to shift resulting in this apparently optimistic curve.

The lab results for the temperature test series (Tables 4-7) show less than .1% CaS in the lower bed at the end of the five hours during which CaS was being generated and delivered along with the char from the pyrolyzer to the char burner lower bed. The unburned carbon in the char burner ash was less than 3.05% of the material collected, which represents a carbon utilization efficiency in excess of 99% for all four runs.

3.3.10 24 Hour Run

The 24 hour run was a major undertaking requiring around-the-clock monitoring and periodic sample taking, solids weighing, bin filling, SO_2 , and NO_x readings. The material collected in the ash cyclone hopper, the second cyclone char hopper, and the sorbent recirculation hopper were all weighed and sampled every 4 hours. The sorbent recirculation hopper material was added to the pyrolyzer sorbent hopper after each 4 hour period. The char burner upper bed was sampled by letting



Resource Engineering Incorporated

80 Bacon Street, Waltham, Massachusetts 02154 (617) 894-6720

February 27, 1981

ANALYSIS REPORT

YOUR PURCHASE ORDER #P.O. #3348

SAMPLE RECEIVED - 1/19/81

(1600°F)

ANALYSIS REPORT #RA-203

RECEIVED FROM: Mr. Charles Lowell
Wormser Engineering
212 S. Main
Middleton, MA 01949

Sample	%Sulfide	%Sulfate	%CO ₂	%Ca	%C _{total}	%Cunburned*
Upper Bed 1/13/81	< .005	3.02	2.18	32.8	---	---
Lower Bed 1/13/81	.019	15.70	1.71	29.1	---	---
Recirculating Pot. 1/13/81	.017	5.11	11.98	27.9	---	---
Ash Cyclone 1/13/81	.078	---	4.23	---	4.20	3.05

* % Carbon Unburned = %C_{total} - %C_{CO₂}

Assuming all Sulfide, Sulfate, and CO₂ are combined with calcium, the following calculations result:

Sample	%CaS	% CaSO ₄	%CaCO ₃	%CaO
Upper Bed 1/13/81	< .01	4.28	4.96	41.3
Lower Bed 1/13/81	.044	22.24	3.89	29.4
Recirculating Pot 1/13/81	.039	7.24	27.24	20.8
Ash Cyclone 1/13/81	.175	---	---	---

TABLE 4.

RESPECTFULLY SUBMITTED BY

Thomas Schuler
Thomas Schuler
Laboratory Manager



Resource Engineering Incorporated

80 Bacon Street, Waltham, Massachusetts 02154 (617) 894-6720

February 27, 1981

ANALYSIS REPORT

YOUR PURCHASE ORDER #P.O. #3344

SAMPLE RECEIVED - 1/13/81

(1700°F) MAR 3 1981

ANALYSIS REPORT #RA-202

RECEIVED FROM: Mr. Charles Lowell
Wormser Engineering
212 S. Main
Middleton, MA 01949

Sample	%Sulfide	%Sulfate	%CO ₂	%Ca	%C _{total}	%C _{unburned*}
Upper Bed 1/8/81	< .005	3.14	5.08	32.5	---	---
Lower Bed 1/8/81	.022	13.91	1.22	30.1	---	---
Ash Cyclone 1/8/81	.060	---	7.68	---	4.61	2.51

* % Carbon Unburned = %C_{total} - %C_{CO₂}

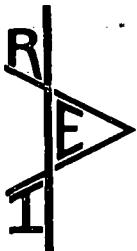
Assuming all Sulfide, Sulfate, and CO₂ are combined with calcium, the following calculations result:

Sample	%CaS	% CaSO ₄	%CaCO ₃	%CaO
Upper Bed 1/8/81	< .01	4.45	11.55	37.2
Lower Bed 1/8/81	.050	19.72	2.77	32.4
Ash Cyclone 1/8/81	.135	---	---	---

TABLE 5.

RESPECTFULLY SUBMITTED BY

Thomas Schuler
Thomas Schuler
Laboratory Manager



Resource Engineering Incorporated

80 Bacon Street, Waltham, Massachusetts 02154 (617) 894-6720

ANALYSIS REPORT

FEB 24 1981

SAMPLE RECEIVED - 1/7/81

ANALYSIS REPORT #RA-201

(1800°F)

RECEIVED FROM: Mr. Charles Lowell
Wormser Engineering
212 S. Main
Middleton, MA 01949

Sample	%Sulfide	%Sulfate	%CO ₂	%Ca	%C _{total}	%C _{unburned*}
Upper Bed 12/30/80	<.005	3.91	1.30	34.7	---	---
Lower Bed 12/30/80	<.005	14.73	2.29	32.2	---	---
Ash Cyclone 12/20/80	.027	---	2.74	---	2.37	1.62

* % Carbon Unburned = %C_{total} - %C_{CO₂}

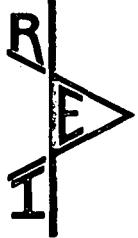
Assuming all Sulfide, Sulfate, and CO₂ are combined with calcium, the following calculations result:

Sample	%CaS	% CaSO ₄	%CaCO ₃	%CaO
Upper Bed 12/30/80	<.01	5.54	2.94	44.6
Lower Bed 12/30/80	<.01	20.87	5.20	33.5
Ash Cyclone 12/30/80	.048	---	6.23	---

RESPECTFULLY SUBMITTED BY

Thomas Schuler
Thomas Schuler
Laboratory Manager

TABLE 6.



