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FINAL TECHNICAL REPORT:
SRC BURN TEST IN 700-hp OIL-DESIGNED BOILER

Integrated Report

September 1983

Work Performed Under Contract No. AC05-78OR03054

International Coal Refining Company
Allentown, Pennsylvania

and

Southern Company Services, Inc.
Birmingham, Alabama

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United States Department of Energy

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FINAL TECHNICAL REPORT:
SRC BURN TEST IN 700-hp OIL-DESIGNED BOILER.
VOLUME 1: INTEGRATED REPORT

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for the

UNITED STATES DEPARTMENT OF ENERGY

Office of Solvent-Refined Coal Products
Under Contract DE-AC05-78-ORO-3054

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**FINAL TECHNICAL REPORT:
SRC BURN TEST IN 700-hp OIL-DESIGNED BOILER**

Volume 1: Integrated Report

September 1983

**International Coal Refining Company
Allentown, Pennsylvania**

MASTER

ABSTRACT

This burn test program was conducted during the period of August 1982 to February 1983 to demonstrate that Solvent Refined Coal (SRC) products can displace petroleum as a boiler fuel in oil- and gas-designed boilers. The test program was performed at the U.S. Department of Energy's Pittsburgh Energy Technology Center (PETC). Three forms of SRC (pulverized SRC, a solution of SRC dissolved in process-derived distillates, and a slurry of SRC and water) and No. 6 Fuel Oil were evaluated in the 700-hp (30×10^6 Btu/hour) watertube, oil-designed boiler facility at PETC.

The test program was managed by the International Coal Refining Company (ICRC) and sponsored by the Department of Energy. Other organizations were involved as necessary to provide the expertise required to execute the test program.

This final report represents an integrated overview of the test program conducted at PETC. More detailed information with preliminary data can be obtained from separate reports prepared by PETC, Southern Research Institute, Wheelabrator-Frye, Babcock & Wilcox, and Combustion Engineering. These are presented as Annex Volumes A-F.

**FINAL TECHNICAL REPORT
SRC BURN TEST
IN 700-hp OIL-DESIGNED BOILER**

Overall Contents

Volume 1	Integrated Report
Volume 2	Engineering Evaluation
Annex Volume A:	Southern Research Institute Report
Annex Volume B:	DOE-Pittsburgh Energy Technology Center Report
Annex Volume C:	Boiler Emission Report (Wheelabrator-Frye, Inc.)
Annex Volume D:	Electrostatic Precipitator, Mass Train and Operating Data (Wheelabrator-Frye, Inc.)
Annex Volume E:	Evaluation of Fabric Filter for Particulate Emission Control (Wheelabrator-Frye, Inc.)
Annex Volume F:	Independent Test Evaluations (Babcock & Wilcox, Combustion-Engineering)

FINAL TECHNICAL REPORT: SRC BURN TEST IN 700-hp OIL-DESIGNED BOILER VOLUME I: INTEGRATED REPORT

TABLE OF CONTENTS (SHEET 1 OF 3)

	Page
1.0 Executive Summary	1
1.1 Introduction	1
1.2 Combustion Conclusions	2
1.3 Flue Gas Area Conclusions	11
1.3.1 Electrostatic Precipitators	11
1.3.2 Fabric Filter Dust Collectors	12
1.3.3 Dry Cyclone Dust Collectors	12
1.4 Future Research Needs	12
2.0 Introduction	15
2.1 Background	15
2.2 Objectives	17
2.2.1 Overall Objectives	17
2.2.2 Program Objectives	18
2.3 Test Program Organization	19
2.4 Documentation for the Test Program	19
2.5 Directions for SRC Development	20
3.0 Facility Description	25
3.1 Onsite Fuel Handling	25
3.1.1 No. 6 Fuel Oil	25
3.1.2 SRC Fuel	25
3.1.3 SRC Residual Fuel Oil	31
3.1.4 SRC-Water Slurry	33
3.2 Boiler	33
3.3 Combustion Air System	37
3.4 Burner Design	37
3.5 Instrumentation and Data Acquisition System	49
3.6 Flue Gas Area	51
3.6.1 Electrostatic Precipitator	51
3.6.2 Pulse-Jet Fabric Filter	57
3.6.3 Reverse Air Fabric Filter	57
4.0 Fuels	61
4.1 Fuel Preparation	61
4.1.1 SRC Fuel	61
4.1.2 SRC Residual Fuel Oil	65
4.1.3 SRC-Water Slurry	68
4.2 SRC Demonstration Plant	68

TABLE OF CONTENTS (SHEET 2 OF 3)

	Page
5.0 Test Program	71
5.1 Introduction	71
5.2 Fuel Analyses	71
5.3 Boiler Performance	73
5.3.1 No. 6 Fuel Oil	73
5.3.2 SRC Fuel	74
5.3.3 SRC Residual Fuel Oil	78
5.3.4 SRC-Water Slurry	78
5.4 Flame Characteristics	79
5.5 Flue Gas Analyses and Particulate Emissions at Boiler Outlet	81
5.6 Combustion Results	82
5.6.1 No. 6 Fuel Oil	82
5.6.2 SRC Fuel	82
5.6.3 SRC Residual Fuel Oil	85
5.6.4 SRC-Water Slurry	86
5.7 Combustion Conclusions	86
5.8 Flue Gas Assessment	87
5.8.1 Electrostatic Precipitator Performance Evaluation	88
5.8.1.1 EPA/SoRI ESP Model	90
5.8.1.2 Ash Resistivity Measurements	92
5.8.1.3 Particulate Size Distribution Measurement	94
5.8.1.4 Particulate Mass Measurements	104
5.8.1.5 Sulfur Dioxide and Sulfur Trioxide Measurements	104
5.8.1.6 Computer Modeling of the ESP	104
5.8.1.7 ESP Results and Conclusions	108
5.8.2 Fabric Filter Evaluation	114
5.8.2.1 Pulse-Jet Fabric Filter	115
5.8.2.2 Reverse Air Fabric Filter	116
5.8.2.3 Performance Evaluation	119
5.8.2.4 Conclusions and Recommendations	121
5.8.3 Alternate Control Considerations	122
6.0 Assessments of Test Program	125
6.1 Southern Company Services Viewpoint	126
6.2 Babcock & Wilcox Viewpoint	133
6.3 Combustion Engineering Viewpoint	139
6.4 Florida Power and Light Company Viewpoint	144
6.5 Commonwealth Electric Company Viewpoint	145

TABLE OF CONTENTS (SHEET 3 OF 3)

	Page
Appendix A Organization	A-1
References	
Glossary	

LIST OF FIGURES (SHEET 1 OF 3)

Figure No.		Page
1	No. 6 Fuel Oil Flow Diagram	26
2	Pulverized SRC Fuel Flow Diagram	27
3	SRC Residual Fuel Oil Flow Diagram	28
4	SRC-Water Slurry Flow Diagram	29
5	Flue Gas Area Flow Diagram	30
6	SRC Fuel Feed Bin	32
7	700-hp Oil-Designed Boiler	34
8	Typical Burner Nozzle for No. 6 Fuel Oil or SRC-Water Slurry	39
9	Slow Mix Burner Showing Nozzle and 67° Elbow	40
10	Modified Six-Inch Slow Mix Burner With Concurrent Spinvanes and Cone	41
11	Tangential Inlet	42
12	Modified Six-Inch Slow Mix Burner with Tangential Inlet and Concurrent Spinvanes	43
13	Modified Six-Inch Slow Mix Burner with Tangential Inlet, Concurrent Spinvanes and Straight Fuel Tube	44
14	Modified Six-Inch Slow Mix Burner with Tangential Inlet, Counter Current Spinvanes, and Straight Fuel Tube	45
15	Five-Inch Fast Mix Burner	46
16	Water-Cooled Cone for Fast Mix Burner and Diverging Fuel Tube Nozzle for Slow Mix Burner	48
17	SRC-Water Slurry Burner	50
18	Flue Gas Splitter	52

LIST OF FIGURES (SHEET 2 OF 3)

Figure No.		Page
19	Pilot Electrostatic Precipitator	53
20	Pilot Electrostatic Precipitator Inlet and Outlet Gas Sampling Arrangement	55
21	700-hp Boiler Pulse-Jet Fabric Filter	58
22	Reverse Air Fabric Filter	60
23	SRC Refinery Process Diagram (Demonstration Plant Configuration)	69
24	Correlation of Flame Length with Burner Firing Rate	80
25	Point-to-Plane Resistivity Probe	93
26	Ash Particle Size Distributions Used in the ESP Model to Estimate Full-Scale Precipitator Collection Efficiency	95
27	Modified Brink Model BMS-11 Cascade Impactor	96
28	University of Washington Mark III Source Test Cascade Impactor	97
29	Operation Principle and Typical Performance for a Cascade Impactor	98
30	The Five-Stage Series Cyclone System	101
31	SoRI Ultrafine Particle Sample Extraction-Dilution System (SEDS)	102
32	Flow Schematic and Electronic Block Diagram of the Electrical Aerosol Size Analyzer (EASA)	103
33	Diagram of the SoRI Large Particle Sampling System (LPSS)	105
34	Schematic Diagram of Apparatus for Collection of SO ₂ and SO ₃	106
35	Measured and Computed Performance of the ESP	109

LIST OF FIGURES (SHEET 3 OF 3)

Figure No.		Page
36	Modeling Estimates of ESP Collection Efficiency for Various SCAs	110
37	Computed Examples of Degradation in Precipitator Performance Due to Rapping Reentrainment	112
38	Estimates of Minimum SCA for a Specified Inlet Mass Loading and a Range of Outlet Mass Loadings	113
39	SRC Ash Samples, Plant Mitchell Burn Test	130
40	Inlet Impactor Stage 3 Samples: PETC-SRC Burn Test	131
41	SRC Ash Char Sample Shown at Different Levels of Magnification from Acurex Corporation Burn Tests	132

LIST OF TABLES

Table No.		Page
1	Summary of Test Program Results	3
2	Test Program Organization	22
3	Analysis of SRC Fuel	62
4	Analysis of SRC Residual Fuel Oil	63
5	Analysis of SRC-Water Slurry	64
6	Typical Properties of Process-Derived Distillate	67
7	Fuel Analysis	72
8	Operating Conditions and Boiler Performance	75
9	Flue Gas Analyses and Particulate Emissions	83
10	Summary of ESP Operating Conditions and Test Results	89
11	Electrical Operating Points Used in the ESP Model to Estimate Full-Scale Precipitator Collection Efficiency	107
12	Estimates of Collection Efficiency and Minimum SCA for Precipitators Collecting Ash from Five Different Fuels, for a Specified Inlet Mass Loading and a Range of Outlet Mass Loadings	114
13	Summary of Results for Pulse-Jet Fabric Filter	117
14	Summary of Results for Reverse Air Fabric Filter	120
15	Inlet Impactor Cumulative Mass Loadings at Indicated Sizes	123

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

With our nation determined to reduce dependence on foreign oil and protect the environment from harmful pollutant, Solvent Refined Coal (SRC) represents an important new technology and a clean, alternative, domestic fuel for the electricity utility industry and other commercial users. This test program constitutes a continuation of SRC development and a major step toward the commercialization of the fuel.

During this program both combustion and flue gas evaluations were performed to demonstrate that SRC products can displace petroleum. Boiler population and fuel consumption data indicate that the primary candidate boilers for retrofit firing of SRC are wall-fired and tangentially fired large industrial and utility boilers which currently fire oil.

SRC is a low sulfur and very low ash synthetic fuel produced from the nation's most abundant natural resource, coal. The SRC preparation procedure is a direct coal-liquefaction process in which coal, hydrogen, and process-derived distillates are reacted at elevated temperature and pressure. The process removes most of the sulfur and ash, the chief pollutants in bituminous coals. The process stream is flashed to release light gases; fractionated to separate by-product gases, net distillate product liquids, and recycled process solvent; and deashed using the Kerr McGee Critical Solvent Deashing Process to produce the SRC product. SRC is the hydrocarbon fraction with a boiling point of 850°F or higher. The basic SRC product at room temperature is a shiny black, friable solid material with a heating value closer to that of No. 6 Fuel Oil than coal. An advantage of SRC is the much lower vanadium content when compared to utility fuel oils.

SRC is a versatile fuel and has been successfully combusted in several different physical forms. During this test program, the three forms listed below were evaluated in a 700-hp watertube, oil-designed boiler at the U.S. Department of Energy's Pittsburgh Energy Technology Center (PETC).

- A. SRC Fuel; pulverized SRC.
- B. SRC Residual Fuel Oil; pulverized SRC Fuel dissolved in SRC process-derived distillates; 55-percent solids and 45-percent SRC distillates; a liquid fuel.
- C. SRC-Water Slurry; pulverized SRC Fuel suspended in water; 66-percent solids and 33-percent water. Studies conducted at PETC showed that approximately 0.5 percent of Lomar-D wetting agent would be required for the slurry. Fuel and flue gas analyses indicated that approximately 1 percent was actually added.

The test program involved the determination of appropriate fuel transportation, preparation and handling procedures, combustion characteristics, boiler operation, flue gas emissions,

and particulate control equipment design. Actual combustion testing began in August 1982 and was completed in early February 1983. Over 50, 4-hour ASME combustion tests were successfully completed. The tests consumed approximately 300 tons of SRC Fuel, 30,000 gal of SRC Residual Fuel Oil, and 20,000 gal of SRC-Water Slurry. Test periods for each fuel are listed below.

Fuel	Test Period
No. 6 Fuel Oil	August 18 through September 3, 1982
SRC Fuel	October 24 through November 19, 1982
	January 25 through February 2, 1983
SRC Residual Fuel Oil	December 7 through December 16, 1982
SRC-Water Slurry	January 3 through January 14, 1983

The primary component of the PETC combustion facility is a 700-hp, two-drum, "D" type package, watertube, industrial boiler designed for oil firing. At full capacity the boiler fires 30×10^6 Btu/hour of fuel to generate 24,000 pounds of saturated steam per hour at 175 psig, with a heat liberation rate of 47,100 Btu/ft³-hour.

1.2 COMBUSTION CONCLUSIONS

The principal goal of demonstrating the combustion of SRC in an oil-designed boiler was successfully achieved as a result of the tests in the 700-hp boiler. The boiler was operated without derating when burning SRC in the three listed forms. Table 1 gives a summary of the test results obtained at PETC. The following is an abbreviation of the combustion and flue gas results.

	No. 6 Fuel Oil	SRC Fuel Slow Mix	SRC Fuel Fast Mix	SRC Residual Fuel Oil	SRC-Water Slurry
Boiler efficiency (%)	82.0	82.2	84.7	85.3	81.8
Carbon conversion efficiency (%)	99.9	98.7	98.9	99.8	98.9
SO ₂ (lb/10 ⁶ Btu)	0.8	1.3	1.1	0.7	1.3
NO _x (lb/10 ⁶ Btu)	0.3	1.1	1.3	0.7	0.5
Particulate emissions (lb/10 ⁶ Btu)					
Electrostatic precipitator outlet	0.004	0.005	-a	0.002	0.006
Pulse-jet fabric filter outlet	-a	-b	-a	0.004	0.004
Reverse air fabric filter outlet	0.010	0.002	-a	0.002	0.011

a. Not tested.

b. See Table 1.

TABLE 1 (SHEET 1 OF 4)
SUMMARY OF TEST PROGRAM RESULTS

FUEL ANALYSIS^a								
	No. 6 Fuel Oil		SRC Fuel		SRC Residual Fuel Oil		SRC-Water Slurry	
	Avg of 8 Parametric Test Analyses	Avg of 16 Duration Test Analyses	Slow Mix Burner Avg of 19 Analyses	Fast Mix Burner Avg of 6 Analyses	Avg of 6 Parametric Test Analyses	Avg of 11 Duration Test Analyses	Avg of 6 Parametric Test Analyses	Avg of 8 Duration Test Analyses
Ultimate analysis	WT-% ON MOISTURE-FREE BASIS							
Hydrogen	11.72	12.15	6.15	6.04	8.01	8.03	7.82	7.67
Carbon	82.38	83.21	86.44	86.84	86.42	86.55	56.92	57.81
Nitrogen	0.23	0.20	2.00	1.94	1.31	1.29	1.23	1.20
Sulfur	0.65	0.60	0.99	0.82	0.44	0.48	0.70	0.67
Oxygen	4.93	3.72	4.27	4.24	3.76	3.56	32.87	32.26
Ash	0.10	0.11	0.16	0.12	0.06	0.09	0.46	0.36
Moisture (%)	6.48	5.04	0.56	0.35	0.43	0.49		
Heating value (Btu/lb)	17469	17752	15870	15871	16765	16708	10460	10598
SRC concentration (%)							65.85	66.61
Particle size (% minus 200 mesh)			97	98			90	90

a. Data from report by PETC. (See reference 21.)

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

TABLE 1 (SHEET 2 OF 4)

FLUE GAS ANALYSES AND PARTICULATE EMISSIONS^a

	No. 6 Fuel Oil		SRC Fuel				SRC Residual Fuel Oil		SRC-Water Slurry	
	Parametric Test Range	Avg of 18 Duration Tests	Slow Mix Burner		Fast Mix Burner		Parametric Test Range	Avg of 11 Duration Tests	Parametric Test Range	Avg of 8 Duration Tests
	Test Range	Tests	Parametric Test Range	Avg of 19 Duration Tests	Parametric Test Range	Avg of 6 Parametric Tests	Test Range	Tests	Test Range	Tests
Flue gas analysis										
O ₂ (%)	0.6 - 5.1	2.4	3.1 - 5.4	5.3	2.7 - 5.5	4.0	0.4 - 4.4	2.6	2.1 - 4.0	3.0
CO ₂ (%)	11.8 - 15.4	13.6	12.8 - 14.7	12.8	12.9 - 15.2	14.1	13.8 - 16.7	14.7	14 - 16	14.9
CO (ppm)	22 - 190	31.5	70 - 370	88	41 - 56	49	25 - 123	32.5	51 - 280	76
SO ₂ (ppm)	455 - 560	433	566 - 653	580	477 - 550	512	315 - 409	367	714 - 797	687
SO _x (lb/10 ⁶ Btu)	0.90 - 0.95	0.84	1.23 - 1.29	1.28	0.98 - 1.14	1.05	0.59 - 0.71	0.68	1.38 - 1.47	1.33
NO _x (ppm)	210 - 241	199	402 - 494	655	777 - 925	862	468 - 533	496	321 - 440	366
NO _x (lb/10 ⁶ Btu)	0.25 - 0.34	0.26	0.56 - 0.80	1.05	1.17 - 1.37	1.27	0.57 - 0.76	0.67	0.42 - 0.65	0.51
Total hydrocarbons (ppm)	0.2 - 2.0	0.5	1 - 2	1	1	1	0.2 - 0.8	0.60	1	1
Opacity, ^b Uncontrolled (%)	1 - 6	3.5	15 - 48	18	10 - 11	10.5	6 - 17	7	10 - 14	12
Particulate										
Emissions (lb/hr) ^{b,c}	0.60 - 1.15	0.92	28.5 - 35.5	23.06	11.9 - 23.4	18.1	2.39 - 6.52	4.08	23.36 - 31.75	22.13
Emissions (lb/10 ⁶ Btu) ^{b,c}	0.02 - 0.04	0.03	0.07 - 0.126	0.35	0.44 - 0.87	0.67	0.09 - 0.243	0.154	0.86 - 1.15	0.86
Carbon content's (%) (loss on ignition method)	24.9 - 72.5	35.0	60.9 - 93.3	82.3	86.0 - 93.5	90.7	50.8 - 88.7	82.01	67.4 - 71.2	70.0

^a Data from report by PETC (See reference 21.)^b Boiler outlet.^c ASME test procedure

TABLE 1 (SHEET 3 OF 4)

OPERATING CONDITIONS AND BOILER PERFORMANCE^a

	No. 6 Fuel Oil		Slow Mix Burner		SRC Fuel		Fast Mix Burner		SRC Residual Fuel Oil		SRC-Water Slurry	
	Parametric Test Range	Avg of 18 Duration Tests	Parametric Test Range	Avg of 19 Duration Tests	Parametric Test Range	Avg of 6 Parametric Tests	Parametric Test Range	Avg of 11 Duration Tests	Parametric Test Range	Avg of 8 Duration Tests		
Thermal input (10 ⁶ Btu/h)	29.03 - 30.45	29.49	29.33 - 30.26	30.33	29.22 - 29.91	29.52	29.03 - 30.10	29.23	29.23 - 31.35	28.78		
Steam flow (lb/h)	23360 - 24390	23990	23920 - 24050	23884	23520 - 24410	24035	23760 - 24500	24191	23000 - 24430	23126		
Flue gas O ₂ (%)	0.6 - 5.1	2.4	3.0 - 5.4	5.3	2.7 - 5.5	4.0	0.4 - 4.4	2.6	2.1 - 4.0	3.0		
Excess air (%)	3.1 - 31.0	12.76	14.5 - 32.0	32.4	12.9 - 33.8	22.4	2.3 - 25.4	13.95	9.6 - 21.8	15.44		
Stoichiometric airflow (lb/h)	20280 - 21000	20708		20523	20070 - 20310	20191	19970 - 20440	19871				
Secondary airflow (lb/h)	18830 - 23250	21545	19860 - 23630	23085	18930 - 23840	21618	17880 - 23040	20371	17350 - 20560	17720		
Secondary air temp (°F)	495 - 610	503	503 - 615	578	504 - 601	563	502 - 604	595	499 - 570	600		
Primary airflow (lb/h)	1180 - 4446	2019	4450 - 4916	5296	3200 - 3508	3409	463 - 4573	2726	4380 - 5205	4549		
Primary air temp (°F)	63 - 76	69	44 - 56	74	71 - 89	79	44 - 94	36	492 - 561	591		
Fuel flow (lb/h)	1524 - 1573	1522	1690 - 1781	1673	1700	1700	1578 - 1626	1579	2568 - 2700	2444		
Fuel temp (°F)	210 - 217	208					288 - 304	301	101 - 165	97		
Fuel pressure at burner (psig)	61.7 - 62.3	59					90 - 100	94	85 - 90	89		
Atomizing air/steam (lb/h)	236 - 242	243					290 - 338	291	931 - 1350	1098		
Atomizing air/steam pressure (psig)		66.6					96 - 108	104	85 - 86	86		
Burner position (in.)	1 - 1	1	1/2 - 1 1/8	1/2	2 1/8	2 1/8	5/8 - 1 1/4	1/2	0	0		
Swirl setting	5 - 6	4	7 1/2 - 8	6 1/2	3 - 3 1/2	3 1/2	4 - 4 1/4	4	2 - 2 1/4	2		
Average flue gas temp (°F)	528 - 613	553	526 - 606	554	482 - 509	498	485 - 515	493	515 - 536	513		
Carbon conversion efficiency (%)	99.93 - 99.99	99.98	97.8 - 98.8	98.7	98.6 - 99.3	98.9	99.6 - 99.9	99.75	98.5 - 98.9	98.9		
Boiler efficiency (%) (heat loss method)	79.6 - 83.5	82.0	81.5 - 83.7	82.2	83.7 - 85.6	84.7	84.3 - 86.2	85.3	80.2 - 81.6	81.8		
Natural gas flow (scfm)			0	25.23 ^d	0	0						

^a Data from report by PETC. (See reference 21.)^d Average of 11 tests during which natural gas was used.

TABLE 1 (SHEET 4 OF 4)

PARTICULATE CONTROL DEVICE PERFORMANCE SUMMARY^a

	lb/10 ⁶ Btu	MMD	Inlet Average SCA	ACR	% Removal	Outlet Average lb/10 ⁶ Btu	ΔP/in. W.G.
Electrostatic Precipitator							
No. 6 Fuel Oil	0.050	0.25	240	-	91.35	0.004	-
SRC Fuel	0.959	21.8	230	-	99.46	0.005	-
SRC Residual Fuel Oil (Case 'A' only)	0.196	10.3	240	-	99.08	0.002	-
SRC-Water Slurry (Case 'A' only)	0.930	17.8	220	-	99.34	0.006	-
Pulse-Jet Fabric Filter (Data derived from reference 25; Evaluation of Fabric Filter, Tables 5, 6.1, 6.2, and 6.3.)							
	Inlet Average Gr/SDCF	ACR	Gr/SDCF	%Removal	Outlet Average lb/10 ⁶ Btu	ΔP, in. W.G.	
No. 6 Fuel Oil	Not tested				Not tested		
SRC Fuel ^a	0.39	3.9	0.026 ^d	93.5 ^d	0.06 ^d	1.4	
SRC Residual Fuel ^b	0.10	2.9	0.0018 ^d	98.1 ^d	0.005 ^d	1.3 ^e	
SRC Water-Slurry ^c	0.49	3.1	0.0017	99.7	0.004	2.1	
Reverse Air Fabric Filter (Data derived from reference 25; Evaluation of Fabric Filter, Tables 8, 9.1, 9.2, 9.3, 9.4, and 10.)							
	Inlet Average Gr/SDCF	ACR	Gr/SDCF	%Removal	Outlet Average lb/10 ⁶ Btu	ΔP, in. W.G.	
No. 6 Fuel Oil	0.015	2.1	0.005 ^h	73.8 ^h	0.011 ^h	1.5	
SRC Fuel ^a	0.46	2.3	0.001	99.8	0.002	3.2	
SRC Residual Fuel ^a	0.09	3.2	0.001	99.1	0.002	3.2	
SRC Water-Slurry ^a	0.39	3.3	0.005	98.7	0.011	3.3	

MMD = Mass median diameter in micrometers.

SCA = Specific collection area = $\frac{\text{ft}^2 \text{ of collection plate}}{1000 \text{ ACFM}}$ ACR = Air-to cloth ratio = $\frac{\text{ft}^3/\text{min}}{\text{ft}^2 \text{ cloth}} = \frac{\text{ft}}{\text{min}}$ through cloth.

W.C. = Water column in inches.

- Average of runs PJ-1, 6, 7, 8, 9, 10 (no inlet data available for runs 2-5).
- Average of runs PJ-11, 12, 13, 14, 15 (run 16 was at 50% ACR%).
- Average of runs PJ-17, 18, 19.
- Leaking bypass valve may affect data adversely.
- No data available for run PJ-12.
- Data from reports by Southern Research Institute and Wheelabrator-Frye. (See references 19, 24, and 25.)
- Average based on all data in Table 10, reference 25, time averaged [i.e., $\Sigma (\text{data point} \times \text{duration}) / \text{total duration}$] to offset variability.
- Low inlet dust loadings and short durations may have adversely affected data.

Parametric ASME combustion testing was conducted to evaluate the boiler and to determine optimum boiler operating conditions. The variables adjusted were excess air, secondary air temperature, and burner design parameters. Conditions for the steady-state duration tests were based on the parametric test results.

The carbon conversion efficiencies obtained in all SRC tests conducted at full boiler load were high, ranging from 97.8 to 99.9 percent. The duration tests, conducted at full boiler load with approximately 600°F air preheat, resulted in average carbon conversion efficiencies of 99.75 percent for SRC Residual Fuel Oil and 98.9 percent for SRC-Water Slurry. Parametric tests with the fast mix burner, at full boiler load with an average 563°F secondary combustion air preheat, resulted in an average carbon conversion efficiency of 98.9 percent for pulverized SRC Fuel.

Average boiler efficiencies (ASME PTC 4.1 procedures) obtained in the SRC Fuel and SRC Residual Fuel Oil tests were higher (84.7 percent and 85.3 percent, respectively) than when burning No. 6 Fuel Oil (82.0 percent) at full boiler load with 503°F air preheat. The average boiler efficiency obtained in the SRC-Water Slurry tests (81.8 percent) was comparable to that achieved when burning No. 6 Fuel Oil.

Since the PETC combustion facility was designed for oil, modifications were required to permit the firing of SRC. Some operational problems were encountered because of the modifications. Facility modifications and the resulting problems were most easily handled with the SRC Residual Fuel Oil. The SRC-Water Slurry required constant agitation but in other respects approached the SRC Residual Fuel Oil in terms of handling ease. The SRC Fuel testing required extensive system modifications and as a result presented the most difficult operational problems.

The problems with the SRC Fuel were related to fuel handling and burner design. The fuel handling problems would be eliminated in a commercial installation by feeding the SRC Fuel directly from a pulverizer to the boiler without storing the pulverized material in a bin as was required for this test program. At PETC, a carefully developed handling arrangement was necessary to achieve uniform forwarding of the fuel from the bin to the boiler.

