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**ADVANCED COAL-FUELED GAS TURBINE SYSTEMS:
SUBSCALE COMBUSTION TESTING**

Topical Report - Task 3.1

May 1993

Work Performed Under Contract No. DE-AC21-86MC23167

**Prepared for
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, WV**

**by
Textron Defense Systems
2385 Revere Beach Parkway
Everett, MA 02149
as a subcontractor to**

**Westinghouse Electric Corp.
Power Generation Business Unit
Orlando, FL 32826-2399**

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TABLE OF CONTENTS

	<u>Page</u>
1 EXECUTIVE SUMMARY	1-1
2 INTRODUCTION	2-1
2.1 SCOPE OF REPORT	2-1
2.2 PROGRAM OBJECTIVES	2-1
2.3 PROGRAMMATIC HISTORY	2-2
2.4 COMBUSTOR CONCEPT DEVELOPMENT	2-3
3 SUBSCALE SLAGGING COMBUSTOR APPARATUS PLAN AND METHOD	3-1
3.1 TEST FACILITIES AND APPARATUS	3-1
3.1.1 PREHEATED AIR SUPPLY	3-4
3.1.2 COOLING AND QUENCH WATER SYSTEMS	3-5
3.2 FUEL FEED SYSTEMS	3-6
3.2.1 PULVERIZED COAL FEED	3-6
3.2.2 COAL WATER MIXTURE FEED	3-6
3.3 COMBUSTOR TEST RIG	3-8
3.3.1 HARDWARE DESIGN	3-8
3.3.1.1 Combustor Stress Analysis	3-8
3.3.1.2 Mechanical Design	3-9
3.3.2 INITIAL COMBUSTOR TEST RIG	3-12
3.4 INSTRUMENTATION AND CONTROL SYSTEM	3-12
3.4.1 INSTRUMENTATION SYSTEM	3-15
3.4.1.1 Combustor Measurement Ports	3-15
3.4.1.2 Parameters to be Measured	3-15
3.4.1.3 Transducer/Instrument Types	3-16
3.4.1.4 Gas Analysis System	3-20
3.4.1.5 Signal Conditioning	3-20

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
3.4.2 COMPUTER SYSTEM	3-20
3.4.2.1 Computer Hardware	3-20
3.4.2.2 Software System	3-23
3.4.3 CONTROL SYSTEM	3-24
3.4.3.1 System Inputs	3-24
3.4.3.2 System Outputs	3-25
3.4.3.3 Control Panel	3-25
3.4.3.4 Logic Protocols	3-25
3.4.3.5 Safety Features	3-28
3.4.4 CONTROL ROOM ARRANGEMENT	3-28
3.5 SORBENT FEED SYSTEM	3-29
3.6 COALS TESTED	3-30
3.7 SORBENTS TESTED	3-33
3.8 NOMINAL TEST CONDITIONS	3-34
3.9 HISTORY OF COMBUSTOR TEST CONFIGURATIONS	3-34
4 SUBSCALE SLAGGING COMBUSTOR TEST RESULTS AND DISCUSSION	4-1
4.1 RESULTS OF THE ORIGINAL TOROIDAL VORTEX COMBUSTOR	4-1
4.1.1 GENERAL OPERATION	4-1
4.1.1.1 Initial CWM Results	4-3
4.1.2 CARBON BURNOUT AND COMBUSTION EFFICIENCY	4-4
4.1.2.1 PC-Firing	4-4
4.1.2.2 Carbon Conversion and Exhaust Carbon Monoxide	4-4
4.1.2.3 CWM-Firing	4-5
4.1.2.4 CWM Viscosity	4-6
4.1.2.5 Injector Location	4-7
4.1.2.6 Sampling Location	4-8
4.1.2.7 Residence Time	4-9
4.1.2.8 CWM Injector Location and Atomization	4-9
4.1.2.9 Relative Performance of CWM and PC	4-10

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
4.1.3 NO _x EMISSIONS	4-12
4.1.3.1 PC-Firing	4-12
4.1.3.2 CWM-Firing	4-13
4.1.4 SO _x EMISSIONS AND SULFUR CAPTURE	4-14
4.1.4.1 Baseline SO _x Measurements	4-14
4.1.4.2 Sulfur Capture with Calcia Based Sorbent	4-17
4.1.4.3 Mechanism of Capture with Calcia	4-22
4.1.4.4 Sulfur Capture with Iron Based Sorbents	4-24
4.1.5 PARTICULATE EMISSIONS & SLAG REMOVAL	4-26
4.1.5.1 Slag Rejection	4-26
4.1.5.2 Particulate Emissions	4-26
4.1.6 ALKALI LEVELS	4-27
4.1.7 COMBUSTOR TEMPERATURES AND TEMPERATURE PATTERN FACTOR	4-30
4.1.7.1 Flame Temperatures in the Primary Zone	4-30
4.1.7.2 Combustor Exit Temperature Pattern Factor	4-30
4.1.8 HEAT LOSS & PRESSURE LOSS	4-31
4.1.8.1 Heat Loss	4-31
4.1.8.2 Pressure Loss	4-32
4.2 DISCUSSION OF ORIGINAL TOROIDAL VORTEX COMBUSTOR RESULTS	4-32
4.3 RESULTS OF THE TOROIDAL VORTEX COMBUSTOR MODIFICATIONS	4-33
4.3.1 SLAGGING CYCLONE SEPARATOR ADDITION	4-33
4.3.1.1 General Operation	4-33
4.3.1.2 Cyclone Performance	4-33
4.3.1.3 Particle Size Distributions	4-34
4.3.1.4 Material Balances for Cyclone Tests	4-36
4.3.2 SLAG TAP AND REVISED IMPACT SEPARATOR ADDITION	4-36
4.3.2.1 General Operation	4-36
4.3.2.2 Slag Tap Performance	4-37
4.3.2.3 Slag Tap/Sulfur Reduction Tests	4-37

TABLE OF CONTENTS (Cont'd)

		<u>Page</u>
	4.3.2.4 NOx Control	4-37
	4.3.2.5 CO Emissions	4-38
	4.3.2.6 Heat Loss & Pressure Loss	4-38
	4.3.2.7 Sorbent Feed Modifications	4-39
	4.3.2.8 Sulfur Reductions	4-40
4.3.3	CHAR CARRY-OVER PROBLEM AND SOLUTION	4-41
	4.3.3.1 Attempted Solutions	4-41
	4.3.3.2 The Solution: Increase the Coal/Air Injection Velocity	4-43
4.3.4	AMES ALKALI MEASUREMENTS	4-45
4.3.5	DISCUSSIONS OF TEST RESULTS FOR CURRENT COMBUSTOR CONFIGURATION	4-46
5	ANCILLARY STUDIES	5-1
5.1	COLD-FLOW CYCLONE TESTS	5-1
	5.1.1 SCALING OF CYCLONE FLOWS	5-1
	5.1.2 EXPERIMENTAL ARRANGEMENT	5-2
	5.1.2.1 Test Hardware	5-2
	5.1.2.2 Instrumentation	5-5
	5.1.3 TEST RESULTS	5-5
	5.1.3.1 Conventional Vortex Finder Exit	5-5
	5.1.3.2 Slot Exit	5-7
	5.1.3.3 Pressure Drop	5-7
5.2	SUBSCALE CASCADE DESIGN	5-11
	5.2.1 DESCRIPTION OF DESIGN	5-12
	5.2.2 DESIGN CHARACTERISTICS	5-14
	5.2.3 INSTRUMENTATION	5-14
5.3	ANCILLARY SULFUR STUDIES	5-15
	5.3.1 SPENT SORBENT STABILITY IN MOLTEN SLAG	5-15
	5.3.2 BASIC SULFUR CAPTURE STUDY	5-17

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
5.4 SUBBITUMINOUS COAL TESTING FOR NORTHERN STATES POWER COMPANY	5-18
5.4.1 TEST OBJECTIVES	5-19
5.4.2 OPERATING EXPERIENCE	5-19
5.4.3 FUEL SPECIFICATIONS	5-19
5.4.4 CARBON BURNOUT AND COMBUSTION EFFICIENCY	5-22
5.4.5 NO _x EMISSIONS	5-23
5.4.6 PARTICULATE EMISSIONS	5-25
5.4.7 ALKALI LEVELS	5-26
5.4.8 SO _x EMISSIONS AND SULFUR CAPTURE	5-27
5.4.9 HEAT LOSS AND PRESSURE LOSS	5-28
5.4.10 COMPOSITION AND HEATING VALUE FOR FUEL-RICH GASES PRIOR TO THE LEAN-QUENCH COMBUSTOR	5-29
6 CONCLUSIONS	6-1
APPENDIX A - TEST MATRIX	A-1

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
2-1	Artist's Rendering of Combustor	2-4
3-1	Haverhill Test Facility	3-1
3-2	Overall Test System Schematic	3-2
3-3	Plumbing Diagram	3-3
3-4	Air Supply System	3-4
3-5	Preheater Operating Range and Upgrade	3-5
3-6	Installed Coal Tank	3-7
3-7	Schematic of Coal-Water Mixture Storage and Feed System	3-8
3-8	Layout of First Combustor Stage	3-10
3-9	Mechanical Design of Impact Separator	3-11
3-10	Schematic of Original Subscale Slagging Combustor Test Rig	3-13
3-11	Instrumentation and Control System Block Diagram	3-14
3-12	Measurement Planes in Subscale Combustor	3-15
3-13	Control Panel	3-26
3-14	Control Room Layout	3-29
3-15	Sketch of Vibrating Louver Apparatus Added to Sorbent Feed System	3-30
3-16	Schematic of Original Subscale Slagging Combustor Test Rig	3-38
3-17	Schematic of Subscale Slagging Combustor Test Rig as Utilized During Slagging Cyclone Testing	3-36
3-18	Schematic of Subscale Slagging Combustor Test Rig with Real-Time Slag-Tapping Capability and Slagging Cyclone	3-36
3-19	Curved Body Impact Separator with Slag Tap and Collection Vessel	3-37
4-1	Uniformly Distributed Residual Slag on the Dome of Primary Combustion Chamber	4-1

LIST OF FIGURES (Cont'd)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
4-2	Uniformly Distributed Residual Slag on the Wall of the Primary Combustion Chamber Looking Towards the Exit Nozzle	4-2
4-3	Cross Section View of the Primary Combustor Showing Refractory Lining and Slag Buildup	4-2
4-4	Uniformly Distributed Residual Slag on the Impact Separator Following a Typical Run	4-3
4-5	Subscale Slagging Combustor Primary Zone Carbon Conversion Results as a Function of Primary Zone Equivalence Ratio	4-5
4-6	Carbon Conversion Measured at the Exit of the Impact Separator as a Function of the Primary Zone Equivalence Ratio for Initial CWM Tests and the PC Tests Made Previously	4-6
4-7	Carbon Conversion Measured at the Exit of the Impact Separator as a Function of the Primary Zone Equivalence Ratio for Tests Where CWM Viscosity Varied, and for Previous PC Results	4-7
4-8	Schematic Showing Location of Air-Atomizing CWM Injector Inside Primary Zone Combustor Air Feed Tube	4-8
4-9	Carbon Conversion as Measured at the Primary Zone Exit for More Definitive Data Gathering During Injector Location, Atomization, and L/D Studies	4-9
4-10	Comparison of Primary Zone Carbon Conversion for CWM and PC; Primary Zone Exit Data	4-10
4-11	Primary Zone Carbon Conversions Measured for CWM's Made from Dorchester and Pittsburgh No. 8 Coals	4-11
4-12	Subscale Combustor NO _x Emissions for Bituminous (Dorchester and Pittsburgh No. 8) and Subbituminous (Wyoming Rosebud) Pulverized Coals	4-12
4-13	Measured NO _x Emissions as a Function of Third Stage Combustor Exit Temperature; Dry Basis; Corrected to 15% O ₂	4-13
4-14	Comparison Between Combustor NO _x Emissions for PC and for CWM Firing, as Measured at Lean Stage Exit	4-14
4-15	Predicted Equilibrium concentrations for Sulfur-Containing Gases in Products of Combustion for Pittsburgh No. 8 Coal; (Note Normalized to 15% O ₂ ; Not "Dry Basis")	4-15

LIST OF FIGURES (Cont'd)

Figure	Title	Page
4-16	Measured and Predicted Primary Zone Concentrations of SO ₂ Plus H ₂ S in the Products of Combustion for Pittsburgh No. 8 - No Sorbent Injection; Wet Basis, not Corrected to 15% O ₂	4-16
4-17	Measured and Predicted SO ₂ as a Function of Equivalence Ratio and Time	4-16
4-18	Measured Sulfur Reduction at Three Locations in Subscale Slagging combustor, -325 Mesh Limestone Sorbent, Ca/S = 2-4	4-17
4-19	Measured Sulfur Reduction with Sorbent in Primary Zone, as a Function of Temperature of Combustion Products, Tests 5-2 Through 8-10	4-18
4-20	Measured Sulfur Reduction with Sorbent at Various Sampling Ports Along the Path from Primary Zone, through Impact Separator, to Lean Zone Exit	4-18
4-21	Primary Zone Sulfur Capture - Effect of Limestone Sorbent Particle Size; Calcium to Sulfur Ratio = 2 to 4	4-19
4-22	Primary Zone Sulfur Reduction - Effect of Sorbent Injection Angle	4-20
4-23	Port No. 3 Sulfur Reduction - Effect of Sorbent Type	4-20
4-24	Port No. 8 Sulfur Reduction - Effect of Sorbent Type	4-21
4-25	Sulfur Capture Based on Slag Analysis (Ca/S = 2 to 4)	4-22
4-26	Measured and Predicted Sulfur Capture as a Function of Equivalence Ratio for Ports No. 3 and No. 8	4-23
4-27	Measured and Predicted Sulfur Capture as a Function of Equivalence Ratio for Ports No. 4 and No. 5	4-23
4-28	Combustor Exhaust SO ₂ Reduction as a Function of Primary Zone Equivalence Ratio for a Variety of Sorbents - Gas Samples Taken at Port No. 8	4-24
4-29	Primary Zone Sulfur Reduction as a Function of Primary Zone Equivalence Ratio for a Variety of Sorbents - Gas Samples Taken at Port No. 3	4-25
4-30	Slag Rejection Data for Subscale Slagging Combustor Test	4-26

LIST OF FIGURES (Cont'd)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
4-31	Measured Exhaust Gas Particulate Loadings as a Function of Particle Size for Dorchester and Pittsburgh No. 8 Pulverized Coal with and without Limestone Sorbent; (Wet Basis; NO _x O ₂ Correction)	4-27
4-32	Hot Gas and Alkali Probe Schematic	4-28
4-33	Primary Zone Flame Temperature as a Function of Equivalence Ratio	4-30
4-34	Subscale Slagging Combustor Third Stage Exit Temperature Profiles at Several Average Exit Temperatures	4-31
4-35	Combustor Heat Loss	4-32
4-36	Particle Size Distributions from Cyclone Bucket. Measured Size Distributions for: (1) 200 Mesh Dorchester Coal; (2) Sample from Cyclone Bucket, Test C1-1; (3) Sample No. 1 from Cyclone Bucket, Test C1-2; (4) Sample No. 2 from Cyclone Bucket, Test C1-2.	4-35
4-37	Particle Size Distributions from Isokinetic Sampler. Measured Size Distributions for: (1) Sample No. 1 from Cyclone Bucket, Test C1-2; (2) Unburned Coal from Particle Sampler, Test C1-2; (3) Fly Ash from Particle Sampler, Test C1-2.	4-35
4-38	Equivalence Ratio (ϕ) and NO _x for Test SL1-3	4-38
4-39	Percent of Total Sulfur Present and Ca/S Molar Ratio for Test SL1-3	4-40
4-40	Sulfur Capture with Pittsburgh No. 8 Coal	4-41
4-41	Coal/Air Injector Assembly as Originally Installed	4-42
4-42	Coal/Air Injector Assembly, Showing Melted Injector Tubes	4-42
5-1	Cyclone Separator Experimental Arrangement	5-3
5-2	Model Cyclone Dimensions	5-3
5-3	Model Cyclone Exit Geometries	5-4
5-4	Mean Inlet Particle Size Distribution	5-5