Resource Engineering Incorporated

80 Bacon Street, Waltham, Massachusetts 02154 (617) 894-6720

February 27, 1981

ANALYSIS REPORT

YOUR PURCHASE ORDER #P.O. #3351

SAMPLE RECEIVED - 1/26/81

(1980^{op})

ANALYSIS REPORT #RA-204

RECEIVED FROM: Mr. Charles Lowell
Wormser Engineering
212 S. Main
Middleton, MA 01949

Sample	%Sulfide	%Sulfate	%CO ₂	%Ca	%C _{total}	%C _{unburned*}
Upper Bed 1/20/81	<.005	6.67	0.34	32.5	---	---
Lower Bed 1/20/81	<.005	20.95	0.41	29.2	---	---
Recirculating Pot. 1/20/81	.029	5.81	17.41	26.8	---	---
Ash Cyclone 1/20/81	.038	---	8.84	---	4.00	1.59

* % Carbon Unburned = %C_{total} - %C_{CO₂}

Assuming all Sulfide, Sulfate, and CO₂ are combined with calcium, the following calculations result:

Sample	%CaS	%CaSO ₄	%CaCO ₃	%CaO
Upper Bed 1/20/81	<.01	9.46	0.77	41.1
Lower Bed 1/20/81	<.01	29.69	0.93	28.1
Recirculating Pot 1/20/81	.065	8.24	39.59	11.8
Ash Cyclone 1/20/81	.085	---	---	---

TABLE 7.

RESPECTFULLY SUBMITTED BY


Thomas Schuler
Laboratory Manager

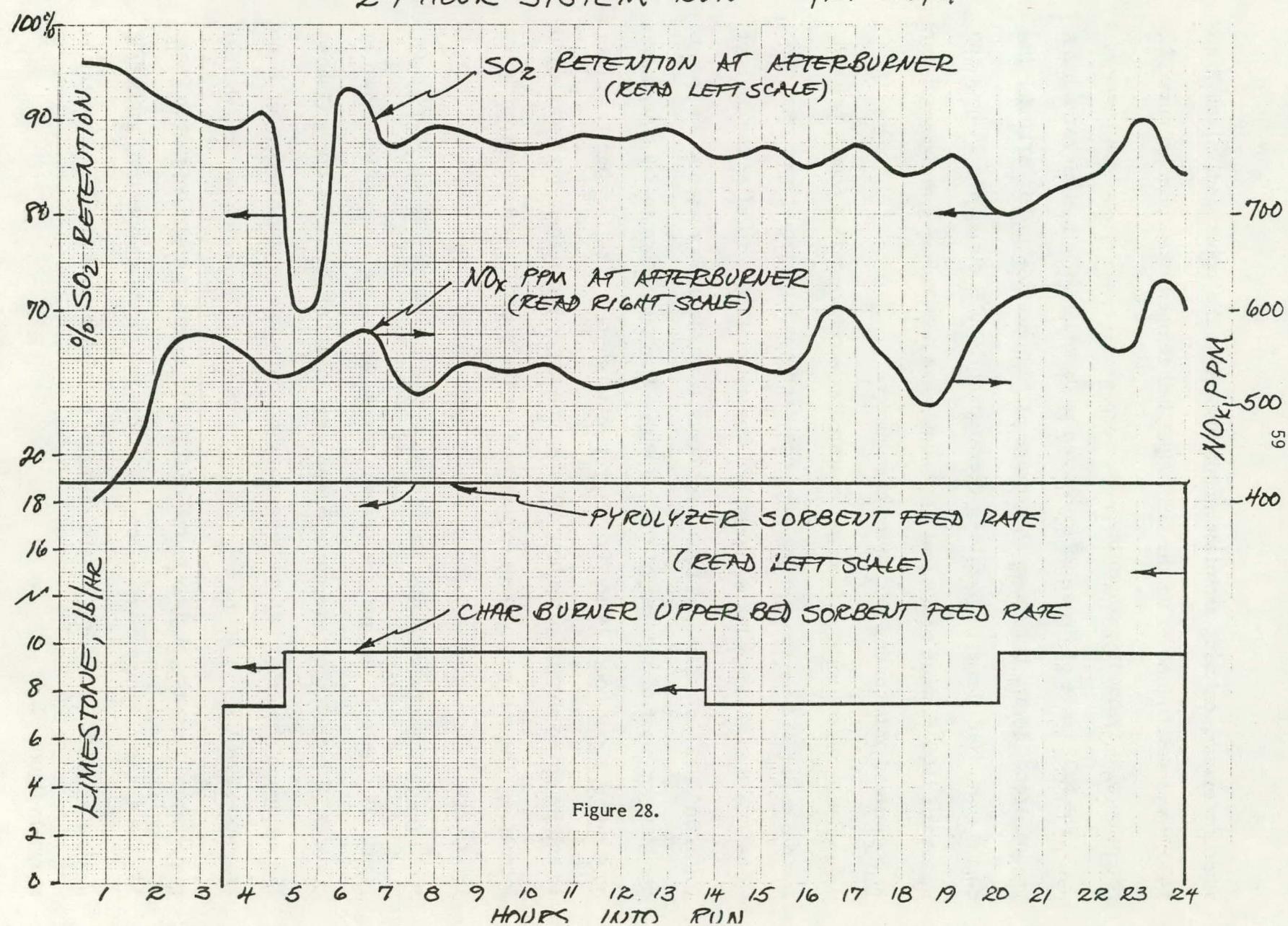
a small amount of bed material out through a small letdown valve arranged especially for the 24 hour run. SO_2 , NO_x , and O_2 readings were taken every 15 minutes and the coal bin and pyrolyzer sorbent bin were filled as necessary. Except for one slight leak at the char burner flange requiring a shutdown of about 10 minutes, and a bridge in the coal hopper resulting in a shutdown of about 4 minutes, the system ran smoothly and without any problems. The upper bed was run at between 1400°F and 1450°F as we have shown this range to be the best for Tymochtee dolomite.

3.3.10.1 Results

The gas sampling analyzed by the Thermoelectron equipment show very encouraging results. Figure 28 shows the percent SO_2 retention, the parts per million NO_x generated, and the pounds per hour of sorbent feed rates to the pyrolyzer, and char burner upper bed. The SO_2 retention is good considering that the net system calcium sulfur ratio was 2.17. The large dip in the SO_2 retention curve at about 5 hours was caused by the second cyclone downcomer becoming filled to capacity when the slide valve to the second cyclone char hopper was accidentally left closed after the hopper was emptied. Char that would have been collected by the second cyclone was passing through with the volatiles from the pyrolyzer to the afterburner where SO_2 in the char was released. Shortly after the problem was identified and corrected, the SO_2 capture efficiency returned to a more typical percentage.