Two different burner designs, designated as fast mix and slow mix were evaluated with the SRC Fuel. The fast mix burner represents a significant step in the development of a commercial burner for SRC Fuel; stable combustion was easily achieved, reasonable excess air levels were attainable, and carbon conversion was good. Unfortunately, this burner was developed too late in the program for duration testing. The slow mix burner was tried first and used for most of the SRC Fuel tests. (It was similar to the design used previously in SRC Fuel testing with a multiburner, coal-designed boiler at Georgia Power Company's Plant Mitchell.) The slow mix burner yielded clinkers at the burner tip and required higher than normal excess air levels and natural gas support for over half the slow mix duration tests.

The tested SRC forms and, in general, coal-derived fuels which have not undergone extensive hydrotreating have an inherently higher than normal level of fuel bound nitrogen.

The results of the test program are consistent with the expectation of generating high levels of NO_x when NO_x control measures are not employed. During the planning phases of this test program, discussions were held to evaluate what modifications to the burner and/or boiler could be accomplished. Modifications reviewed included use of a dual-register burner and staged combustion; however, capital restrictions and, most important, the need to avoid permanent modification to the boiler precluded any NO_x control efforts.

Current research indicates that NO_x problems are created by a high oxygen concentration at the point of combustion. Refinements to reduce the oxygen concentration in the initial combustion zone have been developed for similar component fuels with excellent results.

In retrospect, the problems encountered with all the fuels were not combustion performance related but were mechanical problems and limitations. The problems were in most related to shortcomings of this burn test program and would not be experienced in a commercial facility.

The overall results from the 700-hp boiler SRC combustion tests have shown that oil-designed boilers can utilize SRC fuel forms, achieving high boiler efficiencies and full boiler rating.

1.3 FLUE GAS AREA CONCLUSIONS

In addition to the combustion evaluation, this program included a detailed characterization of the flue gas particulates for each fuel and real time evaluation of particulate removal devices.^{19, 23, 24, 25} The particulate removal devices evaluated were:

- A pilot electrostatic precipitator.
- A pulse-jet fabric filter dust collector.
- A pilot reverse air fabric filter dust collector.

1.3.1 ELECTROSTATIC PRECIPITATORS

The tests performed with the electrostatic precipitator (ESP) were: mass loading, particle size distribution (inlet and outlet), efficiency, flue gas analysis, and electrical operating parameters. The data from these tests were used as input parameters for the Environmental Protection Agency/Southern Research Institute computer modeling program.¹³

In summary, the test program demonstrated that an ESP will work with high collection efficiency on the flyash from all fuel forms of SRC as fired in an oil-designed boiler. (See Table 1.) The ESP for any of the SRC fuel forms would be of conventional design.¹⁴

Since over 99 percent of the ash has been removed from the parent coal used to prepare SRC, less flyash is produced from the combustion of the SRC fuels. With the burners

available at PETC, high carbon content was found in the ash, thereby increasing the potential fire hazard. However, commercial ESPs have operated for years without problems in the coke and carbon black industries where the percentage of carbon in the ash is very high. Therefore, a properly designed and maintained ESP should experience minimal fire hazard risk with SRC ash. Burner optimization to provide for better burnout could further reduce or eliminate this risk.

1.3.2 FABRIC FILTER DUST COLLECTORS

Both pulse-jet and reverse air fabric filter collectors will also work at very high efficiencies on all three forms of SRC tested. (See Table 1.) There is no irreversible bag blinding and pressure drops are within the normal design range. A fabric filter collector for any of these applications would be of conventional design.¹⁴

1.3.3 DRY CYCLONE DUST COLLECTORS

Many utility oil-fired boilers are not equipped with electrostatic precipitators or fabric filter collectors but do have cyclone or multiclone mechanical collectors. Assuming that the total mass loadings and particle size distribution produced at PETC are representative of a full-scale boiler, the outlet loadings given below were calculated for dry cyclone collectors.

Fuel	Outlet Loading (lb/10 ⁶ Btu)	Pressure Drop (in. W.C.)	Cyclone Efficiency (%)
No. 6 Fuel Oil	0.034	6.0	6.4
SRC Fuel	0.072	6.0	91.0
SRC Residual Fuel Oil	0.041	6.0	76.9
SRC-Water Slurry	0.181	6.0	81.5

1.4 FUTURE RESEARCH NEEDS

This program accomplished its objectives and also identified some specific directions where future development effort should be channeled. The future research needs identified include:

- Further development of the demonstration plant configuration, to maximize production of the SRC Residual Fuel.
- Dilute-phase and dense-phase pneumatic transport study for pulverized SRC Fuel.
- Demonstration of the fuels in a large field-erected boiler designed for firing fuel oil at high heat release rates typical of utility boilers.
- Burner optimization to improve combustion efficiency for each fuel form.
- NO_x combustion control techniques for each fuel.

- A study of SRC heat transfer characteristics within the boiler to determine impact on boiler design.
- Further studies into problems associated with mixing SRC Residual Fuel Oil and No. 6 Fuel Oil.
- Longer term electrostatic precipitator studies.
- Longer term fabric filter studies.
- Organic-based surfactants investigation for the SRC-Water Slurry.¹⁴
- Engineering tests and comparative economic evaluation of mechanical collectors.

2.0 INTRODUCTION

2.1 BACKGROUND

Initial SRC combustion tests in this country were performed in 1964 by Babcock & Wilcox with fuel prepared by the Pittsburgh & Midway Coal Mining Company.¹⁷ This work was done under contract to the U. S. Office of Coal Research. Earlier work had been done in Germany in the 1920's and 1930's, and later the direct-coal liquefaction technology was applied to the preparation of aviation fuels for the German air force in World War II.

The Pittsburgh & Midway Coal Mining Company has been involved in SRC process development since the early 1960's and in recent years emphasized the development of liquid products at their pilot plant in Ft. Lewis, Washington. This pilot facility was recently dismantled, but at its peak it produced 25 to 30 tons of SRC per day. A second, smaller facility completed in 1973 is still in operation at Wilsonville, Alabama (adjacent to Alabama Power Company's Plant Gaston). The Wilsonville Advanced Coal Liquefaction Research and Development Facility, funded by the Electric Power Research Institute (EPRI) in conjunction with the Department of Energy (DOE) and managed by Southern Company Services (SCS), is capable of producing about 3½ tons of SRC per day from about 6 tons of coal and can also produce SRC Residual Fuel Oil.²⁰ This facility has performed various tests in support of the SRC Demonstration Plant Project. (See Section 4.2.) The Wilsonville facility is currently working on the development of a two-stage liquefaction process for the production of clean liquid fuels from coal.

In 1976, SRC combustion tests were conducted by the U. S. Energy Research and Development Administration at the Pittsburgh Energy Research Center (now the Pittsburgh Energy Technology Center (PETC)). This testing was performed in a 500 lb/hour coal-designed fuel furnace.¹⁵ During that same period, studies were conducted under EPRI sponsorship by Combustion Engineering (C-E) and Babcock & Wilcox (B&W).^{4, 5, 6, 7, 11}

The environmental and economic advantages of SRC Fuel (pulverized SRC) were confirmed during a major burn test conducted in 1977 by SCS in a 22-MW coal-designed electric utility boiler at Georgia Power Company's Plant Mitchell, near Albany, Georgia.¹⁸ The test, supported by the U.S. Energy Research and Development Administration (now DOE), the U.S. Environmental Protection Agency (EPA), and EPRI, was an unqualified success and a significant milestone in the overall objective of qualifying coal-derived fuels for a variety of future energy needs. During the 18-day test program, 3000 tons of pulverized SRC Fuel (the total Pittsburgh & Midway inventory at that time) was burned with essentially the same efficiency as coal. Only minimal modifications to the system were necessary to handle and burn the SRC Fuel. During the test, SRC Fuel revealed these distinct advantages:

- No slag or ash buildup.
- Need for a minimum of soot blowing.

- Compliance with 1971 New Source Performance Standards (NSPS) for SO₂ and NO_x emissions.
- Ninety percent less particulate emissions than the levels resulting from burning coal.
- A precipitator of conventional design could be used to meet the then applicable particulate emission standards.
- Twenty-five percent lower power requirements for pulverizing SRC Fuel versus coal.
- Transportation and handling with conventional equipment.

Results of this burn test also showed that SRC Fuel has a combustion efficiency of 98.5 percent and a boiler efficiency of 86 percent which are similar to those results achieved when burning coal. The SO₂ emission rate of 0.94 lb/10⁶ Btu at the boiler outlet is comparable to burning a low-sulfur coal. The NO_x and particulate matter emissions at the boiler outlet of 0.45 and 0.1 lb/10⁶ Btu, respectively, were lower than for the coal normally burned at the plant.

Subsequent analysis of the properties and performance of pulverized SRC at Plant Mitchell indicated that SRC could be a substitute for No. 6 Fuel Oil in oil-fired, coal-capable utility boilers and suggested that it may be used as substitute fuel in oil-designed, noncoal-capable boilers as well. This hypothesis, however, needed to be tested in a more compact oil or gas-designed boiler that had a significantly higher heat release rate than the Plant Mitchell boiler and which could be operated with the limited quantities of SRC available.

In 1980, the International Coal Refining Company (ICRC) was commissioned by DOE to ascertain the technical and marketing aspects associated with burning SRC in oil- and gas-designed boilers. It was determined that the most economical and expedient way of obtaining the necessary information on technical feasibility and boiler scaleup was through a test program that was ultimately conducted at PETC.

The overall PETC combustion test program involved two phases. The first phase of the PETC program was completed in October 1980. SRC in pulverized, slurried, and melted forms was successfully fired in the 100-hp (184 x 10³ Btu/ft³-hour, 3450 pounds of saturated steam per hour at 100 psig) four-pass firetube boiler designed for burning oil at very high volumetric heat release rates. Concurrently with the combustion tests, a pilot scale reverse air fabric filter particulate control device was tested by Wheelabrator-Frye and it exhibited excellent particulate collection efficiency.¹⁶

This test program showed that SRC could be burned in a 100-hp oil-designed firetube boiler. Combustion efficiencies of more than 99 percent and boiler efficiencies of 82 percent were similar to those achieved with No. 6 Fuel Oil. Uncontrolled SO₂ emissions were less than 1.2 lb/10⁶ Btu, which was below the NSPS at that time; particulate emissions were similar for SRC and No. 6 Fuel Oil. A higher level of NO_x was expected and observed due to the higher nitrogen content in the SRC and the very high heat release rate of the furnace.

The second phase of the SRC combustion test program at PETC was initiated in August 1982 in the 700-hp boiler (30×10^6 Btu/hour). The combustion test plan for each fuel was essentially the same. A full week of parametric ASME combustion tests was scheduled to determine optimum boiler operating conditions using a multifuel burner. The principal operating variables addressed were excess air, secondary combustion air temperature, and burner operating parameters (design, swirl, and position) as time would permit. Steady-state duration tests were then conducted at selected operating conditions for a minimum of 1 week to evaluate the performance of particulate control equipment. Duration conditions were determined from the previous week of parametric tests.

The results of this second phase of SRC combustion testing at PETC represent a major milestone in the development of the ICRC Product Demonstration and Applications Engineering (PD&AE) Plan. This plan provides for the full demonstration of the pulverized form during the 3-year demonstration period following the startup of the plant and further application development of the SRC Residual Fuel Oil form during that time. The success of the initial SRC-Water Slurry burn test indicates that this potential product should be developed in conjunction with the residual fuel.

As a result of these developmental tests, the product flexibility of the SRC-I Demonstration Plant has been increased which will provide for the utilization of all the products of the plant by more and varied end users.

2.2 OBJECTIVES

2.2.1 OVERALL OBJECTIVES

Oil-designed boilers have been identified as the primary market application for SRC, and it is the intent of ICRC to demonstrate that SRC can be reasonably substituted for No. 6 Fuel Oil in these boilers.

A need for a domestically based substitute fuel exists in the oil-designed boiler area because of the foreign control, diminishing supply, decreasing quality, and rising cost of No. 6 Fuel Oil. The three problems below are essentially responsible for these developments.

- A. The availability of quality No. 6 Fuel Oil, as defined by the electric utility industry (specifications given on the next page), is diminishing and the price is increasing because the oil wells being drilled today are deeper, more costly, and often yield a poorer quality product.

NO. 6 FUEL OIL SPECIFICATIONS

	Typical ^a	Used at PETC
Ultimate analysis (%)		
Hydrogen	10-11	11.72
Carbon	~ 85	82.38
Nitrogen	0.3-0.8	0.23
Sulfur	~ 1	0.65
Oxygen	~ 1	4.93
Ash	0.02-0.04	0.10
Moisture	~ 0.3	6.48
Vanadium (ppm)	20-150	not available.
Heating value (Btu/lb)	18,300-18,800	17,469

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

- B. For economic reasons, petroleum refineries are installing additional equipment to produce more distillate fuel and less No. 6 Fuel Oil per barrel of crude oil.
- C. The heavy consumption of No. 6 Fuel Oil to fire refinery cokers further reduces the supply of fuel available commercially.

These problems will certainly continue and worsen with time. So, in the future, acceptable quality No. 6 Fuel Oil will be available to utilities only at a premium price and will in time be priced on parity with crude oil. Poor quality No. 6 Fuel Oil with high sulfur, high asphaltene, and high metal content, including vanadium, will probably be available but it will present operational problems and require the installation of electrostatic precipitators, scrubbers, and other cleanup equipment.

SRC products can directly serve this market with a viable alternate domestic fuel source. This is extremely important to utilities with newer oil-fired electric generating plants that have expected lives of 30 years or more and will continue to demand alternate fuel well beyond the year 2000. Signed letters of intent to purchase the SRC from the SRC Demonstration Plant have been received by ICRC from Florida Power and Light Company and Commonwealth Electric Company.

2.2.2 PROGRAM OBJECTIVES

The specific objectives of the SRC burn test program for the 700-hp watertube, oil-designed boiler support the overall objective of ICRC. These specific objectives are defined here.

- A. Demonstrate combustion of SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry.

a. Provided by Florida Power and Light Company.

1. Confirm that combustion can be accomplished in a watertube, oil-designed boiler.
 2. Confirm that the full rating of the boiler can be obtained.
 3. Obtain design information for fuel handling and combustion equipment modifications.
 4. Define combustion properties of SRC fuels.
 5. Pinpoint future development needs.
- B. Demonstrate the applicability of current emission control equipment to the SRC Fuel forms tested.
1. Determine levels of particulates and gaseous emissions.
 2. Obtain design data for electrostatic precipitators.
 3. Obtain design data for fabric filter dust collectors.
 4. Obtain design data for mechanical dust collectors.
- C. Assemble a comprehensive report on SRC.
1. Discuss and review combustion performance and fuel preparation and handling.
 2. Suggest research and development areas for future programs.
 3. Evaluate commercial scale design considerations and economics of conversion. (Discussed in Volume II of this report.)

2.3 TEST PROGRAM ORGANIZATION

In order to bring a wide range of expertise to the test program, many participants were involved. Table 2 at the end of this section summarizes their roles. A detailed discussion of participant qualifications and test program responsibilities is given in Appendix A.

2.4 DOCUMENTATION FOR THE TEST PROGRAM

This test program yielded literally volumes of data, observations, and results. The efforts of many individuals were required to evaluate and report this information. Major individual participant reports were prepared by PETC,²¹ SoRI,¹⁹ WFI,^{23, 24, 25} B&W,³ and C-E.¹⁰ This final report represents an integration of these reports and an overview of the entire test program. Detailed information that does not appear in the final report can be obtained as referenced from the individual reports. These are available as Annex Volumes A-F.

The preparation of this final report was managed by the Engineering Publications Section of SCS with assistance from the SCS Research and Development Department and ICRC. The Engineering Publications Section also scheduled and coordinated the production of the participant reports.

2.5 DIRECTIONS FOR SRC DEVELOPMENT

The PETC test program represents a culmination and integration of several PD&AE Plan programs. These programs include:

- Combustion of solid, liquid, and slurry forms of SRC.
- Viscosity and stability studies.
- Small boiler evaluation.
- Coordination with customers and vendors.
- Alternative process design studies.

In reviewing the test objectives and the results obtained, the SRC burn test program at PETC has confirmed that these fuels can be combusted satisfactorily in an oil-designed watertube boiler and that conventional particulate control equipment will perform satisfactorily. This scale of testing has provided the basis for continued fuel development toward full-scale utility application. The results of this test program also point the way to specific development programs. These development programs include:

- A. As a result of the success with SRC Residual Fuel Oil in the PETC tests, further development of the demonstration plant configuration is appropriate to determine the most cost effective means of producing this fuel.
- B. In accordance with the SRC PD&AE plan, the SRC fuels require demonstration in a full-scale, oil-designed boiler. In addition, the SRC Residual Fuel Oil research should be expanded and the SRC-Water Slurry should be added to this program.
- C. There is a need to study the dilute-phase and dense-phase pneumatic transport of pulverized SRC Fuel in more detail. This is the system which transports the pulverized fuel from the pulverizers to the boiler burners in a full-size unit. There were some indications that pulverized SRC Fuel performs differently from pulverized coal in this application.
- D. Burner optimization is required for the SRC Fuel and further optimization with the SRC Residual Fuel Oil and SRC-Water Slurry would probably improve the performance of these SRC Fuel forms also.

- E. NO_x combustion control techniques need to be applied to these fuels. Current research by others on synthetic fuels indicates the NSPS standard of 0.5 lb/10⁶ Btu can probably be accomplished by one or more techniques.
- F. The heat transfer characteristics of SRC within the boiler are different from that of No. 6 Fuel Oil. The SRC forms, as fired in this program, release more heat in the furnace box and less in the convection section. It is presumed that the highly luminous SRC flame radiates more heat than No. 6 Fuel Oil. Operating changes to the steam side of the boiler can be used. Alternatively, this might be compensated for by different firing techniques such as what might be used for NO_x control. These points need to be evaluated as to their impact on boiler operation.
- G. Longer term electrostatic precipitator studies should be performed in order to evaluate the degree of particulate reentrainment from rapping.
- H. Longer term fabric filter studies are needed to adequately determine differential pressure and filter cake release characteristics.
- I. Long-term compatibility studies are necessary for SRC Residual Fuel Oil in a full range of No. 6 Fuel Oils to determine the effects on sludge formation.
- J. Rheology studies are needed to develop higher SRC-Water Slurry concentrations, in conjunction with lower-ash wetting agents.
- K. Long-term storage tests with the SRC-Water Slurry are needed.

In addition, it is important to relate the findings of this test program to a commercial scale, utility-size installation. Working with the Massachusetts-based Commonwealth Electric Company, B&W, and SCS, ICRC selected the Canal Unit No. 2, a nominal 500-MW oil-fired unit, for an SRC economic and engineering assessment. This assessment takes the data from the PETC tests and evaluates the capital and operating costs associated with conversion to each of the three SRC forms. The findings are presented in Volume II of this report.

TABLE 2 (SHEET 1 OF 2)**TEST PROGRAM ORGANIZATION**

Company	Function
United States Department of Energy - Oak Ridge Operations	SRC Project Manager
International Coal Refining Co.	Program Development Program Management
Southern Company Services, Inc.	Onsite Management Report Preparation Program Development Technical Advisor
United States Department of Energy - Pittsburgh Energy Technology Center	Host Facility Program Design Facility Management Combustion Data Compilation
General Electric Maintenance and Technical Services Co.	Facility Operational Contractor-PETC
Southern Research Institute	Electrostatic Precipitator Analysis Flue Gas Particle Characterization Fabric Filter Collector Analysis Electrostatic Precipitator Supplier and Operator
Wheelabrator-Frye, Inc.	
Babcock & Wilcox, Inc.	Boiler Vendor Technical Observer
Combustion Engineering, Inc.	Boiler Vendor Technical Observer
Florida Power & Light	Product Demo Customer Technical Advisor
Commonwealth Electric	Product Demo Customer Technical Advisor
Electric Power Research Institute	Technical Observer

TABLE 2 (SHEET 2 OF 2)

Company	Function
Massachusetts Institute of Technology	Technical Observer
Beard, Diaz, & Weidman and Associates, Inc.	Burner Design
Jenike & Johansen, Inc.	Solids Handling Design
Catalytic, Inc.	Facility Operational Contractor-Wilsonville Residual Oil Preparation
Empire Coke, Inc.	SRC Crushing Contractor

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3.0 FACILITY DESCRIPTION

The burn test program involved determination of appropriate fuel handling procedures, combustion parameters, and particulate control equipment for each fuel tested. This section of the report discusses the facilities and procedures implemented during the test program. Flow diagrams for fuel handling and for the flue gas treatment area are given in Figures 1 through 5. For a more detailed description of the combustion facility see Reference 21 and for more information on the flue gas area see References 19, 24, and 25.

3.1 ONSITE FUEL HANDLING

In order to successfully demonstrate that SRC products are an attractive alternative fuel for oil-designed utility and industrial boilers, it was important to develop appropriate and reasonable fuel storage and handling procedures for each fuel tested and to compare these to No. 6 Fuel Oil. The procedures and the equipment employed for each fuel are presented here, beginning with No. 6 Fuel Oil.

3.1.1 NO. 6 FUEL OIL

No. 6 Fuel Oil was stored in an insulated 60,000-gal carbon steel storage tank equipped with an internal steam coil capable of maintaining the fuel oil at 100°F. A Brown Fin Tube Company suction heater heated the fuel oil from 100°F to 140°F as a Roper Type 1 pump fed the oil through a fuel strainer manufactured by Zurn Industries, Inc., and into the suction side of a variable speed, progressing cavity, 3-hp Moyno pump located inside the combustion test facility. A Brown Fin Tube Company steam shell-and-tube heat exchanger raised the No. 6 Fuel Oil temperature from 140°F to 220°F immediately upstream of the burner. Fuel flow was measured with a mass flowmeter manufactured by Micro Motion, Inc., and a volumetric flowmeter by International Telephone and Telegraph.

3.1.2 SRC FUEL

Crushed SRC was prepared and shipped as described in Section 4 and stored in five enclosed railroad cars at the Hazelwood railyard about 10 mi from PETC. The SRC was unloaded with a portable conveyor into a covered dump truck for transport to the facility. Each truck carried approximately 10 tons of SRC to PETC where it was unloaded into a 22-ton storage bin. A Mikropul ACM-10 rotating hammermill pulverizer was modified to process 1500 lb/hour of SRC Fuel at 90 percent through a 200-mesh sieve (later at 70 percent through 200 mesh to improve handling characteristics). This pulverizer was well suited for this application because of its low internal operating temperatures.

The ACM-10 pulverizer fed a Petrocarb pulverized solid fuel storage and injection system which was used to store approximately 6 tons of pulverized SRC Fuel and deliver it to either the 400-ft³ Vibra Screw pulverized solid feed bin or the 18-ton pulverized solid storage bin. The 18-ton storage bin was used to feed pulverized SRC Fuel to the Vibra Screw feed bin using a dense-phase pneumatic transport system.

FIGURE 1
NO. 6 FUEL OIL FLOW DIAGRAM

FIGURE 2
PULVERIZED SRC FUEL FLOW DIAGRAM

FIGURE 3
SRC RESIDUAL FUEL OIL FLOW DIAGRAM

FIGURE 4
SRC-WATER SLURRY FLOW DIAGRAM

*TO OBTAIN AN ELECTROSTATIC PRECIPITATOR INLET TEMPERATURE OF ABOUT 300°F, THE FLUE GAS LINE TO THE ELECTROSTATIC PRECIPITATOR WAS NOT INSULATED.

FIGURE 5
FLUE GAS AREA FLOW DIAGRAM

The pulverized SRC Fuel was transported to the top of the Vibra Screw feed bin, which held about a 6-hour supply of fuel. The feed bin, shown in Figure 6, was equipped with vibrators on the hopper, load cells, and an explosion vent rupture disc. The bin was maintained under a positive nitrogen pressure with a continuous purge venting out the top through a backpressure regulating valve. Several nitrogen purge and/or fluidizing taps were located on the bin bottom and on the feed screw for use as required. A rotary airlock was installed to isolate the dust collector at the top from the feed bin.

Two air blowers staged in series (described in the combustion air system discussion) were used to carry the pulverized SRC Fuel through a 6-in. transport line to the boiler some 70 ft distant. The 6-in. transport system was designed to withstand at least a 50-psig explosion pressure, and a similarly designed containment was constructed around the blower. At full load, approximately 1800 lb/hour of SRC Fuel was fed from the bin into the downstream blower suction using a Vibra Screw Model HD-2 variable speed feeder. Any agglomeration of SRC Fuel particles that occurred in the handling and storage of the fuel was to be broken up by feeding the SRC Fuel through the downstream primary air blower which incorporated a 21-in. diameter wheel rotating at 3600 rpm.

A 6-in. butterfly valve located downstream of the blowers was used to control the primary airflow. This flow was measured using a Brandt flowmeter located upstream of the feed screw. Also, an 8-in. automatic butterfly valve was installed between the blowers, and a knife-gate valve was used at the screw discharge to provide a positive shutoff of the SRC Fuel flow.

3.1.3 SRC RESIDUAL FUEL OIL

The SRC Residual Fuel Oil, approximately 55-percent pulverized SRC dissolved in SRC process-derived solvent, was prepared by Catalytic, Inc., at Wilsonville, Alabama, and shipped to PETC in six insulated 6000-gal tank trucks. (See Section 4.1.2.) A nitrogen blanket was maintained over the fuel in the tank trucks to prevent volatiles in the fuel from escaping. Low pressure steam was connected to the parked trucks to maintain the fuel at a temperature between 150°F and 180°F.

When required for testing, the fuel was unloaded from one of the trucks into a 3500-gal storage tank. The storage tank was sealed and inerted with a nitrogen blanket maintained at 1.0 to 1.5 psig; a rupture disc set at 2.5 psig provided overpressure protection. External steam coils maintained the SRC Residual Fuel Oil in the tank at 200°F. Any vapors from the tank passed through a recycle condenser and a charcoal filter to remove the vapors from the vent gas.

A fuel delivery system was designed to supply 200 gal/hour of SRC Residual Fuel Oil at 325°F and 100 psig to the boiler. An AC frequency-controlled, variable speed motor driving a DeLaval positive displacement pump fitted with Kalrez seals was used to pump and control fuel flow. Fuel flow was measured with a Micro Motion flowmeter. Two series-connected Brown Fin Tube Company steam heaters were used to heat the fuel to about 325°F. The fuel was then routed to the boiler or recirculated back into the storage tank by means of an air actuated block valve and an air actuated recirculation valve which

FIGURE 6
SRC FUEL FEED BIN

were interlocked. These valve positions were interlocked with the boiler flame monitoring system and determined whether the fuel was recirculated or fed into the boiler. An effort was made by operating personnel to minimize the amount of hot fuel recirculated to reduce the quantity of vapors generated in the tank. One hundred seventy-five psig steam was available at the burner to atomize the SRC Residual Fuel Oil.

3.1.4 SRC-WATER SLURRY

The slurry feed system employed was an existing coal slurry feed system; only a few minor modifications were required. SRC-Water Slurry mixtures were prepared in an 1800-gal mix tank equipped with an agitator motor driving two sets of turbine blades within the tank. Mixtures were prepared by charging a measured amount of ambient temperature water into the mix tank, starting the agitator motor and the air-powered Sandpiper diaphragm recirculation pump, adding a measured amount of wetting agent, Lomar D, (approximately 0.5 percent of the total weight), and then adding SRC pulverized to 90 percent through 200 mesh (70 percent through 325 mesh). The mixture was continuously agitated and recirculated while the SRC was dropped into the tank. Using this method, approximately 1200 gal of a 65- to 67-weight percent mixture were prepared in each batch.

The prepared slurry mixture was transferred by a Sandpiper air-powered diaphragm pump to a 2800-gal steam-jacketed, hold tank equipped with an agitator motor driving two turbine blades and a Moyno recirculation pump driven by a fixed speed AC motor. The SRC-Water Slurry flowrate to the boiler was regulated by a variable speed, progressive cavity, 5-hp Moyno pump and was measured by a Micro Motion mass flowmeter. The pump was fitted with an elastomer liner, Buna-N stator, and a 0.010-in. undersized chrome-plated rotor.

3.2 BOILER

A 700-hp, two-drum, D-type packaged, watertube, industrial boiler designed for oil firing was used for all tests. The boiler front and a horizontal cross-sectional plan view are given in Figure 7. The boiler was manufactured by the Nebraska Boiler Company and is designed to generate 24,000 lb of saturated steam per hour at 175 psig with a heat liberation rate of 47,100 Btu/ft³-hour at full capacity. About 1600 to 1700 lb/hour of SRC Fuel corresponds to full load for the boiler.