LIST OF FIGURES (Cont'd)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
5-5	Outlet Size Particle Distributions - Vortex Finder Exit	5-6
5-6	Overall Collection Efficiency - Vortex Finder Exit and Slot Exit	5-6
5-7	Grade Efficiency - Vortex Finder Exit	5-7
5-8	Outlet Size Distribution - Slot Exit	5-8
5-9	Grade Efficiency - Slot Exit	5-8
5-10	Measured Pressure Drop of Vortex Finder and Slot Cyclones	5-9
5-11	Grade Efficiency Comparisons	5-10
5-12	Predicted Cyclone Exit Particulate Size Distributions; The Present Industry Consensus is That Expander Gas Should Meet the Criterion of Being in the Region Beneath the Curve Defined by the Dashed Line (Arrows)	5-11
5-13	Sketch of Cascade Rig for Installation in Exhaust of Slagging Combustor at TDS' Haverhill Facility (Elevation)	5-12
5-14	Section of Subscale Cascade Rig (Plan View)	5-13
5-15	Section View of Upstream Portions of Subscale Cascade Rig (Vertical Section)	5-13
5-16	Schematic of Sorbent/Slag Kinetics Experimental Apparatus	5-16
5-17	Time History of Spent Sorbent Decomposition in Bench-Scale Apparatus	5-16
5-18	Schematic of the Hot Flow Facility	5-17
5-19	Measured Primary Zone Carbon Conversions	5-24
5-20	NO _x Exhaust Emissions	5-25

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
3-1	Cooling Water Manifold Specifications	3-6
3-2	Location of Combustor Instrumentation Ports	3-17
3-3	Required Measurements and Data in Combustor Testing	3-18
3-4	Parameters to be Measured On-Line and Transducer Types	3-19
3-5	Subscale Combustor Data Acquisition Computer Specifications	3-21
3-6	Ultimate and Proximate Analyses of Coals Tested	3-31
3-7	Ash Fusion Temperatures in Reducing Atmosphere and Related Data for Coals Tested During this Program	3-32
3-8	Ash Analysis for Coals Tested	3-33
3-9	Nominal Test Conditions	3-34
4-1	Subscale TVC: Alkali Emissions During Typical CWM-Fueled Testing	4-29
4-2	Fly Ash Loading and Overall Slag Collection Efficiency Estimates with Slagging Cyclone	4-34
4-3	Slag Material Balances	4-36
5-1	Comparison of Properties of Glycerine at Ambient Conditions and Coal Ash at Combustor Conditions	5-2
5-2	Design Conditions for Cyclone Modeling Experiments	5-4
5-3	Experimental Conditions for Cyclone Tests	5-11
5-4	Design Specifications for Subscale Cascade Rig	5-14
5-5	List of Subscale Cascade Rig Instrumentation	5-15
5-6	Northern States Power Coal Test Matrix	5-20
5-7	Nominal Test Conditions	5-20
5-8	Analyses for Coals Tested	5-21
5-9	Ash Analysis and T-250s	5-22
5-10	Carbon Burnout and Combustion Efficiency	5-23

LIST OF TABLES (Cont'd)

<u>Table</u>	<u>Title</u>	<u>Page</u>
5-11	Particulate Emissions Levels and Collection Efficiencies	5-26
5-12	Alkali Levels	5-27
5-13	Heat Loss Data	5-28
5-14	Combustor Subsystem Pressure Losses	5-29
5-15	Composition of Fuel-Rich Gases	5-30
5-16	Fuel Heating Values	5-30

EXECUTIVE SUMMARY

This is the final report on the Subscale Combustor Testing performed at Textron Defense Systems' (TDS) Haverhill Combustion Laboratories for the Advanced Coal-Fueled Gas Turbine System Program of the Westinghouse Electric Corp. under DOE METC Contract DE-AC21-86MC23167. This program was initiated by the Department of Energy in 1986 as an R&D effort to establish the technology base for the commercial application of direct coal-fired gas turbines.

The combustion system under consideration incorporates a modular staged, rich-lean-quench, slagging combustor concept. The primary zone is based on 25 years of Textron development on a slagging Toroidal Vortex Combustor (TVC) which was originally designed for magnetohydrodynamics (MHD) applications. Fuel-rich conditions in the first stage inhibit NO_x formation from fuel-bound nitrogen; molten coal ash and sulfated sorbent are removed, tapped and quenched from the combustion gases by inertial separation in the second stage. Final oxidation of the fuel-rich gases and dilution to achieve the desired turbine inlet conditions are accomplished in the third stage which is maintained sufficiently lean so that here, too, NO_x formation is inhibited.

The configuration of the subscale combustor has evolved during the six years of this program from a system using only an impact separator to remove particulates to a system which also includes a slagging cyclone separator before the lean-quench combustor. The system also now includes active slag tapping after the impact separator rather than a bucket to collect the slag.

The subscale 12 MM Btu/hr slagging combustor has demonstrated excellent coal-fired operation at 6 atm. The combustor has fired both coal-water mixtures (CWM) and pulverized coal (PC). Three Wyoming subbituminous coals and two eastern bituminous coals have been successfully fired in the TVC. As a result of this active testing, the following conclusions may be drawn:

- It was possible to achieve the full design thermal capacity of 12 MM Btu/hr with the subscale slagging combustor, while burning 100% pulverized coal and operating at the design pressure of 6 atm.
- Because of the separate-chamber, rich-lean design of the subscale slagging combustor, NO_x emissions that easily meet the New Source Performance Standards (NSPS) limits are readily achieved.
- The TDS toroidal-vortex subscale slagging combustor readily achieves in excess of 99% carbon burnout efficiency when 100% coal-fired.
- Ninety percent of the ash can be separated as slag in the impact separator, and a total 98 to 99% removed with the addition of the slagging cyclone separator.
- Objectives for third-stage exit temperature (1850°F), and exit temperature pattern factor (14%) were readily achieved.
- Overall pressure loss is currently an acceptable 5 to 6% without cyclone separator and 7.9% with the cyclone.

- Feeding pulverized coal or sorbent into the combustor against 6 atm pressure is achievable.
- NSPS demands in the area of particulate removal indicate an additional cleanup stage, over-and-above the impact separator is needed. A slagging cyclone has been designed, manufactured and tested successfully. Based on the results of this testing, the NSPS levels can be approached. The size distribution of the particulates entering the Westinghouse combustion turbine should be small enough to prevent erosion damage to the blades.
- Sulfur reductions at the third-stage exhaust of up to 50% have been achieved. The NSPS goal is 70 to 90% reduction, depending on coal sulfur content. To meet the new Environmental Protection Agency (EPA) goals based on acid rain legislation will require additional sulfur capture.
- Vapor alkali measurements done with the Ames alkali monitor indicate that slag tapping and slagging cyclone separating reduce vapor Na and K levels down to around the 20 ppbw levels as recommended by gas turbine manufacturers. This could eliminate the need for additional alkali removal and simplify the commercial combined cycle approach.

INTRODUCTION

This is the final report on the Subscale Combustor Testing performed at Textron Defense Systems' (TDS) Haverhill Combustion Laboratories for the Advanced Coal-Fueled Gas Turbine System Program of the Westinghouse Electric Corp. This program was initiated by the Department of Energy in 1986 as an R&D effort to establish the technology base for the commercial application of direct coal-fired gas turbines. The combustion system under consideration incorporates a modular staged, rich-lean-quench, Toroidal Vortex Slagging Combustor (TVC) concept. Fuel-rich conditions in the first stage inhibit NO_x formation from fuel-bound nitrogen; molten coal ash and sulfated sorbent are removed, tapped and quenched from the combustion gases by inertial separation in the second stage. Final oxidation of the fuel-rich gases, and dilution to achieve the desired turbine inlet conditions are accomplished in the third stage, which is maintained sufficiently lean so that here, too, NO_x formation is inhibited.

2.1 SCOPE OF REPORT

This report covers work associated with the subscale combustion testing performed under DOE METC Contract DE-AC21-86MC23167, Advance Coal-Fueled Gas Turbine Systems, for the period July 1986 through December 1992. TDS' work during this time frame has been divided between Subtask 3.1, Subscale Combustion System, and three smaller subtasks: 9.0, Sorbent/Slag Study; 10.0, Slag Tap; and, 11.0, Basic Sulfur Capture Studies.

Subtask 3.1 involves the design, fabrication, testing and evaluation of a 12 MM Btu/hr toroidal vortex slagging combustor for utility gas turbine applications. Subtasks 9.0 and 11.0 were bench-scale sulfur control experiments performed in parallel with 3.1, in separate facilities. Subtask 3.1 efforts will be reported here in considerable detail; the other subtasks were the subject of separate topical reports, and will only be summarized briefly. There was also a Subtask 7.0, which called for the design, fabrication, and testing of a stationary turbine cascade rig. Following completion of the design during the 1988-1989 period this subtask was put on hold until it was officially deleted from the work scope by METC in 1991.

2.2 PROGRAM OBJECTIVES

The primary objective of this work was to verify the feasibility of a direct coal-fueled combustion system for combustion turbine applications. This has been accomplished by the design, fabrication, testing and operation of a subscale development-type coal-fired combustor. Because this was a complete departure from present-day turbine combustors and fuels, it was considered necessary to make a thorough evaluation of this design, and its operation in subscale, before applying it in commercial combustion turbine power systems.

Another objective was to keep fuel costs acceptably low by burning raw or moderately cleaned coal, as is normal utility practice. Both bituminous and subbituminous coals have been tested. Coal grinding has been, and, is to be, consistent with that considered practical and economical for electric utility utilization. The coal was burned exclusively as dried PC during the 1988-1989 reporting period and then burned as CWM during much of the 1989-1990 period. Testing revealed PC to be the preferred fuel both from performance and economic standpoints. Therefore, the slagging combustor system was reconfigured to burn PC for the balance of the program.

The ultimate goal for the coal combustion system was to attain efficient combustion of the coal, and simultaneously to satisfy all of the current environmental emission regulations, such as the NSPS, for coal-fired steam generators and combustion turbine power system requirements.

Program Objectives

1. Attain high efficiency with emphasis on effective fuel utilization (burn-out) and low pressure and heat losses.
2. Achieve stable and reliable operation.
3. Control and limit NO_x formation in the gas to meet or exceed NSPS.
4. Remove sulfur to meet or exceed NSPS.
5. Demonstrate efficient removal of slag and all particulates in the gas with the ultimate objective to meet or exceed NSPS.
6. Retain alkalies in ash/slag removed from the combustor.

Specific Performance Goals

1. Demonstrate self-sustaining coal combustion at the thermal design rating of 12 MMBtu/hr.
2. Burn utility grade bituminous and subbituminous coal, both in the pulverized form, and as coal-water mixture.
3. Produce a lean-zone exit gas stream having an average temperature of at least 1850°F, and having a uniformity such that the exit temperature pattern factor will be 20% or less.
4. Achieve combustion efficiency greater than 98%.
5. Demonstrate stable and reliable operation and acceptable refractory performance.
6. Show that heat and pressure losses are acceptable; (interim values of 8% and 7%, respectively, are being used in Task 8.0, for example).
7. Operate with NO_x emissions less than the NSPS limit of 0.6 lb/MM Btu.
8. Limit SO_x per the NSPS to a maximum of 1.2 lb/MM Btu, where 90% reduction is required for SO_x greater than 0.6 lb/MM Btu, and 70% reduction is required for SO_x less than 0.6 lb/MM Btu.

2.3 PROGRAMMATIC HISTORY

The Westinghouse Advanced Coal-Fueled Gas Turbine System Program (DE-AC21-86MC23167) was originally split into two major phases - a Basic Program and an Option. The Basic Program contained two phases: 1) design, fabrication, and extensive testing of a 6 atm, 12 MM Btu/hr TVC; and, 2) 100 hrs of testing of the subscale TVC integrated with a small 500 kW Garrett Gas Turbine. The Option phase was to have been devoted to performing a verification test of a utility sized (70 MM Btu/hr) TVC.

In 1987, the program underwent two major revisions. First, in a 9/23/87 Westinghouse proposal for restructuring the program, it was recommended that all three stages of a utility-sized combustor be designed and manufactured for the nominal operating conditions projected for one full-size gas turbine combustor. A Westinghouse restructured proposal (dated 4/9/87) had not included the testing of the third stage of the utility combustor which was a deviation from the contract's original SOW. The September proposal also recommended that the utility-sized combustor test be performed at the Allison Gas Turbine Division of General Motors Corp.

Second, in the proposal submitted (12/18/87), it was recommended that a stationary cascade test in which two sets of turbine vanes, designed to simulate the first stage of a Westinghouse 501 combustion turbine engine, replace a 100 hr Garrett gas turbine test.

Both of these above mentioned Westinghouse proposals were officially accepted in a contract modification (A006) received from METC on 7/1/88.

In 1989 two add-on tasks to the Base testing program were approved: 1) fabrication and testing of the slagging cyclone separator; and, 2) design, fabrication and testing of the slag tapping section.

On 4/6/89, METC placed the stationary cascade manufacture on hold until a better definition of the subscale combustor testing program could be made. In 1991 METC decided to delete the remaining portion of the Task 7.0, Cascade. This was based on their decision to discontinue funding of the hardware portion of this program at the conclusion of the subscale combustor testing.

In the later part of 1991, it was decided by METC to terminate the experimental portion of this program at the conclusion of the slagging combustor testing in 1991. In December 1991, testing was suspended for three months in order to perform combustion tests on Northern States Power Co. (NSP) coals. This work was done under private funding not supported by DOE. The results of these tests were to be used to guide the commercialization efforts of this technology. The intention of the final period of testing (October - December, 1992) was to measure TVC exhaust alkali levels using the Ames alkali monitor, since this is a crucial issue for commercialization.

2.4 COMBUSTOR CONCEPT DEVELOPMENT

As shown in Fig. 2-1, the original slagging combustor is a modular unit with three stages. The first stage is the primary combustion zone. Coal and preheated air enter the primary zone coaxially through four injection nozzles which are equally spaced around the combustion chamber. This coaxial injection promotes intense air/coal mixing and rapid particle heat-up/devolatilization, which minimizes carbon burnout time.

The four incoming coal-air jets coverage at the combustor centerline and form one vertical jet which impacts the combustor dome. This forms a toroidal vortex which provides the mechanisms for: (1) flame stabilization; and, (2) centrifugal separation of larger ash/slag particles. The separated ash/slag forms a stable flowing layer on the combustor walls. The vertical geometry of this stage allows gravity to assist in the removal of the molten slag.

Fuel-rich conditions in this stage inhibit NO_x formation from fuel-bound nitrogen. It also provides the necessary reducing conditions for removal and capture of sulfur. The sulfur sorbent, limestone or dolomite, is counter-flow injected (dry) into the downstream end of the primary

Fig. 2-1 Artist's Rendering of Combustor

zone. The first stage was designed for a coal particle residence time of about 100 ms (for 75 micron sized particles).

The second stage is an efficient impact separator which is closely coupled to the first stage. The impact separator removes particulates carried over with the gas from the primary zone, whether they are sorbent or fine particles of ash. Additional gas cleanup was required to meet NSPS particulate standards; therefore, a slagging cyclone separator was considered in addition to the impact separator.

The third stage is used to complete combustion and to temper the products to meet turbine inlet requirements. The rapid mixing between gases coming from the second stage and secondary air insures that the peak gas temperatures, and hence, thermal NO_x formation is minimized. This stage is designed based on conventional gas turbine combustor practices.