The char burner lower bed was operated at 1750°F for the entire run and the upper bed was held at 1400°F to 1450°F with the addition of cold secondary air

24 HOUR SYSTEM RUN 1/27-28/81



when necessary, entering from air manifolds below the upper bed. 1400°F to 1450°F was determined to be the best upper bed temperature for maximum SO_2 retention with Tymochtee dolomite.

The NO_x curve of Figure 28 (corrected to stoichiometric fuel/air ratio) has a gradual trend upward but shows an average of 550 ppm (.66 lb/10⁶ BTU) for the entire run. Had the pyrolyzer been operated at 1600°F during the 24 hour run instead of 1400°F , more of the fuel NO_x would have been released in the pyrolyzer as N_2 instead of becoming NO_x in the char burner.

The pyrolyzer sorbent feed was operated at a constant 18.8 pounds per hour for the entire 24 hour run starting when coal feed was initiated at hour zero. The sorbent feed to the char burner upper bed was not started until after the $3\frac{1}{2}$ hour point, and was then set at 7.4 pounds per hour. It was later increased to 9.6 pounds per hour for most of the rest of the run with a six hour return to 7.4 pounds per hour during about hours 14 to 20. SO_2 retention seemed to suffer slightly at hour 14 and improved slightly after hour 20 when the upper bed sorbent rate was again increased. There is no apparent explanation for the poor SO_2 retention from hours 19 $\frac{1}{2}$ to 21.

The indicated afterburner flame temperature for the 24 hour run is plotted in Figure 29, curve A, against the percent excess air in the afterburner shown as curve B. Extrapolating from curve B, and with the aid of Figure 38, curve C shows the maximum theoretical flame temperatures achievable in the afterburner if no sensible heat were lost by the system. Curve C indicates an afterburner temperature averaging slightly below 3000°F , (the contract objective met in Phase I.) The Curve C temperature is consistent with the pyrolyzer operating at 1450°F instead of 1600°F resulting in devolatilization of 56% instead of 62% by weight as shown in figure 12.

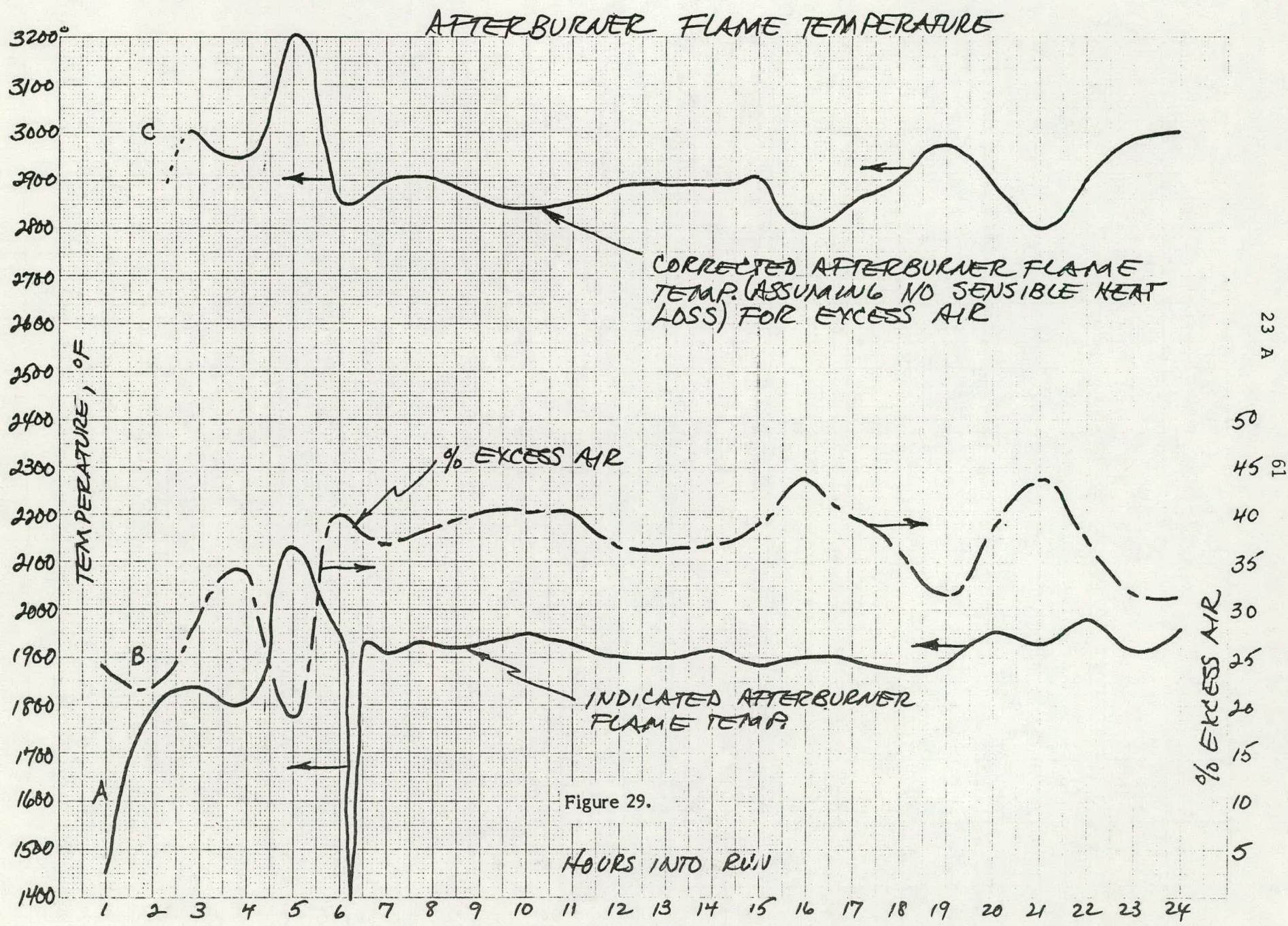


FIGURE 37.