FIGURE 7 (SHEET 1 OF 2)
700-hp OIL-DESIGNED BOILER

FIGURE 7 (SHEET 2 OF 2)
700-hp OIL-DESIGNED BOILER
(PLAN VIEW)

DESIGN AND OPERATING SPECIFICATIONS FOR THE 700-hp BOILER

Boiler ID: Watertube "D" NS-B-40

Convection heating surface: 1956 ft²

Radiant heating surface: 518 ft²

Furnace size: 6.3 ft W x 13.3 ft L x 7.4 ft H

Design steam capacity: 24,000 lb/hour

Design pressure: 250 psig

Operating pressure: 175 psig

Feedwater supply temperature: 227°F

Sootblower: One Boyer Type VH valve-in-head

The radiant section of the furnace is comprised of a welded-wall construction of finned, 2-in. o.d., electric resistance welded carbon steel boiler tubes. The tubing bank in the convection section of the boiler consists of the same carbon steel tubing employed in the radiant section. The combustion gases flow from the radiant section of the boiler through the convection section. Four baffles of 18 gauge 304 stainless steel plates are positioned in the convection section of the boiler to direct combustion gases, maximize residence time, and alter gas velocity. The open cross-sectional area of the convection section, excluding the baffle is 8.2 ft² and the cross-sectional area in the plane of the baffle is 4.906 ft².

The convection section of the boiler is supplied with a sootblower, Boyer Type VH valve-in-head. Two Tate-Jones sight glasses are located on the back furnace wall and two are located on the side of the boiler to afford the boiler operator a good view of the flame when making critical boiler operating parameter adjustments.

The 175-psig steam generated by the boiler is condensed in an air-cooled condenser, collected in a hotwell tank, forwarded through a subcooler section of the air-cooled condenser, and passed on to a deaerator tank. The flue gas leaving the boiler passes through a damper valve which controls furnace pressure. The flue gas then enters a shell and tube heat exchanger cooler which uses ambient air to control the flue gas temperature at the cooler exit.

3.3 COMBUSTION AIR SYSTEM

The combustion air system supplied about 6000 scfm of primary and secondary air for the 700-hp boiler. As indicated in Figures 1 through 4, the combustion air system arrangement depended on the fuel being tested.

For the No. 6 Fuel Oil and the SRC Fuel Residual Oil tests, a Buffalo Forge forced draft fan designed to supply a volumetric airflow of 1500 scfm at a static pressure of 24 in. W.C. was used to supply primary air. For the pulverized SRC Fuel tests, two Buffalo Forge primary air fans were required to achieve the fuel flow necessary to reach full load and to increase primary air velocity to prevent fallout of fuel in the transport line; one fan was installed upstream of the SRC Fuel feed point to put the feed point under positive pressure and the other fan was located downstream of the feed point to provide suction on the pulverized fuel. Because the SRC Fuel passed through the downstream fan which incorporated a 21-in. diameter wheel rotating at 3600 rpm, any agglomerations of the SRC Fuel that may have developed in handling and storage were broken up. For the SRC-Water Slurry, primary air was actually provided by the secondary air fan as shown in Figure 4. Ambient temperature primary air was used for all fuel tests except the SRC-Water Slurry test which used preheated primary air.

Primary airflow for all fuel tests except the SRC-Water Slurry was measured with an 8-in. Brandt Industries flowmeter located upstream of the fan(s). The SRC-Water Slurry primary airflow was measured with a 10-in. Brandt Industries flowmeter. A silencer was provided on the inlet and an 8-in. butterfly valve was incorporated upstream of the SRC Fuel feed point to provide positive shutoff of the primary airflow if so actuated by the blower logic system. A primary air control valve was located between the blower and the burner to control primary airflow. Secondary airflow was measured with an 18-in. Brandt Industries flowmeter. The secondary combustion air could be heated up to 600°F by combining heated air from a Joy centrifugal compressor, preheated to 1100°F in two oil-fired, closed-cycle indirect heaters located downstream of the Joy compressor, with ambient temperature air from a Buffalo Forge forced draft fan. This arrangement is shown in Figure 1.

3.4 BURNER DESIGN

The air register assembly, manufactured by the Coen Company, was a packaged single-air-zone type with a wide-flare refractory throat 21 in. deep incorporating a 9-in. offset extension. This assembly was used for all tests and with all burners discussed. Surrounding the burner was a 2-ft 3/8-in. diameter gas ring bustle pipe for the admission of natural gas as a startup fuel. The basic air register, extended tile throat, and gas ring bustle pipe are commercially available equipment.

The consulting firm of Beard, Diaz, and Weidman and Associates, Inc., was retained by ICRC to design a multifuel burner suitable for all fuels tested. The original burner design was modified by PETC in several ways prior to fabrication. First, instead of welding the burner to the single air zone cover flange, a slide fit and seal was designed to allow axial movement of the burner during operation. This arrangement allowed for relatively easy burner removal and maintenance. A jack screw was used to make the axial burner

adjustments. Second, instead of welding an elbow to the burner, the elbow was flanged to the burner for easier maintenance, and the angle of the elbow was changed from 90° to 67° to clear the boiler instrument panel. Third, to improve burner performance with pulverized SRC Fuel, 30° spinvanes were installed on the guide tube to impart a spin cocurrent with the secondary airstream and the primary tangential inlet swirl.

The burner incorporated a guide tube to support and locate a Coen Company Model No. 2 mV oil burner gun assembly. The nozzle is illustrated in Figure 8. The guide tube was 2 1/2-in. schedule 40 steel pipe. The pipe was positioned concentrically inside the 6-in. burner tube. The guide tube exited on the horizontal center line of the long radius elbow that connected the burner to the primary air system.

The modified burner, shown in Figures 9 and 10, was used for the No. 6 Fuel Oil tests, the SRC Residual Oil tests, and with spinvanes added, for the initial phase of the pulverized SRC Fuel tests. The burner in Figure 10 is identified as the modified 6-in. slow mix burner with cocurrent spinvanes because a subsequent design provided faster mixing of the primary air fuel stream.

Because of problems encountered with the modified 6-in. slow mix multifuel burner during the SRC Fuel burn test, the 67° elbow was replaced with a tangential inlet elbow (Figure 11) to achieve better distribution of the SRC Fuel in the burner. This modification is illustrated on a slow mix burner in Figure 12. A 6-ft section of specially designed flexible hose was used to make the connection from the tangential inlet to the primary air line.

To increase the exit velocity at the burner tip and reduce deposit buildup on the burner, the burner depicted in Figure 13 was fabricated. The burner offered the ability to increase and control the velocity of the primary air and thereby control the secondary airflow without destroying flame shape. In addition, this burner design permitted control of the ignition zone of the flame. This control kept the flame the proper distance off the burner and reduced the burner tip temperature and problems associated with deposit buildup on the burner tip. In an attempt to improve the burner performance even more, 30° spinvanes were installed in the primary airstream to impart a spin counter current to that of the secondary air and the primary air tangential inlet swirl (Figure 14). This improved mixing and yielded better combustion by breaking up any agglomerations that came through the primary airstream. Because the 6-in. burner incorporated a flat 1-in. wide, donut-shaped burner tip as part of the cooling water jacket, eddy currents developed during operation and some deposits still built up on the end of the burner.

The burner that performed best with SRC Fuel is referred to as the five-inch fast mix burner. This design, shown in Figure 15, incorporated a 5-in. diameter burner pipe. A water-cooled cone at the burner tip deflected the SRC Fuel into the secondary airstream more quickly than with the slow mix burner nozzle (Figure 16). The cone also increased exit velocity of the fuel by reducing the annular exit space at the burner tip. The fuel deflection into the combustion airstream increased exit velocity, and the cooled burner nozzle each helped to eliminate the dispersion and firing problems often associated with firing SRC Fuel. It should be noted, however, that this design represents a significant departure from the Plant Mitchell burner design.

FIGURE 8
TYPICAL BURNER NOZZLE FOR NO. 6 FUEL OIL
OR SRC-WATER SLURRY

FIGURE 9
SLOW MIX BURNER SHOWING NOZZLE AND 67° ELBOW

FIGURE 10
MODIFIED SIX-INCH SLOW MIX BURNER
WITH COCURRENT SPINNVANES AND CONE

FIGURE 11
TANGENTIAL INLET

FIGURE 12
MODIFIED SIX-INCH SLOW MIX BURNER
WITH TANGENTIAL INLET AND COCURRENT SPINNVANES

FIGURE 13
MODIFIED SIX-INCH SLOW MIX BURNER WITH TANGENTIAL INLET,
COCURRENT SPINVANES AND STRAIGHT FUEL TUBE

FIGURE 14
MODIFIED SIX-INCH SLOW MIX BURNER WITH TANGENTIAL INLET,
COUNTER CURRENT SPINVANES AND STRAIGHT FUEL TUBE

FIGURE 15 (SHEET 1 OF 2)
FIVE-INCH FAST MIX BURNER

FIGURE 15 (SHEET 2 OF 2)
FIVE-INCH FAST MIX BURNER

FIGURE 16
WATER-COOLED CONE FOR FAST MIX BURNER AND
DIVERGING FUEL TUBE NOZZLE FOR SLOW MIX BURNER

The burner employed during the SRC-Water Slurry tests involved a design previously used at PETC for coal-water slurry work. This burner is shown in Figure 17. The slurry was pumped into a conventional No. 6 Fuel Oil gun employing a tip with carbide inserts. Hot primary air, taken from the hot secondary air supply, entered the air zone around the guide tube that supported the oil gun. Compressed air was utilized for atomization of the SRC-Water Slurry.

It must be noted that this burn test program was not intended to be a burner design study. The burner designs discussed here are not optimal but were adequate to accomplish test objectives.

3.5 INSTRUMENTATION AND DATA ACQUISITION SYSTEM

Instrumentation for the 700-hp boiler facility included both continuous online and periodic inflow measurement equipment. With the exception of a few measurements read locally from gauges mounted in the boiler room and acquired by sampling probes, most measurements were transmitted by pneumatic or electrical signals to the facility data acquisition system and displayed and/or recorded in the control room.

The data acquisition system used at PETC is extensive for a combustion test facility. This is one reason the site was chosen for the test program. The system consisted of a Digital Equipment Corporation PDP-11/40 computer and a data acquisition cabinet which included a 100-point scanner for electrical signals and a 64-point scanner for pneumatic signals. The scanners were controlled remotely by the PDP-11/40 computer. Signals were accepted six times per minute and their average values for each minute were permanently stored on a computer disc. Error due to the data acquisition system was less than 0.1 percent of instrument range.

Seven flue gas components (O_2 , NO, NO_2 , CO, CO_2 , SO_2 , and total hydrocarbons) and opacity were monitored continuously as they exited the boiler. Each flue gas sample was drawn by pump suction through a Pall particulate filter into a Hankinson compressed air dryer, then further dried by a Perma Pure Dryer, and delivered to the gas analyzers. The types and ranges of analyzers used are given below.

FLUE GAS ANALYSIS EQUIPMENT

Component	Analyzer	Operation Range
O_2	Beckman Model 755	0 - 25 percent
NO/ NO_2	Beckman Model 951	0 - 1000 ppm
CO	MSA Lira 303	0 - 1000 ppm
CO_2	MSA Lira 303	0 - 25 percent
SO_2	MSA Lira 303	0 - 4000 ppm
Hydrocarbons	Beckman Model 400	0 - 100 ppm
Opacity	Lear Siegler Model 611	0 - 100 percent

FIGURE 17
SRC-WATER SLURRY BURNER

On each test day before actual runs, the flue gas analyzers were manually checked by technicians and recalibrated if needed. This was also done during the test day if the boiler operations personnel suspected a malfunction in the instrument.

3.6 FLUE GAS AREA

Flue gas leaving the boiler passed through a damper valve that controlled furnace pressure and flowed through a shell and tube cooler. Ambient air was blown across the tubes to control the flue gas temperature. The flue gas was then routed to the electrostatic precipitator and the pulse-jet fabric filter collector by a special Y-type flow splitter. A diagram of the flue gas area is given in Figure 18. To evaluate alternative filter operating conditions, a pilot reverse air fabric filter sampled a small volume of flue gas between the flow splitter and the electrostatic precipitator.

The flow splitter, designed and fabricated as a joint effort by ICRC, SCS, and GE-MATSCO, had a 20-in. diameter inlet and two 16-in. diameter outlets leading to the electrostatic precipitator and the baghouse. The splitter was mounted horizontally to split the boiler flue gas stream as evenly as possible; that is, an attempt was made to ensure that the splitter was a minimum of eight pipe diameters downstream and two upstream of the nearest flow obstruction to help achieve even flow and particulate distribution. Flow measurements were made to assure that the flue gas was being split into representative streams and that segregation was not occurring. A reasonable flow split was found to exist.

The flow velocity was a nominal 60 ft/s in each 16-in. duct. All ductwork was made of 304 stainless steel. Finally, a bypass duct was installed around the baghouse. This was done for the following reasons:

- A. To alleviate the problem of loading the filter bags during startup.
- B. To permit the conditioning of new filter bags under steady-state conditions.
- C. To prevent exposing the filter bags to excessive temperatures.

3.6.1 ELECTROSTATIC PRECIPITATOR

A three-field ESP was provided and operated by Wheelabrator-Frye, Inc. The ESP was trailer mounted and complete with automatic voltage controls, rappers, vibrators, hoppers, and an induced draft fan. The unit was operated at approximately 5000 acfm (3.5 ft/s face velocity) and 300°F. The ESP is pictured in Figure 19 and the sampling arrangement is given in Figure 20.

Each of the three fields consisted of a discharge electrode pipe frame with 12 wires per frame and a collecting surface plate consisting of four interlocking strips with spacing arranged for five 10-in. gas passages. This arrangement resulted in a collection area of 1218.75 ft². The discharge electrode pipe frame and the collecting surface plates are of the Lurgi design; the interlocking strips are of the Lurgi CSH design. Each high voltage

FIGURE 18
FLUE GAS SPLITTER

FIGURE 19 (SHEET 1 OF 2)
PILOT ELECTROSTATIC PRECIPITATOR

FIGURE 19 (SHEET 2 OF 2)
PILOT ELECTROSTATIC PRECIPITATOR

FIGURE 20
PILOT ELECTROSTATIC PRECIPITATOR INLET
AND OUTLET GAS SAMPLING ARRANGEMENTS

support frame was suspended from the precipitator casing with a three-point insulator configuration. Insulators were also provided for each rapper and high voltage feed. The insulators were cleaned of any deposited ash with induced purge air. During the tests the induced purge air was not sufficient to maintain clean insulators and compressed air was supplied to assist in maintaining clean insulators.

Each collecting surface was individually bottom rapped with a rotating, falling 8- to 10-lb hammer of the modified Lurgi discharge surface type. The discharge electrode pipe frames in each field were cleaned with a side-mounted Eriez P-150 vibrator. Both rappers and vibrators were manually controlled for each field.

The ash removal system consisted of two trough hoppers per field with screw conveyors. The screws emptied into two pyramidal hoppers that were emptied into 55-gal drums by a vacuum system.

The airflow through the precipitator was induced with a Garden City Fan & Blower Company RF19 fan. This fan was capable of pulling 9000 acfm at 700°F, well above the requirements of this test program. The actual flow was controlled by an opposed louver damper located at the ESP inlet. The specific collecting area (SCA) in ft²/1000 acfm and the gas face velocity for the ESP with 10-in. spacing are given below.

SCA AND GAS FACE VELOCITY THROUGH ESP

acfm	SCA	ft/s
3000	406	1.9
5000	244	3.1
7000	174	4.3
9000	135	5.5

The automatic voltage controls were Allen-Bradley Bulletin 1082 AVC and the transformer/rectifiers were manufactured by Nothelfer Winding Laboratories (NWL Transformers). For this burn test program the transformer/rectifiers were set at 60 kV with 50-percent reactance and negative polarity. The current density for the ESP at 10-in. spacing was 25 $\mu\text{A}/\text{ft}^2$ and 132.4 $\mu\text{A}/\text{ft}^2$ at 10- and 50-mA field current settings, respectively.

The gas distribution devices consisted of an inlet nozzle with two perforated plates and an egg crate flow straightener and an outlet nozzle with one perforated plate. The gas distribution had been measured with a hot wire anemometer and found to be 30-percent root mean square (RMS) at the inlet and 10-percent RMS at the outlet.

3.6.2 PULSE-JET FABRIC FILTER

A pulse-jet fabric filter collector supplied by American Air Filter Company and a Zurn Clarage Series 1270 size 223 induced draft fan were used in this test program. (See Figure 21.) This equipment is permanently installed as part of the 700-hp boiler facility at PETC, and was sized originally to accept the total gas flow from the 700-hp boiler; however, during the SRC burn test program only one-half of the flue gas passed through the fabric filter.

The fabric filter contained 120 Huyglas bags manufactured by Huyck Felt, Division of Huyck Corporation. These bags are widely used commercially at typical installations. The bags were arrayed in 10 rows of 12 bags each and were 5 1/4 in. in diameter by 11 ft 9 in. long, providing a total cloth area of 1979 ft². The bags were 100-percent fiberglass needle felt fiber that could be operated continuously at 500°F and could handle excursions to 550°F. One of the reasons for the popularity of these bags is a unique resin system which coats and protects the fiberglass from abrasive and corrosive effluent.

The bags were cleaned using a reverse pulse of clean air. Two air header manifolds, one on each side of the unit, provided the pulsing air. Each header manifold was 79 in. long by 6 in. in diameter. The pulse pressure was maintained at 75 psig and the frequency of pulsing was such that the pressure drop across the fabric filter was maintained between 2 and 4 in. of water.

3.6.3 REVERSE AIR FABRIC FILTER

The reverse air fabric filter is a device designed to evaluate fabric filtration in the field under actual operating conditions. This device was used in this burn test program to determine the feasibility of controlling particulate emissions from the SRC Fuel products by using a reverse air-cleaned fabric filter. The reverse air fabric filter arrangement is shown in Figure 22.

Flue gas was extracted from the ESP duct and piped into a test chamber where filtration took place through a 1-ft² sample of filter fabric. Heating jackets maintained the chamber and sample lines at an elevated and constant temperature of about 350°F.

The length of a filtration cycle and the frequency of cleaning the cloth depended upon the pressure drop across the fabric filter. The filtration and cleaning cycle were repeated using the same sample of cloth for each fuel for the duration of each test. The reverse air-to-cloth ratio was chosen to be 1:1.

FIGURE 21 (SHEET 1 OF 2)
700-hp BOILER PULSE-JET FABRIC FILTER

FIGURE 21 (SHEET 2 OF 2)
700-hp BOILER PULSE-JET FABRIC FILTER

FIGURE 22
REVERSE AIR FABRIC FILTER

4.0 FUELS

The fuels evaluated during the burn test program at PETC were obtained from the Wilsonville Advanced Coal Liquefaction Research and Development Facility at Wilsonville, Alabama.²⁰ This facility is jointly funded by EPRI and DOE with management provided by SCS.

The Wilsonville facility is capable of producing SRC at a rate of about 3.5 tons/day or about 90 tons during a typical run of 30 days. Since the amount of SRC needed for the PETC burn test was about 500 tons, a single production run at Wilsonville could not produce a sufficient quantity of specification SRC (less than 0.16-percent ash and less than 0.85 percent sulfur) to perform the tests. Therefore, the SRC was collected from several runs and stored.

The reactor operating conditions at the Wilsonville facility were established to simulate the conditions proposed for the SRC-I Demonstration Plant described in this section. These conditions included an operating temperature of 840°F and a pressure of 2100 psig. Kentucky No. 9 Fies Mine was the preferred coal source because of its potential use at the demonstration plant.

The test program consumed about 300 tons of pulverized SRC Fuel, 30,000 gal of SRC Residual Fuel Oil, and 20,000 gal of SRC-Water Slurry. The analysis for each of these three fuels is presented in Tables 3 through 5.

4.1 FUEL PREPARATION

4.1.1 SRC FUEL

The major steps involved in preparing the SRC Fuel included crushing, transporting, and pulverizing the SRC. These steps were an important part of the test program because they may provide an indication of commercial scale preparation considerations.

Approximately 1300 drums of SRC were placed on trucks and shipped to Empire Coke Company near Tuscaloosa, Alabama, for crushing. The equipment at Empire Coke is normally used for crushing coal. Therefore, the initial batches of crushed SRC were discarded to avoid possible contamination of the SRC with coal particles. The drums were emptied into hoppers and the SRC was crushed to minus 1-in. size.

The crushed SRC was transferred into sealed railroad hopper cars to prevent ash contamination. (Commercial open coal cars were successfully used for the Plant Mitchell tests and would be acceptable for large quantities of SRC.¹⁸) The cargo capacity of each hopper car was about 75 tons. Because some dusting was observed during this transfer step, it is recommended that commercial scale units employ a dust control system to minimize the dusting situation during SRC transfer steps.

TABLE 3
ANALYSIS OF SRC FUEL^a

	Slow Mix Burner, Avg of 19 Analyses	Fast Mix Burner, Avg of 6 Analyses
Ultimate analysis (wt % MF)		
Hydrogen	6.15	6.04
Carbon	86.44	86.84
Nitrogen	2.00	1.94
Sulfur	0.99	0.82
Oxygen (by diff.)	4.27	4.24
Ash	0.16	0.12
Percent moisture (by distillation)	0.56	0.35
Higher heating value (Btu/lb) (as received)	15,870	15,871
Particle size (% minus 200 mesh)	97	98

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

a. PETC analyses.

TABLE 4
ANALYSIS OF SRC RESIDUAL FUEL OIL

		Avg of 6 Parametric Test Analyses	Avg of 11 Duration Test Analyses
Ultimate analysis ^a (wt %) on a moisture-free basis			
Hydrogen		8.01	8.03
Carbon		86.42	86.55
Nitrogen		1.31	1.29
Sulfur		0.44	0.48
Oxygen (by diff.)		3.76	3.56
Ash		0.06	0.09
Percent moisture ^a (by distillation)		0.43	0.49
Higher heating value ^a (Btu/lb) (as received)		16,765	16,708
Density ^b		Average	Range
Specific gravity		1.119	1.117 - 1.121
API gravity (60°/60°)		-22	-21 - -23
Viscosity ^b	Temp (°F)	Shear Rate (sec⁻¹)	Viscosity (cP)
	180	4.08	2113
	200	10.20	675
	220	20.40	274
	240	20.40	126
	260	20.40	71

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

a. PETC analyses.

b. ICRC analyses.

TABLE 5
ANALYSIS OF SRC-WATER SLURRY^a

	Avg of 6 Parametric Test Analyses	Avg of 8 Duration Test Analyses
Ultimate analysis (wt % Water and Lomar-D inclusive basis).		
Hydrogen	7.82	7.67
Carbon	56.92	57.81
Nitrogen	1.23	1.20
Sulfur	0.70	0.67
Oxygen (by diff.)	32.87	32.26
Ash	0.46	0.36
Higher heating value (Btu/lb)	10,460	10,598
SRC-I concentration (wt %)	65.85	66.61
Lomar-D concentration (wt %)	0.5	0.5

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

a. PETC analyses.

Several precautionary steps were taken to prevent contamination of SRC with coal or ash particles in the hopper cars. The cars were cleaned with brooms and water to remove any loose sand in the cars. These cleaning steps would not, of course, be necessary in a commercial scale unit because all the equipment used in handling SRC would be dedicated to only SRC.

The hopper cars were moved by rail to Hazelwood, Pennsylvania (near Pittsburgh). At Hazelwood, hopper cars were bottom unloaded and the SRC was transferred as required to a precleaned dump truck via a belt conveyor. A wetting agent was sprayed during the transfer to prevent dusting. A form fitted canvas top was specially prepared for the truck so that the cover would seal the truck bed and also make a seal between the truck and the hopper top at the PETC facility as well. The truck traveled about 10 mi to the PETC site where the SRC was transferred. A dust collector installed on top of the hopper collected small amounts of dust.

The SRC was pulverized (90 percent through 200 mesh) as described in the pulverized SRC Fuel discussion in Section 3.1.2 and stored in a bin. The bin was cylindrical in structure with a cone at the bottom. It was suspected that the SRC Fuel tended to develop arches near the bottom of the cone contributing to unsteady flowrates. In a commercial scale unit the pulverized SRC would be fed directly from the pulverizer into the boiler, thereby avoiding the unsteady fuel forwarding rates encountered by storing the pulverized fuel during the testing at PETC.

4.1.2 SRC RESIDUAL FUEL OIL

The physical properties of the SRC Residual Fuel Oil depend largely on the properties of the SRC and process-derived distillate and the ratio of each in the solution and the temperature of operation. For this test program, 55-percent SRC was blended with 45-percent distillate. This ratio was selected based on viscosity tests in which varying proportions of SRC and process solvent were blended.

The ratio and the operating temperature can be adjusted to meet the desired levels of viscosity and atomization characteristics of the blend. The rule of thumb upper limit on viscosity for pumpability is 1000 cp and for atomization is 30 cp. The SRC Residual Fuel Oil was blended to meet the upper limits of viscosity at a temperature about 100°F higher than that for No. 6 Fuel Oil.

The process-derived distillate used was produced over approximately an 8-month period at Wilsonville. This distillate is a major recycle solvent and an end product at the Wilsonville facility. A list of typical properties of the process-derived distillate is shown in Table 6. Approximately 13,500 gal were used in preparing the SRC Residual Fuel Oil.

To prepare SRC Residual Fuel Oil, SRC was crushed to minus 1-in. and pulverized at Empire Coke Company to 90 percent through a 200 mesh size screen. The pulverized SRC was then transported in bins back to the Wilsonville pilot plant where the SRC Residual Fuel Oil was prepared. All the crushing and pulverizing equipment and the containers handling the SRC were thoroughly cleaned to minimize any possibility of contamination

of the SRC with ash or coal particles. The pulverized SRC samples were analyzed for ash content to confirm no contamination.

The preparation vessel and all external piping were heated to the desired temperature with steam. Selecting and maintaining the blend temperature were crucial to preparing the SRC Residual Fuel Oil. The blend mixing temperature was limited by the steam temperature (approximately 300°F) but was high enough to ensure the blend viscosity to be less than 1000 cp for adequate pumping. The temperature was maintained between 180° and 220°F and the pulverized SRC was added to the heated process solvent through a closed feed port. An inert atmosphere of nitrogen was maintained in the vessel and a low shear recirculating pump provided adequate mixing.

The fuel was stored and transported to PETC under a nitrogen blanket in insulated heat traced tanker trucks. The transit time to PETC was approximately 1 to 2 days. The tanker trucks were not heated in transit and the temperature of the fuel dropped from 200°F at Wilsonville to about 140°F by the time the trucks reached PETC. The steam coils were reactivated at PETC to maintain the fuel temperature between 150°F and 180°F. The nitrogen blanket was maintained in the truck tank while the fuel was stored. The fuel was fed to a steam heated tank for pumping into the boiler. All the interconnecting piping between the truck, the tank, and the boiler was steam traced and insulated.

In a commercial scale operation, the middle distillate and heavy oil needed for SRC Residual Fuel Oil would be produced in much larger quantities. Furthermore, the SRC Residual Fuel Oil would be prepared online at the plant using molten SRC and the pulverization steps required for this test would be eliminated. Even though a commercial scale unit would eliminate the need to pulverize the SRC, it would still have to retain the light volatile components during the preparation of the SRC Residual Fuel Oil to maintain its viscosity stability.

It should be noted that the viscosity stability of the blend was found to be significantly influenced by its composition, especially the low boiling components. Therefore, careful planning was required in preparing the blend. Based on the experience gained at the Wilsonville facility, the following three steps are important in preparing the SRC Residual Fuel Oil.

- A. Retain all light volatile components by installing a refluxed vent condenser which would reinject everything except the noncondensable gases.
- B. Maintain an inert atmosphere, such as nitrogen, in the tank to minimize oxidation.
- C. Minimize the agitation of the blend by installing a low shear recirculating pump instead of an agitator to minimize surface area available for oxidation.

TABLE 6

TYPICAL PROPERTIES OF PROCESS-DERIVED DISTILLATE

1. Specific gravity at 60°F 1.0287

2. Elemental analysis, percent by weight

Carbon	86.69
Hydrogen	8.47
Oxygen	3.61
Nitrogen	0.69
Sulfur	0.53
Ash	0.01

3. Viscosity

Temperature (°F)	Viscosity (cP)
68	34.4
73	29.6
78	25.4
88	18.4
97	14.2
108	11.2
124	8.6
129	7.2
149	5.5

4. Distillation (ASTM D2887)

Percent Distilled	Temperature (°F)
IBP	407
5	438
10	456
20	483
30	511
40	539
50	568
60	607
70	641
80	682
90	746
95	816
99	948
FBP	983

4.1.3 SRC-WATER SLURRY

The primary considerations in preparing the SRC-Water Slurry were to assure that the mixture was pumpable and that the SRC particles were fine enough for atomizing. It was also important to add a wetting agent to enhance mixing of the SRC and water and reduce mixture viscosity.