Based on experimental results acquired prior to 1990, the current concept now includes a slagging cyclone separator as an integral part of the slagging combustor system (see Figure 3-17, page 3-36).

The hot gases, once leaving the impact separator, enter into a water-cooled and refractory-lined slagging cyclone separator where particulate emissions are further reduced. The cleaned fuel-rich gases then pass into the third stage, the lean-quench combustor. The secondary combustor is a cylindrical water-cooled section having two circumferential rings of air jets, each ring containing 16 jets. The first ring of jets bring in secondary air to oxidize the fuel-rich gases, which burn spontaneously. The second ring of jets admit dilution (quench) air, which drops the burning gases to a turbine inlet temperatures of 1850° to 2000°F.

Following the lean quench zone, the hot gases pass through a water-cooled instrumentation section, and then through a water-cooled orifice plate which drops the pressure to near atmospheric pressure. Emissions, pressure and temperature profile are detected in the instrumentation section. Following the orifice plate, the gases pass through a water spray quench and then to an exhaust stack.

SUBSCALE SLAGGING COMBUSTOR APPARATUS, PLAN AND METHOD

3.1 TEST FACILITIES AND APPARATUS

All combustion tests reported here were conducted at the TDS facility located in Haverhill, MA. A schematic of the facility (Fig. 3-1) shows the relative location of the gas turbine combustor test rig and various subsystems. A computer room was dedicated for data acquisition and reduction. The control room was modified to incorporate the gas turbine combustor controls. Fig. 3-2 is an overall test system schematic showing the new or modified systems. Fig. 3-3 shows a plumbing diagram for the test rig.

Fig. 3-1 Haverhill Test Facility

Fig. 3-2 Overall Test System Schematic

Fig. 3-3 Plumbing Diagram

3.1.1 PREHEATED AIR SUPPLY

The air supply system is shown schematically in Fig. 3-4. A 6-in. air supply line dedicated to the combustor test rig was installed with three (3) 4-in. riser lines dripping down to the three combustor stages. Orifice flanges and control valves were added to meter and control the oxidant supplied to the primary and secondary combustion zones and the dilution air to the last stage.

Fig. 3-4 Air Supply System

The original high temperature piping system was supported in a manner which allowed unconstrained motion due to thermal growth throughout much of the system. This design approach was continued in the high temperature piping added to the system. A test was run using maximum preheat capability to determine the extent and direction of pipe growth with the original system. This information was then used to determine the type and location of pipe system supports for the new piping. Pipe supports were also been ordered for the riser lines and control valves leading to each combustor stage. These additional supports are designed to bear the load of the pipe and valves while allowing room for about 1.5-in. of thermal growth of the risers. They will also be capable of swinging to allow for the 3.0-in. of thermal growth of the horizontal 6-in. line. Sway braces have been ordered to eliminate unnecessary movement from vibration or other causes while allowing room for thermal growth.

The air preheater was upgraded. The appropriate components were purchased and installed at the appropriate time. Fig. 3-5 displays the present preheater performance envelope and the capabilities of the upgraded preheater. The existing preheater could supply 7 lb/s of air at a temperature of approximately 710°F. The upgrade enabled it to supply the same flowrate at approximately 920°F. With a reduction in airflow to 6.5 lb/s, the preheater should be capable of supplying 1000°F air.

Fig. 3-5 Preheater Operating Range and Upgrade

As a safety precaution, a 6-in. burst disc was installed just downstream of the preheater. This is to protect both the preheater and the combustor against an over pressure condition. The burst disc is designed to rupture between 190 to 210 psig for a metal temperature of 200°F. The burst disc was sized for the 25 MM Btu/hr slagging retrofit coal combustor.

3.1.2 COOLING AND QUENCH WATER SYSTEMS

Each component of the combustor is double walled. The combustor is cooled by flowing water through the passages formed between a component, inner and outer walls. The water originates in a cooling tower with a capacity of 43.5 MM Btu. It is filtered, and then pumped to a manifold for distribution to the individual components. Each component has a dedicated control valve and flow meter. Table 3-1 gives the coolant flowrate and line size for each of the components. Temperatures are monitored at the inlet manifold and the exit manifold of each component. The water completes the circuit by returning to the cooling tower. Additional water is added to replace that lost to evaporation and leakage.

The exhaust quench section has an annular ring of water spray nozzles that inject water into the hot gas stream (approximately 2000°F), thereby cooling the gas and simultaneously the walls of the exhaust duct. The quench water is collected and recirculated without passing through the cooling tower. Makeup water is added as needed.

Table 3-1
Cooling Water Manifold Specifications

	<u>Flowrate (GPM)</u>	<u>Line Size (in.)</u>
Component	23	0.75
Dome	26	0.75
Combustor	11	0.5
Spool	13	0.5
Injector Tubes	42	1
Injector	35	1
Nozzle	150	2
Exhaust Housing	100	1.5
Centerbody	60	1
Adapter	22	0.75
Dilution Zone	21	0.75
Spool/Instrumentation	50	1
Orifice Plate	5	0.5
Exhaust Tube	70	1

3.2 FUEL FEED SYSTEMS

During the course of testing both PC and CWM were fed at 6 atm pressure to the primary zone combustor. A splitter just prior to the combustor provided a uniform homogeneous mixture of fuel and carrier gas to the four combustor injectors when firing PC. A Mogno pump was used to supply four air assisted atomizers for injecting slurry when burning CWM.

3.2.1 PULVERIZED COAL (PC) FEED

The coal was fed to the combustor from a 10,000 lb capacity, conical-bottom storage tank (Fig. 3-6) designed for a pressure of 250 psig. The coal tank is pressurized with inert nitrogen and has a pressure relief valve. Directly below the tank is a ball valve which turns on and off the coal flow. The coal is then pneumatically transported by carrier air via an eductor, with coal to air mass ratios as high as eight (8:1). The feed rate of coal is controlled by the flow rate of transport air, and the difference in pressure between the coal tank and the feed line. The feed rate of PC is measured by means of a weight rate readout connected to load cells supporting the coal tank. A flow splitter divides the two-phase flow equally to each of the four (4) coal-air injectors which feed the primary combustor.

3.2.2 COAL-WATER MIXTURE FEED

The CWM prepared on site just prior to the run, was stored, heated and continually recirculated into a 500 gallon storage tank located inside the test facility. A schematic of the CWM feed system appears in Fig 3-7. Along with the tank, it includes a pumping, metering, and control system built on a skid and located next to the subscale combustor. A progressive cavity pump is used to feed the CWM. The same coal-air injectors used for the PC are used for the CWM. However, the PC injector tube placed inside the coal-air injector body is replaced by a shorter CWM injector nozzle with a Parker Hanovan nozzle at the end of it. All the primary combustion air is introduced coaxially around the CWM injection nozzles. High pressure compressed air warmed to room temperature is used to atomize the CWM into the primary combustor.

Fig. 3-6 Installed Coal Tank

Fig. 3-7 Schematic of Coal-Water Mixture Storage and Feed System

3.3 COMBUSTOR TEST RIG

3.3.1 HARDWARE DESIGN

3.3.1.1 Combustor Stress Analysis

The combustor components were designed within the constraints of the ASME Code for Unfired Pressure Vessels, Section VIII. Design pressure was chosen as 180 psia (12 atm). This pressure corresponds to the compressor exit pressure of the Garrett IEB31-800 gas turbine which was to have been tested with the subscale combustor. The combustor was designed as a double-walled structure with cooling water passages between the two walls. Only the inner wall was considered to contain the design pressure, the outer wall was not considered to add any strength; although it does add strength by reinforcing the inner wall through the wires used to establish the cooling water flow passages, and through the flange walls. The outer wall was considered to require only enough strength to withstand the pressure of the circulating cooling water. Experience with similar structures and cooling networks was used to design the coolant passages.

Thermal analysis showed that the water-cooled inner wall would have metal temperatures under 300°F this is well under the 650°F temperature at which carbon steel strength begins to decrease. All components were analyzed unless the designs were identical, in which case a representative component was analyzed.

Cylindrical shells were analyzed for circumferential and longitudinal stresses. Spherical shell stresses were examined to determine adequate wall thickness for the various heads and curved sections. Flat plate regions were analyzed for shear stress and flexure stress. Care was taken in the design of flanges their size and weight were kept to a minimum to make the combustor components as manageable as possible, and still have adequate strength and stiffness. The

incorporation of the cooling water manifolds into the flanges and the problems associated with fabricating a double-walled structure also increased the complexity of the design and increased the difficulty of limiting size and weight.

All flanges were fabricated from forgings as required by code. O-rings were chosen to seal joints between adjacent components. One of the two flanges between each matching flange pair has an O-ring groove machined in its face. The O-ring material is 75 durometer Viton, a fluorocarbon. Viton has excellent heat, acid, and flame resistance. The 75 durometer rating indicates an intermediate hardness allowing the O-ring to be compressed fairly easily without locally deforming the flange; this will insure the seal at the flanges. Bolt stresses were analyzed and a sufficient number of bolts were specified per flange to insure the integrity of the combustor and to eliminate any possible gas leakage.

Leak testing of the cooling water flange manifolds was conducted hydrostatically to 180 psig. This test pinpointed several leaks along weld seams which, if uncorrected, would have allowed water to accumulate between the refractory and the metal wall. The leak testing also confirmed the strength of the outer wall as well as being an indicator of the strength of the inner wall. After the combustor was assembled, it was pressure tested with nitrogen gas to 160 psig (125% of maximum compressor outlet pressure). This served as both a safety check and a leak check. Should the combustor ever be required to run at its design pressure (180 psia), another pressure test would have to be conducted at 210 psig which is approximately 125% of design pressure. Ordinarily, a hydrostatic test at 150% of design pressure would be required, but with the problems associated with intentionally introducing water into the refractory lined combustor, the planned test was an acceptable substitute.

3.3.1.2 Mechanical Design

Stage I

The layout and mechanical design developed for the first combustor stage is shown in Fig. 3-8. The first combustor stage consists of four (4) major parts (i.e., an upper dome, a cylindrical section, a fuel/air injector housing with four co-axial coal/air injectors equally spaced around the combustor circumference, and an exiting nozzle for acceleration and delivery of the fuel-rich gases produced to the impact separator). The combustor is of modular design which enables testing at various parametric conditions. Sections can be added to change the combustor aspect ratio (L/D) and flexibility is incorporated in the injector design to vary injection angles both vertically and horizontally.

The outer shell and walls, which contain the combustion pressure, are of metal construction and are water-cooled. The inner walls are lined with refractory. Refractory lining was considered preferable for the subscale development combustor because of the small size of the combustor and because combustor tests will be of relatively short duration with multiple starts and stops. For such conditions, refractory lining would serve the important function of minimizing heat losses and facilitating slagging of the walls.

Stage II

The outline and mechanical design for the impact separator is shown in Fig. 3-9. Gas velocities in the vicinity of flowing slag on the centerbody walls have been kept as low as possible, in order to minimize re-entrainment of separated slag, and the overall size of the separator has also been minimized to limit heat losses. The separated slag flows down the centerbody and collects, while the gas exits above the centerbody top surface. The impactor centerbody can be raised or lowered relative to the combustor nozzle outlet. The impactor has been sized to collect the slag generated in a typical combustor test. The slag collection bucket, together with the centerbody, can be detached from the combustor assembly for removal of collected slag between tests.

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Fig. 3-8 Layout of First Combustor Stage

Fig. 3-9 Mechanical Design of Impact Separator

The impact separator has water-cooled metal walls partially lined with refractory, to promote slagging and to reduce heat losses. The lower section of the impact separator housing and the impact separator dome are also covered with refractory. The materials used in the construction of the impactor are the same as for the first combustor stage. An optical port is situated so as to allow a view of the top of the centerbody. Provision has been made for the insertion of the necessary gas and particulate sampling probes, as well as pressure and temperature probes.

Stage III

A simple water-cooled metal wall construction was chosen for the combustor's third stage. This is preferable for the subscale development combustor because it avoids the complexity of a regeneratively air-cooled design and it provides far more flexibility during combustor testing for changing the division between amounts of secondary air for quench/oxidation and for dilution/tempering.

Regenerative air cooling is contemplated in the utility-size combustor system to maximize cycle efficiency. However, in this case the third stage would probably be common for several individual modules of the first and second combustor stages, which makes regenerative air cooling more acceptable (smaller surface to volume ratio and favorable scaling relationship).

Combustion air is supplied to the third stage through two manifolds. One for the secondary combustion process, and the second for final combustion/dilution. Each manifold is supplied

from four circumferentially spaced flexible metal hoses. The hoses direct the air against four splash plates which disperse the incoming jets and diffuse the flow throughout the manifold. Sixteen pipes, in turn, direct the air into the combustion and dilution chambers, respectively.

Pressure Drop Orifice Plate

The pressure drop orifice plate is double-walled, water-cooled and serves to control the total flowrate through the combustor at a given temperature and pressure by choking the flow. The orifice open area was fabricated undersized to allow room for more accurate sizing of the orifice after the complete flow system is assembled and flow tested.

3.3.2 INITIAL COMBUSTOR TEST RIG

The overall layout of the initial combustor test rig is shown in Fig. 3-10. This configuration was used prior to the inclusion of the slagging cyclone separator in late 1990. In the upper left of the figure is the dome-topped primary zone. Air and PC or CWM are injected upward into this primary zone through four angled fuel injectors, equally spaced around the zone. For simplicity, only one is shown in the figure. When needed, pulverized sorbent, with carrier air, is also injected into the primary zone. Four smaller injectors (one is shown) handle this task.

Rich combustion occurs in the primary zone, and melted coal ash (slag) and hot, fuel-rich gases exit downward out of the zone through the small diameter nozzle shown. The nozzle leads the rich gases into the impact separator, the large vessel shown, at the lower left. A sudden change of direction, and gravity, separate slag and particles. Leaving the liquid and solid matter behind, the cleaned, hot fuel-rich gases move out of the top right-hand side of the impact separator. The primary zone, the impact separator, the internals of the impact separator, and the connecting passages are water-cooled, high-pressure, steel vessels, lined with refractory.

Having left the impact separator, the hot, fuel-rich gases pass to the right, through the diffusing section, to the lean-burn zone. The lean-burn zone is a cylindrical water-cooled section having 32 inclined air jet inlets. The first 16 of these bring combustion air in, to oxidize the fuel-rich gases. The second 16 inlet jets admit dilution air, which drops the burning gases to a 1850 to 2000°F.

Following the lean-burn zone, the hot gases pass through a water-cooled instrumentation section, and then through a water-cooled orifice plate which drops them to near atmospheric pressure. Emissions, pressure, and temperature profile are detected in the instrumentation section. Following the orifice plate, the gases pass through a water spray, and to the exhaust.

3.4 INSTRUMENTATION AND CONTROL SYSTEM

A block diagram of the overall instrumentation and control system for the subscale combustor test hardware is shown in Fig. 3-11. The control system is based on a programmable logic controller. In designing the control system, emphasis has been placed on safe and reliable operation of the subscale combustion system. The instrumentation system is based around a dedicated data acquisition computer. The emphasis in designing a data acquisition system was placed on maximizing the amount of information obtained from each combustor test and facilitating operation of the test hardware. These systems and their use in combustor testing is discussed in detail in this section of the report.

Fig. 3-10 Schematic of Original Subscale Slagging Combustor Test Rig

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Fig 3-11 Instrumentation and Control System Block Diagram

3.4.1 INSTRUMENTATION SYSTEM

3.4.1.1 Combustor Measurement Ports

Fig. 3-12 shows the location of the measurement planes in the subscale combustor. There are a total of 8 planes at which measurements may be obtained, including two planes (7 and 8) downstream of the combustor's third stage. Table 3-2 lists the number, size and angular location of the access ports. There are a total of 37 ports. In addition to ports located in the 8 planes, illustrated in Fig. 3-12, there is one port, No. 14, at the top of the impactor housing. This port is angled so as to provide a view of the top of the impactor centerbody. This distribution of ports provides sufficient access to enable a comprehensive assessment of combustor performance to be made.