Afterburner Temperature-Thermocouple

Radiation Error.

Actual Afterburner Temp. °F

5000
4000
3000
2000
1000

.2 .3 .4 .5 .6 .7

Thermocouple Emissivity

Indicated Temp. °F

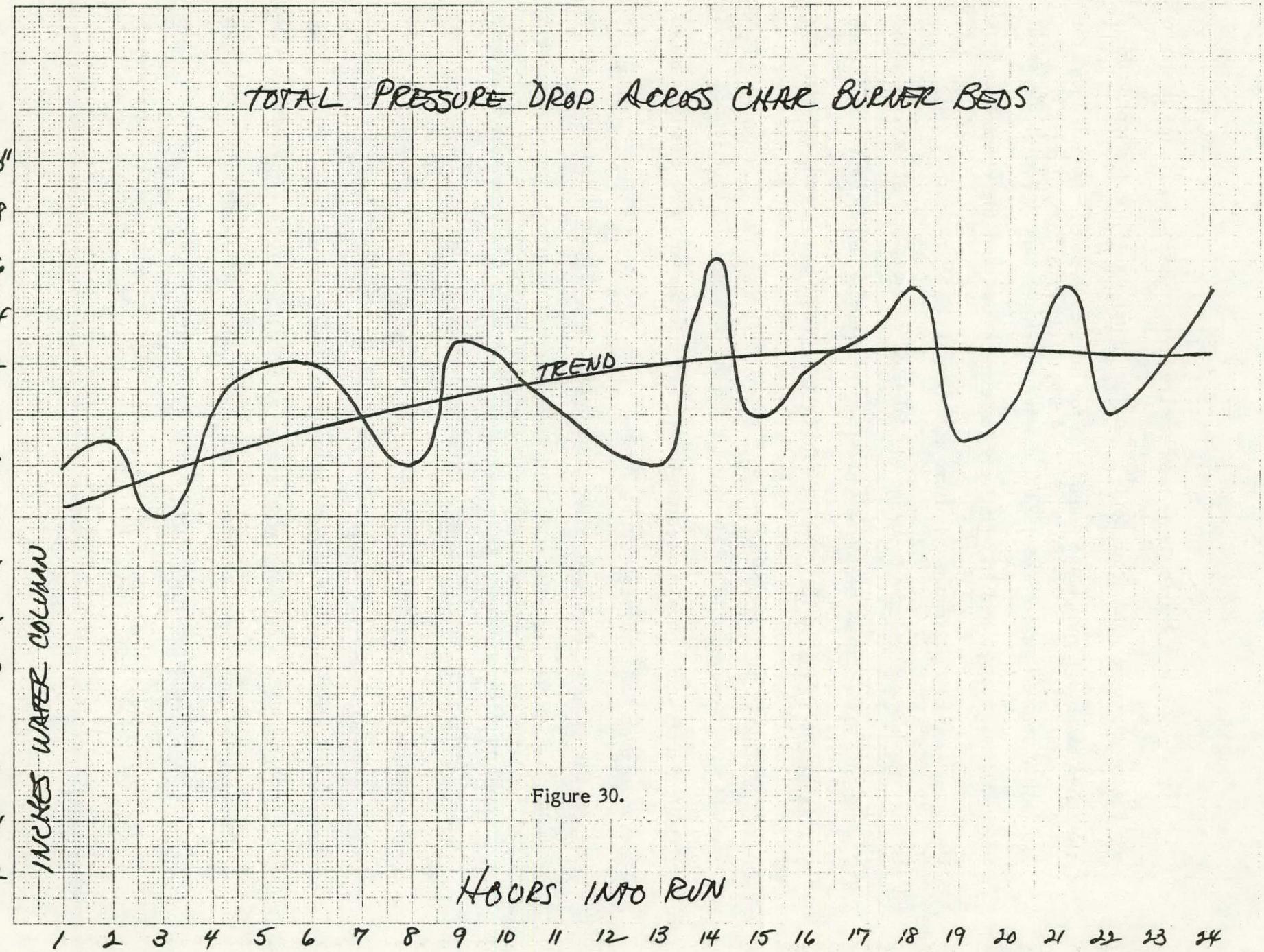
2400
2200
2000
1800
1600

The average indicated flame temperature of the afterburner flame is shown in Figure 29, curve A as about 1900°F. If the emissivity of the thermocouple is assumed to be .3, a reasonable assumption for these conditions, Figure 37 indicates an actual temperature of about 2300°F which would be expected with the small scale of the system and its relatively large heat loss, and the concurrent high percent excess air present in the afterburner flame.