Crushed SRC was shipped from Empire Coke in Tuscaloosa, Alabama, to PETC in railroad cars as described for SRC Fuel. The SRC was pulverized at PETC to 90 percent through 200 mesh and mixed with water. The discussion in Section 3.1.2 of this report describes the equipment involved. Several proportions of SRC in the slurry were tested to observe their viscosity, pumping, and atomizing characteristics. Based on those results, about 66 percent by weight of SRC in the mixture was selected for combustion testing. The slurry was stored in an agitated tank and pumped directly to the boiler.

To enhance wetting characteristics, a surfactant, Lomar-D, was added to the slurry. Lomar-D is a sodium based surfactant which resulted in increasing the sodium content of the fly ash. Lomar-D accounted for over 60 percent of the fly ash in the flue gases during the SRC-Water Slurry tests. Alternative additives should be tested in the future to minimize the impact of a surfactant on the particulate loading in the flue gases.

4.2 SRC-I DEMONSTRATION PLANT

Because of the production limitations of the Wilsonville Advanced Coal Liquefaction Research and Development Facility and the fact that the Ft. Lewis pilot plant was recently dismantled, it is difficult to properly evaluate the commercialization of SRC fuels. A large scale burn test in a utility boiler, e.g., a 50-MW unit for 30 days, is impossible because the necessary fuel can not be provided.

To demonstrate the feasibility of commercializing SRC, the International Coal Refining Company has proposed a demonstration facility, the SRC-I Demonstration Plant, to convert 6000 tons of coal per day into the equivalent of 20,000 barrels per day of oil-equivalent products.¹¹ The facility would prove the technical feasibility, environmental acceptability, and economic viability of the SRC process. The demonstration facility will use commercial-size equipment and generate products in near-commercial scale quantities. Figure 23 illustrates the proposed demonstration plant process.

The SRC-I Demonstration Plant will use a combination of SRC-I direct coal liquefaction, catalytic hydrocracking, and coking/calcining to produce high Btu fuels and energy products.

The flexibility of the plant's process train will allow ICRC to vary the ratio of solid to liquid products to respond to the demands of the marketplace. Coal refining consists primarily of adding hydrogen to the carbon in coal while removing most of the sulfur and ash—the two chief pollutants in bituminous coals. In the SRC-I process, raw coal is pulverized, mixed with solvent derived from the process, and heated under pressure in a fired heater. Hydrogen produced by gasifying coal and process residues is added to

FIGURE 23
SRC REFINERY PROCESS DIAGRAM
(DEMONSTRATION PLANT CONFIGURATION)

the coal/solvent mixture and the mixture flows into a reactor vessel where liquefaction is completed.

The mixture then flows to separation and deashing steps where sulfur and ash are removed. This first series of refinery operations yields a naphtha and distillate liquid stream and a small quantity of gas which is recycled into the process as fuel. Most of the sulfur present in the raw coal feedstock is drawn off in this series of operations. The low consumption of hydrogen and self-contained hydrogen generation make the process less costly.

The chief product of this first process step is SRC Fuel which, when cooled, becomes a shiny black solid material which can be burned in utility and industrial boilers and furnaces designed to burn oil. The heating value of SRC Fuel approximates that of No. 6 fuel oil and is approximately 45 percent higher than that of raw bituminous coal from which it is derived (about 16,000 Btu/lb, versus 11,000 Btu/lb for raw coal). The mineral ash content of SRC Fuel is comparable to No. 6 fuel oil (about 0.1 percent).

A portion of the SRC Fuel will be treated with hydrogen in a catalytic hydrocracker to produce additional distillate fuels, petrochemical and gasoline feedstocks, and very low sulfur SRC Fuel. Another portion of the SRC Fuel will be further processed to yield anode coke for the aluminum industry and specialty carbon products. With the addition of mixing equipment an SRC-Water Slurry product can be produced.

Direct coal liquefaction yields approximately three barrels of oil equivalent products per ton of coal versus two barrels per ton of coal from indirect coal liquefaction.

5.0 TEST PROGRAM

5.1 INTRODUCTION

The test program was designed to evaluate boiler parameters such as fuel handling, fuel atomization, flame characterization, boiler efficiency, combustion efficiency, and excess air requirements. The program also involved studies to determine ESP performance, pulse-jet fabric filter performance, reverse air fabric filter performance, particulate loading, SO₂ emissions, NO_x emissions, and stack opacity.

Actual testing began in August 1982 and was completed in early February 1983. PETC, Southern Research Institute (SoRI), Wheelabrator-Frye (WFI), Babcock & Wilcox (B&W), and Combustion Engineering (C-E) each prepared reports in conjunction with this final report. Test results and sample numbers for these reports can be compared by checking the date and time given in the test data in each report. For a more detailed discussion of the combustion tests and a presentation of data see Reference 21. For more information on the flue gas area see References 19, 23, 24, and 25. In addition, a paper describing the test program was presented at the 1983 EPRI contractor's conference on coal liquefaction. (See Reference 14.)

Both parametric and steady-state tests were conducted with No. 6 Fuel Oil, SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry. A description of the equipment and facilities implemented for each fuel test is given in Section 3.

5.2 FUEL ANALYSES

The average ultimate analyses of samples of the four fuels tested are given in Table 7. Carbon contents for the SRC fuel forms were very close to the No. 6 Fuel Oil when considered on a dry basis. The carbon/hydrogen (C/H) ratios for the SRC fuels were higher than for the No. 6 Fuel Oil due to inherently lower hydrogen content. The higher C/H ratios improve the efficiency of the SRC fuel forms because less water vapor is formed during combustion. Nitrogen contents of the SRC fuels (1.20 to 1.99 percent) were much higher than for the No. 6 Fuel Oil (0.20 to 0.23 percent). Inherent oxygen content, calculated by difference, was grouped closely for all of the fuels except the SRC-Water Slurry which reflects the increased oxygen due to the water added during preparation of this fuel. Ash content of the SRC Fuel and SRC Residual Fuel Oil was 0.12 to 0.16 percent while No. 6 Fuel Oil ranged from 0.10 to 0.11 percent. The SRC-Water Slurry had a higher ash content than the other SRC fuels due to the addition of Lomar-D, a wetting agent used to aid in mixing the SRC and water. Lomar-D itself has a 36-percent ash content. In addition, Lomar-D added both sodium and sulfur to the fuel.

Moisture content of the No. 6 Fuel Oil varied from 5.04 to 6.48 percent. The unusually high moisture content was due to the low level of No. 6 Fuel Oil in the storage tank becoming mixed with the 3- to 4-in. layer of water in the storage tank bottom. The moisture contents for the SRC Fuel and SRC Residual Fuel Oil were 0.35 to 0.52 percent and 0.43 to 0.49 percent, respectively. The SRC-Water Slurry moisture content was the highest,

TABLE 7
FUEL ANALYSIS^a

	No. 6 Fuel Oil		SRC Fuel		SRC Residual Fuel Oil		SRC-Water Slurry	
	Avg of 8 Parametric Test Analyses	Avg of 16 Duration Test Analyses	Slow Mix Burner Avg of 19 Analyses	Fast Mix Burner Avg of 6 Analyses	Avg of 6 Parametric Test Analyses	Avg of 11 Duration Test Analyses	Avg of 6 Parametric Test Analyses	Avg of 8 Duration Test Analyses
Ultimate analysis (wt %) on a moisture-free basis:								
Hydrogen	11.72	12.15	6.15	6.04	8.01	8.03	7.82	7.67
Carbon	82.38	83.21	86.44	86.84	86.42	86.55	56.92	57.81
Nitrogen	0.23	0.20	2.00	1.94	1.31	1.29	1.23	1.20
Sulfur	0.65	0.60	0.99	0.82	0.44	0.48	0.70	0.67
Oxygen	4.93	3.72	4.27	4.24	3.76	3.56	32.87	32.26
Ash	0.10	0.11	0.16	0.12	0.06	0.09	0.46	0.36
Moisture (%)	6.48	5.04	0.56	0.35	0.43	0.49		
Heating value (Btu/lb)	17469	17752	15870	15871	16765	16708	10460	10598
SRC concentration (%)							65.8	66.6
Particle size (%) minus 200 mesh)			97	98			90	90

NOTE: Ultimate analysis, moisture content, and heating value were determined according to ASTM Section 5 (Petroleum Product Lubricants and Fossil Fuels) Standards.

a. Data from report by PETC. (See Reference 21.)

of course, at 33.3 percent average. Hydrogen and oxygen contents were proportionally higher in the slurry fuel due to the high water content.

An important advantage of SRC, as compared to No. 6 Fuel Oil, is the much lower vanadium content. During combustion the vanadium will oxidize forming vanadium pentoxide which is a catalyst for the formation of sulfur trioxide from sulfur dioxide. Sulfur trioxide is then further reacted in the flue gas stream to form sulfuric acid which when allowed to condense is detrimental to flue gas ductwork and equipment. Typical vanadium content values for SRC are around 5 ppm, whereas for No. 6 Fuel Oil, 170 ppm is an average value. The average vanadium content in No. 6 Fuel Oil has been increasing recently and the upward trend is expected to continue as the overall quality of crude oil decreases.

5.3 BOILER PERFORMANCE

5.3.1 NO. 6 FUEL OIL

Baseline tests were conducted over a period of 3 weeks at full boiler load. A total of 26 boiler tests (8 parametric and 18 steady state) were performed following ASME boiler testing procedures (ASME PTC 4.1). Parametric boiler tests were conducted at two secondary air preheat temperatures, approximately 500°F and 600°F, while flue gas oxygen levels were varied from 0.6 percent to 5.1 percent (excess air levels from 3.1 percent to 31.0 percent).

Boiler operations during parametric testing involved boiler shutdown in the late evening and early morning hours as evaluation of the ESP was not required. During steady-state duration testing of each fuel, the boiler was operated during the night to maintain a constant heat flux through the ESP, facilitating its performance evaluation. At times, nighttime operation of the boiler was performed with the particular fuel being evaluated, depending on the supply available for testing. This was never the case with the SRC-Water Slurry due to the limited quantities that could be produced daily.

Based on results of the boiler parametric tests, steady-state boiler test conditions were established at a secondary air preheat temperature of approximately 500°F and a flue gas oxygen level of approximately 2.4 percent (excess air levels of 12.5 percent). Typical boiler operating conditions and boiler performance data collected during the steady-state test period are given in Table 8.

The burner used during the No. 6 Fuel Oil test period is described in Section 3.4 and shown in Figures 9 and 10.

5.3.2 SRC FUEL

Fuel tests were conducted over a period of approximately 6 weeks. A total of 23 ASME full-load boiler tests (4 parametric and 19 steady state) were performed during this period. Parametric tests were performed at secondary air temperatures of 500°F to 600°F and at flue gas oxygen levels of 3.0 percent to 5.4 percent (excess air levels of 14.5 percent to 32.0 percent).

Initial parametric testing was performed using a modified version of the burner design by Beard, Diaz, and Weidman and Associates. This design (a slow mix burner) was based on the Babcock & Wilcox dual register burner used in the 1977 SRC burn test at Georgia Power Company's Plant Mitchell.¹⁵ This design was a logical first step since good performance was observed during the Plant Mitchell test. It was found, however, that the modified slow-mix burner (Figure 12) was extremely sensitive to fluctuations in the SRC Fuel feed system. Initial burner related problems included the inability to move the flame ignition point off the burner tip, clinker buildup on the burner tip, flame instability, and flame impingement on the interior boiler surfaces.

In an effort to correct the initial slow mix burner problems, modifications to both the fuel feed system and the burner design were made. Modifications to the fuel feed system included the following:

- Removal of the original 6-in. primary air line and installation of a new 6-in. line without 90° elbows.
- Removal of the 5-in. screw feeder from the feed bin and installation of a 6-in. screw feeder. (Later, the 5-in. screw feeder was returned to service.)
- Installation of pressure regulators on the feed bin and screw feeder hopper.
- Installation of a second primary air blower in series with the original blower increasing primary airflow capacity by approximately 75 percent.
- Enlargement of the feed bin bottom opening from 10 in. to 12 in. to increase fuel flow.
- Bin vibration amplitude increase of 40 percent.
- Fuel particle size increase from 90 percent through 200 mesh to 70 percent through 200 mesh.

The overall result of these fuel feed system modifications was improved fuel feed; however, burner performance was still not satisfactory. Burner modifications included replacement of the 60° radial elbow with a tangential inlet elbow, and installation of spinvanes (both cocurrent and counter current to secondary air swirl)

TABLE 8

OPERATING CONDITIONS AND BOILER PERFORMANCE^a

	No. 6 Fuel Oil		SRC Fuel				SRC Residual Fuel Oil		SRC-Water Slurry	
	Parametric Test Range	Avg of 18 Duration Tests	Slow Mix Burner Parametric Test Range	Avg of 19 Duration Tests	Fast Mix Burner Parametric Test Range	Avg of 6 Parametric Tests	Parametric Test Range	Avg of 11 Duration Tests	Parametric Test Range	Avg of 8 Duration Tests
Thermal input (10 ⁶ Btu/h)	29.03 - 30.45	29.49	29.33 - 30.26	30.33	29.22 - 29.91	29.52	29.03 - 30.10	29.23	29.23 - 31.35	28.78
Steam flow (lb/h)	23360 - 24390	23990	23920 - 24050	23884	23580 - 24410	24035	23760 - 24500	24191	23000 - 24430	23126
Flue gas O ₂ (%)	0.6 - 5.1	2.4	3.0 - 5.4	5.3	2.7 - 5.5	4.0	0.4 - 4.4	2.6	2.1 - 4.0	3.0
Excess air (%)	3.1 - 31.0	12.76	14.5 - 32.0	32.4	12.9 - 33.8	22.4	2.3 - 25.4	13.95	9.6 - 21.8	15.44
Stoichiometric airflow (lb/h)	20260 - 21000	20708		20523	20070 - 20310	20191	19970 - 20440	19871		
Secondary airflow (lb/h)	18830 - 23250	21545	19860 - 23630	23085	18930 - 23840	21618	17880 - 23040	20371	17350 - 20560	17720
Secondary air temp (°F)	495 - 610	503	503 - 615	578	504 - 601	563	502 - 604	595	499 - 570	600
Primary airflow (lb/h)	1180 - 4446	2019	4450 - 4916	5296	3200 - 3508	3409	463 - 4573	2726	4380 - 5205	4549
Primary air temp (°F)	63 - 78	69	44 - 56	74	71 - 89	79	44 - 94	36	492 - 581	591
Fuel flow (lb/h)	1524 - 1573	1522	1690 - 1781	1673	1700	1700	1578 - 1626	1579	2568 - 2700	2444
Fuel temp (°F)	210 - 217	208					288 - 304	301	101 - 165	97
Fuel pressure at burner (psig)	61.7 - 62.3	59					90 - 100	94	65 - 80	89
Atomizing air/steam (lb/h)	236 - 242	243					290 - 338	291	931 - 1350	1098
Atomizing air/steam pressure (psig)		63.6					96 - 108	104	85 - 86	86
Burner position (in)	1 - 1	1	1/2 - 1 1/8	1/2	2 1/8	2 1/8	5/8 - 1 1/4	1/2	0	0
Swirl setting	5 - 8	4	7 1/2 - 8	6 1/2	3 - 3 1/2	3 1/2	4 - 4 1/4	4	2 - 2 1/4	2
Average flue gas temp (°F)	528 - 613	553	526 - 606	554	482 - 509	498	485 - 515	493	515 - 536	513
Carbon conversion efficiency (%)	99.93 - 99.99	99.98	97.8 - 98.8	98.7	98.6 - 99.3	98.9	99.6 - 99.9	99.75	98.5 - 98.9	98.9
Boiler efficiency (%) (heat loss method)	79.6 - 83.5	82.0	81.5 - 83.7	82.2	83.7 - 85.6	84.7	84.3 - 86.2	85.3	80.2 - 81.6	81.8
Natural gas flow (scfm)			0	25.23 ^b	0	0				

^a Data from report by PETC (See reference 21.)^b Average of 11 tests during which natural gas was used.

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on the burner guide tube. The modified slow mix burners used during the parametric test period are shown in Figures 12 through 14. The burner shown in Figure 14, with the tangential inlet elbow, counter current spinnvanes and straight fuel tube, improved combustion stability. It was also found that a natural gas support flame of about 25 scfm improved combustion stability significantly.

Due to time constraints and the need for steady particulate loading for testing the ESP, the decision was made to run the boiler steady-state tests using the burner shown in Figure 14 with a natural gas support of approximately 25 scfm. Operating conditions and boiler performance data for the duration testing are given in Table 8.

After completion of the formal test program, further SRC Fuel combustion testing was performed using a new fast mix burner design. The burner design was conceived in an attempt to reduce or eliminate the problems encountered during formal combustion testing of the SRC Fuel. The burner consisted of a 5-in fuel tube, a water-cooled cone at the burner tip and a 30° cocurrent spinnvane located on the burner centertube. This arrangement, shown in Figure 15, allowed for a primary air/fuel stream burner exit velocity of 125 ft/s. It was thought that the high primary air/fuel burner exit velocity would allow for more flame control. Also the water-cooled cone protected the incoming fuel from furnace radiation and the resultant melting of the fuel.

With the cocurrent spinnvanes set 12-in. back from the deflector cone, excellent combustion was attained at a 5-percent oxygen level. The ability to shape the flame by moving the secondary air louvers from the No. 3 to the No. 6 louver setting, increasing swirl while adjusting the inner cone deflector, was very effective. The flame appearance was short and bright and rotating in a tight ball at the 5-percent oxygen level; however, it became smoky as the oxygen level was lowered. As the secondary air temperature was reduced to 300°F, CO₂ levels remained relatively stable at 70 ppm with oxygen levels at 3 to 4 percent. However, as the secondary air temperature was lowered below 300°F, the firebox became smoky and the boiler experienced a flameout due to the fireeye losing sight of the flame.

The boiler was brought back up with the spinnvanes placed at a position 6-in. back from the deflector cone. At 5-percent excess oxygen the flame was very bright; however, it was broader and fuller in appearance when compared to the flame achieved with the diffuser set at position 12-in. back from the cone. A clinker formed at this condition and by adjusting the deflector cone inward, the clinker was eliminated.

Further testing indicated that the SRC Fuel could be burned with flue gas oxygen levels as low as 2.7 percent with good flame appearance. Secondary air temperatures ranged from 500 to 600°F while CO and NO_x levels averaged 49 ppm and 862 ppm, respectively.

A total of six tests was conducted using the 5-in. fast mix burner shown in Figure 15. The operating conditions and boiler performance data for the fast mix burner are also shown in Table 8.

5.3.3 SRC RESIDUAL FUEL OIL

SRC Residual Fuel Oil tests were conducted over a three week period. A total of seventeen ASME full-load boiler tests (6 parametric and 11 steady state) were performed. During parametric testing secondary air temperatures of 500°F and 600°F were used while excess air levels were varied. Steady-state boiler operation used an average secondary air temperature of 595°F and an average flue gas oxygen level of 2.6 percent (average excess air level of 13.95 percent).

The 6-in. slow mix burner with the tangential inlet and cocurrent spinvanes (Figure 12) was used during the SRC Residual Fuel Oil test series. This burner configuration was the same one used during No. 6 Fuel Oil testing and is described in Section 3.4. The Coen burner cap, with eight 5/32-in. nozzle holes, each fitted with tungsten carbide inserts and having a 75° spray angle, was used. Modifications required on the burner assembly included increasing the center hole of the nozzle body from 1/2 in. to 11/16 in. to reduce the pressure drop caused by the increased amount of atomizing steam needed for good atomization. A center rod was also placed in the nozzle body and cap to reduce carbon buildup. Steam, available at a maximum pressure of 175 psig, was used to atomize the SRC Residual Fuel Oil. Operating conditions and boiler performance data for the Residual Fuel Oil tests are given in Table 8.

5.3.4 SRC-WATER SLURRY

SRC-Water Slurry combustion tests were conducted over a 2-week period. Fourteen full-load boiler tests (six parametric and eight steady state) were performed following ASME guidelines. Parametric testing was conducted using secondary air temperatures ranging from 499°F to 570°F and at flue gas oxygen levels ranging from 2.1 percent to 4 percent.

Conditions for the steady-state tests were selected based upon parametric test results. The selected conditions were a secondary air temperature of about 600°F and a flue gas oxygen level of 3.0 percent (excess air of 15.4 percent).

The Coen burner gun, modified by PETC for coal-water mixture firing, was used for the SRC-Water Slurry tests (Figure 17). The Coen Model No. 2 mV atomizer was used in conjunction with a nozzle cap containing eight 15/64-in. openings at a 60° spray angle.

The atomizer assembly is shown in Figure 8. Compressed air, at 86 psig, was used for atomization. During final testing, additional nozzle caps were evaluated. A nozzle cap with eight 3/16-in. orifices at a 75° spray angle caused heavy flame impingement on the refractory cone regardless of adjustments to air register louver settings, fuel and air flowrates. Testing with a nozzle cap having eight 3/16-in. openings and a 60° spray angle produced higher atomizing air and slurry pressures at the nozzle with no appreciable difference in flame shape or boiler performance.

Operating conditions and boiler performance during the SRC-Water Slurry tests are given in Table 8.

5.4 FLAME CHARACTERISTICS

During testing of the fuels, observations were made of the burner flame shape and length.

Both the No. 6 Fuel Oil and the SRC Residual Fuel Oil flames were in the shape of a ball, centered concentrically in the firebox. Flame length was approximately 7 feet, or about half the length of the firebox. In contrast, the SRC-Water Slurry and pulverized SRC Fuel flames were longer and narrower. The SRC Fuel flame from the slow mix burner impinged on the back wall of the firebox (13 ft), but was about 9 ft in length for the fast mix burner. The SRC-Water Slurry flame was approximately 8 ft in length and was slightly wider than the SRC Fuel flame.

The major concern with respect to flame structure is that long flames may lead to back wall flame impingement for retrofit firing of SRC. To address this question, a correlation of flame length with burner size is needed.

Work performed by the Acurex Corporation (Reference 1) produced data shown in Figure 24. This information is based on subscale and pilot-scale work done under contract to the United States Department of Energy. Burner size and flame length information obtained from the Plant Mitchell full-scale SRC-Fuel burn test and from the PETC 100-hp firetube boiler and 700-hp watertube boiler SRC burn tests are also shown in Figure 24. As can be seen in this figure, both the Plant Mitchell and PETC data correlate reasonably well with predictions made by Acurex.

Also shown in Figure 24 is the typical firing rate range of utility scale burners (100×10^6 to 200×10^6 Btu/hour) and the furnace depth range (20 to 30 ft). The ranges indicate that slow mix SRC Fuel burners used in full-scale units may cause flame impingement problems whereas fast mix SRC Fuel burners will provide acceptable performance. However, since the flame lengths identified in Figure 24 are approximations, the flame length limits should be used only as guidelines.

FIGURE 24
CORRELATION OF FLAME LENGTH WITH BURNER FIRING RATE

5.5 FLUE GAS ANALYSES AND PARTICULATE EMISSIONS AT BOILER OUTLET

The type of chemical constituents in a fuel has a definite effect on the amount and type of emissions. Table 9 gives the flue gas analyses and particulate emissions of each fuel tested during the PETC program. Sulfur oxide (SO_x) emissions are generally higher for fuels containing more sulfur. As a result, the SRC Fuel and the SRC-Water Slurry had the highest average sulfur dioxide levels; 580 ppm and 687 ppm, respectively, for the duration tests. The slurry fuel had the highest sulfur dioxide emissions due to the increased sulfur content from the addition of Lomar-D. SRC Residual Fuel Oil had the lowest sulfur dioxide emissions of the SRC forms at 367 ppm average. No. 6 Fuel Oil sulfur dioxide emissions averaged 433 ppm for the duration tests.

Nitrogen oxide (NO_x) emissions are affected by a number of factors. The amount of fuel bound nitrogen has the most impact on NO_x emissions, of course. Other important factors involved in NO_x formation are the amount of oxygen available in the combustion zone (excess air) and the combustion air temperatures. NO_x emissions as well as pertinent fuel and combustion parameters for each of the fuels tested are tabulated below.

Fuel	Fuel Bound Nitrogen (%)	Excess Air (%)	Secondary Air Temp. (°F)	NO _x (ppm)	Emissions (lb/10 ⁶ Btu)
No. 6 Fuel Oil	0.20	12.76	503	199	0.26
SRC Fuel					
Slow Mix Burner ^a	1.99	32.40	578	655	1.05
Fast Mix Burner ^b	1.93	22.40	563	862	1.27
SRC Residual Fuel Oil	1.29	13.95	595	496	0.67
SRC-Water Slurry	1.20	15.44	600	366	0.51

a. Average of parametric tests.

b. Average of duration tests.

From the above data it can be seen that, in general, NO_x emissions appear to be directly proportional to nitrogen content of the fuel and excess air in the combustion zone for the SRC-related fuels:

Also shown in Table 9 are the particulate emissions for each of the fuels tested. As expected, No. 6 Fuel Oil with an average emission rate of 0.03 lb/10⁶ Btu had the lowest emission rate of all the fuels tested. The SRC Residual Fuel Oil had an average emission rate of 0.154 lb/10⁶ Btu, while the SRC Fuel averaged 0.85 lb/10⁶ Btu for the slow mix burner. The SRC-Water Slurry averaged 0.86 lb/10⁶ Btu. This increase in emission rate over the SRC Fuel was due to ash content of the wetting agent, Lomar-D. The average carbon content of the ash varied a great deal with the SRC Fuel having the highest value at 90 percent. No. 6 Fuel Oil ash contained the lowest average percentage of carbon at 35 percent.

5.6 COMBUSTION RESULTS

5.6.1 NO. 6 FUEL OIL

The No. 6 Fuel Oil baseline testing was conducted with only very minor problems. Full boiler load was achieved during both parametric and steady-state test periods. Operating conditions selected for steady-state testing were 12.5-percent excess air and 500°F secondary air temperature. These conditions are the design operating parameters for the 700-hp boiler when firing No. 6 Fuel Oil.

Average duration test carbon conversion efficiency was 99.98 percent. Average boiler efficiency was 81.96 percent for the duration tests.

5.6.2 SRC FUEL

The SRC Fuel tests using the slow mix burners were conducted with some difficulty. The slow mix burner design was used initially at PETC because a similar design had been successfully used in the 1977 SRC burn test at Plant Mitchell. There are, however, significant differences in the basic designs of the boilers and the fuel handling systems used at PETC and Plant Mitchell.

The impact of these design differences on flame stability was not fully realized until testing was begun at PETC with a slow mix burner installed in the 700-hp boiler. The Plant Mitchell design employed six dual register burners firing directly from pulverizers; PETC used a single register burner firing from a fuel storage bin. These design differences resulted in a stable flame at Plant Mitchell and an unstable flame situation at PETC.

Stable firing conditions were finally achieved during the PETC test by modifications to the fuel handling and storage system to maintain uniform fuel flow, by the addition of spinvanes to the burner, and by using a natural gas support flame. Stable operating conditions were then attained at an average excess air level of 32.4 percent and a 578°F secondary air temperature.

Under these conditions, boiler emissions were steady enough for particulate flue gas analyses. Carbon conversion efficiency averaged 98.7 percent for the duration tests. Boiler efficiency averaged 82.2 percent.