Fig. 3-12 Measurement Planes in Subscale Combustor

3.4.1.2 Parameters to be Measured

Table 3-3 lists both the parameters to be measured and the necessary information to be obtained during the subscale combustor testing and evaluation. The parameters in Table 3-3 may be divided between three categories: 1) material properties; 2) parameters to be measured on-line during a combustor test; and, 3) parameters to be measured off-line, after a combustor test.

Coal and sorbent properties are obtained both from the respective suppliers and also from independent laboratory analysis. Those parameters which are measured on-line during combustor testing and the various transducer or measurement types used are listed in Table 3-4. All gas flow rates are measured using conventional ASME sharp-edged orifice plates instrumented with thermocouples and pressure transducers. Cooling and quench water flow rates are measured using paddle wheel flow meters. Coal mass flows are measured using two transducer types: (1) load cells, which monitor the weight change of the coal hopper (PC); and, (2) triboelectric probes (CWM).

The triboelectric technique is discussed in more detail below. Sorbent flow rates are also measured using load cells. Cooling water temperature rises are measured using Resistance Temperature Detectors (RTDs). Gas temperatures in the combustor are measured using three techniques: thermocouples, optical pyrometers and optical fiber thermometers. The optical fiber thermometers are also discussed in more detail below.

Gas samples may be drawn from any of the ports listed in Table 3-2 for either on-line gas analysis or for storage and subsequent off-line analysis using gas chromatographic techniques. Particle samples may also be drawn from any access port for subsequent off-line analysis in order to determine slag and particle composition. Standard chemical analysis, SEM (morphology), X-ray diffraction and fluorescence, spectroscopy and atomic absorption, and emission techniques have been used in order to determine carbon, sulfur, fixed nitrogen and alkali content, as well as physical characteristics.

3.4.1.3 Transducer/Instrument Types

Transducer types used during combustor tests are as follows:

Pressure:	Sensotec Model Z Absolute, and Model A-5 Differential Pressure Transducers with on-board signal conditioning.
Thermocouples:	Type T, B, and E.
RTD:	100 ohm platinum
Load Cells:	BLH Model KIS-2-20KN with E-1-TAD Indicator/Analyzer.
Pyrometers:	Coloratio Model 9210
Flowmeters:	Omega Model FP-5300 Paddle Wheel Flowmeters

Table 3-2**Location of Combustor Instrumentation Ports**

<u>No.</u>	<u>Plane</u>	<u>Location</u>	<u>Position (degrees)</u>	<u>Size (in.)</u>
1	1	Stage 1 - Dome Section	0	0.75
2	1	"	0	1.25
3	1	"	135	1.25
4	1	"	270	1.25
5	1	"	315	1.25
6	2	Stage 1 - Combustor Section	45	1.00
7	2	"	90	1.00
8	2	"	225	1.00
9	2	"	270	1.00
10	3	Stage 1 - Injector Section	45	1.25
11	3	"	135	1.25
12	3	"	225	1.25
13	3	"	315	1.25
14	4a	Stage 2 - Impactor Housing	225	1.00
15	4	"	67.5	1.00
16	4	"	97.5	1.25
17	4	"	127.5	0.75
18	4	"	247.5	1.00
19	4	"	277.5	1.25
20	4	"	307.5	0.75
21	5	Stage 3 - Diverging Inlet	45	1.00
22	5	"	75	0.75
23	5	"	135	1.25
24	5	"	225	1.00
25	5	"	255	0.75
26	5	"	315	1.25
27	6	Stage 3 - Dilution Zone	0	1.00
28	6	"	90	0.75
29	6	"	270	0.75
30	7	Spool Piece - Entrance	0	2.00
31	7	"	90	2.00
32	7	"	180	2.00
33	7	"	270	2.00
34	8	Spool Piece - Exit	0	2.00
35	8	"	90	2.00
36	8	"	180	2.00
37	8	"	270	2.00

Table 3-3

Required Measurements and Data in Combustor Testing

First Combustor Stage

Coal fuel and ash specifications
Sorbent specifications
Fuel mass flow rate
Sorbent mass flow rate
Primary air mass flow rate, temperature and pressure
Combustor pressure
Gas temperature
Coolant mass flow rate, inlet and outlet temperature metal skin temperatures

Second Combustor Stage

Particle loading, size and size distribution, inlet and exit
Slag (including sorbent) removed
Gas pressure, inlet and exit
Gas temperature
Gas exit composition (CO_2 , CO , O_2 , H_2S , COS , HCN , NH_3 , NO_x , HC)
Vaporized alkalis in gas (if possible)
Coolant mass flow rate, inlet and outlet temperature
Metal temperatures
Composition and characteristics of slag removed and particles collected (C, S, N, alkalis, etc.)

Third Combustor Stage

Secondary air mass flow rate, pressure and temperature
Dilution air mass flow rate, pressure and temperature
Products of combustion pressure and temperature (including pattern factor)
Products of combustion composition (CO_2 , CO , O_2 , NO_x , HC)
Vaporized alkalis (if possible)
Products of combustion particle loading, size and size distribution
Coolant mass flow rate, inlet and outlet temperature
Metal temperatures
Composition and characteristics of particles removed

Table 3-4**Parameters to be Measured On-Line and Transducer Types**

<u>Parameter</u>	<u>Transducer Type</u>	<u>No. Channels</u>
Coal Flow Rate	Load Cell	4
	Triboelectric Probes	2
Sorbent Flow Rate	Load Cell	4
Primary Air Mass Flow Rate	Pressure Transducer	2
	Thermocouple	1
Secondary Air Mass Flow Rate	Pressure Transducer	2
	Thermocouple	1
Dilution Air Mass Flow Rate	Pressure Transducer	2
	Thermocouple	1
Coal Carrier Air Flow Rate	Pressure Transducer	2
	Thermocouple	1
Sorbent Carrier N ₂ Flow Rate	Pressure Transducer	2
	Thermocouple	1
Coolant Mass Flow Rate	Flowmeter	15
Quench Water Mass Flow Rate	Flowmeter	1
Coolant Inlet Temperatures	RTD	15
Coolant Outlet Temperatures	RTD	15
Metal Temperatures	Thermocouple	20
Primary Air Inlet Temp	Thermocouple	4
Secondary Air Inlet Temp	Thermocouple	4
Dilution Air Inlet Temp	Thermocouple	4
Combustor Gas Temperature	Optic Fiber Thermometer	4
	Optical Pyrometer	2
	High Temp. Thermocouple	4
Products of Combustion Temp. Pattern Factor	Thermocouples	25
Combustor Pressure	Pressure Transducer	5
Products of Combustion Velocity Pattern Factor	Pressure Transducers	25
Gas Composition	Gas Analyzers	5

3.4.1.4 Gas Analysis System

Samples may be drawn from any of the combustor instrumentation access ports through stainless steel and Teflon sample lines. Samples are filtered before being passed through liquid membrane dryers and water ice nitrogen cooled cold traps to remove moisture. Then the samples are passed to the following analyzers:

CO:	Beckman Model 868-18 Non-Dispersive Infrared
CO ₂ :	Beckman Model 868-23 Non-Dispersive Infrared
SO ₂ :	Thermo Electron Model 40 Pulsed Fluorescence
H ₂ S, SO ₂ :	Western Research Model 721A Ultraviolet
O ₂ :	Beckman Model 755 Paramagnetic
NO/NO _x :	Thermo Electron Model 10 Chemiluminescence

Each of the above analyzers produces a high-level voltage output signal, which is digitized and stored by the dedicated Masscomp computer system.

In addition to continuous gas sampling using the above system, gas samples may be taken during the combustor test for off-line analysis using a Perkin-Elmer Sigma II gas chromatograph.

3.4.1.5 Signal Conditioning

The combustor instrumentation system has an Analog Devices 58 Series modular signal conditioning system. Analog input modules are available to accept inputs from all thermocouple types, RTDs, millivolt and volt sources, variable frequency inputs and 4-20 mA process current inputs.

Standard and custom ranges are available and it is possible to mix module types within the system. The modules provide a high level output, +/- 5V or 0 - 5V, which is suitable for digitization by the Masscomp computer and they have high accuracy, (+/- 0.05%), good non-linearity (+/- 0.02%) and low thermal drift (+/- 1 microvolt per degree). The system, as installed has (12) 3845 frequency input modules, (20) 5B37 Type T thermocouple modules, (2) 5B37 Type E thermocouple modules, (6) 5B37 Type B thermocouple modules, and (30) 5B34 RTD modules.

3.4.2 COMPUTER SYSTEM

3.4.2.1 Computer Hardware

The subscale combustor data acquisition and processing system is based around a dedicated Masscomp computer system. The components of the computer system are listed in Table 3-5.

Table 3-5

Subscale Combustor Data Acquisition Computer Specifications

Masscomp MC5550S System Base:

- RTU Unix-based Real-time Operating System
- C Language
- SP-70 Ethernet Kernel Code
- 32-bit Virtual Memory 5550 CPU with MC6B8BI Floating Point Co-Processor, 4 Serial Lines and Integral Ethernet
- 4 Megabytes Parity Memory
- SCSI Controller
- 650 Kilobyte 5.25-in. Floppy
- 50-in. Cabinet Package
- 15-slot 12.25-in. CPU Box with +5V 140 A Power Supply

142 Megabyte 5.25-in. Winchester Disk Drive

1/4-in. 45 Megabyte Cartridge Tape Drive

Aurora 19-in. Color Independent Graphics System:

- 1152 x 910 x 2Fb x 4 pixels
- MC-Windows, Graphics and Data Presentation Software

Analog-to-Digital System:

- Data Acquisition and Control Processor (DACP)
- 5-slot STO+ Bus
- Data Acquisition and Control Software
- EF-12M 12 bit, 16 Channel, 333 kHz A/D Converter with 2 Channel, 12 bit D/A Converter, 16 Channel Parallel Output, 16 Channel Parallel Input and 5 Programmable Clocks
- AD-12FA 12-bit, 16 Channel, 1 MHz Programmable Gain A/D Converter
- MX-256 Channel A/D Multiplexer for EF-12M

ANSI-Validated FORTRAN-77 Language

QMS Lasergrafix Laser Printer with Tektronix 4014 Emulation

In order to measure the parameters listed in Table 3-4 on-line during combustor tests, signals from a total of more than 150 transducers or devices must be recorded on-line. Combustor component flow time scales are on the order of a few milliseconds, therefore, data acquisition at a rate on the order of several thousand samples per second is appropriate for critical combustor parameters.

Combustor health monitoring duties, which include recording coolant flow rates and temperatures, fuel, sorbent and air flow rates, metal skin temperatures and products of combustion (POC) composition, require a data rate on the order of several samples per second only. The computer data acquisition system has been designed such that the bulk of the channels identified in Table 3-4 are sampled at a few Hz and up to 16 channels, including combustor pressure and temperature channels, are sampled at a few kHz. Continuous sampling for the duration of a combustor test at this higher rate would generate an unmanageably large data set. This higher speed sampling thus occurs intermittently at relatively short (tens of seconds) bursts throughout the combustor test.

A typical combustor test of two hours duration can generate approximately five to ten megabytes of raw data, depending on the data rates used. Data is stored as it is acquired, for further off-line processing. This off-line processing enables a complete and thorough assessment of combustor performance to be made. The data from each combustor test is also archived on magnetic tape for subsequent further processing, and for use in the preparation of graphical output for presentations and reports.

In addition to recording and storing the data generated during a combustor test, the data acquisition and processing system is capable of generating and displaying in real-time, during the test, a number fundamental combustor parameters. These parameters include fuel and sorbent mass flow rates, primary, secondary and dilution air mass flow rates (and hence combustor stoichiometry), combustor pressures and temperatures, exit gas compositions and pattern factors. This greatly facilitates the conduct of the experiments and improves the ability of the test controller to maintain the desired test point conditions in the combustor.

This continuous data processing and displaying does not affect data acquisition timing or the storage of data on disk. The present system provides displays of multiple variables in either bar-graph or numerical format. Planned enhancements include an oscillograph display which will enable time histories of raw and processed data to be studied during a test.

In order to permit safe operation of the combustor system, cooling water temperature rises, flow rates and combustor metal temperature are continuously monitored and alarms are generated, if these parameters exceed certain predetermined values. In addition to improving the safety of combustor testing, this again greatly facilitates testing procedures.

In summary, the subscale combustor data acquisition and processing system:

- Acquires and stores data on more than 150 channels from a variety of transducers at rates which vary from a few samples per second to a few thousand samples per second.
- Computes and displays in real-time important combustor parameters, in order to facilitate combustor control.
- Monitors combustor health and generates appropriate alarms in the event that a specified parameter exceeds a specified limit.
- Further processes the test data after the combustor test and generates output (including graphical output) to enable assessment of combustor performance.
- Provides a means and medium for storage of the combustor test data generated.

The Masscomp system has multiple independent processors in addition to the central processor. These independent processors handle data acquisition, graphic display and floating point computation so as not to significantly degrade the main CPU performance.

The system has 4 Mbytes of memory and has 2 available bus slots for further expansion. An integrated data acquisition front end allows high-speed data acquisition over an STD bus. It is able to acquire data at 300 Kbytes per second directly to main memory. A high capacity (142 Mbyte), high-speed (> 500 Kbytes per second) disk drive and a 45 Mbyte cartridge type drive are used for data storage. The system has an independent high resolution color graphics system.

There are dual frame buffers on the graphics system to allow for fast screen updating. The RTU operating system, based on the UNIX standards of the Bell System V and BDS 4.2, provides for portability of software and real-time operation. C and FORTRAN callable routines allow easy access to data acquisition front end modules.

The computer system described above is an integral part of the dedicated diagnostic system for the subscale combustor test hardware.

3.4.2.2 Software System

The data acquisition processing and display software is designed to:

- Record and store data from a large number of analog to digital (A/D) inputs simultaneously and for a number of sequential time frames
- Calibrate A/D inputs.
- Reduce and present results.
- Be used directly by the test operators.

The software design incorporates an extensive command-driven input and a structure which allows for ease of modification. The software system is high modularized. The principal components of the system are the CALIB, DATA, MATH and PLOT routines.

CALIB Program

This program reads in a sensor/transducer definition file which contains information concerning the transducer types listed by A/D channel numbers. These transducers are calibrated in an interactive manner using a known signal substituted for or generated by each transducer. Examples of suitable signals include a known gas composition, a known pressure, a known voltage, a signal from a thermocouple calibrator or from a frequency generator. The entire signal conditioning and analog-to-digital data input path is calibrated in this manner. Inputs to the CALIB program can be from commands or from prepared macro files. Program output is a file that the DATA and MATH programs subsequently use.

DATA Program

DATA is a master program that handles all standard data acquisition requirements. Inputs to the DATA program can be from commands or from prepared macro files. The program is divided into four major segments, which are:

- **Setup** Defines the various input data streams, control paths, timing sequences, real-time display requirements, and output data streams. It creates tables that are used for the acquisition segment.
- **Acquisition** Carries out the data acquisition according to the tables defined by the setup segment.
- **Display** Generates real-time displays of raw and processed data according to tables generated by the setup segment.
- **Storage** Separates data streams into individual channels and stores them on disk along with related calibration and pointer files.

MATH and PLOT Program

MATH handles all standard data manipulation and processing functions. PLOT produces standard graphical output on a variety of display devices. Inputs to the MATH and PLOT programs can be from commands or from prepared "macro" files. Plots may be generated and changed interactively on a graphic terminal before a hard copy is produced on the system laser printer.