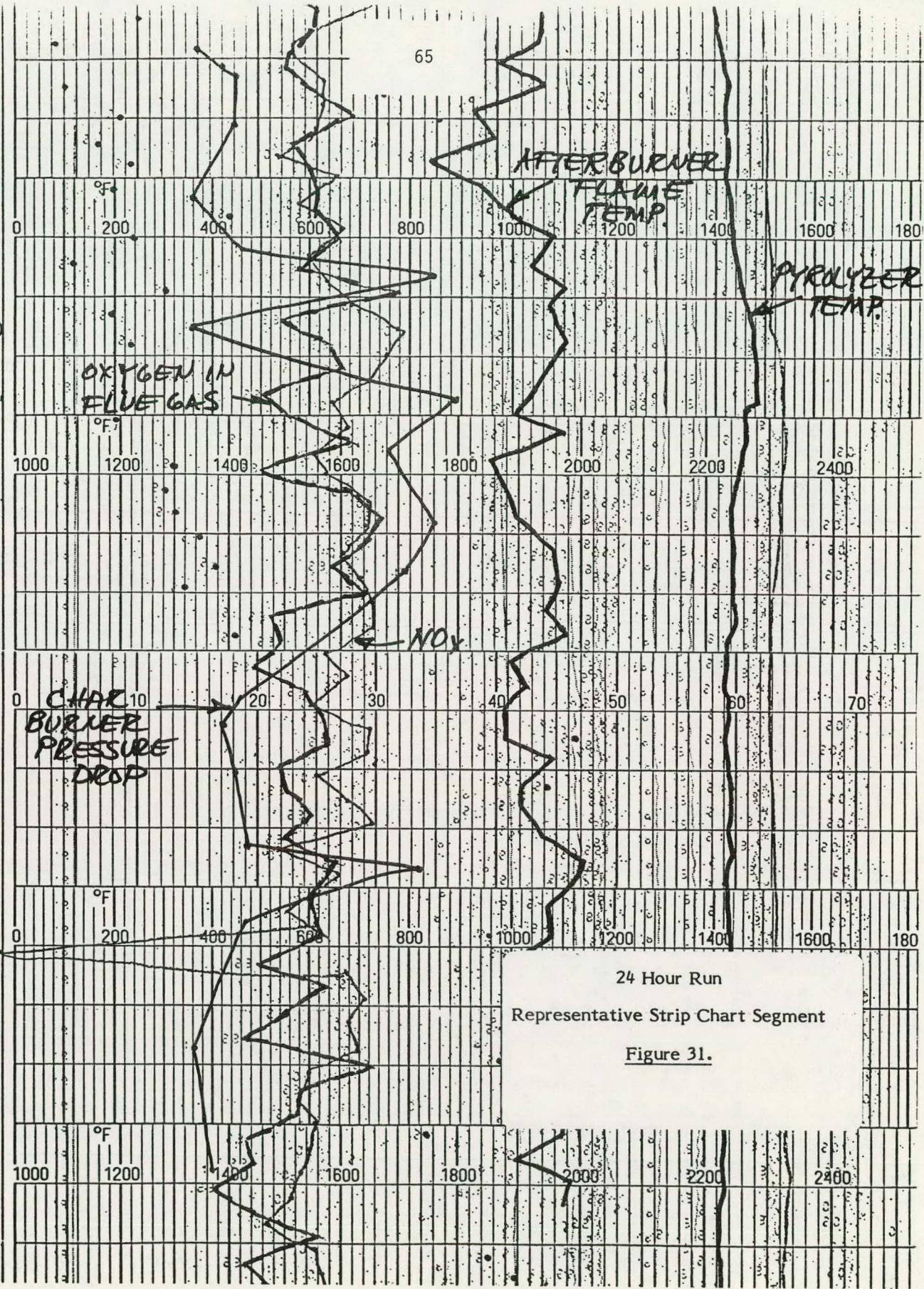
The primary objective during the 24 hour run was one of demonstrating endurance rather than performance. The afterburner pilot light contributes substantially to the overall percent excess air. Had it been turned off after the afterburner had come up to operating temperature, the average system excess air would have been more like 25%, rather than the 35% actually experienced. This single change would have allowed the theoretical afterburner flame temperature to average over 3000°F as shown in Figure 38.

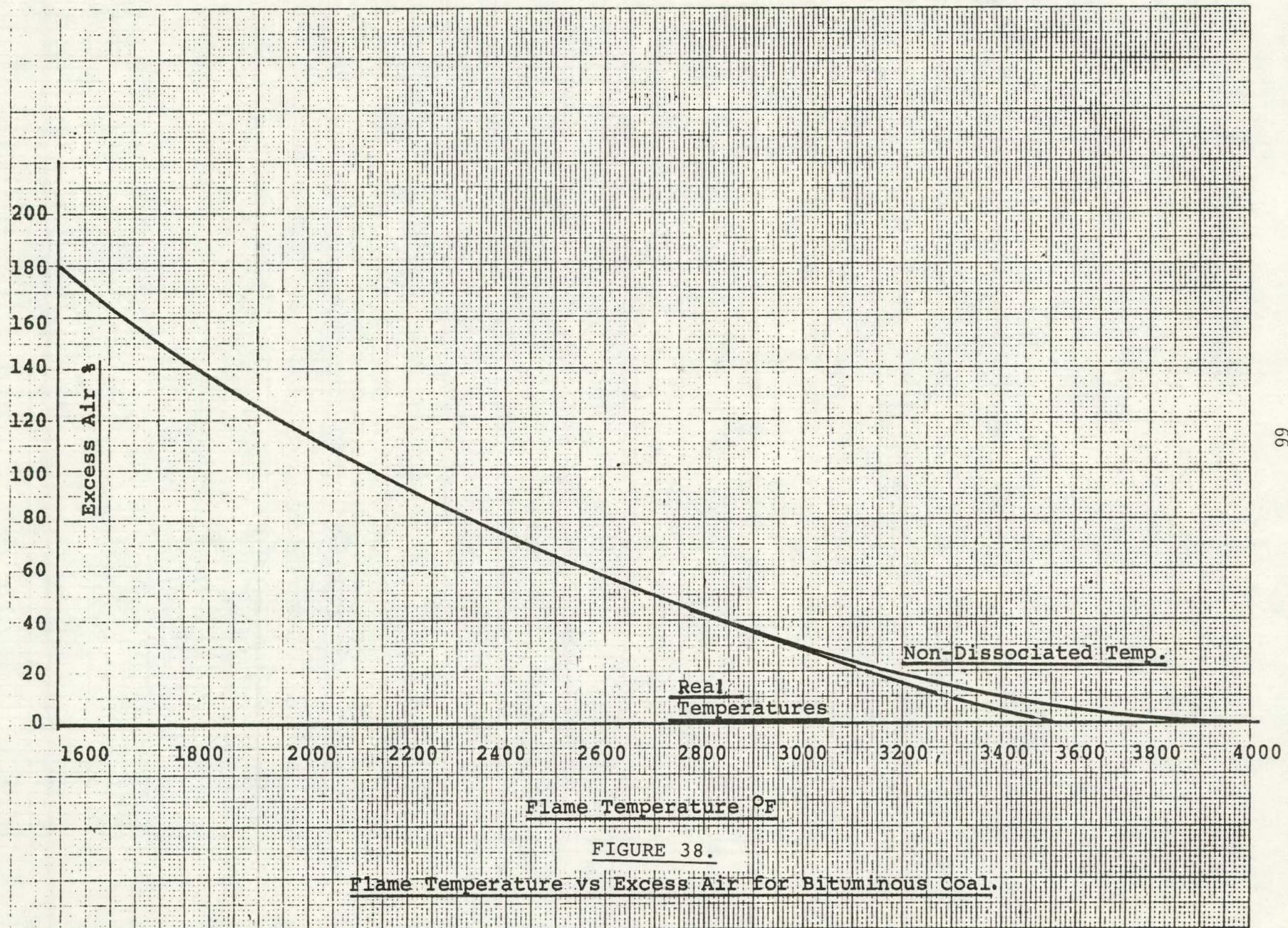
The pressure drop across the char burner beds (Figure 30) shows a gently increasing and leveling off trend. Both the upper and lower beds were fed sorbent throughout the run resulting in a gradual increase in bed depths as both beds reached their equilibrium depths above their starting levels. No significant plugging of the upper bed distributor plate occurred during the 24 hour run. The 35% average increase in pressure drop shown in Figure 30 resulted from the increase in bed depths of both beds, as was expected.