TABLE 9

FLUE GAS ANALYSES AND PARTICULATE EMISSIONS^a

	No. 6 Fuel Oil		SRC Fuel		SRC Residual Fuel Oil		SRC-Water Slurry			
	Parametric Test Range	Avg of 18 Duration Tests	Slow Mix Burner Parametric Test Range	Avg of 19 Duration Tests	Fast Mix Burner Parametric Test Range	Avg of 6 Parametric Tests	Parametric Test Range	Avg of 11 Duration Tests	Parametric Test Range	Avg of 8 Duration Tests
Flue gas analysis										
O ₂ (%)	0.6 - 5.1	2.4	3.1 - 5.4	5.3	2.7 - 5.5	4.0	0.4 - 4.4	2.6	2.1 - 4.0	3.0
CO ₂ (%)	11.8 - 15.4	13.6	12.8 - 14.7	12.8	12.9 - 15.2	14.1	13.8 - 16.7	14.7	14 - 16	14.9
CO (ppm)	22 - 190	31.5	70 - 370	88	41 - 56	49	25 - 123	32.5	51 - 280	76
SO ₂ (ppm)	455 - 560	433	566 - 653	580	477 - 550	512	315 - 409	367	714 - 797	687
SO ₂ (lb/10 ⁶ Btu)	0.90 - 0.95	0.84	1.23 - 1.29	1.28	0.98 - 1.14	1.05	0.59 - 0.71	0.68	1.38 - 1.47	1.33
NO _x (ppm)	210 - 241	199	402 - 494	655	777 - 925	862	468 - 533	496	321 - 440	366
NO _x (lb/10 ⁶ Btu)	0.25 - 0.34	0.26	0.56 - 0.80	1.05	1.17 - 1.37	1.27	0.57 - 0.76	0.67	0.42 - 0.65	0.51
Total hydrocarbons (ppm)	0.2 - 2.0	0.5	1 - 2	1	1	1	0.2 - 0.8	0.60	1	1
Opacity ^b	1 - 6	3.5	15 - 48	18	10 - 11	10.5	6 - 17	7	10 - 14	12
Particulate										
Emissions (lb/h) ^{b,c}	0.60 - 1.15	0.92	28.5 - 35.5	23.06	11.9 - 23.4	18.1	2.39 - 6.52	4.08	23.36 - 31.75	22.13
Emissions (lb/10 ⁶ Btu) ^{b,c}	0.02 - 0.04	0.03	1.07 - 1.26	0.85	0.44 - 0.87	0.67	0.09 - 0.243	0.154	0.86 - 1.15	0.86
Carbon contents (%) (loss on ignition method)	24.9 - 72.5	35.0	60.9 - 93.3	82.3	86.0 - 93.5	90.7	50.8 - 88.7	82.01	67.4 - 71.2	70.0

^a Data from report by PETC. (See reference 21.)^b Boiler outlet^c ASME test procedure

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Combustion testing of SRC Fuel using the 5-in. fast mix burner yielded great improvement in flame control. No natural gas support flame was necessary for consistent combustion and the flame could be shaped as desired by adjusting the secondary air louvers in combination with the water-cooled center cone. The flue gas analyses and particulate emission results with the fast mix burner are given in Table 9.

Carbon conversion efficiencies during the fast mix burner tests ranged from 98.6 percent to 99.3 percent. Boiler efficiencies ranged from 83.7 percent to 85.6 percent. Operating conditions and boiler performance are presented in Table 8.

As a result of the combustion data obtained from burning SRC Fuel in the 700-hp oil-designed boiler, the following conclusions can be drawn:

- SRC Fuel can be successfully combusted in a small industrial scale oil-designed boiler.
- The boiler can be operated at full load.
- Carbon conversion efficiencies are high (98 percent or higher).
- Boiler efficiencies obtained in SRC Fuel tests are higher than those obtained when burning No. 6 Fuel Oil.
- The normal method of direct firing from a pulverizer would be preferred over the storage bin and feedscrew system used during the PETC tests.
- Combustion problems encountered during testing were due to mechanical limitations of the facility and not fuel limitations.
- The fast mix burner design developed during the PETC test program seems to be the best starting point for further burner developments.

5.6.3 SRC RESIDUAL FUEL OIL

The SRC Residual Fuel Oil tests were conducted with no significant problems. All tests were conducted at full boiler load. Average operating conditions during duration tests were 13.95-percent excess air and 595°F secondary air.

The resulting carbon conversion efficiency averaged 99.8 percent while boiler efficiency was 85.3 percent. Boiler efficiency averaged four percentage points higher than that for No. 6 Fuel Oil. Operating conditions and boiler performance are presented in Table 8. This higher efficiency with the SRC Residual Fuel Oil is thought to be due to three factors.

- Combustion of the SRC Residual Fuel Oil resulted in a lower average flue gas temperature which resulted in less flue gas heat loss.
- The SRC Residual Fuel Oil had a lower moisture content.
- The C/H ratio is higher in SRC Residual Fuel Oil.

It should also be noted that the SRC Residual Fuel Oil testing produced very little boiler bottom ash. Prior to the test series, the boiler radiant section was thoroughly cleaned. After over 70 hours of full-load testing, only 1.5 pounds of ash were collected in the radiant section of the boiler.

5.6.4 SRC-WATER SLURRY

The SRC-Water Slurry combustion tests proceeded smoothly with the main problem being atomizing air capacity. During all of the slurry tests, atomizing airflow was at the upper limit of supply capacity. A small increase in atomizing air capacity may have greatly aided in the development of trends in both carbon conversion and boiler efficiency as functions of secondary air temperature and excess air levels.

Steady-state combustion test conditions averaged 15.44-percent excess air and 600°F secondary air temperature. Carbon conversion efficiency averaged 98.9 percent. Boiler efficiency averaged 81.8 percent. Boiler efficiency during the slurry tests was the lowest of all of the SRC forms. Obviously this is due to the large amount of water contained in the fuel. However, the boiler efficiency during slurry testing is still comparable to that achieved during the No. 6 Fuel Oil testing. Operating conditions and boiler performance are presented in Table 8.

Upon completion of testing, measurements were made on the nozzle cap orifices. The measurements revealed a size increase of 0.0025 in. from the original 15/64-in. diameter orifice after approximately 90 hours of operation.

5.7 COMBUSTION CONCLUSIONS

In general, the principal goal of demonstrating the combustion of SRC-derived fuels in an oil-designed boiler was successfully achieved in the 700-hp PETC test program. The 700-hp watertube boiler operated without derating when burning the SRC Fuel, the SRC Residual Fuel Oil, and the SRC-Water Slurry.

The carbon conversion efficiencies obtained in all of the SRC combustion tests were high, ranging from 97.8 percent to 99.9 percent. The steady-state duration tests, conducted at full boiler load with approximately 600°F air preheat, resulted in average carbon conversion efficiencies of 99.8 percent for SRC Residual Fuel Oil and 98.9 percent for SRC-Water Slurry. Parametric tests, at full boiler load with an average 563°F air preheat, resulted in an average carbon conversion efficiency of 98.9 percent for pulverized SRC Fuel when using the improved design 5-in. fast mix burner.

Average boiler efficiencies obtained in these same pulverized SRC Fuel and SRC Residual Fuel Oil tests were higher (84.7 percent and 85.3 percent, respectively) than when burning No. 6 Fuel Oil (82.0 percent) at full boiler load with 503°F air preheat. The average boiler efficiency obtained in the SRC-Water Slurry tests (81.8 percent) was comparable to the average boiler efficiency (82.0 percent) obtained when burning No. 6 Fuel Oil.

The NO_x emissions when burning the SRC-Water Slurry were lower than when burning SRC Fuel under similar operating conditions. This was due to lower flame temperatures associated with the high water content of the slurry fuel. Due to the short time span available for testing, no attempt was made to minimize NO_x emissions via combustion modifications. Uncontrolled NO_x emissions averaged 0.51 lb/10⁶ Btu for the slurry fuel to 1.27 lb/10⁶ Btu for SRC Fuel when using the fast mix burner (Table 9). The NSPS NO_x emission limit is 0.50 lb/10⁶ Btu. It is believed that with better burner design and conventional control techniques, the NO_x emissions of the SRC forms can be reduced to meet current standards.

Particulate emissions for the SRC forms were also higher than No. 6 Fuel Oil emissions, but results of the different particulate control equipment tests indicate that this equipment can be used to limit emissions to within acceptable limits (Table 9).

The three forms of SRC utilized during this combustion program have demonstrated, in most areas, desirable handling and combustion characteristics. The test firings consumed approximately 300 tons of SRC Fuel, 30,000 gal of SRC Residual Fuel Oil, and 20,000 gal of SRC-Water Slurry.

The overall test results from the PETC 700-hp boiler SRC Fuel combustion tests demonstrate that SRC Fuel is a viable alternative for No. 6 Fuel Oil in oil-designed boilers.

5.8 FLUE GAS ASSESSMENT

There were two main areas to be evaluated when the test program at PETC was undertaken. The first was the combustion area to determine if SRC could be burned in an oil-designed boiler. The second was to provide flue gas and particulate matter from the combustion of the SRC forms to particulate control devices to enable evaluation of these devices under actual operating conditions.

In addition, an ESP computer modeling program, developed by SoRI,¹³ was used to extrapolate the PETC pilot ESP results to a full-scale ESP installation. This information is also included in this discussion.

It is reasonable to believe that some form of particulate control device will be needed to control the emissions from an SRC fired boiler. This belief is based on data that were available from previous burn tests which indicated that it would be difficult to meet compliance with the NSPS without some form of particulate control device.

In 1977, SCS conducted a test burn of SRC Fuel at Georgia Power Company's Plant Mitchell. This test was successful in demonstrating that SRC Fuel could be fired in a commercial coal-designed plant with few modifications. However, there were several questions that were not adequately answered by the results of that test. Two of the major questions were:¹⁸

- A. Could an ESP be considered a viable control device for SRC?
- B. What design criteria should be used for the design of an ESP to control the emissions from a SRC Fuel fired boiler?

With these questions in mind, the PETC burn test was devised to provide the necessary data to size and design emission control devices for SRC. Since the Mitchell tests in 1977, there has been an increased interest in the use of fabric filters rather than precipitators for the control of particulates from boilers. Therefore, the PETC burn tests provided data on fabric filter devices as well as on an ESP. The ESP requires more testing to quantify its operating parameters, and to accurately assess performance.

Both the ESP and the fabric filter data are discussed in detail.

5.8.1 ELECTROSTATIC PRECIPITATOR PERFORMANCE EVALUATION

The data presented in this discussion include the particulate concentrations at the inlet and outlet of the pilot scale precipitator and the operating parameters of the ESP.

For each type fuel at least one set of operating conditions was tested. The primary test condition was to operate the ESP at 5000 acfm at the inlet which resulted in a specific collection area (SCA) of approximately 240 ft²/1000 acfm. This is a relatively low SCA considering that the normal range for SCA is 200 to 700 ft²/1000 acfm. The current input to each field was limited to 10 mA, resulting in a current density of approximately 19 μ A/ft².

Table 10 gives a summary of ESP operating conditions and test results for all fuels tested.

The No. 6 Fuel Oil tests were run only at the primary condition (5000 acfm). The average ESP inlet loading was 0.05 lb/10⁶ Btu with an outlet loading of 0.004 lb/10⁶ Btu which resulted in an efficiency of 91.35 percent. No operating problems were encountered with the ESP. ESP electrical operating conditions during the test period are given in Table 10.

When the SRC Fuel was burned there were both boiler and ESP problems. The slow mix burner had clinker buildup problems which resulted in poor burnout, CO spikes, and opacity spikes. The poor burnout resulted in high carbon ash which caused ESP high voltage insulator fouling or partial grounding of the ESP fields. A better burnout was achieved and flame stability was improved by adding 5-percent total thermal input with natural gas. The insulator fouling problem was solved by adding insulator purge air. The unsteady boiler operation and opacity spikes resulted in erratic data. As a result, only one operating

TABLE 10

SUMMARY OF ESP OPERATING CONDITIONS AND TEST RESULTS^c

Fuel	Average Secondary Current/Field (mA)	Average Secondary Voltage/Field (kV)	Avg. Current Density ($\mu\text{A}/\text{ft}^2$)	SCA ($\text{ft}^2/10^3 \text{ ACFM}$)	Inlet ESP ($\text{lb}/10^6 \text{ Btu}$)	Outlet ESP ($\text{lb}/10^6 \text{ Btu}$)	Percent Eff
No. 6 Fuel Oil	10	38	24	240	0.050	0.004	91.35
SRC Fuel	8	41	20	230	0.959	0.005	99.46
SRC Residual Fuel Oil ^a	8	40	19	240	0.196	0.002	99.08
	5	38	12	240	0.195	0.001	99.43
	5	39	12	173	0.204	0.008	96.13
SRC-Water Slurry ^b	7	45	17	220	0.930	0.006	99.34
	7	44	11	145	0.999	0.026	97.36

a. Three sets of operating conditions are reported here.

b. Two sets of operating conditions are reported here.

c. Data from WFI (reference 24).

condition (Table 10) was tested to obtain the best data average. The average inlet particulate loading was 0.959 lb/10⁶ Btu. The ash collected easily with a 0.005 lb/10⁶ Btu outlet loading and an ESP efficiency of 99.46 percent. The ESP was not operated or tested during the fast mix burner tests due to time and money constraints.

The SRC Residual Fuel Oil was burned with a steady particulate emission rate and opacity. This allowed three operating conditions to be tested. Table 10 gives the ESP electrical data for the three operating conditions. The inlet loading averaged 0.197 lb/10⁶ Btu. The first operating condition tested yielded an outlet loading of 0.002 lb/10⁶ Btu with an efficiency of 99.08 percent. Since the amount of flyash at the outlet was so small and difficult to measure, the current was lowered in each field from 8 mA to 5 mA. Contrary to theory, the outlet loading decreased to 0.001 lb/10⁶ Btu with an efficiency of 99.43 percent. The third condition tested was to increase the gas volume to 7000 acfm which decreased the SCA to 173 ft²/100 acfm. The outlet loading was 0.008 lb/10⁶ Btu with an efficiency of 96.13 percent. Evaluation at the three test conditions allowed SoRI to run the computer program three times to evaluate a full-scale unit.

The SRC-Water Slurry flame was very stable and, therefore, the particulate emissions were more consistent. This allowed for testing at the two operating conditions given in Table 10. The average loading over both operating conditions was 0.96 lb/10⁶ Btu. The first condition tested yielded an outlet loading of 0.006 lb/10⁶ Btu with an efficiency of 99.34 percent. This performance is quite similar to the SRC Fuel. The second condition tested was with two fields energized with the 5000 acfm. This lowered the SCA to 145 ft²/1000 acfm. The test results showed the outlet loading to increase to 0.026 lb/10⁶ Btu with an efficiency of 97.36 percent. These two conditions were used in the SoRI computer model.

The SRC flyash is a relatively easy ash to collect. Low SCAs of 240 ft²/1000 acfm have given high efficiencies. The flyash resistivities measured by SoRI show the ash to have low resistivities. This made for easy collection, but may result in excessive rapping reentrainment. A larger SCA may be required to control the reentrainment. Further investigation is needed to evaluate reentrainment.

5.8.1.1 EPA/SoRI ESP Model

One of the major design tools available to the ESP design engineer today is the EPA/SoRI computer program that simulates an ESP.¹³ This program was developed by SoRI under contract to the U.S. Environmental Protection Agency. This program is used by ESP manufacturers and by many of the electric utilities to size and evaluate their ESPs. SCS uses this program to aid in the evaluation of existing ESPs and to help size new or retrofit ESPs.

If the necessary input data for the ESP model can be obtained, the performance of the ESP can be simulated using the computer. By using actual test data for the input parameters of the model, the model can essentially be calibrated for the conditions that have been measured in the field. At that point it is possible to change the input data and the modeling parameters to simulate different operating conditions and characteristics, and to determine the effect that those conditions have on the performance of the ESP. It should be

noted that the model is only as good as the input data. Care must be exercised in the collection of data that is to be used for input to the model.

There are certain data that must be collected to adequately utilize the model. These data are usually obtained through field testing and are listed below:

- Inlet grain loading of particulate.
- Inlet particle size distribution.
- Electrode geometry of the ESP.
- Electrical operating conditions of the ESP.
- Fuel chemical analysis.
- Gas flow distribution.
- Efficiency of the ESP.
- Operating temperature.

There are also a number of parameters that must be assumed since the practical measurement of these data is difficult if not impossible. However, the confidence level of these assumptions is increased by the initial calibration of the model with the field data.

Two major input parameters that are typically assumed are gas sneakage and rapping reentrainment losses. The sneakage problem is important because it represents a portion of the gas that will make its way through the ESP without being cleaned. The particulate that this gas carries will be present in the outlet gas stream. The losses due to rapping can be measured with some degree of accuracy but it is difficult and adds to the overall cost of a test program. These more accurate rapping measurements were not performed during the PETC test because of time limitations. However, there were some comparative measurements of these losses made by the large particle sizing system (LPSS). These measurements provide only a relative indication of the mass and not an actual mass as could be obtained through other, more time consuming, testing.

Assuming that the required input data are obtained and the necessary assumptions are made, the model would then predict an ESP efficiency based on the input data. Comparison of predicted efficiency and actual measured efficiency would allow for proper calibration of the model. If predicted and actual values are in agreement, then it can be concluded that values assumed for the parameters are realistic. If the efficiencies do not agree, then values assumed for the parameter must be adjusted until good agreement is achieved.

Assuming that the required input data are obtained and the necessary assumptions are made, the model would then predict an ESP efficiency based on the input data. Comparison of predicted efficiency and actual measured efficiency would allow for proper calibration of the model. If predicted and actual values are in agreement, then it can be concluded that values assumed for the parameters are realistic. If the efficiencies do not agree, then values assumed for the parameter must be adjusted until good agreement is achieved.

Provided that the ESP model has been calibrated to the actual measured operating conditions, it can be used to predict the performance of the ESP under different operating conditions. This is the major benefit of the model. A small pilot-scale ESP can be used to help determine how to size a full-scale ESP for a given application.

It must be noted that determination of the inlet particle size distribution is one of the most critical of all the input parameters, and one of the most difficult tests to perform accurately. Also the use and evaluation of the ESP model must be tempered with sound experience and knowledge of the precipitation process.

5.8.1.2 Ash Resistivity Measurements

The electrical resistivity of the ash produced from the combustion of the SRC Fuels and the No.6 Fuel Oil was measured with the SoRI point-to-plane insitu resistivity probe.¹⁹ The point-to-plane probe is designed to be inserted in the gas stream and energized by a high voltage power supply. The probe consists of a corona point and a small circular collecting plate. These are housed in a cylinder that can either permit the passage of flue gas through the probe collecting region or block the gas flow. When the corona point is energized in the presence of particulate laden flue gas, the probe will collect a small sample of particulate by electrostatic precipitation in a manner similar to the way a normal electrostatic precipitator will collect particulate. Figure 25 is a schematic drawing of the probe and its main components. The probe is allowed to equilibrate to the flue gas temperature and is then energized. After a given time period, the thickness of the collected layer is measured with the built-in measurement system. The measurement system consists of a circular plate the same size as the collecting plate that is lowered until it contacts the ash layer. At that time increasing voltages are applied to the dust layer and the current obtained is recorded until the dust layer breaks down electrically and sparkover occurs. The geometry of the dust sample, together with the applied voltage and current, provide sufficient information for the determination of the ash resistivity. There are other methods that are sometimes used to measure ash resistivity, but this is the preferred method.

The determination of ash resistivity is not critical to the modeling process, provided that the electrical operating conditions of the ESP are known. This was the case at PETC, as the electrical conditions were not limited by the ash resistivity, but were set to desired levels by the operating personnel. Ash resistivity will affect the reentrainment of previously collected ash; therefore, an attempt was made to measure the resistivity.

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FIGURE 25
POINT-TO-PLANE RESISTIVITY PROBE

The point-to-plane resistivity probe was operated at the ESP inlet during each test series. However, only the No. 6 Fuel Oil produced an ash from which meaningful data could be obtained. The ash produced from the combustion of SRC Fuel contains a large percentage of unburned carbon. Even when carbon conversions in the boiler are in the 99-percent range the inherently low ash content of the SRC Fuel leads to high carbon percentages in the flyash. This being the case, all three SRC forms had sufficient carbon in the ash to make the measurement of the resistivity difficult, as the carbon in the ash tends to short circuit the resistivity probe. The data that were obtained from the SRC fuels indicated that the resistivity was less than 10^9 ohm-cm. The No. 6 Fuel Oil ash was successfully measured at a resistivity of about 1×10^9 ohm-cm. This is roughly an order of magnitude lower in resistivity than a typical medium sulfur coal.

5.8.1.3 Particulate Size Distribution Measurement

The particulate size distribution and inlet mass loadings used in the model were taken from impactor and ultrafine particle sizing system (UPSS) data.¹⁹ The particle size distribution is shown in Figure 26.

Experimental measurements of particle size normally can not be made with a single instrument if the size range of interest extends over much more than an order of magnitude. Size distributions covering broad ranges of sizes then must include data points which may have been obtained using different physical mechanisms. Particle sizing work is frequently done on a statistical basis where large numbers of particles, rather than individuals, are sampled. For this reason the particles are normally assumed to be spherical. An ideal particle size measurement device would be located insitu and would give real time readout of particle size distributions and particle number concentration over the size range from $0.01 \mu\text{m}$ to $10.0 \mu\text{m}$ diameter. At the present time, however, particle size distribution measurements are made using several instruments which operate over limited size ranges and do not yield instantaneous data. During the test program at PETC, various methods for measuring particle size distributions were used which included inertial methods (cascade impactors and cyclones), optical methods (Climet and Royco optical particle counters), and an electrical mobility method (Electrical Aerosol Analyzer).

Two types of cascade impactors were used during the PETC testing. These were the Brink impactor and the Modified University of Washington Mark III impactor and they are illustrated in Figures 27 and 28. The major difference between these two impactors is the flowrate at which they operate. These impactors are operated insitu and traverse the duct to obtain a representative sample. Cascade impactors are capable of measuring particle size distributions for particle diameters from 0.5 to $10.0 \mu\text{m}$.

The mechanism by which a cascade impactor classifies particulate is illustrated in Figure 29. In each stage of an impactor, the gas stream passes through an orifice and forms a jet which is directed toward an impaction plate that collects the particle. This plate has been weighed prior to installation in the impactor and will be weighed following the sampling run to determine the amount of particulate collected by that stage. For each stage of an impactor there is a characteristic particle diameter which has a 50-percent probability of impaction upon the collection plate. This characteristic diameter is referred to as the

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FIGURE 26
ASH PARTICLE SIZE DISTRIBUTIONS USED IN THE ESP MODEL
TO ESTIMATE FULL-SCALE PRECIPITATOR COLLECTION EFFICIENCY

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FIGURE 27
MODIFIED BRINK MODEL BMS-11 CASCADE IMPACTOR

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FIGURE 28
UNIVERSITY OF WASHINGTON MARK III
SOURCE TEST CASCADE IMPACTOR

A. TYPICAL IMPACTOR JET AND COLLECTION PLATE

B. GENERALIZED STAGE COLLECTION EFFICIENCY CURVE

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FIGURE 29
OPERATION PRINCIPLE AND TYPICAL PERFORMANCE
FOR A CASCADE IMPACTOR

D₅₀ of the stage. The schematic diagram in Figure 29 shows a single jet for illustrative purposes, but commercial impactors may have from one to several hundred jets in a single stage. Typical impactors have from 5 to 10 stages. Particle collection efficiency of a given stage is determined by factors such as particle shape and density, viscosity of the gas, and the design of the stage. The type of collection surface will also influence stage collection characteristics. The selection of the proper impactor for a given test situation is primarily dependent upon the mass loading of the gas stream and how long one must sample the gas stream to obtain a usable sample. There are three major criteria to be met in the selection of the proper impactor to use:

- A. The sampling period must be of sufficient duration to provide a reasonable averaging of transient conditions in the stack.
- B. The loading of a given impactor stage must be low enough to prevent reentrainment of the particles.
- C. The sampling rate through the impactor must be sufficiently low to prevent scouring of impacted particles by high gas velocities.

For these reasons, an impactor with a comparatively low sample rate must be used in a gas stream with a high mass loading, and one with a high sampling rate must be used in a low mass gas stream if one is to obtain a significant sample in a reasonable length of time.

The sample collection plates of the impactors are either coated with a special grease or are composed of specially treated glass fiber material. Care must be used when selecting the impaction material as significant interferences exist. Blank impactor runs must be made and used in the calculation of the data to account for gas phase reactions between the collection material and the flue gas. Following sampling and determination of the weight of the particulate collected on each stage, the following procedures are used to obtain the final data.

1. Stage weights are corrected for blank weight gains.
2. Cut points for the individual stages for each impactor are calculated based on calibration studies conducted previously in the laboratory with particles of known sizes.
3. The data are then used as input to a computer program which calculates the size distribution.

A detailed description of the data reduction program is available in the EPA publication, "A Computer Based Cascade Impactor Data Reduction System."¹³

A five-stage cyclone of SoRI design was used at the ESP inlet sampling location to obtain inlet size distribution measurements and larger size-fractionated samples for chemical analyses.¹⁹ The cyclone will collect approximately 1 g of particulate per cyclone compared to only about 10 mg for the typical impactor stage. The cut points (D₅₀) of the stages

of the cyclone are 7.5, 2.6, 1.3, 0.6, and 0.3 μm . Figure 30 shows the five-stage cyclone used at PETC.

An ultrafine particle sampling system (UPSS) developed by SoRI was used at the ESP inlet and outlet during the PETC tests. The instrumentation for ultrafine particle distribution measurements is still in the developmental stage. This instrumentation is state-of-the-art in its field and the data base for comparison of the validity of the data is small. However, the field and laboratory studies which SoRI has performed lends a reasonable confidence level to the data and the instrumentation used. There are two physical properties of ultrafine particles which are size dependent and which can be predicted with sufficient accuracy under controlled conditions to be used to measure particle size. These properties are the particle diffusivity and the electrical mobility of the particle.

The UPSS developed by SoRI is composed of three main parts:

- The sample extraction and dilution system (SEDS).
- A Climet optical particle counter.
- An electrical aerosol size analyzer (EASA).

The SEDS shown in Figure 31 extracts a continuous flue gas sample from the duct, conditions it to prevent the formation of an interference condensation fume, and dilutes it to temperatures and concentrations allowable for use in the optical particle counter and electrical aerosol size analyzer. The conditioned sample thus provided for sizing has a lower size limit of 0.01 μm and an upper size limit of 2.0 μm . The limits are due to particulate transport losses within the SEDS system itself rather than to the operating ranges of the sizing instruments. Real time concentration information in the 0.3- to 2.0- μm size range can be obtained with the Climet optical particle counter in conjunction with the SEDS system. Figure 32 presents a schematic of the EASA which operates on an electrical mobility principle and when used with the SEDS covers the size range from 0.01 to 1.0 μm .

A large particle sampling system (LPSS) that was designed by SoRI was operated at the ESP outlet during the PETC testing. This system is composed of three parts.

- A sample extraction and dilution system.
- A Royco optical counter.
- A computerized data acquisition system.

The particle size distribution at the outlet of an ESP is comprised of many fine particles and a lesser number of large particles. It is desirable, however, to quantify the large particles in the flue gas stream as they contribute a large portion to the outlet mass loading, and are generally associated with rapping reentrainment losses, or the scouring of previously collected ash particles by high gas flow in the ESP. The LPSS sample dilution system

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FIGURE 30
THE FIVE-STAGE SERIES CYCLONE SYSTEM

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FIGURE 31
SoRI ULTRAFINE PARTICLE SAMPLE
EXTRACTION-DILUTION SYSTEM (SEDS)

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FIGURE 32
FLOW SCHEMATIC AND ELECTRONIC BLOCK DIAGRAM
OF THE ELECTRICAL AEROSOL SIZE ANALYZER (EASA)

is designed to be a size selective device. The geometry of the diluter is such that the large particles, having high inertia, tend to pass directly from the inlet to the sample exit of the diluter while small particles, having relatively low inertia, are mixed to varying degrees, depending on their sizes, with the dilution air. This procedure produces a substantial reduction in the concentration of small particles and condensable vapors within the sample stream while maintaining the concentration of the less numerous large particles. A diagram of the LPSS is given in Figure 33.

5.8.1.4 Particulate Mass Measurements

The amount of particulate at the boiler exit, the fabric filter inlet, the ESP inlet, and the ESP outlet was measured by either EPA Method 5 or 17. These are standard test methods established for the uniform sampling of stationary sources. The details of the procedures and the equipment used can be found in the boiler emission report submitted by Wheelabrator-Frye Inc., Air Pollution Control Division.²³

5.8.1.5 Sulfur Dioxide and Sulfur Trioxide Measurements

Measurements of sulfur dioxide (SO_2) and sulfur trioxide (SO_3) were made at locations between the boiler outlet and the ESP outlet to determine the amount and the fate of sulfur oxides (SO_x) through the system. The Cheney-Homolya SO_x sampling train was used. The instrument consists of a heated quartz filter followed by a controlled temperature condenser for selectively retaining condensed sulfur trioxide and a series of hydrogen peroxide bubblers for absorbing sulfur dioxide. The heated filter removes any sulfate-bearing particles that might interfere with determination of the gas phase sulfur trioxide while preventing the loss of sulfur trioxide vapor in the filter. The filter is maintained at a temperature of about 250°C and the condenser at about 60°C . The recovered condensate and peroxide solution is titrated by the barium-perchlorate procedure using Thorin as the indicator (EPA Method 6). Figure 34 presents a diagram of the sampling train used at PETC.