3.4.3 CONTROL SYSTEM

A Gould Programmable Logic Controller (PLC) is used to control all combustor operations. The PLC continuously monitors inputs from the combustor and the control panel and sets system outputs appropriately. The system as installed has: (128) 24 VDC input channels in (4) modules; (16) transistor-transistor logic (TTL) input channel in (1) module; (8) 4-20 mA output channels in (2) modules; (64) 24 VDC output channels in (2) modules; (32) 115 VAC output modules in (2) modules; and, (16) TTL output channels in (1) module.

3.4.3.1 System Inputs

PLC Inputs comprise:

- (53) combustor control panel switches.
- (15) valve position microswitches.
- (15) air supply, nitrogen supply, combustor, coal tank, sorbent tank, pilot burner, cooling water, and quench water pressure switches.
- (13) cooling and quench water flow switches.
- (2) UV flame detectors.
- (2) relays in compressor and air heater control systems.

All the above inputs are 24 VDC.

3.4.3.2 System Outputs

PLC outputs comprise:

- (7) 4-20 mA analog outputs to flow control valves and pressure regulators.
- (15) 115 VAC solenoid valves.
- (2) 115 VAC control relays in compressor and air heater control systems.
- (35) 24 VDC indicator lamps on control panel.
- (10) 24 VDC alarm indicators on control panel.
- (5) TTL system state indicators.

Industry-standard 4-20 mA control protocols are used for all flow control valves. Current control systems have a high noise immunity and are conventionally used in much noisier environments than that at the Haverhill test site.

3.4.3.3 Control Panel

The combustor control panel is shown in Fig. 3-13. The control panel is of a mosaic tile construction. This design allows for flexibility in operation and also for future expansion (for example, addition of slurry fuel system control switches and indicators). The combustor control panel contains combustor specific controls and indicators only. All connections to the panel are electrical. In addition to valve and pressure regulator control switches and valve position indicator lamps, the panel contains nine (9) digital panel meters. These meters display in engineering units the following parameters:

- Differential pressures across all air flow orifice plates.
- Differential pressures between coal and sorbent tanks and their respective carrier gas lines to facilitate accurate control of solids feed rates.
- Combustor chamber pressure.
- Preheated air temperature.

These signals are derived from transducers located in the combustion system. All these parameters are also recorded by the dedicated data acquisition computer during a test.

Many of the important system pressures are already monitored on the existing control panel at the Haverhill Facility. Additional backup dial gauges were added to the existing panel, as needed.

3.4.3.4 Logic Protocols

Combustor operating procedures and interlocks were specified carefully, with prime importance being given to safe operation of the combustor. A series of clearly identified combustor and

Fig. 3-13 Control Panel

combustor support system states were specified. The conditions which would allow the test operator to proceed from one state to the next were identified. If all of the required conditions are not fulfilled, then the Programmable Logic Control would not allow the combustor state to change until the remaining conditions were satisfied.

Ten potential alarm conditions were specified:

- (1) Flame-out in the primary combustion zone.
- (2) Flame-out in the secondary combustion zone.
- (3) Low-cooling water flow rate in the first combustor stage.
- (4) Low-cooling water flow rate in the second combustor stage.
- (5) Low-cooling water flow rate in the third combustor stage.
- (6) Low-quench water flow rate.
- (7) Over-pressure in the combustor.
- (8) Over-pressure in the coal hopper.
- (9) Over-pressure in the sorbent hopper.
- (10) Compressor trip.

All of these alarm conditions cause the same controlled shut-down sequence to be executed by the PLC:

- Stop coal flow
- Stop fuel oil flow, if applicable
- Stop pilot flow, if applicable
- Stop coal carrier gas flow
- Turn preheater off
- Stop sorbent flow, if applicable
- Stop sorbent carrier flow, if applicable
- Main air flow stays on
- Cooling and quench water stays on

In specifying the control system components, provision was made for implementation of proportional control of such parameters as coal-feed rate and preheated air mass flow rates. Initially, however, such rates are set and controlled manually through the combustor control panel. It could be advantageous to implement proportional control of such parameters for longer duration testing. Implementation of proportional control is a matter of additional logic programming.

All logic programming was done on an IBM-PC before being down-loaded to the PLC. The PC provided a means of easily examining, changing and archiving combustor control logic programs.

3.4.3.5 Safety Features

It was desirable that the control system be configured such that the power-off state was an inherently safe state. Valves were specified as normally open or normally closed in order to ensure that this was the case. The main compressor, the air preheater and the water pumps have their own dedicated controls, with built in safety devices such as over-pressure and over-temperature switches. The compressor has standard lubrication pressure and temperature switches, as well as vibration monitor and check valve downstream of the compressor outlet. The compressor, water pumps and preheater controls are separate from the combustor controls.

A burst disc was installed in the air delivery system downstream of the preheater. This is to prevent a combustor over-pressure from propagating back to the preheater and compressor. The coal tank and the sorbent tank have spring-loaded pressure relieve valves, in addition to normally open vent valves. The coal tank is pressurized with nitrogen, to ensure that the coal is stored in an inert environment.

There are two UV flame detectors, one for the primary combustion zone and one for the third stage combustion zone, which provide positive indication of combustion. Each of the cooling water loops in the combustor has a flow switch to indicate the presence of coolant flow. The quench water supply also has a flow switch and there is a dedicated pressure switch for the coolant flow for the oxy-methane pilot burner. Under- and over-pressure switches are provided on the combustor itself, as well as the coal and sorbent tanks. Pressure switches are provided on the nitrogen supply, the fuel oil supply and the pilot methane, oxygen and nitrogen purge supplies.

Microswitches are provided on key valves, including, most importantly, the coal flow valve, in order that a positive indication of valve position be available to the PLC. An emergency stop switch is provided on the combustor control panel. Three remote TV cameras are located in the test cell and oriented so as to provide a comprehensive view of the combustor area and the coal tank area. TV monitors are provided adjacent to the control panel, to enable test operators to ensure that no personnel enter the test cell during a test and to provide a visual check of the combustor integrity.

3.4.4 CONTROL ROOM ARRANGEMENT

Fig. 3-14 shows the layout of the combustor control room. The combustor data acquisition computer and programmable logic controller are side by side in the computer room. Also in this room are the gas analyzers, with associated flow conditioning and cold traps. The control panel, remote TV monitors and color graphics terminal are located in the main control room adjacent to the computer room. Locations of compressor, water pumps and preheater controls are indicated. The signal conditioning system is mounted in a rack which is situated in the test cell adjacent to the combustor.

Fig. 3-14 Control Room Layout

3.5 SORBENT FEED SYSTEM

The sorbent feed system is analogous to the PC feed system, but smaller. A smaller conical-bottom feed tank, smaller fluid-dynamic flow splitter, and set of four (4) small sorbent injectors are employed.

Sorbent was carried into the combustor by streams of air, densely packed with particles, in response to the pressure difference between the sorbent hopper and the combustor. A conical-bottom feed tank, fluid-dynamic flow splitter, and a set of four (4) small injectors for the combustor are employed. This system is satisfactory for large sorbent flows. A different system, needed to handle small flows was installed. It utilizes a vibrating horizontal louvered plate to meter the sorbent, rather than air pressure differential.

Fig. 3-15 shows a sketch of the vibrating louver system used to improve sorbent feed. A pressure shell houses the feeder, and attaches to the bottom of the conical sorbent feed hopper. The key feature of the feeder is a set of variable speed vibrating louvers which meter the solid material into a sheet metal cone. This cone guides the sorbent into a carrier line. Feeder speed is determined by a 4-20 mA signal from the combustor programmable logic controller.

Fig. 3-15 Sketch of Vibrating Louver Apparatus Added to Sorbent Feed System

3.6 COALS TESTED

Based on a coal fuel specification study (issued 1/87) by the Amax Corp., it was decided to look at minimally cleaned pulverized coal as the target fuel for the Direct Coal-Fired Gas Turbine (DCFGT) system. High volatility bituminous coals were recommended for the TVC because these coals have high heating values and relatively high volatile contents. High flame temperatures and rapid combustion can be achieved using these coals. Amax also suggested alkali and sulfur contents from environmental and corrosion standpoints. Alkali in the form of sodium and potassium should be minimized. Sulfur content should be below 1.0% to minimize sorbent additions.

Combustor testing was decided by Westinghouse and TDS to be conducted with three different test coals:

1. Bituminous PC and CWM with S-content < 1%
2. Bituminous PC and CWM with S-content > 2-3%
3. Subbituminous PC with S-content < 1%.

The coals actually selected and tested in this program were:

1. Dorchester seam coal from Virginia
2. Pittsburgh No. 8 seam coal from West Virginia
3. Hanna Rosebud from Wyoming.

All coals were used as utility grind, with a particle size such that 95% would pass through a 200 mesh screen. Table 3-6 shows the ultimate and proximate analysis for the coals tested. Table 3-7 shows the ash fusion data, which is important for achieving proper slag flow in slagging combustors. These coals were chosen to have adequately low slag viscosities at temperatures in the 2200-2400°F region. Table 3-8 gives the ash analysis for each coal supplied by Resource Engineering Inc., Waltham, MA.

Table 3-6

Ultimate and Proximate Analyses of Coals Tested - (Dry Basis)

	<u>Coal Type</u>		
	Eastern Bituminous	Eastern Bituminous	Western Subbituminous
	<u>Dorchester, Virginia</u>	<u>Pittsburgh, No. 8</u>	<u>Hanna, Wyoming</u>
<u>Percent</u>			
Ash	6.49	7.71	5.91
Volatile Matter	34.02	38.86	42.16
Fixed Carbon	<u>59.49</u>	<u>53.43</u>	<u>51.93</u>
	100.00	100.00	100.00
Sulfur	1.04	2.39	0.62
Chlorine	0.04	0.14	0.05
Carbon	80.80	77.89	73.79
Hydrogen	5.37	5.29	5.57
Nitrogen	1.43	1.36	1.59
Oxygen*	4.83	5.22	12.47
Ash	6.49	7.71	5.91
<hr/>			
* By Difference			
Heating Value, Btu/lb	14,390	14,031	12,962
Ash Free Htg. Value, Btu/lb	15,389	15,203	13,776
Percent Moisture in the As-Received Condition	6.13	1.49	9.09

Table 3-7

**Ash Fusion Temperatures in Reducing Atmosphere and Related Data
for Coals Tested During this Program**

	<u>Coal Type</u>		
	Eastern Bituminous	Eastern Bituminous	Western Subbituminous
	<u>Dorchester, Virginia</u>	<u>Pittsburgh, No. 8</u>	<u>Hanna, Wyoming</u>
<u>Temperature (°F)</u>			
Initial Deformation	2183	1900	2000
Softening	2305	2080	2110
Hemispherical Drop Formation	2379	2140	2160
Becomes Fluid	2466	2210	2200
Viscosity = 250	2340	2295	2190
<u>Related Data</u>			
Base Acid Ratio	0.46	0.41	0.80
Water Soluble Sodium (ppm)	110.00	200.00	135.00
Water Soluble Potassium (ppm)	52.50	22.80	23.50
Calcium (Calculated) - Ash Basis	3.14	4.68	17.77

Table 3-8
Ash Analysis for Coals Tested

<u>Constituent</u>	<u>Coal Type</u>		
	Eastern Bituminous	Eastern Bituminous	Western Subbituminous
	Dorchester, Virginia	Pittsburgh, No. 8	Hanna, Wyoming
SiO ₂	44.78	39.40	31.46
Al ₂ O ₃	20.89	21.80	15.92
Fe ₂ O ₃	22.65	22.79	8.97
CaO	4.40	6.55	24.86
MgO	1.20	2.10	8.86
Na ₂ O	0.51	1.45	1.38
K ₂ O	1.85	1.51	1.02
TiO ₂	1.51	1.27	0.74
P ₂ O ₅	0.52	0.40	0.58
SO ₃	1.54	--	--
Undetermined	0.15	2.73	6.21

The CWM was prepared on site using the bituminous PC. To prepare the CWM for these tests, the PC was mixed in barrels by TDS at their Haverhill, MA test site with water, dispersant, stabilizer, and surfactant, under the direction of the coal supplier, Resource Engineering, Inc., located in Waltham, MA. The CWM was prepared on-site, as needed. After mixing, it was stored in a 500 gallon tank adjacent to the test rig. When full, this tank held enough for two to three runs. The nominal design CWM solids loading was 65%. The first barrel was mixed to this loading. The resulting slurry was of extremely high viscosity. A second barrel of 63% CWM was then mixed, and discovered to be much higher in viscosity than the first. The second barrel was reduced to 60% coal loading, at which point its physical properties appeared satisfactory. Further experimentation established that, with this utility grind coal, 60% solids CWM could be made reliably and repeatably.

3.7 SORBENTS TESTED

Both calcia and iron oxide based sorbents were tested during this program. Sorbent feed methods used during this program included mixing as dry powder with the coal, mixing with CWM before firing, and injecting as dry sorbent into the primary zone of the combustor.

3.8 NOMINAL TEST CONDITIONS

The nominal test conditions in the subscale slagging combustor were set to essentially the same values for each test during this program, and are summarized in Table 3-9. Parameters associated with fuel delivery were, of course, affected by the change from PC fuel to CWM, and therefore two separate columns have been provided in the table.

Table 3-9
Nominal Test Conditions

<u>Fuel Type</u>	<u>PC</u>	<u>CWM</u>
Compressor Delivery Pressure, psia	130	130
Combustion Air Pressure, psia	87	87 to 92
Combustion Air Temperature, °F	650	610 to 650
Primary Air Mass Flow Rate, lb/s	1.8 to 2.2	1.8 to 2.2
Secondary Air Mass Flow Rate, lb/s	2.1 to 2.3	2.1 to 2.3
Dilution Air Mass Flow Rate, lb/s	2.1 to 2.3	2.1 to 2.3
Fuel Mass Flow Rate, lb/min	12 to 16	12 to 27
Coal Carrier Gas Mass Flow, lb/s	0.03	0.20 to 0.40*
Sorbent Mass Flow Rate, lb/min	1 to 5	0.5 to 1.5
Primary Zone Equivalence Ratio	1.2 to 1.7	1.0 to 1.4
Molar Ratio, Ca/S or Fe/S	2 to 4	1.5 to 3.0

*Actually not coal carrier gas, but atomizing air.

3.9 HISTORY OF COMBUSTOR TEST CONFIGURATIONS

The overall layout of the initial combustor test rig is shown on Fig. 3-16. All the initial testing of the three PC's and the two CWM's was performed with this configuration.

In 1990, a hardware modification was made on the test rig so as to include the slagging cyclone separator (see Fig 3-17).

Following the successful slagging cyclone separator tests a further hardware change was made with the redesign of the impact separator section and the inclusion of a slag tap and water quench for the molten slag. A schematic of this current configuration is shown in Fig. 3-18.

The curved body impact separator was designed to minimize slag droplet re-entrainment, to better control the bucket wall slag flow and also to reduce heat losses. Illustrated schematically in Fig. 3-19, the curved body impact separator also includes a slag tap. Separated slag flows out of the bucket, via the centrally located slag tap hole, and is collected in a water bath below the tap. The exhaust housing has been redesigned to reduce the exit gas velocities and also to reduce heat losses by reducing surface area. Also, with the slag now being collected in a separate slag vessel, the slag bucket itself has been reduced in size considerably, again reducing heat losses.

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Fig. 3-16 Schematic of Original Subscale Slagging Combustor Test Rig

Fig. 3-17 Schematic of Subscale Slagging Combustor Test Rig as Utilized During Slagging Cyclone Testing

Fig. 3-18 Schematic of Subscale Slagging Combustor Test Rig with Real-Time Slag-Tapping Capability and Slagging Cyclone

Fig. 3-19 Curved Body Impact Separator with Slag Tap and Collection Vessel

The problem of slag flow out of the bucket exit has been addressed by both recontouring the exit duct and by re-designing the centerbody to be asymmetric. The intention here was to direct the high momentum inlet jet away from the bucket exit. Inertial separation of slag will take place both on the asymmetric centerbody and on the bucket walls in the region of jet impingement. By intent, the slag is separated onto the wall opposite the exit, and the upper part of the asymmetric centerbody acts as a shield to prevent slag being directed towards the exit. The strong re-circulation in the vicinity of the slag tap also helps to keep the slag tap clear by increasing the heat flux in that region.