Figure 31 is a representative sample of the strip chart for the 24 hour run. The various points are connected with dark lines and labeled for what they represent. The afterburner temperature is read on the higher temperature scale; the pyrolyzer temperatures on the lower. Please note that the afterburner



10:00
9:00
8:00





temperature indicated on the strip chart has not been corrected for thermocouple radiation error or system sensible heat loss. The NO_x and O_2 curves are useful for trends, but the actual readings for plotting purposes (including SO_2) were taken directly off the analyzers every 15 minutes throughout the run.

The Thermoelectron equipment calibration was checked and adjusted at the beginning and rechecked at the end of the 24 hour run. For the duration of the run, neither instrument had drifted more than 5% off calibration; the SO_2 analyzer was reading 2% higher than actual, and the NO_x analyzer 5% lower than actual at the end of the run. The curves of Figure 28 have not been corrected for these small errors.

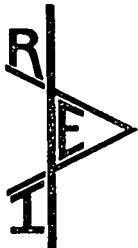
Six samples of the lower bed recirculating material were analyzed and show a low and increasing sulfide percent of from .062% to .387% (Table 8). It is not understood why there is an increasing trend for the last 12 hours of the run, but the absolute percents are nevertheless well below the 2% maximum project goal.

The unburned carbon in the ash cyclone is 4.4% of the ash (Table 8) which converts to a carbon utilization of 96.9% for the system. This percent is typical for the system and well exceeds the contract minimum of 90%.

4.0 Conclusion

Results for the COHOGG System have been very encouraging. It appears that all of the contract goals have been met or exceeded. The system has demonstrated the capability of providing an environmentally clean flame in excess of 3000°F while burning low or high sulfur coal, and is suitable as an alternative to, or as a retrofit for, gas or oil burners.

APR 2 1981



Resource Engineering Incorporated

80 Bacon Street, Waltham, Massachusetts 02154 (617) 894-6720

March 30, 1981

ANALYSIS REPORT

YOUR PURCHASE ORDER #3355

SAMPLE RECEIVED 2/12/81

ANALYSIS REPORT #RA-206

RECEIVED FROM: Mr. Charles Lowell
 Wormser Engineering
 212 S. Main Street
 Middleton, MA 01949

SAMPLE	%Ca	%SO ₄ % Sulfate.	%CO ₂	%S % Sulfide	%C
<u>Recirculating Material</u>					
#2A 1/27/81 2:30	26.6	4.69	6.99	.062	---
#4A 1/27/81 6:30	25.5	17.95	1.45	.066	---
#6A 1/27/81 10:30	26.0	23.14	0.84	.062	---
#8A 1/28/81 2:30	23.9	28.66	0.51	.090	---
#10A 1/28/81 6:30	24.1	27.67	0.59	.280	---
#12A 1/28/81 10:30	24.7	34.88	0.58	.387	---
<u>Upper Bed</u>					
#3B 1/27/81 4:45	30.9	5.18	2.92	<.005	---
#4B 1/27/81 6:45	29.9	6.68	6.50	<.005	---
#6B 1/27/81 10:45	28.7	7.27	6.02	<.005	---
#8B 1/28/81 2:45	28.3	8.86	5.42	<.005	---
#10B 1/28/81 6:45	28.9	8.87	7.40	<.005	---
#12B 1/28/81 10:45	29.3	9.36	6.32	<.005	---
<u>Ash Cyclone</u>					
#6C 1/27/81 11:00	18.1	8.18	6.49	.089	4.23
#12C 1/28/81 11:00	20.7	9.31	13.71	.036	4.43

TABLE 8.