5.8.1.6 Computer Modeling of the ESP

Precipitator performance, whether measured or computed with the model is very sensitive to the fine particle fractions of the mass loading. The finer particles are much harder to collect because they require longer charging times, and, therefore, will penetrate the ESP much further than will larger particles. A large particle will typically receive an adequate charge for precipitation very quickly in comparison to a small one.

Following the data reduction, the ESP model was run to simulate the pilot scale ESP used at PETC. The electrical operating conditions used in the simulations were averages of the operating conditions measured during the actual tests, and were different for each fuel. For the No. 6 Fuel Oil test, the ESP was capable of operating at high voltage and current levels. For the SRC tests, the operating voltage and current levels were reduced to more conservative values. However, in the subsequent SRC tests the operating points showed varying degrees of degradation due to current tracking across the surface of the high voltage insulators. These voltage and current fluctuations were small during the No. 6

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FIGURE 33
DIAGRAM OF THE SoRI
LARGE PARTICLE SAMPLING SYSTEM (LPSS)

FIGURE 34
SCHEMATIC DIAGRAM OF APPARATUS FOR COLLECTION OF SO₂ AND SO₃

Fuel Oil tests, which were performed first, but were much greater during the later tests. Variations of up to 10 kV were seen in one of the SRC Residual Fuel Oil tests. A typical variation was in the 3- to 5-kV range. The electrical operating conditions were not limited by the electrical resistivity of the collected ash layer. The fouling of the high voltage insulators in the pilot-scale ESP was due to the particular design of the insulator arrangement within the unit, and an inadequate insulator purge air system. Full-scale ESPs use various designs and insulator purge air arrangements to avoid this problem.

The modeling of the full-scale ESP used estimated values for the electrical operating points in each electrical bus section as listed in Table 11. Values for the coal comparison case were predicted for flyash of electrical resistivity 1×10^{11} ohm-cm, based on correlations of electrical operating data from 17 full-scale utility flyash precipitators. The resistivity values for the SRC fuels are speculative, and were therefore chosen to be the same as the No. 6 Fuel Oil. This was due to the difficulty experienced during the PETC tests in obtaining an accurate value for the flyash resistivity of the SRC fuels. Since the electrical operating points were not limited by the resistivity of the ash layer on the collecting plate, the nominal parameters shown in Table 11 merely indicate a reasonable limit on the electrical power input. Because of the testing experience at PETC with degraded electrical conditions caused by low-resistivity ash deposits on the surface of the high voltage insulators, precipitator performance was computed also for the degraded electrical parameters shown in Table 11 as an indication of possible consequences of inadequate purging of the high voltage insulators. Computations of precipitator collection efficiency will vary with changes in the specified operating voltage, and less so with variations in the operating current.

TABLE 11
ELECTRICAL OPERATING POINTS USED IN THE ESP MODEL
TO ESTIMATE FULL-SCALE PRECIPITATOR COLLECTION EFFICIENCY

SRC Fuels and Fuel Oils

Section	Nominal Parameters			Degraded Parameters		
	kV	$\mu\text{A}/\text{ft}^2$	nA/cm^2	kV	$\mu\text{A}/\text{ft}^2$	nA/cm^2
1	45	26.0	28.0	41	9.3	10.0
2	41	27.9	30.0	37	11.1	11.9
3	38	28.8	31.0	35	11.6	12.5
4	37	28.8	31.0	34	12.1	13.0

Medium-Sulfur Bituminous Coal

Section	Nominal Parameters		
	kV	$\mu\text{A}/\text{ft}^2$	nA/cm^2
1	39	8.1	8.7
2	38	11.8	12.7
3	37	14.8	15.9
4	35	19.1	20.6

The numbers given show the electrical operating points used in the model runs.

The parameters that are used to make approximate corrections for nonideal gas flow conditions are chosen to be: $S = 0.10$ and $\sigma_{\text{gas}} = 0.25$. The degrading effects of gas sneaking in an ESP are represented by a decimal fraction S (typically 0.05 to 0.10) as specified by the person using the model. Nonuniformity in the gas flow distribution is represented by the normalized standard deviation σ_{gas} of the inlet gas velocity (typically 0.15 to 0.25) of a matrix of gas velocity measurements over the face of the precipitator. Both of these nonideal parameters enter into the calculation of correction factors that are applied to the overall precipitation rate parameter for each particle size. These parameters should be reasonably representative of a retrofit situation where the existing precipitator is in good mechanical condition, with good gas flow distribution and baffling.

5.8.1.7 ESP Results and Conclusions

For all the uncertainties in full-scale precipitator performance projections, the overriding consideration is that the PETC pilot-scale ESP performed very well in collecting ashes from SRC fuels. Both measurements and mathematical modeling demonstrate that there are no fundamental problems that would prohibit the use of ESPs for cleaning the flue gas from a full-scale utility boiler firing SRC.

The PETC test results indicate that SRC ashes may be collected satisfactorily with a fairly wide latitude in electrical operating conditions. This is particularly important in determining if an existing ESP will perform adequately with the ash from SRC.

The results of the mathematical simulation are shown in Figure 35. In this figure, the measured collection efficiency is plotted against the computed value for $S = 0.10$ and $\sigma_{\text{gas}} = 0.2, 0.3, \text{ and } 0.4$. Perfect agreement between measured and computed values is indicated by the diagonal dashed line. The relationship between particle size distribution and collection efficiency is reflected in this figure, with pulverized SRC ash having the greatest fraction of large particles and the highest collection efficiency. The No. 6 Fuel Oil has a large number of fine particles and the lowest collection efficiency. The poor agreement for SRC Residual Fuel Oil is probably due to large fluctuations in the electrical operating conditions during the testing. An increase of a few kilovolts in the average operating voltage used in the computations would bring the computed values of collection efficiency in line with the measured efficiency. The measured values of collection efficiency shown in Figure 35 are taken from impactor measurements. The level of agreement between computed and measured collection efficiency of the pilot-scale ESP are shown in Figure 35, and give a qualitative indication of the level of confidence in using the ESP model to estimate the performance of a full-scale precipitator collecting ash from SRC fuels.

The results of model runs for a full-scale ESP are shown graphically in Figure 36. This is a plot of the ESP efficiency versus the specific collection area (SCA) of the ESP.

Because the electrical operating conditions are assumed to be the same for each fuel, the differences between the three curves reflect the difference in the particle size distribution.

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FIGURE 35
MEASURED AND COMPUTED PERFORMANCE OF THE ESP

ADAPTED FROM REPORT BY SOUTHERN RESEARCH INSTITUTE¹⁹

FIGURE 36
MODELING ESTIMATES OF ESP COLLECTION
EFFICIENCY FOR VARIOUS SCAs

The computations of collection efficiency for ashes from SRC Residual Fuel Oil and SRC-Water Slurry lie along the same curve in Figure 36 because the two measured particle size distributions are so similar. Figure 36 also illustrates the decrease in efficiency with degraded electrical conditions due to contaminated high voltage insulators.

Finally, an indication of the possible degradation in ESP performance due to rapping reentrainment is shown in Figure 37. The curves for the SRC-Water Slurry (no rap) and the bituminous coal (no rap) are quite close on this figure and allow for the comparison of known rapping losses, in the case for the bituminous coal which represents actual field test data obtained by SoRI, and the unknown rapping losses of the SRC-Water Slurry. The curve for the bituminous coal (rapped) represents a loss of approximately 10 percent of the collected ash in the outlet field of the ESP. The curves labeled 20 percent and 40 percent are calculated for the SRC-Water Slurry ash by a modeling technique that models rapping losses from each electrical section of the ESP on a specified rapping sequence, analogous to the rapping sequence of a full-size ESP. This figure illustrates the lowering of ESP efficiency with an increase in the rapping reentrainment losses. Since no actual data were obtained during the PETC tests, these numbers (20 percent and 40 percent) are speculative; however, they may represent real problems that must be factored into the design of a full-scale ESP for the collection of high carbon SRC ashes.

Figure 38 illustrates the estimates of the minimum SCA required for a given inlet and outlet mass loading, as listed in Table 12. For example, the pulverized SRC Fuel with an inlet loading of $0.78 \text{ lb}/10^6 \text{ Btu}$ requires an ESP with an SCA of 170 to meet an emission standard of $0.01 \text{ lb}/10^6 \text{ Btu}$, and SCA of 130 to meet $0.03 \text{ lb}/10^6 \text{ Btu}$, and an SCA of 80 to meet $0.10 \text{ lb}/10^6 \text{ Btu}$. It must be remembered that these numbers do not include rapping losses or engineering design margins. The inclusion of rapping losses and design margins would shift the SRC curves upward, requiring larger SCAs to meet a given outlet loading.

The limits of uncertainty in using the ESP model can be narrowed considerably with some test data on the precipitability of ashes from firing SRC in a full-scale utility boiler. For estimating the adequacy of an existing ESP or designing a new ESP, additional data are needed in the specific areas listed below.

- A. The possibility of improved carbon burnout in a full-scale utility boiler is a major source of uncertainty. Small changes in the ash chemistry and morphology could cause order of magnitude changes in the electrical resistivity of the ash. If the ash resistivity could be increased to the order of $1 \times 10^{10} \text{ ohm-cm}$, the precipitability would remain good and the following problem (B) would be alleviated.
- B. Electrical problems associated with contamination of the high voltage insulators need to be investigated with ash from a full-scale utility boiler. If the ash resistivity remains low then much care should be used in assessing the design for the insulator purge air system. The volume of purge air required or a design which does not subject the insulators to the low resistivity ash should be considered.

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FIGURE 37
COMPUTED EXAMPLES OF DEGRADATION IN
PRECIPITATOR PERFORMANCE DUE TO RAPPING REENTRAINMENT

ADAPTED FROM REPORT BY SOUTHERN RESEARCH INSTITUTE¹⁹

FIGURE 38
ESTIMATES OF MINIMUM SCA FOR A SPECIFIED INLET MASS LOADING
AND A RANGE OF OUTLET MASS LOADINGS

TABLE 12

**ESTIMATES OF COLLECTION EFFICIENCY AND MINIMUM
SCA FOR PRECIPITATORS COLLECTING ASH FROM FIVE
DIFFERENT FUELS, FOR A SPECIFIED INLET MASS
LOADING AND A RANGE OF OUTLET MASS LOADINGS**

	Inlet Loading (lb/10⁶ Btu)	Outlet Loading (lb/10⁶ Btu)	Collection (Eff. %)	SCA (ft²/10³ ACFM)
No. 6 Fuel Oil	0.035	0.01	71	90
SRC Fuel	0.78	0.01	98.7	170
		0.03	96.2	130
		0.10	87	80
		0.01	94.4	130
SRC Residual	0.18	0.01	94.4	130
Fuel Oil		0.03	83	80
SRC-Water Slurry	0.98	0.01	99.0	230
		0.03	96.9	165
		0.10	90	105
Bituminuous	5.90	0.01	99.83	410
Coal Med.		0.03	99.49	320
Sulfur		0.10	98.3	235

- C. The rapping reentrainment of ashes from SRC fuels is another major source of uncertainty. Reentrainment from the collecting plates can vary widely with the mechanical construction of the plates and the distribution of the rapping forces on the plates.

5.8.2 FABRIC FILTER EVALUATION

To evaluate the feasibility of fabric filters for control of emissions from SRC fired boilers, two types of fabric filters, namely a pulse-jet fabric filter (PJFF) and a pilot-scale reverse air fabric filter (RAFF) were tested. This section of the report discusses the design and operation of the fabric filters and the performance of these units. The particulate emissions from all fuel types were easily controlled by the fabric filters to less than 0.01 lb/10⁶ Btu, well within the particulate emission limit of the NSPS of 0.03 lb/10⁶ Btu for electric utility steam generating units. The amount of controlled particulate emissions from the SRC fuels combustion was equal to or less than the controlled particulate emissions from the No. 6 Fuel Oil combustion. A conservative full-scale design approach with a RAFF at a nominal 2 to 1 air to cloth ratio or a PJFF at 4 to 1 air to cloth ratio should provide more than adequate particulate control.

5.8.2.1 Pulse-Jet Fabric Filter

5.8.2.1.1 Design

The exhaust gases of the 700-hp, oil-fired boiler pass through an American Air Filter PJFF. The fabric filter unit is described in Section 3.6.2 of this report and is shown in Figure 21 (Reference 25). The PJFF is 11 ft square and 27 ft high with one hopper equipped with an air-operated double dump valve that continually empties the hopper. The PJFF is designed to clean 16,000 acfm at up to 400°F, 12-percent moisture, and 6 to 1 air to cloth ratio (ACR). The cleaned gas from the PJFF is drawn by an ID fan and discharged to the atmosphere via an insulated, sheet metal stack.

The PJFF contains 120 filter bags arranged in 10 rows of 12 filter bags each. Each bag is 11 ft 9 in. long with a diameter of 5 1/4 in. The PJFF has a total cloth area of 1924 ft². The bags were cleaned with a pulse of 75-psig clean air jet. There are two compressed air manifolds, one on each side of the PJFF such that each manifold cleans the corresponding half (six bags) of any one of the ten rows. The two manifolds together clean 12 bags of a row simultaneously.

5.8.2.1.2 Operation

The PJFF was operated from 4 to 12 hours per day, depending upon the number of tests performed. When not in use at night it was not possible to maintain the normal operating temperature in the PJFF. The boiler load was reduced at night and the flue gas volume was not sufficient to maintain operating temperature in the ESP and the PJFF. As an ESP requires many hours at operating temperature to reach equilibrium, a failure to maintain the ESP at operating temperature overnight severely impacted the next days testing. Therefore, the flue gas was directed to the ESP during the night while the boiler was at low load.

Prior to the SRC burn test programs, the PJFF was fitted with a new set of felt filter bags manufactured by Huyck Felt Division of BTR Paper Group. Before performance testing of the PJFF, the bags were conditioned with flue gas of the 700-hp boiler burning pulverized SRC Fuel as its primary fuel. The PJFF flue gas volume rate was dependent on the boiler flue gas volume rate required through the ESP. After setting the desired level of ESP flue gas volume, the balance of the boiler flue gas was sent to the PJFF.

The PJFF was designed for twice the flow actually required during this test program. Whenever the boiler encountered combustion difficulties, the PJFF was bypassed to avoid blinding the bags with oily, sticky flyash, and other undesirable products of incomplete or improper combustion.

On the first day of PJFF testing it was determined that the outlet particulate concentration was abnormally high for a fabric filter unit. The butterfly valve in the bypass ductwork was not sealing well and was letting the inlet (dirty) gas into the stack. This situation was corrected during December 1982, just prior to SRC-Water Slurry testing.

Table 13 is a summary of the results from the PJFF. Note the low efficiency during the SRC Fuel, and SRC Residual Fuel Oil tests due to the leaking bypass damper. This problem was solved by placing a blank plate in front of the bypass valve following the SRC Residual Fuel Oil tests.

5.8.2.1.3 Testing

The PJFF is not equipped with indicators or recorders for monitoring its performance, except for an air pressure gauge to show the pressure of cleaning air supplied to the air header manifolds. To monitor the performance during testing, an additional air pressure gauge was installed near one of the manifolds. Also, a U-tube manometer was installed on the air lines from the dirty and clean sides of the PJFF to monitor the pressure drop. The pulse interval was measured by using a digital wrist watch.

The gas flow and particulate emissions were measured at the PJFF stack approximately eight diameters downstream from the ID fan and four diameters upstream from the stack opening to the atmosphere. The particulate emissions were measured by an instack filter as per EPA Method 17. An integrated sample of flue gas was analyzed for CO₂ and O₂ content. The gas velocity and temperature were measured at each particulate traverse point in the stack. The particulate sampling at the stack consisted of traversing the stack cross section at a total of 12 points for 10 or more minutes per point. The PJFF inlet gas flow properties and particulate emissions values were based on the results of the boiler exit gas and the ESP inlet gas testing reported separately.

5.8.2.2 Reverse Air Fabric Filter

5.8.2.2.1 Design

The RAFF is a small, portable fabric filter test unit containing 1 ft² of cloth in a vertical position.²⁵ Instead of a set of fabric bags, it uses one 12 in. by 12 in. piece of filter fabric, framed taut in a vertical, diamond position, serving as a bag of infinite diameter, inside a test chamber where the cavity on either side of the fabric is equal in shape and in volume. The performance of such a comparative device may be different from a full-scale unit.

The nature and extent of differences among the performance characteristics of the RAFF, a pilot unit, and a full-scale reverse air fabric filter unit have not been investigated.

Figure 22 in Section 3.6.3 is a schematic diagram of the RAFF. The flue gas is extracted from a source emission duct and piped to the test chamber where filtration takes place under actual temperature and moisture conditions. Heating jackets maintain the flue gas lines and the filter chamber at constant temperature. In the filtration mode, valves 1 and 2 are closed while valves 3 and 4 are open. In this mode the gas passes from the hopper side of the chamber, through the filter cloth, through the tubular, Balston filter No. 3, the condenser, the dryer, the vacuum pump, the rotameter, and the dry test meter and finally is discharged into ambient air.

TABLE 13

SUMMARY OF RESULTS FOR PULSE-JET FABRIC FILTER^b

	Symbol	Units	SRC Fuel	SRC Residual Fuel Oil	SRC-Water Slurry
Pulse Jet Operation Range					
Air-to-cloth ratio	ACR	ft/min	3.6 - 4.0	1.6 - 3.0	3.1 - 3.2
Pressure drop	ΔP	in. W.C.	0.8 - 2.5	1.0 - 1.5	1.8 - 2.3
Drag	S		0.2 - 0.7	0.4 - 0.5	0.6 - 0.8
Specific resistance	k		0.9 - 5.0	4.5 - 36.0	2.1 - 4.3
Inlet Dust Loading					
At actual conditions	Gr/ACF	Gr/ft ³	0.19	0.06	0.24
At 68°F, 29.92 in. Hg, dry	Gr/SDCF	Gr/ft ³	0.39	0.10	0.49
Loss on ignition at 750°C	LOI	% Wt	82 - 92	79 - 88	64 - 71
Outlet Dust Emissions					
At actual conditions	Gr/ACF	Gr/ft ³	0.017 ^a	0.001 ^a	0.001
At standard conditions	Gr/SDCF	Gr/ft ³	0.026 ^a	0.002 ^a	0.002
Emission rate heat input basis	lb/10 ⁶ Btu		0.06 ^a	0.005 ^a	
Pulse Jet Efficiency					
Gr/SDCF basis	η	%	93.5 ^a	98.1 ^a	99.7
Dust penetration	1- η	%	6.5 ^a	1.9	0.3
Pulse Jet Gas Volume Rate					
At actual conditions	acfm	ft ³ /min	6900 - 7800	3000 - 5800	5900 - 6200
At 68°F, 29.92 in Hg, dry	SDCFM	ft ³ /min	4400 - 5000	2200 - 3800	3800 - 4000
Pulse Jet Gas Properties					
Gas temperature	t	°F	295 - 308	210 - 280	260 - 270
Gas moisture	H ₂ O	% vol.	4 - 6	6 - 9	8.8 - 9.4
Carbon dioxide	CO ₂	% vol.	8.2 - 13.0	8.8 - 11.2	9.5 - 11.0
Oxygen	O ₂	% vol.	6.0 - 10.4	7.4 - 10.0	7.2 - 8.4
			(dry basis)		
Test Days			10	5	3

a. Leakage past bypass valve.

b. Data from WFI (reference 25).

During reverse air cleaning, valves 1 and 2 are open while valves 3 and 4 are closed. Thus, in the cleaning mode, the flue gas is precleaned by Balston filter No. 1 before it enters the clean air side of the filter chamber. The air passes from the clean air side, through the cloth, to the dirty side in the reverse direction. The particulate removed by reverse air cleaning is trapped by Balston filter No. 2 and the clean gas passes through the condenser and the subsequent components.

The condenser is kept in an ice bath and it condenses moisture from the flue gas before the gas enters the pump, the rotameter, and the dry test meter. The silica gel dryer is placed between the condenser and the pump to remove all residual moisture not removed by the condenser so that driest possible gas will enter the dry test meter.

The fabric filter cloth is first numbered, dried at 105°C, and then tare weighed. When needed, the tared fabric filter cloth is removed from an individually sealed bag and installed in a specially designed frame which snugly fits between two halves of the fabric filter test chamber.

The instrument panel has one, 10-point type J temperature indicator with a pushbutton selector switch and two temperature controllers: one for the test fabric filter chamber and the other for the heated flue gas line. There are six additional power controls to maintain temperatures of the inlet and outlet cavities. A Heise, digital manometer provides eight differential pressure readings.

The test chamber can be operated up to 500°F, 15-percent moisture, and 6 cfm.

5.8.2.2.2 Operation

To operate the RAFF, first a clean filter cloth is installed. Then the three Balston filters are installed. The other components are securely connected and the entire train is leak tested at about 200 in. W.C. vacuum. After a successful leak test, the flue gas sample lines, Balston filters, and the test chamber are set to desired temperatures. Once the desired temperatures are achieved, the forward flow filtration is begun at a rotameter rate to correspond to the predetermined ACR. A typical test data period involves a nominal 60 min of filtration time. Several sets of readings are recorded in a nominal 1-hour period.

When desired, the cleaning of the fabric filter is accomplished by 30 s or 1 min of reverse airflow and subsequent 30 s or 1 min of settling time with no gas flow through the fabric. After this two-part cleaning activity, the forward flow is resumed immediately to determine reduction in pressure drop across the fabric.

For the No. 6 Fuel Oil testing, one new fabric filter cloth was used for each test day except that filter cloth No. 5 was used for 2 consecutive days. For SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry only one new cloth was used for all test days of any one type of fuel. Therefore, six fabric filter cloths for No. 6 Fuel Oil received fewer than 8 hours of particulate exposure time each, whereas, the three fabric filter cloths for the three SRC Fuels each received over 38 hours of particulate exposure time.

The RAFF was operated for as many hours of stable boiler operation as were available. When not in use overnight, the RAFF was kept heated above 220°F to avoid any moisture condensation on the particulate layer and to have the pilot fabric filter quickly available for testing the next day.

Table 14 is a summary of RAFF results.

5.8.2.2.3 Testing

The RAFF was equipped with self-contained sampling components which assist in the determination of the inlet and outlet particulate concentration. The inlet particulate matter is that collected in the hopper, Balston filter No. 2, and the fabric filter cloth. Outlet particulate matter is collected in the Balston filter No. 3. Moisture is collected in the condenser and the silica gel dryer. The sampled gas volume was measured by the dry test meter. Various temperature and pressure readings provide the monitoring data for the pilot filter and assist in determining the gas volume readings at proper reference conditions. The temperature in the test filter chamber is considered the temperature of the inlet gas even though it may have been a few degrees higher or lower than that of the flue gas leading to the ESP. The isokinetic sampling of the flue gas is maintained by adjusting the flowrate throughout the sampling period. The RAFF was first evaluated with the flue gas generated by the firing of the No. 6 Fuel Oil and then the SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry.

5.8.2.3 Performance Evaluation

The fabric filters proved to be a simple and successful choice for the control of flyash from SRC combustion. Thus, the SRC burn test program established that conventional fabric filters should make a feasible control device for emissions from SRC fired boilers.

The reverse air cleaning as well as pulse-jet cleaning proved equally applicable in successful operation of the fabric filters. The RAFF and PJFF used a fabric primarily made of glass fibers. Both fabric filters were operated within their conventional operating limits and they performed at a dust removal efficiency as high as 99.8 percent after a period of operation of only 54 hours. The flyash of SRC fuels was relatively easy to remove from the fabric with normal cleaning procedures.

5.8.2.3.1 Pulse-Jet Fabric Filter

Table 13 summarizes the PJFF performance results. The PJFF outlet emission rate for SRC Residual Fuel Oil and SRC-Water Slurry was 0.004 lb/10⁶ Btu which is significantly less than the NSPS of 0.03 lb/10⁶ Btu. The higher outlet emission rate during SRC Fuel and SRC Residual Fuel Oil firing was a consequence of dirty gas leakage through the bypass valve. Once a blank flange was placed in the bypass valve, effectively sealing it, the PJFF demonstrated a very high collection efficiency of 99.7 percent while collecting ash from the SRC-Water Slurry test. The PJFF operated at an ACR between 1.6 and 4.0 at a pressure drop between 0.8 and 2.5 in. W.C. The PJFF is designed to operate at an ACR of up to 6 to 1. The cleaning time pulse interval was 40 s. This resulted in the entire PJFF being cleaned 13 times every hour. The compressed air

TABLE 14

SUMMARY OF RESULTS FOR REVERSE AIR FABRIC FILTER^a

	Symbol	Units	No. 6 Fuel Oil	SRC Fuel	SRC Residual Fuel Oil	SRC-Water Slurry
Pilot Filter Operation Range						
Air-to-cloth ratio	ACR	ft/min	1.6 - 3.4	2.1 - 2.4	2.7 - 4.1	2.6 - 4.2
Pressure drop	ΔP	in. W.C.	0.1 - 3.6	1.7 - 4.0	1.8 - 3.0	2.0 - 4.5
Specific resistance	k	—	172 - 2988	7 - 19	13 - 82	10 - 39
Drag	S	—	0.1 - 1.3	1.0 - 1.8	0.6 - 1.9	0.5 - 1.7
Inlet Dust Loading						
At 68°F, 29.92 in. Hg. dry	Gr/SDCF	Gr/ft ³	0.02	0.46	0.09	0.39
Loss on ignition at 750°C	LOI	% wt		91	86	77
Outlet Dust Emissions						
At standard conditions	Gr/SDCF	Gr/ft ³	0.005 ^b	0.001	0.001	0.005
Dust Collection Efficiency						
Gr/SDCF basis	η	%	73.8 ^b	99.8	99.1	98.7
Dust penetration	1 - η	%	26.2 ^b	0.2	0.9	1.3
Gas Properties at Fabric						
Gas temperature	t	°F	340 - 386	292 - 342	230 - 318	307 - 318
Moisture content	H ₂ O	% vol.	13	6	9	11
Test Days			7	15	8	8

a. Data by WFI (reference 25).

b. Low dust loadings and short durations led to low recoveries.

for bag cleaning was delivered at 75 psig. The PJFF performed well with all three SRC forms; no irreversible bag blinding occurred, pressure drops were reasonable, and ACRs were satisfactory. PJFF performance for No. 6 Fuel Oil flyash was not tested.

5.8.2.3.2 Reverse Air Fabric Filter

Table 14 presents the summary of RAFF performance results. The pilot filter outlet emission rate for SRC Fuel and SRC Residual Fuel Oil was 0.002 lb/10⁶ Btu and for SRC-Water Slurry and No. 6 Fuel Oil was 0.010 lb/10⁶ Btu. These values are significantly less than the EPA NSPS of 0.03 lb/10⁶ Btu. The higher particulate emission rate during SRC-Water Slurry testing was primarily due to Lomar-D, a wetting agent in the water slurry of the pulverized SRC Fuel. The RAFF was operated with the SRC forms at an ACR between 2 and 4 at a pressure drop between 1.7 and 4.5 in. W.C.

The reverse cleaning ACR was 1 cfm/ft² for a duration of 1 min followed immediately by a 1 min settle time. No settle time was allowed before the reverse cleaning. The decrease in pressure drop after cleaning for the SRC-Water Slurry flyash was not as much as that for the flyash of the other two SRC fuels. On the basis of dust penetration, outlet dust concentration, and frequency of cleaning, the flyash of SRC Fuel and SRC Residual Fuel Oil was much easier to control than that of the SRC-Water Slurry. In addition, the wetting agent in the slurry appeared to change two of the physical characteristics of the SRC ash. There was a noticeable change in the color of the ash, and an increase in the tendency of the ash particles to agglomerate. The use of an organic-based wetting agent would eliminate these problems.

5.8.2.4 Conclusions and Recommendations

The SRC burn test program provided a variety of operating conditions to evaluate fabric filter performance. The main conclusions of the fabric filter feasibility evaluation are:

- A. The flyash emissions of SRC combustion in the 700-hp boiler could be controlled to less than 0.01 lb/10⁶ Btu.
- B. The measured efficiencies of between 98.4 and 99.8 percent should be worst case efficiencies since the fabrics were only subjected to very short exposures to flue gas.