SUBSCALE SLAGGING COMBUSTOR TEST RESULTS AND DISCUSSION

4.1 RESULTS OF THE ORIGINAL TOROIDAL VORTEX COMBUSTOR

4.1.1 GENERAL OPERATION

Shakedown testing of the subscale slagging combustor system was conducted during August 1988 and PC combustion tests commenced the following month. Some difficulties were experienced with PC coal flow during early tests, however, these difficulties were overcome by relatively simple modifications of the geometries and flow conditions in the pneumatic feeding and conveying system.

From the onset of combustion testing, a stable flowing slag layer was formed on the primary zone dome and walls as shown in Figs. 4-1 and 4-2, respectively. Some dissolution of the refractory layer was observed in the early runs, but after a few hours of operation an equilibrium insulation layer of slag and refractory was formed. Equilibrium slag layer thicknesses in the primary zone, where heat fluxes are high, are on the order of 1 mm as shown in Fig. 4-3, while the corresponding thickness in the slag separator is on the order of 3 mm. No obstruction or fouling of any of the primary zone coal/air injectors or of the relatively small diameter primary zone exit nozzle with slag was observed. The impact separator worked as planned, and a flowing slag layer, as shown in Fig. 4-4, was obtained on the top and sides of the impactor center body and on the slag bucket walls.

Fig. 4-1 Uniformly Distributed Residual Slag on the Dome of Primary Combustion Chamber

Fig. 4-2 Uniformly Distributed Residual Slag on the Wall of the Primary Combustion Chamber Looking Towards the Exit Nozzle

Fig. 4-3 Cross Section View of the Primary Combustor Showing Refractory Lining and Slag Buildup

Fig. 4-4 Uniformly Distributed Residual Slag on the Impact Separator Following a Typical Run

When testing was switched to CWM carbon conversion efficiency decreased. The coals were the same as they had been with the PC, and were ground to the same size (95% through a 200 mesh). A series of development steps were taken, involving the CWM itself, its handling, the CWM injectors, and the primary combustion zone, all to improve carbon conversion. As detailed below, they were ultimately effective in achieving the goal.

4.1.1.1 Initial CWM Results

Installation, debugging and commissioning for the CWM feed system was completed in July 1989. Atomizer spray tests were conducted (with water) in order to verify correct operation of the entire system. Some problems were encountered during the installation of the atomizer nozzle within the assembly. The correct location of the atomizer tip within the air inlet assembly was checked by conducting water spray tests. The tip was located as far inside the cooled liner as was possible to minimize spray impinging on liner walls.

After nozzle installation was complete, CWM flow tests were conducted in order to check out the complete CWM feed system. The first attempt to recirculate the CWM through the feed system and back into the tank was unsuccessful. A strainer in the CWM feed line to the combustor plugged completely after a few seconds. This strainer was removed and replaced with a larger one. Having replaced the strainer, successful flow tests were conducted through the atomizer nozzles. System purges were also successfully tested.

CWM tests started August 23, 1989. Barriers to successful CWM firing at the TDS facility were removed one by one as operating experience with this fuel increased. The coal content of the CWM burned was approximately 60%. The combustor startup procedure was normal: air preheating followed by light-off of the methane/oxygen torch, followed by light-off of No. 2 fuel oil at a thermal input of approximately 1 MM Btu/hr. Before lighting the pilot, the atomizing air flow was established. With the oil burning and the pilot off, a small CWM flow (approximately

30% design thermal input) was started. The CWM flow was increased to approximately 80% of design thermal input, at which time the fuel oil was shut-off; the CWM continued to burn steadily. The thermal input was then increased to approximately the design value.

Areas which required improvement to allow reliable CWM combustion were: in-line filters and strainers, control valves, and atomizing air temperature. The atomizing air is supplied from a high pressure (2400 psi) tube trailer. The pressure was dropped to approximately 300 psi by a regulator, which is upstream of the flow control valve and orifice plate. The air expansion caused a large drop in temperature (temperatures at the orifice plate were measured at 14°F). This cold atomizing air lowered the CWM temperature as it entered the nozzle (the two streams flow coaxially in the nozzle for a distance of about 2 ft), causing the CWM viscosity to increase very sharply, which caused freezing or plugging of the lines. The lowering of the CWM temperature, with its attendant increase in viscosity no doubt also affected atomizer performance. Eventually, a heat exchanger was installed between the atomizing air regulator and the nozzle inlet in order to avoid this problem.

4.1.2 CARBON BURNOUT AND COMBUSTION EFFICIENCY

Prior to the introduction of slag tapping, the carbon burnout (gasification) conversions were determined by gas analysis at the exit to the primary zone. Once samples of quenched slag could be obtained the carbon burnout was determined by direct analysis of the carbon in the slag.

The overall combustion efficiency after the lean-quench combustor was determined by analyzing the carbon content of the particulate samples isokinetically collected downstream.

4.1.2.1 PC-Firing

The subscale TVC with the impact separator/ slag bucket demonstrated excellent combustion performance burning all three PCs (i.e., Dorchester, Pittsburgh, and Wyoming Rosebud) selected for the DOE funded program.

4.1.2.2 Carbon Conversion and Exhaust Carbon Monoxide

The subscale slagging combustor demonstrated excellent combustion performance. Fig. 4-5 shows measured primary zone carbon conversion efficiencies for a range of primary zone and combustor overall equivalence ratios, obtained by probing at Port 3. Data is presented for the coals tested in this program, which was obtained from on-line analysis and flow rate measurements. These on-line measurements are in excellent agreement with those obtained by post-run off-line gas chromatograph gas analysis. Primary zone carbon conversion has been typically 98-99% at equivalence ratios up to approximately 1.5. There is a moderate reduction in primary zone conversion as the equivalence ratio is increased, as expected. However, even at a primary zone equivalence ratio of 1.7, the carbon conversion is still very good. The data shown includes the effects of combustion in the primary zone, but not the final burn-out in the lean-burn stage (Stage III). For example, during Test 8-10, at combustor conditions of 12 MM Btu/hr thermal input, primary zone equivalence ratio of 1.3, an overall equivalence ratio was 0.4, and a burner outlet temperature of 1920°F, measured CO emissions at Stage III exit where only 150 ppmv, (dry basis; not corrected to 15% O₂).

Fig. 4-5 Subscale Slagging Combustor Primary Zone Carbon Conversion Results as a Function of Primary Zone Equivalence Ratio

4.1.2.3 CWM-Firing

Carbon conversion measurements during initial CWM tests are compared with the earlier PC carbon conversion results in Fig. 4-6. The solid line shows the mean carbon conversion performance obtained with PC fuel. The symbols show results from the CWM data which is available. The carbon conversion in Test 18-2 was appreciably lower than in PC firing and showed a steep decline with increasing primary zone equivalence ratio. At an equivalence ratio of 1.4, 92% carbon conversion was observed for tests 18-2. Data from the next two tests, (18-3 and 18-4), show markedly better performance. The main reason for this increase in conversion was the difference in atomizing air-to-CWM feed ratio between the two tests. The ratio in Test 18-2 was approximately 0.6. The regulated pressure of the atomizing air feed was increased before Test 18-3 and 18-4 to achieve a ratio of approximately 1.0. It should be noted that for all these CWM tests, the viscosity at the injector tip was probably much higher than the measured value in the CWM tank, because of the cooling caused by the cold atomizing air. This low temperature raised the CWM viscosity and led to poor carbon conversion performance.

Fig. 4-6 Carbon Conversion Measured at the Exit of the Impact Separator as a Function of the Primary Zone Equivalence Ratio for Initial CWM Tests and the PC Tests Made Previously

4.1.2.4 CWM Viscosity

The CWM was mixed on-site in Haverhill by TDS. This enabled tailoring the mixture to each test day's needs, and also reduced the necessity of trying to stabilize a slurry over long periods of time. CWM viscosity was found to depend on coal loading, stabilizer loading, temperature, and, surprisingly the time between initial mixing and final use. Viscosity drops very sharply from 630 cP at 60°F to 90 cP at 165°F. Starting with Test 18-5, a small atomizing air heater was put into service, as well as a CWM heater. With proper mixing, and use of what heat was available, adequately reduced CWM viscosities were achieved for all tests, except for Test 18-6. Test 18-6 was subsequently found to have 0.4% stabilizer, rather than the 0.1% used for the other tests. The effect of the poorer CWM atomization on carbon burnout efficiency is quite apparent in Fig. 4-7, which compares efficiency curves for several CWM tests, and for the best PC results from earlier in the program. For example, at a typical equivalence ratio of 1.2, all the other results, including the PC, are above 98%, but Test 18-6 falls lower at 94%.

Fig. 4-7 Carbon Conversion Measured at the Exit of the Impact Separator as a Function of the Primary Zone Equivalence Ratio for Tests Where CWM Viscosity Varied, and for Previous PC Results

There was also a great difference in the measured viscosities of a newly mixed barrel of CWM and the same barrel the next day. For example, the CWM burned in Test 28-1 was mixed in the morning of 10/25/90: three barrels were mixed, and their measured viscosities were 620, 625, and 668 cP at 68°F. The next day the CWM was loaded into the feed tank and recirculated throughout the by-pass loop for approximately two hours prior to running. This had the effect of heating the CWM considerably. The measured viscosity on 10/26/90 was 185 cP at 88°F. On the morning of 10/27/90, the measured viscosity of the CWM was 120 cP at 72°F. After running the CWM through the by-pass loop for about an hour, the measured viscosity immediately prior to running the test was 103 cP at 76°F. Throughout this period the viscosity had been reduced by a factor of more than six with only a moderate increase in temperature (68° to 76°F). Similar trends were observed with the batch of CWM prepared for the next test: 645 cP at 66°F for the fresh mix and 182 cP at 96°F after two hours of circulation through the by-pass loop the next day.

4.1.2.5 Injector Location

The four CWM injectors are located inside the four tubes that feed combustion air to the primary zone. Combustion air flows at high velocity around the injectors, picking up the CWM spray, and carrying it into the primary zone. Because of the intense flame in the center of the primary zone, the injectors were initially recessed well down inside the air tubes, as seen in Fig. 4-8. However, it appeared from post-test examination that CWM had been impinging on the walls of the injector tubes. A CWM that impinges on the walls may eventually react, but it certainly cannot be said to be well atomized, and its reaction will be less than fully efficient.

Fig. 4-8

4.1.2.6 Sampling Location

During PC testing, earlier in this program, carbon conversion was usually complete before the coal particles left the primary zone. Therefore, carbon conversion efficiencies were very high (98% or better) whether measured at the primary zone exit, or at the impact separator exit. However, it was noted that carbon burnout took longer with CWM. Carbon conversion may continue after the coal particles leave the primary zone and enter the impact separator. Thus, impact separator sampling showed higher apparent carbon conversion than primary zone exit. Figs. 4-6 and 4-7 display the optimistic impact separator results. For fine differentiation between developmental configurations, the primary zone exit data should be used. Fig. 4-9 shows the carbon conversion efficiency as measured at the exit of the primary zone. In the following paragraph on the effects of residence time (and atomization and injector location) the primary zone exit location is used for comparison, with the objective of making them more definitive.

Fig. 4-9 Carbon Conversion as Measured at the Primary Zone Exit for More Definitive Data Gathering During Injector Location, Atomization, and L/D Studies

4.1.2.7 Residence Time

PC carbon conversion efficiencies in excess of 98% were obtained in earlier program tests with a primary zone length of approximately 21 inches. This represented an length to diameter ratio (L/D) of 1.25. With the changeover to CWM, however, carbon conversion was inadequate. For example, in Fig. 4-9, Test 18-7 shows primary zone carbon conversion efficiency of less than 60%. Following Test 18-7, atomization and injection location were significantly improved. However, even with these improvements, the Test 18-8 results fall below 95% as shown in

Fig. 4-9. On the other hand, with exactly the same atomization and injection, but with L/D extended to 1.5, Test 28-3 in Fig. 4-9 shows 98% conversion. The greater L/D was achieved by adding a section of approximately 5-in. length to the primary zone. This greater length, with thermodynamic conditions held constant, allows more residence time in the primary zone for hot carbon particle reaction. This reaction starts more slowly with CWM than with PC, due to the necessity to boil off the water in the CWM.

4.1.2.8 CWM Injector Location and Atomization

In Fig. 4-9, Test 28-1 conversion efficiency falls to the 80% level, in spite of an L/D of 1.5. For Test 28-1, the CWM injectors were in the initial, deeply-recessed position. For Test 28-2, the injectors were advanced closer to the flame, and efficiency rose to the low nineties. For Test 28-3, the injectors were held in the 28-2 location, but atomizing air to the CWM nozzles was

increased 50%. Efficiency rose to the high nineties. At this point, everything else was held constant, and the combustion chamber L/D was reduced to the 1.25 value that had been used with PC. Combustion efficiency dropped back to the low nineties. This is shown by the Test 18-8 data in Fig. 4-9.

4.1.2.9 Relative Performance of CWM and PC

Fig. 4-10 shows carbon conversion data on the basis of primary zone exit measurements, the same basis as Fig. 4-6. However, the scale has been made much more sensitive, and all but the best CWM data eliminated. On this, the best PC data from earlier in the program have been superimposed. It appears that PC achieves the desired 98% level with greater ease than CWM.

Fig. 4-10 Comparison of Primary Zone Carbon Conversion for CWM and PC; Primary Zone Exit Data

Combustion efficiency, as measured by carbon conversion in the primary zone, was excellent in the TVC as long as PC was the fuel. Modifications to the combustor and fuel injectors eventually yielded good carbon conversion results when CWM made from Dorchester seam coal was the fuel. In the same time period CWM made from Pittsburgh No. 8 coal was evaluated for the first time. Fig. 4-11 shows a comparison of carbon conversion efficiencies measured with the two CWM fuels.

Fig. 4-11 Primary Zone Carbon Conversions Measured for CWM's Made from Dorchester and Pittsburgh No. 8 Coals

Carbon conversion efficiencies of less than 90% were obtained with the Pittsburgh No. 8 CWM, whereas 97 to 99% were achieved with Dorchester CWM. Examination of the Fig. 4-11 data leads to the conclusion that inadequate residence time was available to burn out the coal particle agglomerates resulting from the atomization and evaporation processes. It is assumed the need for more residence time is due to the fact that the coal particle agglomerates were larger than with Dorchester CWM, (or PC).

The evidence that the Pittsburgh No. 8 agglomerates were large comes from the shape of the carbon conversion curve in Fig. 4-11. Carbon conversion increases as equivalence ratio increases. Normally, with equivalence ratios this rich, it would decrease. However, in the TDS', another phenomenon is present. To obtain richer equivalence ratios, the method is to reduce airflow, holding fuel flow constant. This reduces internal velocities, increasing available particle residence time. These longer residence times result in better carbon burn-out, as seen in the Fig. 4-11.

Why were the Pittsburgh No. 8 agglomerates so large, following evaporation? Probably, because of poor CWM atomization. Pittsburgh No. 8 coals have been reported by other investigators to be more difficult to slurry effectively than other bituminous coals, and to show a tendency to produce large flocculents and/or agglomerates upon atomization.

In order to address this problem, three approaches were taken. First, different dispersants were evaluated for use with the Pittsburgh coal; second, a shear-enhancing baffling system was fabricated for the barrels in which the CWM is prepared; and third, a high-speed, high shear emulsifier was rented to prepare the CWM. These steps resulted in only slight improvements. If this matter is to be pursued further, more extensive changes will be needed, such as lengthening the primary zone and adding a higher-capacity heater for the atomizing air line.