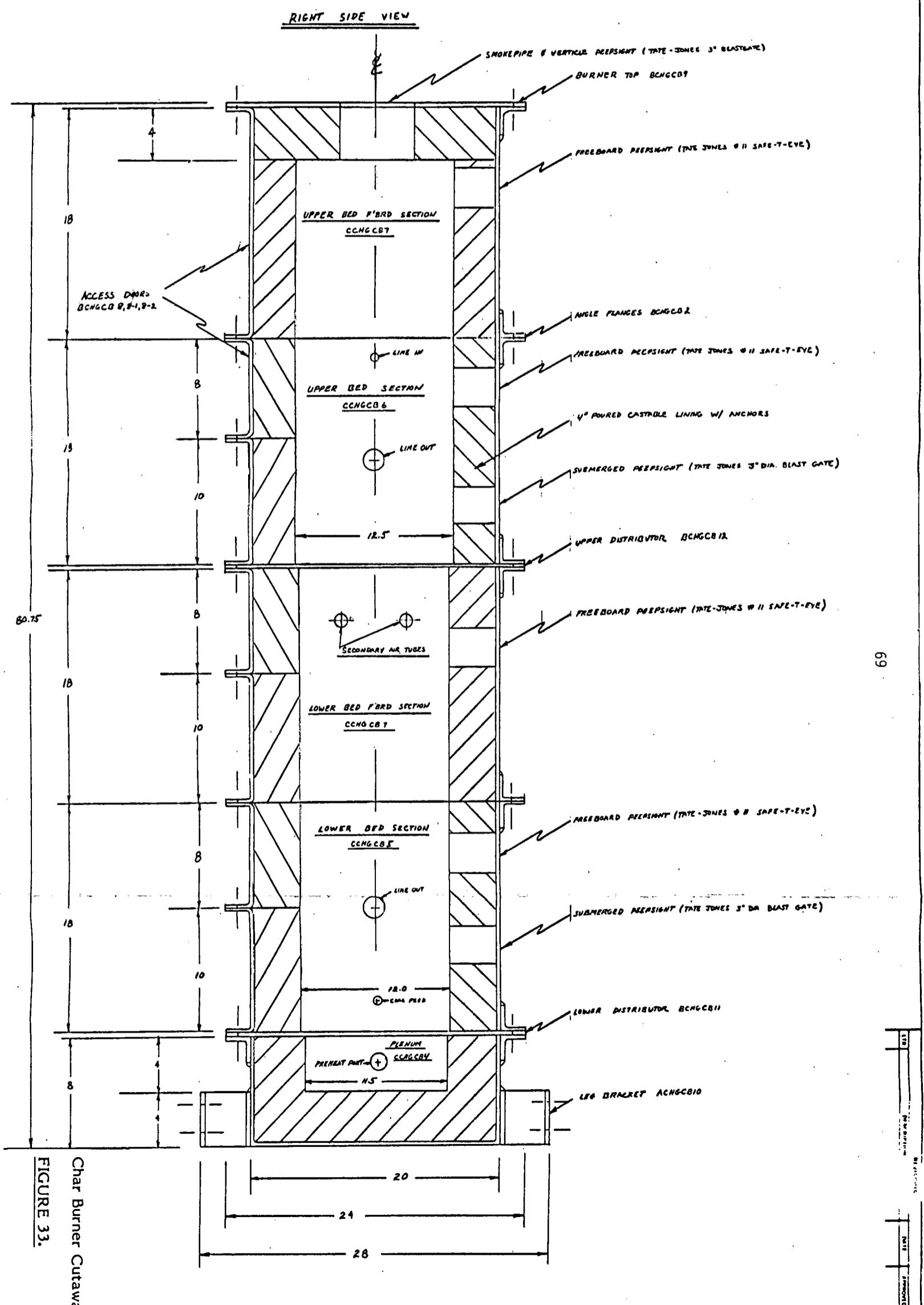
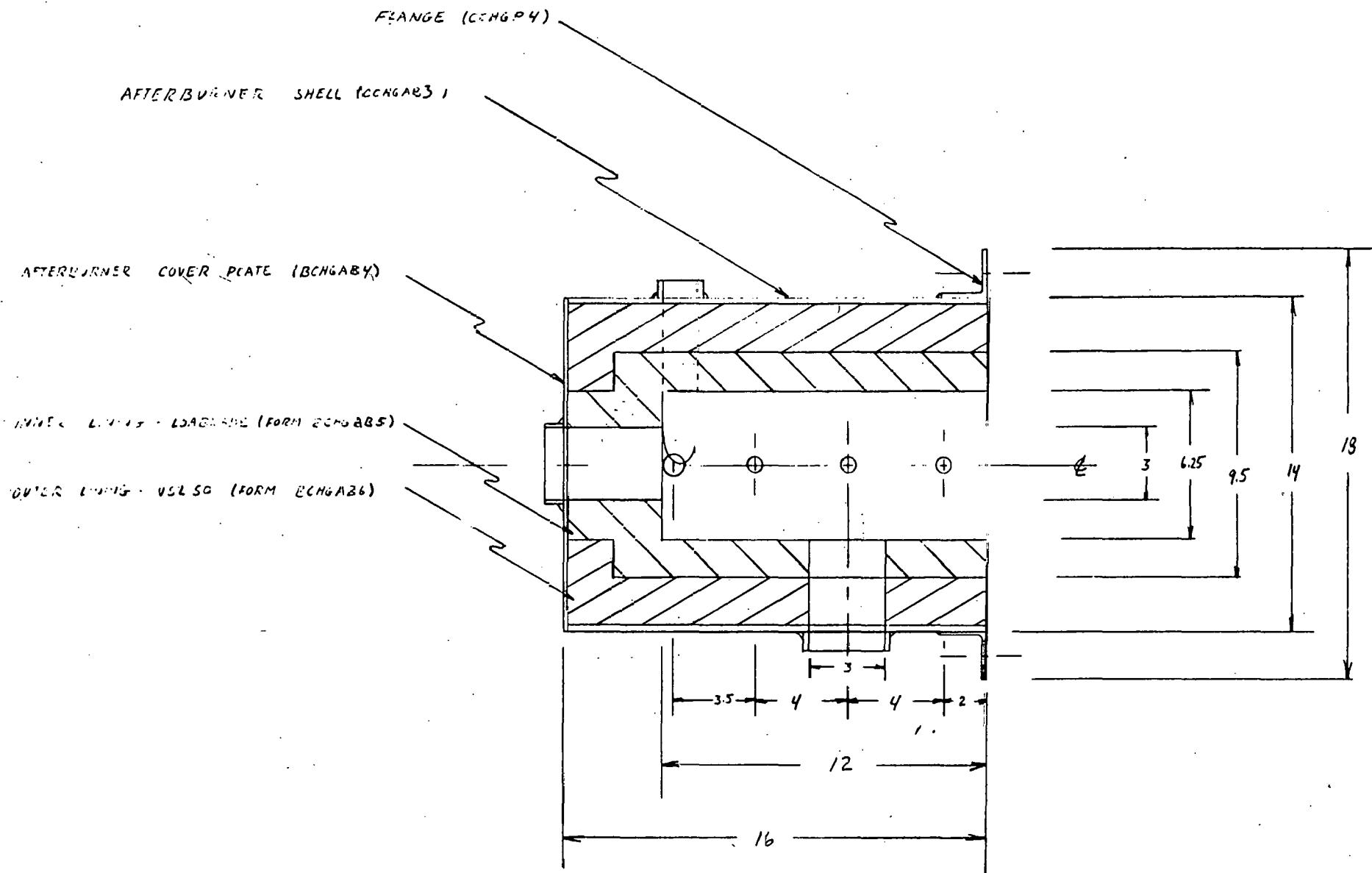