A number of circumstances and test conditions during the burn tests tend to make the results of the fabric filter evaluation very subjective from a fabric filter sizing standpoint. First, and most important, the sizing of a fabric filter for commercial applications is not as exact a science as sizing electrostatic precipitators. There is no computer model available to predict performance based on inlet flue gas, particulates, and operating conditions. Second, the two fabric filters were not operated at design conditions for a long enough period of time to establish normal filter cakes. Tests on utility boilers with both reverse air and pulse-jet fabric filters have shown periods of operation from several weeks to several months before stable differential pressure and filter cake conditions were achieved, and

optimum performance of the fabric filter reached. Third, the cyclic operation of the fabric filter is nonrepresentative of utility operation and may have subjected the filter cakes to either abnormal condensation or excessive cleaning which could bias differential pressure characteristics.

Recommendations for future work are as follows:

- A. Conduct long-term steady-state test with conventional fabric filters to assess differential pressure and filter cake release characteristics as adequate supplies of SRC fuels become available.
- B. Conduct pilot-scale reverse air fabric filter studies to determine operation characteristics since the correlation between the RAFF and full-scale reverse air fabric filters is not known.
- C. Conduct tests to determine if alternative cleaning methods; i.e., shakers or sonic horns; may provide more effective cleaning. Without the benefit of the above mentioned work, the sizing of a fabric filter for an SRC fired boiler application remains an intuitive task. A conservative approach with a reverse air fabric filter at a nominal 2 to 1 air to cloth ratio or a pulse-jet fabric filter at 4 to 1 air to cloth ratio should provide more than adequate particulate control to meet existing NSPS.

5.8.3 ALTERNATE CONTROL CONSIDERATIONS

Many utility oil-fired boilers are not equipped with ESPs but do have cyclones or multiclones primarily for controlling emissions during soot blowing. (See Reference 19.) If cyclones were the only particulate control devices used to collect SRC ash, the data in Table 15 can be used to approximate the outlet emissions which might exist. Cyclones and cyclone theory have been investigated at SoRI under research contracts funded by the EPA. It has been found that cyclone behavior, as well as cyclone theory, is not well understood. Manufacturers of commercial cyclones provided performance data for various sized cyclones at differing pressure drops. One manufacturer produces a cyclone which operates at a critical particle size of $6.0\text{ }\mu\text{m}$, a pressure drop of 6 in. of water, and has a capacity of 104 acfm. Critical particle size is defined by cyclone manufacturers as the smallest particle which can be collected with essentially 100-percent efficiency. The efficiency curve falls off rapidly below that point, and by using the particle size data in Table 15 and assuming that the cyclone conditions stated above would correspond to a cyclone D_{50} of $5\text{ }\mu\text{m}$, an outlet loading could be estimated for the various particulates evaluated at PETC.

Assuming that the total mass loadings and particle size distribution produced at PETC would be representative of a full-scale boiler, the following outlet loadings would be calculated:

No. 6 Fuel Oil.....	0.0336 lb/10 ⁶ Btu at 6.4% Efficiency
SRC Fuel.....	0.0718 lb/10 ⁶ Btu at 91.0% Efficiency
SRC Resid. Oil.....	0.0411 lb/10 ⁶ Btu at 76.9% Efficiency
SRC-Water.....	0.1809 lb/10 ⁶ Btu at 81.5% Efficiency

TABLE 15

**INLET IMPACTOR CUMULATIVE MASS LOADINGS AT
INDICATED SIZES**

	No. 6 Fuel Oil	SRC Fuel	SRC Residual Fuel Oil	SRC-Water Slurry
Total loading, (Gr/dscf)	0.0230	0.3821	0.1007	0.5616
(lb/10 ⁶ Btu)	0.0359	0.7971	0.1782	0.9778
Particulate loading less than:				
8 μ m				
(gr/dscf)	0.0222	0.0592	0.0403	0.1516
(lb/10 ⁶ Btu)	0.0347	0.1235	0.0713	0.2640
5 μ m				
(gr/dscf)	0.0215	0.0344	0.0232	0.1039
(lb/10 ⁶ Btu)	0.0336	0.0718	0.0411	0.1809
2 μ m				
(gr/dscf)	0.0196	0.0218	0.0131	0.0753
(lb/10 ⁶ Btu)	0.0306	0.0455	0.0232	0.1311
2 μ m				
(gr/dscf)	0.0170	0.0164	0.008	0.0618
(lb/10 ⁶ Btu)	0.0266	0.0342	0.0142	0.1076
0.5 μ m				
(gr/dscf)	0.0138	0.0132	0.0056	0.0542
(lb/10 ⁶ Btu)	0.0216	0.0275	0.0099	0.0944
0.25 μ m				
(gr/dscf)	0.0115	0.0107	0.0047	0.0420
(lb/10 ⁶ Btu)	0.0180	0.0223	0.0083	0.0656
Inlet mass median diameter (μ m)	0.25	21.8	10.3	17.8

It should be understood that if cyclones with the above parameters were used at PETC in place of the ESP, that 50 of them would have been required to handle the 5000 cfm gas flow at a pressure drop of 6 in. of water. There is the possibility that improved combustion in a full-scale boiler would result in a reduction in the particle size distribution and would render the cyclones even less effective and would require even larger pressure drops to achieve particle collection.

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6.0 ASSESSMENTS OF TEST PROGRAM

ICRC asked several of the major organizations involved in the test program to express their views on the meaning of the program results. The organizations participating in this assessment are SCS, B&W, C-E, Florida Power & Light, and Commonwealth Electric.

These companies were involved in the burn test directly or as observers, and are knowledgeable in their respective fields regarding the use of SRC in commercial operations.

6.1 SOUTHERN COMPANY SERVICES VIEWPOINT

For SCS, the PETC burn test program represents a continuation of SRC research and development efforts that span more than a decade. During the PETC program, SCS participated in program development, provided technical expertise and onsite management, prepared this final report, and coordinated the preparation of the individual reports prepared by other organizations involved in the program. In addition, this SCS assessment of the burn test is intended to evaluate the program from the utility industry perspective.

The PETC burn test program significantly increased the understanding of how SRC performs in an oil-designed boiler. This assessment evaluates the PETC test program, and develops a correlation with the burn test program conducted at Georgia Power Company's Plant Mitchell in 1977.

6.1.1 TEST PROGRAM EVALUATION

6.1.1.1 SRC Fuel

The PETC tests proved that SRC Fuel can be successfully fired in an oil-designed boiler with high boiler efficiencies, good carbon conversion, and minimal problems. In view of the bulk storage and handling problems associated with the SRC Fuel form during the PETC test program, these tests also demonstrated that direct firing from a pulverizer is the preferred method.

SCS does not concur with the viewpoint that very high (125 ft/s) primary air velocity is necessary for the transport of SRC Fuel from a pulverizer to a burner. A high velocity was required at PETC to break up agglomerations caused by prepulverizing the SRC Fuel and storing the pulverized material. Experience in the direct firing of SRC Fuel in the Plant Mitchell 22.5-MW boiler in 1977 demonstrated that lower transport velocities can be used successfully.

Boiler efficiencies of 81.5 to 85.6 percent were achieved with SRC Fuel at PETC. This is comparable to the 79.6 to 83.5 percent efficiency achieved while burning No. 6 Fuel Oil and in line with efficiencies obtained at Plant Mitchell while burning SRC Fuel. Carbon conversion efficiencies of 97.80 to 99.30 percent were somewhat lower than the 99.98 percent achieved when burning No. 6 Fuel Oil. However, SRC Fuel carbon conversion efficiencies during the PETC tests correlated quite well to the conversion efficiencies of 97.0 to 98.6 percent achieved during the Plant Mitchell burn test. It is believed that the carbon conversion efficiencies could be increased with improvements in burner design.

The NO_x emissions were 0.56 to 1.37 lb/10⁶ Btu for the SRC Fuel in comparison to the New Source Performance Standard of 0.5 lb/10⁶ Btu. The NO_x emissions from No. 6 Fuel Oil were 0.25 to 0.34 lb/10⁶ Btu. However, as stated previously in this report, no NO_x control measures were taken. SCS believes that the NO_x level in the flue gas from all SRC forms can be reduced substantially by incorporating conventional combustion control techniques and burner improvements.

The tests at PETC also demonstrated that an electrostatic precipitator (ESP) is a viable collection device for ash from an SRC Fuel fired boiler. Overall collection efficiencies obtained during the PETC tests averaged 99.45 percent, resulting in an average outlet loading of 0.005 lb/10⁶ Btu which is well below the NSPS level of 0.03 lb/10⁶ Btu for particulate. Also, the data demonstrate that the design of an ESP for collection of SRC Fuel ash could utilize existing technology and be priced comparably to ESPs for coal-fired units. Test data also indicate that conventional fabric filter designs can be used for the collection of SRC Fuel ash.

The burner initially used was patterned after one proven to be effective in SRC Fuel tests in a multiburner, coal-designed boiler at Plant Mitchell. However, it was not suitable for the limited volume furnace of the package boiler. Notable progress was made during the present tests in developing a suitable burner that should prove flexible enough for application in the less critical environment of a utility boiler. By way of illustration, a modern package boiler is designed for a furnace heat liberation rate of 50,000 to 60,000 Btu/hour-ft³, whereas a coal-fired boiler is designed for 15,000 to 16,000 Btu/hour-ft³. A utility boiler designed for oil or gas firing only would have a somewhat higher heat release rate.

In addition there is a need to determine the effects of rapping reentrainment on ESP performance and to evaluate fabric filter performance over a longer test period.

6.1.1.2 SRC Residual Fuel Oil

The PETC tests using the SRC Residual Fuel Oil form of SRC were successful. The handling and firing of the residual oil was completed with conventional No. 6 Fuel Oil technology. Boiler efficiencies were high (84.3 to 86.2 percent) and carbon conversion was very good (98.9 to 99.9 percent). ESP collection efficiencies averaged 99.04 percent, resulting in an outlet loading of 0.002 lb/10⁶ Btu. Again, this outlet emission value is well below the NSPS. NO_x emission levels were 0.57 to 0.76 lb/10⁶ Btu, but application of normal combustion control methods in a full-scale boiler should further reduce these values.

6.1.1.3 SRC-Water Slurry

The burning of an SRC-Water Slurry at PETC was the first burn test for that fuel and was very successful. The tests demonstrated that the preparation and handling of the SRC-Water Slurry can be accomplished without difficulty. Combustion testing of the SRC-Water Slurry was accomplished without any major problems.

Boiler efficiencies ranging from 80.2 to 81.8 percent compared favorably to efficiencies obtained with No. 6 Fuel Oil. Carbon conversion efficiencies of 98.5 to 98.9 percent were lower than efficiencies measured when burning No. 6 Fuel Oil. Increases in carbon conversion efficiencies can be expected with further burner development.

NO_x emission levels ranged from 0.42 to 0.61 lb/10⁶ Btu. These NO_x values are lower than those from the other SRC forms because of the water content of the slurry. Lower values should be attainable with further burner development. ESP collection efficiencies for the SRC-Water Slurry averaged 99.34 percent with an outlet loading of 0.006 lb/10⁶ Btu; this is well below the NSPS level.

One major area in need of development is the utilization of different wetting agents for the SRC-Water Slurry. The additive Lomar-D used at PETC contributed significantly to the flyash mass loadings and SO₂ emissions exiting the boiler. The use of an organic based surfactant would be preferred, as it would not add to the fuel ash or SO₂.

Another benefit of using different wetting agents would be the possible increase in the percentage of solids in the fuel mixture with a corresponding reduction in the amount of water needed to achieve usable viscosities. This would increase the boiler efficiency.

6.1.2 RECOMMENDATIONS

Generally, the three forms of SRC tested at PETC exhibited characteristics favorable for use as a utility fuel. However, it is believed that further testing and development work is needed in the following areas.

- A. Reentrainment losses due to ESP plate and wire rapping.
- B. Long-term fabric filter performance.
- C. NO_x control.
- D. Burner design.

6.1.3 MITCHELL TEST CORRELATIONS

In 1977, SCS conducted a burn test with SRC Fuel in a 22.5-MW coal-fired boiler, at Plant Mitchell.¹⁸ This burn test ran for 18 days and consumed approximately 3000 tons of SRC Fuel. The major emphasis of the test was to determine the feasibility of burning SRC Fuel in a full-size utility boiler, and to provide boiler efficiency data. As part of the program, an ESP was tested to determine the feasibility of using an ESP for the collection of ash from an SRC Fuel fired boiler. However, there were several problems with the existing ESP that prevented the acquisition of good design data. The ESP was in poor mechanical condition and had extremely poor gas flow distribution. The mechanical problems were corrected but the gas flow distribution was not corrected.

During the Mitchell test the resistivity of the SRC Fuel ash was measured and found to contain a high percentage of carbon, which prevented the accurate determination of resistivity. Similar problems were encountered at PETC with the resistivity measurements made there. The testing performed on the ESP at Mitchell did, however, indicate that an ESP would collect the ash from an SRC Fuel fired boiler, but the size of the ESP required was not satisfactorily determined. As a result of the PETC test program,

sizing data are now available that can be used with a reasonable degree of confidence to size an ESP.

Boiler efficiencies of 82 to 86 percent were reported while burning SRC Fuel at Plant Mitchell. Very similar efficiencies were noted with the PETC 700-hp boiler while burning SRC Fuel. There were no problems in attaining full-rated load with either boiler. The excess air levels for the slow mix burner tests were comparable for the Mitchell and PETC tests. Since the pulverized SRC Fuel was the only SRC fuel form fired at Mitchell there are no correlations to the other fuel forms that were fired at PETC.

The exact mechanism for the burning of SRC fuel forms is not fully understood. It is believed that SRC particles melt before burning and that this may influence the combustion mechanism.

This hypothesis is reinforced by examining the photomicrographs of SRC ash shown in Figures 39, 40, and 41. Photomicrographs of the ash collected during the Plant Mitchell test are shown in Figure 39. Figure 40 shows photomicrographs of SRC ash and No. 6 Fuel Oil ash collected during the PETC burn test. In addition to the tests conducted at PETC, ICRC contracted with the Acurex Corporation to conduct a burn test with the SRC forms in three pilot scale combustors. Figure 41 shows photomicrographs of ash collected while firing SRC Fuel in the Acurex combustors. Note the similarities in the shape and appearance of the ash particles from each of the test burns. It is evident that a similar burning process is taking place within each boiler or combustor, even though the burning mechanism is not well understood at this time. Typical coal ash will not exhibit the holes in the ash particles as does the SRC Fuel ash. Coal ash tends to be spherical and without holes.

**550X MICROGRAPH
SRC FLYASH, PRECIPITATOR OUTLET**

**1100X MICROGRAPH
SRC FLYASH, PRECIPITATOR INLET**

**1100X MICROGRAPH
SRC FLYASH, PRECIPITATOR OUTLET**

**110X MICROGRAPH
PHASE II COAL FLYASH**

ADAPTED FROM REPORT BY SOUTHERN COMPANY SERVICES, INC.¹⁸

**FIGURE 39
SRC ASH SAMPLES, PLANT MITCHELL BURN TEST**

NO. 6 FUEL OIL
9/1/82

$D_{50} = 3.46 \mu\text{m}$

PULVERIZED SRC
11/18/82

$D_{50} = 5.12 \mu\text{m}$

SRC-RESIDUAL OIL
12/15/82

$D_{50} = 5.10 \mu\text{m}$

SRC/H₂O
1/11/83

$D_{50} = 4.46 \mu\text{m}$

FIGURE 40
INLET IMPACTOR STAGE 3 SAMPLES, PETC-SRC BURN TESTS

a) 2000X

b) 200X

FIGURE 41
SRC ASH CHAR SAMPLE SHOWN AT DIFFERENT LEVELS
OF MAGNIFICATION FROM ACUREX CORPORATION BURN TESTS

6.2 BABCOCK & WILCOX VIEWPOINT

Babcock & Wilcox was involved in evaluation of the combustion facility and test matrix, observation of the burn tests, and evaluation of the results.³ Overall, the test program was successful with all three forms of SRC indicating their potential as viable boiler fuels and their ability to replace oil or gas in industrial or utility boilers. In ranking the fuels with respect to handling and combustion, SRC Residual Fuel Oil was the easiest followed by SRC-Water Slurry and SRC Fuel.

6.2.1 FACILITY EVALUATION

6.2.1.1 Comparison of Package and Utility Boilers

Package boilers differ from utility boilers in input/volume and input/plan area at the burner's zone. Although the utility boiler fires parallel to the plan area, and the standard package boiler fires perpendicular, it is believed that the same cause-and-effect on combustion holds. Furthermore, the package boiler would not produce as high a heat intensity around the flame perimeter as could be found in the plan area of a utility boiler. These differences in heat intensity between the two boiler designs obviously will have an influence on carbon utilization (particulate emission) and NO_x formation. Although it is difficult to quantify these differences in NO_x and carbon utilization, the following is a brief discussion of the B&W approach in predicting NO_x .

6.2.1.2 Furnace NO_x Design Parameters

This is a general discussion on NO_x design parameters as they apply to a boiler furnace. The parameter B&W uses to predict NO_x emissions, in utility boilers, for a given fuel and burner type, is called HA/SC. The numerator, HA, is the total heat available to the boiler including fuel and sensible heat of the combustion air. The denominator, SC, is a factor related to heat transfer surface in the immediate area of the burners. This surface in the immediate area of the burners includes wall surface from X feet above the top burner centerline to X feet below the bottom burner, and the projected plan area of the furnace, all multiplied by factors related to specific configurations. HA/SC is the ratio of heat input to heat transfer surface of the combustion zone, providing a measure of temperature in the combustion zone. B&W and other boiler manufacturers use this or similar parameters to size combustion zones based on predicted NO_x emissions, with sufficient confidence to guarantee emission levels.

6.2.1.3 Scaleup Evaluation of the Facility and Operating Parameters

Phase II of the SRC combustion test program at PETC was implemented in the 700-hp combustion test facility. The primary objective of the program was to attain successful combustion of three SRC forms in this watertube boiler designed for firing fuel oil at heat release rates typical of those in industrial boilers. The program involved determination of combustion characteristics, flue gas emissions, and particulate equipment design for the three SRC forms: SRC Fuel (pulverized), SRC Residual Fuel Oil (pulverized SRC dissolved in SRC-process liquids), and SRC-Water Slurry. These objectives were coupled

with the intent to assess the potential of these fuels as boiler fuels. As the SRC test program was inclined toward generating data for any possible scaleup considerations to larger industrial and utility oil/gas design boilers, a comparison of the package boiler furnace and that of a utility boiler should be made. Since SRC contains negligible flyash, slagging and fouling will not be a significant problem. Different aromatic structure and illuminosity of SRC from that of fuel oil should impact the heat absorption pattern in the furnace and convection pass.

Significant differences between the design of a package boiler and utility boiler are the "Input/Plan Area at the Burners" and the "Input/Volume in the Burner Zone" (heat liberation rate).

As discussed above, these differences in design coupled with a different heat absorption pattern due to fuel characteristics contribute to the difficulty of any scaleup efforts related to NO_x emissions and carbon utilization (particulate emissions). In addition to NO_x and particulate emissions, following are additional parameters which can not be directly scaled to larger units:

- Burner stability.
- Flame shape and illuminosity.
- Boiler slagging and fouling.
- Pulverizer power requirement and operating conditions.

Although some parameters such as NO_x are difficult, if not impossible, to predict, certain other parameters may be extrapolated from pilot-scale to full-scale boilers with some caution.

- Excess air requirements.
- Air preheat temperature.
- Rheological characteristics of liquid and slurry fuels.
- Fuel preheat temperature.
- Atomizing media flow (air or steam).
- Burner turndown.
- Solid fuel transport system condition (air temperature, air velocity, lb air/lb fuel).

- Fuel compatibility with the system (material wear).
- Solid fuel particle size distribution.
- Fuel storage and handling characteristics.

6.2.2 COMBUSTION TESTS

Parametric combustion tests were conducted for each fuel to determine the optimum test boiler operating conditions using a multifuel circular burner. The principal operating variables addressed were excess air, secondary combustion air temperature, and burner optimization (design, swirl/stability, and register setting). Excess air requirements were evaluated by determining the smoke point (indicated by flue gas opacity and CO measurements) for all four fuels. The testing was done over a wide range of excess air for all four fuels. The secondary air temperature range tested was 500°F to 600°F. This range is an average of approximately 75°F and 125°F high for retrofit applications to oil-designed utility boilers and industrial boilers, respectively. Although this incompatibility between the test program and field boiler operation was pointed out and discussed, a 600°F secondary air temperature was used for the steady-state testing of the SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry, and 500°F was used for the No. 6 fuel oil tests. In addition, many fuel feed problems and burner deposition problems were encountered during the testing of pulverized SRC with the slow mix burner which limited the test matrix.

In preventing clinker formation or fouling of the SRC Fuel water-cooled burner, approximately 6 percent of total thermal input was provided by a natural gas support flame during many of the steady-state tests with the slow mix burner. Addition of natural gas raises concern as to what extent combustion of SRC and its particulate emissions was altered. It is believed that the burner design and the nozzle cooling system could have been improved to avoid the clinker buildup problem.

The clinker buildup was significantly reduced using an improved fast mix burner so that it no longer was considered a problem.

Unfortunately, the improved fast mix burner was not developed in time to be used in performing steady-state tests. Lower clinker formation was accomplished by generating high turbulence which in turn resulted in high NO_x emissions. Although NO_x emissions produced were higher than acceptable levels, it is believed that NO_x reducing combustion techniques such as burners-out-of-service (a boiler operating technique in which selected burners provide only primary air), overfired air ports, etc. could be applied to lower NO_x emissions to acceptable levels.

Another operating condition which differed from usual design limit was the atomizing airflow for SRC-Water Slurry test series. The consumption was approximately 0.45 lb of air per lb of fuel which was much higher than the B&W maximum design limit. Other operating parameters investigated for all fuels tested including pulverizer operating parameters, air distribution, air velocities and temperatures, and primary air to SRC ratios were within design ranges applicable to large units and thus are useful.

6.2.3 TEST RESULTS EVALUATION

6.2.3.1 No. 6 Fuel Oil (Baseline) Combustion Tests

A series of parametric and steady-state combustion tests were conducted firing No. 6 Fuel Oil between August 18, 1982, and September 3, 1982. A conventional fuel oil atomizer with internal mixing using steam as the atomizing medium was used. The tests were performed at full boiler load over a wide range of excess air. The operating conditions for the steady-state tests were 12-percent excess air and 500°F secondary air temperature which are comparable to utility boilers operation. The conditions for this test series were within normal design limits.

The NSPS limits for liquid fuels other than coal-derived liquids or shale oil are: $\text{NO}_x = 0.30 \text{ lb}/10^6 \text{ Btu}$, particulate = $0.03 \text{ lb}/10^6 \text{ Btu}$, and opacity = 20 percent.

6.2.3.2 SRC Fuel Combustion Tests

SRC Fuel combustion evaluation tests took place in two series of tests. In the first series, these tests were conducted with a water-cooled circular burner referred to as slow mix burner. Initially, significant burner deposition (clinker buildup and coking) was encountered. This was further complicated by fuel agglomeration in the SRC transport system.

A number of modifications such as elimination of short radius bends in the transport system, changes in the storage bin, and changes in the burner tip design affecting secondary air swirl and primary air velocity were implemented. As a result of these modifications, the burner deposition was significantly reduced. The small clinker buildup even after the modifications accumulated over a period of time causing burner instability and/or break off resulting in higher carbon levels and opacity in the flue gas which in turn altered electrostatic precipitator (ESP) performance. However, approximately 6 percent of the total thermal input to the boiler was from burning natural gas during many of these steady-state tests in order to prevent clinker buildup on the SRC Fuel burner tip. Although it is difficult to quantify the alteration in combustion results, especially that of ESP results due to natural gas thermal input, the reliability of the data is of concern and remains questionable.

The second series of tests, although parametric, were conducted with an improved fast mix burner. Due to time constraints steady-state tests were not performed. This burner equipped with a water-cooled inverted cone (nozzle) eliminated the buildup formation problem but generated NO_x emission as high as $1.25 \text{ lb}/10^6 \text{ Btu}$ depending on excess air level. Also, the highest carbon conversion efficiency achieved was only 99.3 percent. The higher than acceptable level of NO_x can be reduced by means of NO_x reducing combustion techniques such as overfired air ports and other staged combustion methods. The lower input/plan area of the package boiler contributes to lower carbon conversion (higher particulate emissions) due to less complete burnout. It is believed that higher heat intensity in a utility boiler would somewhat increase the carbon utilization.

6.2.3.3 SRC Residual Fuel Oil Combustion Tests

A series of combustion tests were conducted using a modified No. 6 Fuel Oil atomizer with internal mixing using steam. The tests were conducted at full load over an excess air range of 2.3 to 25.4 percent and secondary air temperature range of 500 to 600°F. Steady-state tests were performed with 14-percent excess air and 600°F secondary air temperature which is of concern. A review of SRC Residual Fuel Oil characteristics and its combustion results show that the handling and burning of SRC Residual Fuel Oil is similar to that of No. 6 Fuel Oil with the following exceptions:

- Fuel temperature requirement for similar viscosity.
- Carbon utilization.
- NO_x emissions.

SRC Residual Fuel Oil needs to be heated prior to atomization to approximately 300°F which is about 100°F higher than that required for No. 6 Fuel Oil. SRC Residual Fuel Oil carbon conversion ranges were from 99.6 to 99.9 percent which is slightly lower than that of No. 6 Fuel Oil. It is believed that the carbon conversion can improve in a utility boiler where furnace heat intensity is higher. Higher NO_x emissions of 0.55 to 0.7 lb/10⁶ Btu are of concern. NO_x reduction methods such as staged combustion can be applied to lower NO_x.

6.2.3.4 SRC-Water Slurry Combustion Tests

The SRC-Water Slurry combustion tests were conducted using a modified No. 6 Fuel Oil atomizer with internal mixing using air as atomizing medium. During the testing period which included shakedown, parametric, and steady-state tests, no major problems were encountered. The following can be considered as problem areas based on the review of the test results:

- Burner clinker formation.
- Relatively high secondary air temperature (600°F).
- Relatively high atomizing air to fuel ratio (approximately 0.45).
- Carbon utilization.
- Atomizer sprayer plate wear.
- Relatively high NO_x emissions.

6.2.4 CONCLUSIONS AND RECOMMENDATIONS

The overall results from the PETC 700-hp package boiler SRC burn test program have indicated that SRC fuels have the potential to replace fuel oil in oil-fired boilers. However, further investigation in evaluating combustion characteristics of the SRC-derived fuels is essential prior to commercial application of these fuels.

NO_x emissions were high when burning all three forms of SRC due to high fuel-bound nitrogen content and burner design. In commercial applications, NO_x control will have to be considered.

As a result of the tests conducted with all three forms of SRC, the handling characteristics of SRC Residual Fuel Oil were the easiest followed by SRC-Water Slurry and SRC Fuel.

Better handling and combustion characteristics of SRC Residual Fuel Oil makes it the easiest SRC form for oil-design industrial and utility boiler retrofit applications (with the SRC Fuel being the poorest). The following are the areas where more testing is recommended for all three fuels (preferably in a boiler more representative of industrial and utility boilers):

- Burner development (clinker formation, NO_x emissions).
- Turndown (flame stability).
- NO_x control (staged combustion, etc.).
- Lower secondary air temperature.
- Slagging and fouling.

6.3 COMBUSTION ENGINEERING VIEWPOINT

Combustion Engineering involvement in this burn test program included an evaluation of the combustion facility and test matrix, observation of the burn tests, and an evaluation of the results.¹⁰ In general, the tests proved to be very successful and have shown that the fuel has a high potential as a replacement fuel for oil and gas as a boiler fuel. The liquid forms of this fuel were the least problematic and should be the easiest to retrofit to industrial and utility boilers. The prime areas of concern still remaining for these fuels are turndown capability, burner deposition, and staged combustion effects.

6.3.1 FACILITY DESIGN AND OPERATING PARAMETERS EVALUATION

The usefulness to a boiler manufacturer of any test data and/or operating characteristics of these new fuels is determined by the ability to scaleup the pilot scale facility results to full scale industrial and utility designs. In the PETC facilities the parameters which may be extrapolated directly to industrial and utility boiler designs include:

- Carbon conversion levels.
- Excess air requirements.
- Air preheat temperature.
- Burner turndown capability.
- Atomizing media flow (liquid fuels).
- Solid fuel transport air requirements (temperature, velocity, and air-to-fuel ratio).
- Materials problems (wear and noncompatibility).
- Fuel preheat (viscosity) requirements (liquid fuels) and maximum fuel preheat limitations (solid fuel).
- Fuel particle size requirements (solid fuels).
- Fuel storage requirements and characteristics.