4.1.3 NO_x EMISSIONS

4.1.3.1 PC-Firing

The coals evaluated in this program have contained from 1.4 to 1.6% chemically-bound nitrogen. If converted in the combustor, this nitrogen would produce hundreds of parts per million NO_x in the exhaust. However, by operating the primary zone at equivalence ratios of 1.2 to 1.4 it was possible to suppress NO_x formation.

Measured NO_x emissions from the combustor are shown as a function of the three PCs burned and burner outlet temperature in Figs. 4-12 and 4-13, respectively. These measurements were made at the combustor exit, downstream of the lean burner/dilution zone. When primary zone equivalence ratio is held in the normal range of 1.2 to 1.6, the NO_x levels of 35 to 55 ppmv are well below what would be required to meet the EPA's NSPS for a coal-fired plant, which in this case would be approximately 165 ppmv. The rich-lean combustion has handled the 1.3% fuel-bound nitrogen in the coal very well. A slight upward trend with temperature may be seen, but even at an exit temperature of 2000° F, the emissions of 55 ppmv are equivalent to only about one-third of the allowable maximum. Since the initial power plant will operate at 1850° F, emissions will be even lower than those shown for 2000° F. Emissions are on a dry basis, corrected to 15% O₂, as noted.

Fig. 4-12 Subscale Combustor NO_x Emissions for Bituminous (Dorchester and Pittsburgh No. 8) and Subbituminous (Wyoming Rosebud) Pulverized Coals

Fig. 4-13 Measured NO_x Emissions as a Function of Third Stage Combustor Exit Temperature; Dry Basis; Corrected to 15% O₂

The EPA NSPS for emissions of NO_x are 0.6 lb per MM Btu heat input for bituminous coal, and 0.5 for subbituminous coal. To convert from these measurement units to the parts per million by volume (ppmv) units commonly used in the measurement instruments, the following steps are employed: First, the heat input of the test burner (MM of Btu/hr) is multiplied by the standard (0.6 lb/MM Btu or 0.5 lb/MM Btu) to give the allowable lb/h of emissions. Next, the total exhaust flow (in lb/h) is measured or calculated. It includes combustion air, coal, carrier gases, sorbent and water, and does not include slag, spent sorbent, and ash removed.

The allowable lb/h of NO_x is divided by the lb/h of exhaust flow, and multiplied by 100 to get the allowable weight percent NO_x in the exhaust. Then the allowable weight percent is multiplied by 10,000 to get the allowable parts per million by weight (ppm_w) in the exhaust. Adjustment, via molecular weights, are used to convert this last result to ppm_v.

4.1.3.2 CWM-Firing

Fig. 4-14 shows the NO_x emissions data points for the best CWM configuration, that of Test 28-3. The NO_x emissions are as measured at the exit of the last stage (lean stage) of the combustor. These are the same as plant stack omissions, since NO_x reactions are essentially "frozen" from this location on through the turbine, and out through the boiler to the atmosphere. (emissions are, nevertheless, plotted vs. primary zone equivalence ratio, as this is a key slagging combustor parameter).

Fig. 4-14 Comparison Between Combustor NO_x Emissions for PC and for CWM Firing, as Measured at Lean Stage Exit

terms of parts per million by volume. As Fig. 4-14 shows, recorded last stage NO_x emissions are 50 to 60 ppmv, well below the limit. Note that emissions with CWM are slightly higher than with PC, as opposed to what would normally be expected. Since the water contained in CWM acts to lower thermally-generated NO_x, it would have been expected that they would be lower.

It is believed that CWM NO_x emissions exceed those for PC due to the action of the fuel-bound nitrogen (FBN), in the coal. The Dorchester, VA coal contains approximately 1.4 weight percent nitrogen. In the rich-burn primary of the subscale slagging combustor, the FBN is broken down by heat, and converted into harmless N₂. It cannot be converted into NO_x in the primary zone, because this rich-burn primary does not contain the free O₂ necessary to form oxides of nitrogen. However, if the chemical breakdown is somewhat slow in the primary zone, a certain fraction of the nitrogen atoms will persist through to the lean zone, where they will find O₂ and form NO_x. The water in the CWM may be slightly delaying the breakdown of the FBN in the primary zone, leaving N ions to form NO_x when O₂ is available.

4.1.4 SO_x EMISSIONS AND SULFUR CAPTURE

4.1.4.1 Baseline SO_x Measurements

An entire test day was dedicated to sulfur measurement verification. A total of 1137 lb of Pittsburgh No. 8 coal were burned in a total of 67 minutes. No sorbent was injected: the purpose of the test was to make good baseline sulfur gas measurements in the rich zone for a wide range of primary zone stoichiometries and to compare results obtained with two different gas sample conditioning systems. The two systems were the membrane drier system, and a heated sample line between the sample probe and the SO_x analyzer. The primary zone equivalence ratio was varied between 1.0 and 1.7. Fig. 4-15 shows the predicted equilibrium sulfur gas concentrations at a temperature 360°F below the predicted adiabatic flame temperature for Pittsburgh No. 8 as a function of equivalence ratio. Because these are equilibrium results, they include combustion-generated moisture (wet basis), and equilibrium amounts of exhaust O₂ (not corrected to 15% O₂).

Fig. 4-15 Predicted Equilibrium concentrations for Sulfur-Containing Gases in Products of Combustion for Pittsburgh No. 8 Coal; (Note Normalized to 15% O₂; Not "Dry Basis")

While the major players are SO₂ and H₂S, a number of minor players (COS, SH, SO, S₂, S) may account for as much as 30% of the total sulfur gas species at certain conditions in the fuel-rich regime. It should be remembered that the exact composition is strongly temperature dependent. Fig. 4-16 shows the total measured SO₂ + H₂S obtained during Test 8-9 as a function of equivalence ratio. Also plotted is the predicted equilibrium concentration of SO₂ + H₂S at a temperature close to that measured at the primary zone exit. Though there is a discrepancy between the two curves, these differences can be accounted for by the presence of minor sulfur gas species in concentrations somewhat different from those predicted at equilibrium conditions. The experimental data in Fig. 4-16 represent a significant improvement over previous attempts to establish a baseline, when only between 20 and 40% of the expected SO₂ + H₂S could be accounted for. To be consistent with Fig. 4-15, Fig. 4-16 data is presented on a wet basis, not corrected to 15% O₂. Thus, a good baseline SO_x (measured as SO₂ + H₂S) curve has been established. Fig. 4-17 shows a comparison of measured and predicted SO₂ at the combustor exit during a portion of Test 7-3. It indicates a high degree of agreement, showing that the steps taken to improve accuracy have been effective.

Fig. 4-16 Measured and Predicted Primary Zone Concentrations of SO₂ Plus H₂S in the Products of Combustion for Pittsburgh No. 8 - No Sorbent Injection; Wet Basis, not Corrected to 15% O₂

Fig. 4-17 Measured and Predicted SO₂ as a Function of Equivalence Ratio and Time

4.1.4.2 Sulfur Capture with Calcia Based Sorbents

The sulfur reduction data from Port No. 3, (primary zone exit) shows a monotonic decrease with increasing equivalence ratios greater than approximately 1.2 (Fig. 4-18). The decrease in sulfur capture can be explained in terms of two phenomena: the lower flame temperature at higher equivalence ratios causes the injected limestone to be heated less rapidly, hereby producing CaO of less specific surface area, and hence less reactivity, and the increasing amount of H₂S present at richer conditions. The bench-scale bomb reactor experiments at TDS, performed under a METC contract modification, showed that under rapid-heating conditions, such as prevail in the combustor, limestone was much more reactive with SO₂ than with H₂S. A significant effect of temperature on capture was observed. Thus, this downward trend agrees with the trends seen in the data from the bench scale experiments. Fig. 4-19 shows the sulfur capture data for Port No. 3 plotted as a function of gas temperature at that location. Similar plots could be made for the data from Port No. 4 for equivalence ratios greater than 1.2. In order to explain the low captures at Port No. 4 for equivalence ratios leaner than 1.2, it is helpful to present the data in another form.

In Fig. 4-20, data from Ports Nos. 3, 4, 5 and 8, at an equivalence ratio of 1.2, are plotted as a function of approximate sorbent residence time. Residence time was estimated using combustor and impact separator geometries, and plug flow velocities. The curve shows a sulfur capture peak at short residence times, followed by a rapid drop in capture. The form is similar to sulfur capture curves generated at TDS in METC-sponsored work on super-equilibrium capture, although the peak appears to occur at a slightly earlier time. This could be due to more rapid sorbent particle heating in the slagging combustor environment.

The reasons for the rapid decrease in sulfur reduction, at times greater than the time of the peak, are currently thought to be due to one or both of the following processes. First the captured sulfur is being released from the slag and sorbent mixture in the slag trap. (Slag analyses show low sulfur contents.) Second, sulfur may be being released from the reacted sorbent before the particle hits the impact separator centerbody.

Fig. 4-18 Measured Sulfur Reduction at Three Locations in Subscale Slagging combustor, -325 Mesh Limestone Sorbent, Ca/S = 2-4

Fig. 4-19 Measured Sulfur Reduction with Sorbent in Primary Zone, as a Function of Temperature of Combustion Products, Tests 5-2 Through 8-10

Fig. 4-20 Measured Sulfur Reduction with Sorbent at Various Sampling Ports Along the Path from Primary Zone, through Impact Separator, to Lean Zone Exit

All but one of the eleven (11) limestone sorbent runs, during the period January to April 1989, used 325 mesh limestone. One test (Test 8-10) was made with a coarser 200 mesh grind limestone, to see if this would facilitate sulfur capture and retention. There was no significant improvement, either in capture noted at the primary zone exit, nor in sulfur retention noted in the slag bucket. These results are shown in Fig. 4-21.

Fig. 4-21 Primary Zone Sulfur Capture - Effect of Limestone Sorbent Particle Size; Calcium to Sulfur Ratio = 2 to 4

For nearly all the sorbent injection tests, the sorbent was injected from a point near the base of the primary zone, aimed upward 30 degrees from horizontal. In this way, the sorbent particles are traveling across the combustor, but with a vertical velocity component that is opposite to the flow direction of the hot, sulfur-bearing gases rushing downward out of the primary zone. This was designed to provide intense mixing between the sorbent and the gases. In one test, however, the angle was lowered to zero degrees above the horizontal. The plan was that the sorbent particles would thus be more quickly swept out of the primary zone, to minimize loss of SO_2 from the particles following capture. Fig. 4-22 shows the results of Test 8-11. Apparently the reduced residence time (10 msec) in the primary zone neither enhanced nor diminished capture.

Three calcium - based sorbents were evaluated during this program. The majority of the work was done with calcium carbonate (limestone), but brief tests were also made with calcium hydroxide (hydrated lime), and calcium acetate. Fig. 4-23 compares the sulfur reduction seen at the primary zone exit for all three sorbents. Calcium-to-sulfur ratios for all three sorbents ranged from 2 to 4. No significant difference is seen between calcium carbonate and the calcium hydroxide test; (Test 7-1). With calcium acetate, (Tests 7-2 and 7-3), substantially poorer sulfur reduction was seen. The mechanism causing this was not pursued, but it has been postulated that the calcined calcium acetate particles are surrounded by miniature over-rich zones, because of the hydrocarbon they contained. Locally, then, they would be much richer than would appear in the figure, which would be unfavorable for SO_2 capture.

Fig. 4-22 Primary Zone Sulfur Reduction - Effect of Sorbent Injection Angle

Fig. 4-23 Port No. 3 Sulfur Reduction - Effect of Sorbent Type

At the exit of the lean combustor zone, Port No. 8, the calcium acetate appears to have released all the sulfur it has captured. The calcium carbonate and calcium hydroxide each show about the same performance: 20% sulfur reduction in the equivalence ratios of interest (1.2 to 1.4). These data appear in Fig. 4-24. They point out the need for considerable improvement as has been discussed earlier.

The sulfur capture data based on gas sampling at the lean-stage exit (Port 8) indicate much less sulfur capture than the measurements in the primary zone, (Port 3), or the slag trap dome, (Port 4), as has been discussed earlier. One possible cause of this is the sorbent is giving up the sulfur it had captured while residing in the slag trap. The slag was analyzed to see if the levels of sulfur it retained, when compared with the sulfur in the coal, would indicate sulfur captures similar to those from the gas analysis. Fig. 4-25 shows the estimated sulfur capture based on slag measurements compared with gas analysis. The data are plotted against the mean primary zone equivalence ratio during the period when the sorbent was flowing. Errors incurred in reducing information from slag sulfur content are considerable for the following reasons: (1) the sorbent is generally only flowing for approximately half of the total period of coal burning; (2) the sulfur capture is stoichiometry dependent, and the primary zone stoichiometry is changed during the run; and, (3) the measured sulfur content of the slag varies with position in the slag bucket. The magnitude of these errors is shown by the error bars for the slag analysis data. In general, however, the agreement between the two sets of data is good.

Fig. 4-24 Port No. 8 Sulfur Reduction - Effect of Sorbent Type

Fig. 4-25 Sulfur Capture Based on Slag Analysis ($\text{Ca/S} = 2$ to 4)

4.1.4.3 Mechanism of Capture with Calcia

The trends measured at the combustor exhaust, and confirmed by slag analysis data, give an insight into the sulfur capture mechanisms occurring in the subscale slagging combustor when calcia-based sorbents are injected. In general, the principal sulfur gas species present in the rich zone are SO_2 and H_2S , with the predominant specie for moderately rich conditions being SO_2 and that for highly fuel-rich conditions being H_2S . The injected limestone calcines rapidly to form highly reactive CaO , which then reacts to form a mixture of CaSO_4 , CaSO_3 and CaS , the composition of the mixture depending on the relative amounts of SO_2 and H_2S . CaSO_4 and CaSO_3 are unstable at primary zone conditions and decompose rapidly, whereas CaS is stable. Thus, the sulfur reductions measured by gas analysis at the combustor exhaust and those inferred from the slag sulfur content reflect only CaS formation.

This hypothesis is compared with the measured sulfur reductions in Fig. 4-26. The solid line indicates the sulfur reduction that would be obtained if all the measured SO_2 plus all the measured H_2S present expressed as a percentage of the total theoretical gaseous sulfur content of the gases in the primary zone were removed, whereas the dashed line indicates the sulfur reduction that would be obtained if only the H_2S present in the primary zone were removed. The measured reductions at Port No. 3 tend to agree with the solid line ($\text{SO}_2 + \text{H}_2\text{S}$ removal), whereas the measured reductions at Port No. 8 (combustor exhaust) tend to agree with the dashed line (H_2S removal only). Measured reductions at gas sample Port No. 4 (top of slag bucket) are compared with the same two lines in Fig. 4-27. In general, the data fall between the two lines, possibly indicating that at this location, the CaSO_4 formed in the primary zone is partially decomposed.

Fig. 4-26 Measured and Predicted Sulfur Capture as a Function of Equivalence Ratio for Ports No. 3 and No. 8

Fig. 4-27 Measured and Predicted Sulfur Capture as a Function of Equivalence Ratio for Ports No. 4 and No. 5

Examination of the sulfur reduction data in these terms would tend to indicate two potential methods for improving the overall sulfur removal from the slagging combustor. These are either to stabilize the CaSO_4 product or slag, (i.e., by quench of reacted sorbent with air or water) or by forcing either globally or locally very fuel-rich conditions.

4.1.4.4 Sulfur Capture with Iron Based Sorbents

Iron oxide based sorbents were also tested for sulfur capture and compared to the calcium-based sorbents. Two compounds were evaluated: hematite, Fe_2O_3 , and magnetite, Fe_3O_4 . The iron oxide based sorbents differ from those based on calcia in that sulfur capture is not limited by the surface properties of the solid particles, sulfur capture is an equilibrium process, and high levels of these sorbents actually improve slag fluidity. In addition, the product of the capture process is a stable sulfide.