FIGURE 33. Char Burner Cutaway



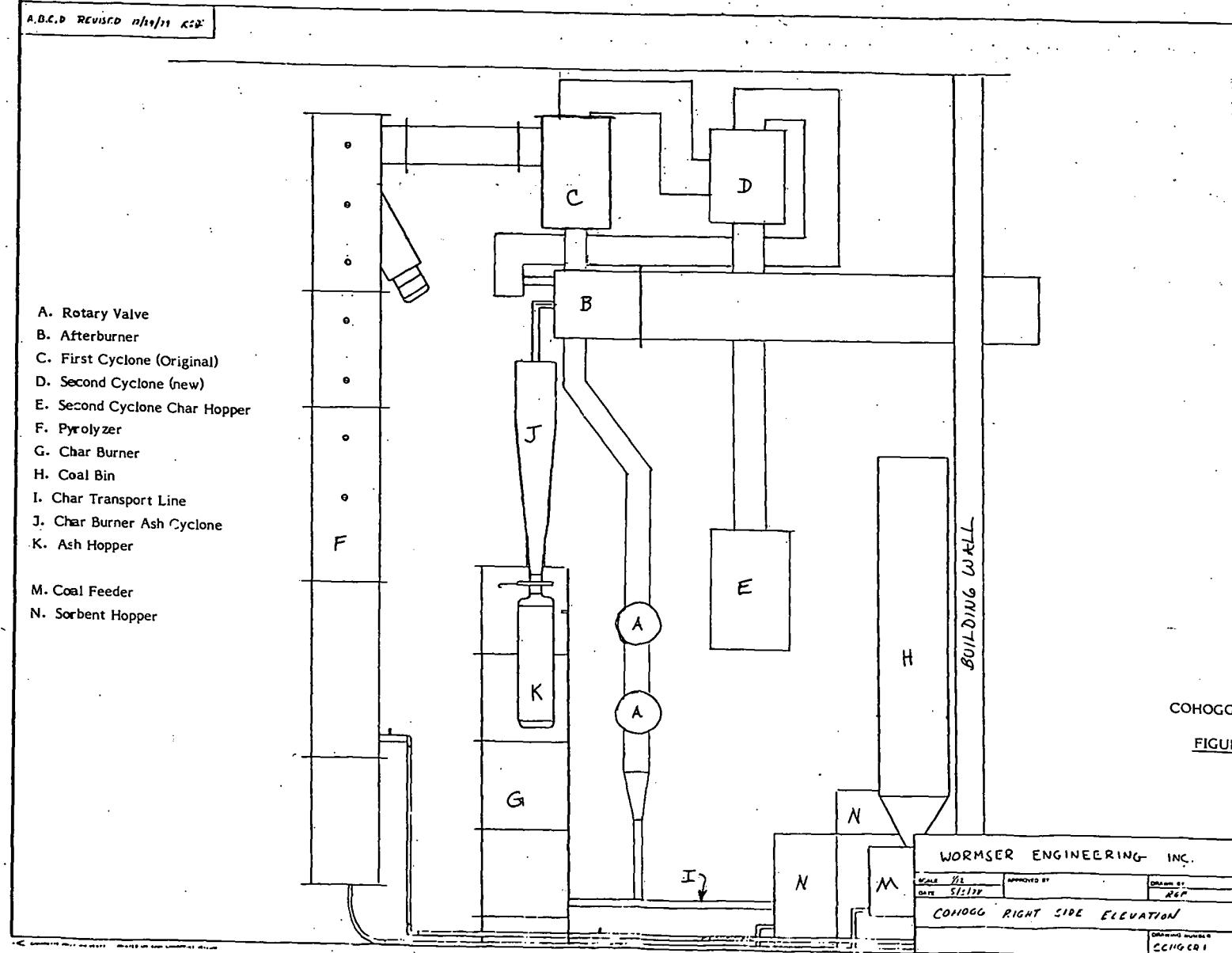
COHOGG Afterburner

Figure 35.

A.B.C.D REVISED 11/19/71 K:2

- A. Rotary Valve
 - B. Afterburner
 - C. First Cyclone (Original)
 - D. Second Cyclone (new)
 - E. Second Cyclone Char Hopper
 - F. Pyrolyzer
 - G. Char Burner
 - H. Coal Bin
 - I. Char Transport Line
 - J. Char Burner Ash Cyclone
 - K. Ash Hopper

 - M. Coal Feeder
 - N. Sorbent Hopper



COHOOG Schematic

FIGURE 36.

List of References

<u>Reference</u>	<u>Title</u>
1.	Boteler and Boley. "Partial Devolatilization of Coal in Two Entrained-Bed Carbonizers" U.S. Bureau of Mines RI 7843 1973.
2.	Landers, et al. "Entrained-Bed Carbonization of Bituminous Coal." U.S. Bureau of Mines RI 6608 1965.
3.	Production of Low BTU Gas Involving Coal Pyrolysis. West Virginia University 1974.
4.	Proceedings, Coal Combustion Seminar. June 19-20, 1973. Research Triangle Park, N.C. NTIS # PB-224-210.
5.	BNL 51229, "Proceedings of a Workshop on the Utilization of Coal Fuels in Process Heaters." March 6-7, 1979