There are several areas where limitations of the test facilities, e.g., boiler, burner, data acquisition equipment, do not allow direct scaleup correlations and thus require that only qualitative trends be developed from the test data and test observations. The parameters for which no quantitative scaleup evaluations can be made include:

- Flue gas emissions of NO_x and CO.
- Flue gas opacity.
- Pulverizer power requirements and operating characteristics.
- Boiler fouling.
- Burner performance (stability, deposition).
- Flyash composition.
- Particulate collection equipment.
- Atomizer wear/life.
- Flame color and shaping characteristics.

Finally, there are several operating parameters for which no trends can be developed because the results will be particular to these facilities or facilities similar in characteristics to them.

However, the test results for these parameters do provide some limited insight into the characteristics of the tested fuels. The parameters are:

- Slagging.
- Dense-phase solid transport system.

6.3.2 TEST PROGRAM EVALUATION

The principal variables addressed during this test program were excess air, secondary air temperature, and burner optimization (design, swirl, and position). Excess air requirements were well evaluated with smoke point determination for all fuels tested. The secondary air temperature range which was tested, 500°F to 600°F, was 50°F to 100°F high for retrofit applications to most oil design utility units and an even larger disparity exists when comparing the test temperature range to many industrial units. (Many industrial units do not have air heaters.) This discrepancy was pointed out during the test matrix review. It is realized that many fuel feed problems and burner deposition problems occurred during the tests and thus limited the matrix. However, the use of 600°F secondary air for the steady-state tests on SRC Fuel, SRC Residual Fuel Oil, and SRC-Water Slurry tests versus 500°F secondary air for the No. 6 Fuel Oil tests is questionable. This point was verified with a perfunctory review of the parametric test data which showed a 0.4 to 1.0 percent decrease in carbon conversion efficiency to 500°F secondary air compared to 600°F secondary air for SRC Fuel and a 0.2 to 0.3 percent decrease for SRC Residual Fuel Oil. Another out of design range operating condition was the atomizing airflow for the SRC-Water Slurry tests. The level used, approximately 0.45 lb air/lb fuel, is more than double the usual maximum design limit.

Most other operating parameters including pulverizer operation, air distribution, velocities and temperatures, and primary air to fuel ratios, for the tests were within normal design ranges and thus have provided useful data. Two areas that were not tested due to deposition and solid fuel feed problems were burner turndown and combustion air staging.

It is felt that due to the high NO_x values occurring during the tests with only 98- to 99-percent carbon conversion that further staged air combustion tests must be completed before full acceptance of the fuel. Also, tests with similar fuels have shown limited turn-down results and therefore necessitate further reduced load testing.

6.3.3 EVALUATION OF RESULTS

6.3.3.1 No. 6 Fuel Oil Combustion Tests

A series of parametric and steady-state combustion tests on No. 6 Fuel Oil was conducted between August 18, 1982 and September 3, 1982. A review of the data showed no operating conditions outside of normal design limits.

6.3.3.2 SRC Fuel Combustion Tests

The burning of SRC Fuel in a pulverized, dilute-phase state was demonstrated during two series of tests. The first series took place between October 24, 1982 and November 19, 1982 and the second series took place between January 27, 1983 and February 2, 1983. Much of the testing during the first series of tests was conducted with a problematic burner deposition (clinkering/coking) condition. This condition was further aggravated by fuel agglomeration and saltation in the dilute-phase fuel transport system. Limited success in solving these problems was attained by the elimination of short radius bends in the transport piping, changes in the pulverized fuel storage system (not applicable to dilute-phase industrial and utility applications), and various changes in the burner tip and fuel/primary air and secondary air swirler configurations. With these modifications the saltation and agglomeration problems (which caused fuel feed pulses, high opacity, CO spikes, and ESP performance swings) were almost completely eliminated. The burner deposition problem was almost eliminated; however, the slight buildup that would occur even with the modified burner tip would eventually grow and either cause flame shaping problems and/or break off, causing flue gas carbon level increases and the associated opacity and ESP problems.

It is felt that the use of natural gas (5 percent of fuel heat input) to stabilize the burner operation during the steady-state tests, in order to conduct the ESP tests, has negated the value of the combustion results for these tests.

The new burner used during the second series of tests which had a water-cooled internal radiation shield (Figure 15) eliminated the deposition and thus produced the most reliable steady-state tests operations and results. Four other areas of concern raised when firing the SRC in a pulverized form are listed below.

- A. The low carbon conversion efficiency which ranged between 97.8 percent and 99.3 percent.
- B. The 600°F secondary air temperature used during the steady-state tests is about 100°F too high.
- C. The high NO_x emission level which ranged between 0.56 lb/10⁶ Btu and 1.37 lb/10⁶ Btu depending on excess air and burner used.
- D. The high primary air velocity in the transport pipe during the second series of tests (approximately 150 ft/s).

It is noted that the carbon conversion efficiencies may be increased with the increased furnace residence time available in a typical industrial or utility boiler, however, the use of a lower secondary air temperature, which would be a high probability in retrofit applications, and the use of the staged combustion technique to reduce NO_x emissions may tend to lower the carbon conversion levels. Also, the minimum ash content in the fuel should allow for some increase in primary air velocities above normal design limits (60 to 100 ft/s) without erosion problems; however, the increase in velocity to limit saltation may be detrimental to burner turndown (which was not evaluated).

Operating parameters other than those discussed above were within design limits and showed that the pulverized form of this fuel does exhibit a high potential for use as a boiler fuel. However, further pilot scale testing should be completed before full approval and/or guarantees can be made regarding the pulverized fuel usage. Also, there is some concern regarding the fire hazard to the particulate collection equipment during a boiler trip or shutdown due to the very high carbon content of the flyash.

6.3.3.3 SRC Residual Fuel Oil Combustion Test

A series of combustion tests using a solution of SRC Fuel and SRC process-derived solvent was conducted between December 7, 1982 and December 17, 1982. A review of the results from these tests has shown that the handling and burning of SRC Fuel in this solution is similar in characteristics to the No. 6 Fuel Oil.

Three areas where the SRC Residual Fuel Oil characteristics appear to differ are carbon conversion, fuel temperature required for similar viscosities, and NO_x emissions. The carbon conversion for this fuel tested out to be 99.6 to 99.9 percent (No. 6 Fuel Oil greater than 99.97 percent) which is acceptable. The fuel temperature was approximately 300°F for a similar viscosity of 25 cp, which is acceptable. The NO_x emissions level was in the 0.56 lb/10⁶ Btu to 0.76 lb/10⁶ Btu which raises a concern in the design of a boiler to use this fuel. This NO_x level would probably be lower with staged

combustion but possibly at the detriment of carbon conversion levels if there is no increase in residence time.

6.3.3.4 SRC-Water Slurry Combustion Tests

During the period from January 3, 1983 to January 14, 1983, a series of shakedown, parametric, and steady-state burn tests were conducted with the SRC-Water Slurry at the PETC facility. These tests appeared to be very successful and a review of the results has shown only two problem areas and four areas of concern. The problem areas during these tests were burner deposition (clinkering), which did not usually appear to affect performance, and the high atomizing air-to-fuel ratio of approximately 0.45. The areas of concern are the NO_x emissions level, the secondary air temperature, carbon conversion, and the wear life of the atomizer tip.

6.3.4 RECOMMENDATIONS

The three forms of SRC examined during these tests have exhibited, in most areas, desirable handling and burning characteristics. Use of this fuel as an alternative to oil firing is acceptable from a boiler manufacturers standpoint. However, several characteristics of this fuel would have to be further tested before performance guarantees could be made.

Based on the testing conducted thus far, the retrofitting of an industrial or utility boiler to fire the SRC Residual Fuel Oil would be easiest, least costly, and have the best performance of the three forms of SRC tested. The second most favorable form would be SRC-Water Slurry and third, the SRC Fuel. These ratings are based on equipment availability at most plants, carbon conversion, and the number and degree of problem areas perceived during the testing. General areas which need further testing for all of the fuels include:

- A. Burner optimization/development effort.
- B. Boiler application engineering study.
- C. Turndown tests.
- D. Lower secondary air temperature tests.
- E. Slagging, fouling and burner deposition tests in a hotter boiler more typical of industrial and utility designs.
- F. Tests to determine carbon conversion as a function of residence time.
- G. Staged combustion tests.

6.4 FLORIDA POWER AND LIGHT COMPANY VIEWPOINT

It is generally believed that, if available in commercial quantities, SRC would be a technically viable substitute for residual fuel oil, because of its inherently low ash and sulfur contents. The combustion tests carried out at DOE-PETC have demonstrated that, within the limits of the equipment used, full rated capacity can be achieved while operating a boiler designed for oil-firing on SRC. However, the test results also demonstrated that uncontrolled particulate emission rates from SRC flames will in all likelihood exceed existing air quality standards for oil-fired power boilers; e.g., 0.10 lb/10⁶ Btu. A different conclusion may be possible with the development of a specific burner for SRC-based fuels.

Oil-fired utility and industrial boiler sites typically do not have materials handling systems for solid fuels. Therefore, of the three fuel forms fired in the test program, pulverized SRC Fuel, SRC-Water Slurry, and SRC solids dissolved in the refining process liquid fraction, the two liquid fuel forms would be of more practical interest as a residual fuel oil substitute. Using the liquid fuel forms reduces boiler retrofit capital requirements, and eliminates the dust problems associated with handling very friable dry SRC solids. Fuel costs, capital requirements for environmental compliance, and the success of future burner development programs will determine which liquid fuel form is preferred.

The future use of SRC boiler fuels will depend on overall economics including the comparative cost and availability of low-sulfur residual fuel oil, and the cost of other residual fuel oil substitutes such as coal-water mixtures. If the solvent refining process can be justified on the basis of the value of the light fraction products, there would be a greater probability that SRC-based residual fuels could find economic application in tightly designed oil-fired power boilers. Time may be of the essence, however, since oil-fired boilers will be operated less frequently and be retired as installed coal-based power generation capacity is increased.

6.5 COMMONWEALTH ELECTRIC COMPANY VIEWPOINT

Commonwealth Electric Company has a strong interest in the utilization of coal-derived fuels as a replacement for heavy oils. Our examination of fuels to use for base and intermediate loads indicates that SRC derived fuels may be considered as a suitable fuel replacement for current as well as future applications.

The test burns conducted at the PETC during 1982 and 1983 were very encouraging and indicate that SRC may be utilized as a heavy oil replacement.

Commonwealth Electric has two existing 500-MW oil-fired units at the Canal Station and a third unit planned for operation in the 1990's for which we would consider using SRC derived fuels. Our current interest would best be served by the oil or water slurry fuels, as the selection of either of these would certainly minimize the changes required at our Canal Station.

Commonwealth Electric Company maintains a strong interest in the utilization of coal-derived fuels as a replacement for heavy oils. However, before utilizing these fuels assurance would be needed that all technical, operational, and environmental considerations could be met with SRC products. Also, the products would have to be offered on a fully competitive basis with oil and other alternative liquid fuels.

Fuel price, facility modifications, combustion efficiency, additional storage capacity, additional operating cost, reliability, and all other economic factors would be considered in determining such competitiveness.

APPENDIX A

ORGANIZATION

Since 1979, ICRC and DOE have worked together with other organizations as necessary to develop combustion systems for the application of SRC to boilers originally designed to fire oil and/or natural gas. The successful completion of this burn test program at PETC required the skills and expertise of many organizations. (The addresses, telephone numbers, and departmental contacts for organizations involved in this test are given at the end of this appendix.) Table 2 identifies the participants and summarizes their roles.

ICRC assumed overall responsibility for this test program and provided project management, program coordination, and technical direction as required. This organization also arranged for the fuels tested to be supplied from the Wilsonville Advanced Coal Liquefaction Research and Development Facility which is jointly supported by EPRI and DOE and managed by SCS.

ICRC was contracted to design, construct, and operate an SRC demonstration plant under DOE contract DE-AC05-78OR03054. (The demonstration plant is discussed in Section 4.2.) The demonstration plant has been the focus of work for over 4 years; therefore, the organization is well qualified for its leadership role in this program. ICRC represents a partnership between the parent companies of Air Products and Chemicals, Inc., and Wheelabrator-Frye Inc. (Signal Company), two companies known for their research and development, design, and construction activities in the fields of synthetic fuels, alternative energy sources, refining, and petrochemicals. Wheelabrator-Frye, Inc., has considerable experience in dust collectors, electrostatic precipitators, and environmental testing. These companies have been involved in SRC Fuel development since the early 70's. ICRC was formed to benefit from the experience of these two companies.

SCS was involved in the program to provide onsite project management during testing and expertise in SRC Fuel combustion and utility boilers. SCS also provided project coordination, produced this ICRC final report for the test program and prepared the boiler conversion feasibility study (Volume II of this report).

SCS is the engineering and research subsidiary of The Southern Company, one of the nation's largest investor-owned utilities with 231 electric generating units and over 2.6 million customers in the southeastern United States. Because of The Southern Company's multibillion dollar investment in the energy industry and its commitment to meet the energy needs of one of the fastest growing regions in the U.S., it has become, in part through SCS, an internationally recognized leader in the development and implementation of energy strategies and programs. SCS has been directly involved in the SRC program since the early 1970's. This involvement includes the construction and management of the Wilsonville facility, the management and preparation of both the interim and final reports for the pulverized SRC burn test at Plant Mitchell (Georgia Power Company), and the role of prime contractor to DOE during the first phase of the SRC-I Demonstration Plant Program.

PETC and their operation subcontractor, General Electric-Maintenance and Technical Services Company (MATSCO), were responsible for designing the combustion test program; for providing and operating the fuel storage, preparation, and feeding systems; for providing and operating the boiler and burner system; and for providing the boiler exhaust system. PETC and MATSCO were also responsible for data collection and the preparation of a combustion report.²¹

PETC is the largest U.S. DOE laboratory facility with a comprehensive research and development program in coal technology. The facility is a research leader in the areas of coal liquefaction, combustion phenomena, alternative fuels combustion, magnetohydrodynamics, synthetic fuels characterization, coal preparation, and flue gas cleanup. PETC has been employed extensively for evaluating conventional and synthetic fuel combustion of fuels such as coal, synthetic fuel oils, petroleum, and coal-water mixtures. PETC conducted SRC combustion tests in 1976 in a 500 lb/hour pulverized coal-designed unit.¹⁵ In 1980, PETC carried out a second SRC combustion test by firing SRC Fuel in three different physical forms (pulverized, molten, and slurried in SRC process distillate) in a 100-hp oil-designed firetube boiler.¹⁶

SoRI was responsible for determining flyash particle size distributions and for interpreting the performance of the pilot ESP relative to commercial designs and installations. Under EPA sponsorship, SoRI developed the EPA-SoRI computer model discussed in this report and used for evaluation of electrostatic precipitator designs.¹³

SoRI brought to the program a broad spectrum of experience with flue gas characterization projects and environmental control system analysis. Specifically, SoRI evaluated the electrostatic precipitator and associated environmental factors for the SRC burn test conducted at Plant Mitchell.¹⁸ As an organization, SoRI is engaged in contract and grant research in the physical, biological, engineering, and social sciences and is regarded as the leading independent field testing and research entity in the area of particulate control and ESP evaluation and operation. SoRI prepared a report evaluating ESP performance and used the EPA-SoRI computer model to evaluate ESP designs.¹⁹

The Air Pollution Control Division of WFI provided and operated a pilot ESP, tested the performance of the PETC pulse-jet fabric filter, and along with PETC was responsible for particulate mass train testing. In addition, WFI provided and operated a reverse air fabric filter to measure and evaluate the performance of fabric filters for the collection of particulates from the combustion of SRC. WFI prepared three separate reports in conjunction with the ICRC final report.^{23, 24, 25}

WFI is one of the nation's major air pollution control equipment suppliers for utility and industrial boilers and has been providing fabric filter equipment for more than 50 years. This company began selling the Wheelabrator/Lurgi precipitator in 1965 and has 39 installations now in operation on coal-fired boilers. In addition, the Air Pollution Control Division provides ESPs for testing and has been involved in stationary source emission testing and precipitator testing for the past 12 years.

B&W supplied engineering evaluation and observation services for the test program and prepared a report evaluating the test program at PETC.³ Because of future plans to demonstrate SRC in commercial B&W boilers, the involvement of this organization should assist in the eventual conversion of commercial boilers for SRC firing.

B&W is one of the two largest utility and industrial steam generator manufacturers in the U.S. B&W has experience in both oil/gas and pulverized coal boiler and burner design and operation. In addition, B&W has performed combustion tests with SRC Fuel and worked with SCS, Georgia Power Company, and the U.S. Energy Research and Development Administration (now DOE) in the Plant Mitchell SRC Fuel testing¹⁸ and is currently involved in proprietary SRC water rheology research.

C-E also provided engineering evaluation and observation services for the program and prepared a report on the burn test.¹⁰ Long range plans also call for demonstrating SRC in a C-E boiler.

C-E is one of the two largest suppliers of utility and industrial boilers and currently supplies combustion equipment that provides about 40-percent of the free world's electrical power. C-E has performed SRC combustion tests in their research facilities. This organization has much experience in relating pilot and bench scale testing to full-scale boilers. Furthermore, C-E has conducted tests with most conventional gaseous, liquid, and solid fuels and many unconventional, synthetic, and offgrade fuels.

Florida Power and Light provided observational and consulting services for the burn test from the utility users standpoint. This company is a major electric utility in southern Florida and is heavily dependent upon fuel oil for the generation of electricity.

Commonwealth Electric also provided observational and consulting services for the tests. The company is based in Massachusetts and represents a second major utility requiring No. 6 Fuel Oil for its boilers. Both utilities are concerned with the future availability of quality No. 6 Fuel Oil, and consider SRC a possible substitute for fuel oil in their existing and future boilers. Florida Power and Light and Commonwealth Electric each prepared a written assessment of the test program.

ORGANIZATIONAL ADDRESSES

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REFERENCES (SHEET 1 OF 3)

1. Acurex Corporation. 1983. Solvent Refined Coal (SRC) Combustion Demonstration Support Program. DOE/OR/03054-18.
2. Arand, J. K., L. J. P. Chrisman, M. N. Mansour, L. J. Muzio, and W. C. Rovesti. 1984. Combustion Evaluation of Residual Fuel Oils from Two-Stage Liquefaction. Proceedings: Eighth Annual Electric Power Research Institute Contractor's Conference on Coal Liquefaction. EPRI AT-3366-SR. Palo Alto, California.
3. Babcock & Wilcox, Fossil Power Generating Division. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. DOE/OR/03054-37 Annex Vol. F.
4. The Babcock & Wilcox Company. January 1978. Characteristics of Solvent Refined Coal: Dual Register Burner Tests. Project 1235-5, Final Report to EPRI. Report No. EPRI-FP-628, p. 118.
5. The Babcock & Wilcox Company. June 1979. Investigating Storage, Handling, and Combustion Characteristics of Solvent Refined Coal. 1976. Project 1235-4, Final Report to EPRI. Report No. EPRI-FP-1028, p. 131.
6. The Babcock & Wilcox Company. June 1979. Investigating Storage, Handling, and Combustion Characteristics of Solvent Refined Coal. 1976. Project 1235-3, Final Report to EPRI. Report No. EPRI-FP-1028.
7. The Babcock & Wilcox Company. June 1979. Investigating Storage, Handling, and Combustion Characteristics of Solvent Refined Coal. 1975. Project 1235-1, Final Report to EPRI. Report No. EPRI-FP-1028.
8. Bechtel National, Inc. March 1979. Compilation and Assessment of SRC Experience: Data Book. Research Project 987-1, Final Report to EPRI. Report No. EPRI-AF-1019, p. 321.
9. Beer, J. M., W. F. Farmayan, M. Toqan, and J. D. Teare. 1983. Design Strategy for the Reduction of Nitrogen Oxides and Particulate (PAH and SOOT) Emissions from Coal Liquid Flames. Paper presented at the Eighth Annual Electric Power Research Institute Contractor's Conference on Coal Liquefaction, Palo Alto, California.
10. Combustion Engineering. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Evaluation and Recommendations. DOE/OR/03054-37 Annex Vol. F.
11. International Coal Refining Company. 1983. Topical Report No. 5 6000 tpd SRC-I Demonstration Plant Support.
12. Jenike and Johanson, Inc. 1982. Handling SRC at Pittsburgh Energy Technology Center.

REFERENCES (SHEET 2 OF 3)

13. Johnson, J. W., G. I. Clinard, L. G. Felix, and J. D. McCain. 1978. A Computer Based Cascade Impactor Data Reduction System. Prepared for U.S. Environmental Protection Agency. EPA-600/7-78-042.
14. Lennon, D. R., E. P. Foster, O. C. Cook, G. T. Bellas, Y. S. Pan, R. B. Snedden, J. I. Joubert, and J. A. Reafsynder. 1984. SRC Fuel for Oil-Designed Boilers: Test Results. Proceedings: Eighth Annual Electric Power Research Institute Contractor's Conference on Coal Liquefaction. EPRI AT-3366-SR. Palo Alto, California.
15. McCann, C. R., J. J. Demeter, and D. Bienstock. 1976. Combustion of Pulverized Solvent Refined Coal. Paper presented at the Spring Meeting of the Combustion Institute's Central States Section, at Battelle-Columbus, Columbus, Ohio.
16. Pan, Y. S., D. E. Wieczenski, R. B. Snedden, G. T. Bellas, J. I. Joubert, A. R. Curio, and D. J. Wildman. Final Test Report on the Combustion of Solvent Refined Coal in a 100-hp Firetube Boiler. DOE/PETC/TR-82/5 (DE 82007670).
17. Sage, W. L. 1964. Combustion Tests on a Specially Processed Low-Ash, Low-Sulfur Coal. The Babcock and Wilcox Company Research Center, Research Report No. 4439. NTIS price: PCA03. Journal announcement: USGRDR 4008.
18. Southern Company Services, Inc. July 1979. Solvent Refined Coal Burn Test Final Report.
19. Southern Research Institute. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Particulate and Electrostatic Precipitator Characterization. DOE/OR/03054-37 Annex Vol. A.
20. Styles, G. A. September 1982. The Wilsonville Advanced Coal Liquefaction Research and Development Facilities Accomplishments and Process Evolution. Energy Progress, Vol. 2, No. 3, pp. 160-162.
21. United States Department of Energy Pittsburgh Energy Technology Center. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Phase II Combustion Test Program. DOE/OR/03054-37 Annex Vol. B.
22. Von KleinSmid, W. H., N. J. Kertamus, and H. Schreiber. 1984. Combustion of Exxon Donor Solvent Distillate Fuel in a 44.5-MW Utility Boiler. Proceedings: Eighth Annual Contractor's Conference on Coal Liquefaction. EPRI AT-3366-SR. Palo Alto, California.
23. Wheelabrator-Frye, Inc., Air Pollution Control Division. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Boiler Emission Report. DOE/OR/03054-37 Annex Vol. C.
24. Wheelabrator-Frye, Inc., Air Pollution Control Division. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Electrostatic Precipitator Mass Train Data and Operating Data. DOE/OR/03054-37 Annex Vol. D.

REFERENCES (SHEET 3 OF 3)

25. Wheelabrator-Frye, Inc., Air Pollution Control Division. 1983. SRC Burn Test in 700-hp Oil-Designed Boiler. Evaluation of Fabric Filter for Particulate Emission Control. DOE/OR/03054-37 Annex Vol. E.

GLOSSARY (SHEET 1 OF 5)

ASME	American Society of Mechanical Engineers.
Atomizer	Device for reducing a liquid to a spray of small particles.
B&W	Babcock & Wilcox, Inc.
Burner	The part of a combustion device where the flame is produced.
C-E	Combustion Engineering, Inc.
Clinker	As used in this report, a problematic burning deposit on a burner tip.
CO	Carbon monoxide.
CO ₂	Carbon dioxide.
Cocurrent	Firing arrangement where the primary and secondary air spin in the same direction.
Counter current	Firing arrangement where the primary and secondary air spin in opposite directions.
Cut point	Impactor particle size calibration point.
Cyclone	A centrifugal device for separating and collecting solid particles according to mass.
Dense-phase transfer	The transport of a pulverized material with a gaseous medium; contains greater than 50-percent solids.
Dilute-phase transfer	The transport of a pulverized material with a gaseous medium; contains less than 50-percent solids.
DOE	United States Department of Energy.
Duration test	An extended test at a preestablished set of conditions primarily to evaluate the flue gas and observe boiler operation. Steady-state test.
EASA	Electrical aerosol size analyzer.

GLOSSARY (SHEET 2 OF 5)

Electrostatic precipitator	Equipment for collecting flue gas particles by utilizing electrically charged electrodes and collecting plates.
EPA	United States Environmental Protection Agency.
EPRI	Electric Power Research Institute.
ESP	Electrostatic precipitator.
Excess air	Amount of air in excess of that theoretically required to supply enough oxygen for combustion.
Excess oxygen	Amount of oxygen in excess of that required for complete combustion.
Fast mix burner	A pulverized fuel burner that quickly mixes the fuel laden primary air with the secondary combustion air, producing a short bushy flame.
Firebox	The chamber within a boiler that contains the fire.
Fireye	The electronic sensor that monitors the presence of a flame at the burner, a boiler safety feature.
Flue gas	The emission from a boiler that exits through a passage or duct.
ICRC	International Coal Refining Company.
Impactor	A device for separating and collecting solid particles according to their mass by directing them through an orifice and onto a surface.
Isokinetic	Sample collection at the velocity of the flue gas stream.
LPSS	Large particle sampling system.
Mesh	A particle size measurement based on the number of openings per linear inch in a screen through which the particles pass.
MSA	Mine Safety Appliance Company.
Multiclone	A grouping of cyclones in parallel.

GLOSSARY (SHEET 3 OF 5)

NO ₂	Nitrogen dioxide.
NO _x	Oxides of nitrogen, primarily NO and NO ₂ .
Nozzle	The discharge pipe in a burner.
No. 6 Fuel Oil	Oil currently used to fire utility boilers.
NSPS	New Source Performance Standards.
Opacity	A measurement of the obstruction of light transmission through a flue gas stream.
Parametric tests	A set of preliminary tests to define operating conditions.
Particulates	Solid particles in the flue gas stream.
PETC	Pittsburgh Energy Technology Center.
PJFF	Pulse-jet fabric filter.
Primary air	The airflow used to transport the fuel to the burner.
Pulse-jet fabric filter	A fabric filter collection device that employs a pulse of air for cleaning.
RAFF	Reverse air fabric filter.
Rap	A hard blow or vibration of a collection plate in an electrostatic precipitator.
Reentrainment	The reintroduction of previously collected particles in an ESP into the gas stream.
Resistivity probe	A device for measuring the bulk resistivity of flyash.
Reverse air fabric filter	A fabric filter collection device that reverses airflow for cleaning.
S	Gas sneakage around the electrified regions of the electrostatic precipitator.
Saltation	The settling of SRC Fuel in the fuel feed line.

GLOSSARY (SHEET 4 OF 5)

Secondary air	The air supplied to the boiler to support combustion.
SCA	Specific collection area.
SCS	Southern Company Services, Inc.
SDCF	Standard dry cubic foot.
SEDS	Sample extraction and dilution system.
σ_{gas}	Normalized standard deviation of the gas velocity distribution.
Slow mix burner	A pulverized fuel burner that slowly mixes the fuel laden primary air with the secondary combustion air, producing a long lazy flame.
Spinvane	The component of the burner that imparts spin to the primary air stream.
SO ₂	Sulfur dioxide.
SO ₃	Sulfur trioxide.
SO _x	Oxides of sulfur, primary SO ₂ and SO ₃ .
SoRI	Southern Research Institute.
SRC	Solvent Refined Coal.
SRC-I	Process for preparing SRC fuels.
SRC Fuel	Pulverized Solvent Refined Coal.
SRC Residual Fuel Oil	Pulverized Solvent Refined Coal blended with excess process-derived distillates.
SRC-Water Slurry	Pulverized Solvent Refined Coal in water.
Steady state	An extended test at a preestablished set of conditions primarily to evaluate the flue gas and observe boiler operation.
Stoichiometric	In the exact proportions required for chemical reaction.

GLOSSARY (SHEET 5 OF 5)

UPSS	Ultrafine particle sampling system.
WFI	Wheelabrator-Frye, Inc.