Due to sorbent feed system difficulties, very high feed rates had to be run (or none at all would flow). Thus, the results are good, due to the high sorbent to sulfur ratios employed.

The sulfur reduction results obtained with iron oxide sorbents were encouraging. Fig. 4-28 shows exhaust SO_2 reductions, measured at gas sample Port No. 8 (downstream of the lean-burn/dilution zone), for both hematite injection (data from Test 7-5) and for magnetite injection (data from Test 7-8). For comparison purposes, data for limestone, calcium hydroxide (hydrate) and calcium acetate (acetate) are shown. In examining Fig. 4-28, it should be noted that the iron oxide feed rates were high ($\text{Fe/S} = 6 - 8$ for hematite, $\text{Fe/S} = 10 - 12$ for magnetite) and that the hematite was introduced via the sorbent spray nozzles at the base of the primary zone, whereas the magnetite was introduced with the coal fuel.

Fig. 4-28 Combustor Exhaust SO_2 Reduction as a Function of Primary Zone Equivalence Ratio for a Variety of Sorbents - Gas Samples Taken at Port No. 8

The SO₂ reductions (Fig. 4-28) obtained at the combustor exhaust indicate that at these conditions both iron oxide sorbents perform considerably better than the calcia based sorbents. In particular, the magnetite results show reductions as high as 70%, at an equivalence ratio of 1.5. Both sorbents show an increase in effectiveness as the primary zone equivalence ratio is increased. At such ratios, more of the sulfur in the primary zone is present as H₂S. The differences in performance between the hematite and the magnetite could be explained by:

- Feed ratios
- Injection locations
- Particle size
- Oxide form

It remains to be seen whether such large SO₂ reductions can be retained as more economical iron oxide feed rates are evaluated.

Fig. 4-29 shows sulfur reductions measured at gas sample Port No. 3 for all sorbent types except hematite. At very fuel-rich conditions, the magnetite (Fe/S = 10 - 12) is clearly far superior to the calcia based sorbents, and reductions as high as 85% are obtained at equivalence ratios greater than approximately 1.6. The reductions measured in the primary zone (Port No. 3) are considerably higher than those obtained at the combustor exhaust (Port No. 8) shown in the previous figure, although this is not nearly such a problem as it is with limestone.

Fig. 4-29 Primary Zone Sulfur Reduction as a Function of Primary Zone Equivalence Ratio for a Variety of Sorbents - Gas Samples Taken at Port No. 3

4.1.5 PARTICULATE EMISSIONS & SLAG REMOVAL

4.1.5.1 Slag Rejection

Slag is removed both by centrifugal separation from the toroidal vortex in the primary zone dome and by inertial separation in the impact separator. Overall slag rejection is determined both by measurement of particulate emissions downstream of the lean-burn zone and by measurement of the weight change of the slag bucket during the run. The two measurements generally agreed to within 5%, with the slag bucket giving a slightly lower slag rejection result. This is to be expected, as the bucket measurement will not always account for all material separated on to the combustor walls. Measured slag/sorbent rejection has been excellent at 90%, plus or minus 5%. Fig. 4-30 shows slag rejection data from these tests. No significant difference in slag rejection with and without sorbent injection has been observed.

Fig. 4-30 Slag Rejection Data for Subscale Slagging Combustor Test

4.1.5.2 Particulate Emissions

Detailed fly ash size analyses were made of fly ash samples obtained by isokinetic probing at the combustor exit, downstream of the lean-burn zone. Analyses were made for combustor tests with and without sorbent injection. Fig. 4-31 shows measured loadings as a function of particle size for recent tests:

Test 5-2	Dorchester coal, no sorbent
Test 5-3	Dorchester coal, limestone sorbent
Test 8-1	Pittsburgh No. 8 coal, no sorbent
Test 8-2	Pittsburgh No. 8 coal, limestone sorbent

Fig. 4-31 Measured Exhaust Gas Particulate Loadings as a Function of Particle Size for Dorchester and Pittsburgh No. 8 Pulverized Coal with and without Limestone Sorbent; (Wet Basis; NO_x O₂ Correction)

Measurements of the as-fired coal show it to be typically 95% below 200 mesh, with a top size of approximately 110 microns. The pulverized limestone sorbent used is 100% below 325 mesh. The loadings with sorbent are for a calcium to sulfur molar ratio of 2:1. At lower ratios, the loadings will decrease. The highest loadings were measured for the higher ash coal when used with sorbent, as would intuitively be expected.

There is no substantial difference in the size distribution for samples with or without sorbent injection, and in general the mass mean diameter of the fly ash was measured to be 8 to 9 microns. It should be recognized that this is above the 5 micron size considered acceptable for turbines. Additionally, a small number of particles are in the range of 20 to 80 microns in diameter. Because of their size, they represent a large percentage of the mass in the exhaust, and are also potentially quite erosive. The appearance of these particles in scanning electron microscope photographs indicates that they are entrained slag droplets. Measures to reduce reentrainment in the impact separator or to provide additional cleanup stages may be needed.

The initial particulate goal of this program has been to meet or better NSPS particulate limits, which for the subscale slagging combustor is 13 ppmw. Without a slagging cyclone, third-stage exit measurements showed particulate loadings of 250 to 500 ppmw.

4.1.6 ALKALI LEVELS

A Westinghouse alkali probe was provided for measurement of particulate alkali and vapor alkali loadings in the hot gases exiting the lean/quench combustor. This probe had been used by Westinghouse Science & Technology Center for measuring alkali in exhaust gases from a coal gasifier.

The major problem with most alkali sampling is that alkali vapor species inevitably condense somewhere in the sampling line and system, often escaping detection. Other problems have been: failure to measure the alkali (especially soluble alkali) in collected particulates, (most insoluble alkali poses no problem to the turbine), and condensation of vapor-phase alkali on particulates in the sampling lines and system. The latter problem results in underestimation of the alkali vapor content of the process gas, or leads to the erroneous conclusion that good particulate cleanup alone can protect the combustion turbine from alkali-induced hot corrosion.

The proposed probe avoids these problems. Rather than using the probe to withdraw a gas stream for external separation of particulates and alkali, these are collected in the probe itself. The probe is inserted into the gas stream and a sample of gas is withdrawn through the probe continuously. The sampling rate should be selected and controlled for isokinetic conditions, as with any particulate probe. Referring to Fig. 4-32, the sample gas passes through a high-temperature ceramic candle filter in the tip end, for removal of particulates, but not alkali vapors. The gas then passes into a cooling section. This section is cooled by the continuous supply of high-pressure gas via a concentric tube assembly in the center.

Fig. 4-34 Subscale Slagging Combustor Third Stage Exit Temperature Profiles at Several Average Exit Temperatures

The outer annulus, through which the sample gas passes, is packed with steel beads to assist heat transfer and to act as collection substrates for condensed alkali. There are one or more thermocouples in this cooling section, to ensure that low temperatures are achieved, but that water will not condense and wash away collected alkali. Gas from the cooling section passes out of the probe and into flow measurement and control instrumentation.

After a desired sample time, the entire probe is removed from the system. The filter section is removed and emptied of collected fines, while the cooling section is rinsed with de-ionized water, with a buffer to establish a pH of at least 3. The rinse solution can then be analyzed for sodium and other potential alkali species anions and cations (e.g., potassium, chloride, sulfate). For simple, on-site analysis, the use of selective-ion electrodes is recommended. Noting the measured concentration in the rinse, the rinse solution volume, and the total amount of gas sampled over the sample period, alkali vapor concentrations can be calculated. The collected particulates should be weighed for calculation of particulate loading, and analyzed for water-soluble alkali content. Other acid-soluble and insoluble alkali components can also be measured, using atomic absorption techniques, to provide further understanding of alkali release mechanisms.

The design of the alkali probes for use in the scheduled testing at the TDS' Haverhill facility was based on the following interface requirements:

- Duct Conditions
 - inside diameter 10.75-in.
 - temperature 2000°F
 - pressure 6 atm
 - gas flow 7 lb/s
 - gas density 0.0935 lb/ft³
 - approximate dust loading 40 ppmw
- Test duration of 2 to 5 hrs.
- Human operator presence at the probe site is not desired.
- Attachment is via a threaded 2-in. pipe nipple.

The need for remote operation and the short anticipated run length were consistent with a simplified operating strategy. The probe was inserted before a test, and removed after a test. No manual operations were conducted at the probe site during a test itself. Flow through the probe was remotely controlled via an electrically operated valve in the gas purge line. This approach avoids the need for block valves for probe removal during a test. Upon removal, the quantities of particulate and alkali collected in the probe are determined.

An extensive review of alternatives for the high-temperature particulate filter cartridges at the tip of the probe was conducted. Sintered metal (Hastelloy X) filters were tested in the laboratory and found to completely lose their permeability when exposed to air at 2000°F. Alundum thimble filters (0.625-in. OD by 2.75-in. long), composed of alumina with a silica binder, were procured from Norton Co. and tested similarly. No loss of porosity occurred.

One remaining concern is that the silica in these filters may react with alkali vapors. To help in evaluating this issue, filter material was exposed to alkali vapors at high temperatures in the laboratory. No significant change in weight or appearance occurred. The exposed sample was analyzed via atomic absorption and the background sodium content was found to have risen from 0.22 wt percent to 0.73 wt percent, indicating active gettering of alkali by the filter. A quantity of these filters were ordered. It was planned to use one per test and to have the filter, as well as the particulate and condensate samples, routinely analyzed for alkali in the test program.

As seen from Table 4-1, measured alkali levels corresponded to between 1 and 2% of the total alkali in the coal. This represents a good reduction in alkali through the action of the impact separator, but it is not low enough to prevent corrosive attack in the expander of the gas turbine.

TABLE 4-1

Subscale TVC: Alkali Emissions During Typical CWM-Fueled Testing

<u>Test</u>	<u>Vapor-phase Sodium</u>	<u>Vapor-phase Potassium</u>
18-4	0.43 ppmw	0.29 ppmw
18-5	0.26	0.22
18-6	0.30	0.20
28-1	0.21	0.25
28-2	0.20	0.22

Long experience with traces of alkali in oil-fired combustion turbines has resulted in the widely accepted guideline that sodium plus potassium may not exceed 0.02 ppmw on an exhaust flow basis. Thus, the 0.42 to 0.71 ppmw found in the coal burner exhaust is an order of magnitude too high. Combustion turbine oil fuel specifications currently limit the sodium plus potassium level in the fuel oil to 1 ppmw. Since the weight ratio of oil fuel mass flow rate to turbine inlet hot gas mass flow rate is approximately 1:50, the 1 ppmw limit in the oil is equivalent to a limit of 0.02 ppmw in the turbine inlet gas.

4.1.7 COMBUSTOR TEMPERATURES AND TEMPERATURE PATTERN FACTOR

4.1.7.1 Flame Temperatures in the Primary Zone

For PC-firing, measured flame temperatures in the primary zone are plotted as a function of equivalence ratio in Fig. 4-33. These measurements are made with a two-color optical pyrometer focused at the center of the dome region in the primary zone. The peak flame temperature (2400°K/3860°F) was measured at an equivalence ratio of approximately 1.05. The flame temperature at the nominal operating point of the primary zone is on the order of 2000 to 2100°K (3140° to 3320°F).

Fig. 4-33 Primary Zone Flame Temperature as a Function of Equivalence Ratio

For CWM-firing, flame temperatures on the order of 1900 to 2000°K (2960° to 3140°F) were measured at equivalence ratios in the range 1.2 - 1.4. These flame temperatures are some 150 to 200°K below the measured flame temperatures for PC firing at the same equivalence ratios.

4.1.7.2 Combustor Exit Temperature Pattern Factor

A thermocouple rake was installed at the combustor third-stage exit in order to provide an indication of the temperature profile. This probe employed six (6) thermocouples, spaced at one-inch intervals, to cover the exit stream from the wall to the centerline. Symmetry is assumed in describing the temperature profile.

Exit profile curves for six (6) different average outlet temperatures are shown in Fig. 4-34. They represent a wide range of combustor primary equivalence ratios, 1.2 to 1.6, and dilution airflows. These yield average exit temperatures of 1600° to 2000°F. At the project design point exit temperature of 1850°F, the calculated pattern factor is 14%, which is well within the project goal, to achieve a pattern factor of 20% or less. Pattern factor is defined as:

$$\frac{(\text{Peak Temperature}) - (\text{Average Temperature})}{(\text{Average Temperature}) - (\text{Inlet Temperature})}$$

4.1.8 HEAT LOSS & PRESSURE LOSS

4.1.8.1 Heat Loss

Currently, all components of the subscale slagging combustor are vigorously water-cooled to assure no local overheating occurs. Although no attempt has been made to tailor the water fluxes to minimize heat loss, the water-cooling system is designed to enable accurate measurement of system heat losses. Thus, measured heat losses from the subscale combustor during testing have been much higher than they would be for a full-scale unit. Combustor heat losses are plotted as a function of primary zone stoichiometry in Fig. 4-35. The heat loss is a function also of primary zone temperature, particulate loading, and combustor wall refractory condition. The best results, a 12% loss, were obtained with a completely intact refractory coating. The combustor has experienced refractory loss, particularly on convex surfaces in the impact separator, due to repeated thermal cycling, and the constantly changing operating conditions that are experienced in a research program. It is estimated that heat losses could be cut to less than half those found presently, when a large, high-pressure full-scale unit is designed.

Fig. 4-35 Combustor Heat Loss

4.1.8.2 Pressure Loss

During the testing period, measured overall combustor total pressure loss declined from 8%, which had been considered normal, to approximately 5 to 6%. It was discovered that this resulted from erosion of the primary zone exit nozzle ceramic lining. This lowered the gas velocity approaching the impact separator, but there is no evidence that slag separation was adversely affected by the lower velocity. It should be remembered, however, that the various trade-offs between overall pressure loss and particle collection efficiency are by no means complete at this point, since additional cleanup is required.

4.2 DISCUSSION OF ORIGINAL TVC RESULTS

During the period of time in which the original design of the TVC was tested, the subscale 12 MM Btu/hr combustor became operational for the first time and demonstrated excellent coal-fired operation at 6 atm. All three coal fuel types were burned successfully. As a result of this active testing the following conclusions may be drawn:

- It was possible to achieve the full design thermal capacity of 12 MM Btu/hr with the subscale slagging combustor, while burning 100% pulverized coal and operating at the design pressure of 6 atm.
- Because of the separate-chamber, rich-lean design of the subscale slagging combustor, NO_x emissions that easily meet the NSPS limits are readily achieved.
- Because of its refractory-lined, toroidal-vortex design, the subscale slagging combustor readily achieves in excess of 99% carbon burnout efficiency when 100% coal-fired.

- 90% of the ash can be captured as slag in the impact separator.
- Objectives for third-stage exit temperature (1850°F), and exit temperature pattern factor (14%) were readily achieved.
- Overall pressure loss is currently an acceptable 5 to 6% (without cyclone separator).
- Sulfur reductions in the third stage exhaust of up to 45% with calcia and 85% with iron oxide have been achieved. The NSPS goal is 70 to 90% reduction, depending on coal sulfur content.
- Feeding pulverized coal into the combustor against 6 atm pressure is achievable, but doing the same with sorbent is more difficult, due to the small flowrates needed.
- The demands of NSPS in the area of particulate removal indicate an additional cleanup stage, over-and-above the impact separator is needed. A slagging cyclone, the prime candidate to meet these requirements was designed, fabricated, and tested, as described next.

4.3 RESULTS OF THE TVC MODIFICATIONS

4.3.1 SLAGGING CYCLONE SEPARATOR ADDITION

4.3.1.1 General Operation

In fall 1990, a slagging cyclone separator was installed between the rich-burn primary and lean-burn secondary combustors. An oil-fired run was made (11/6/90) in order to complete curing of the newly installed refractory layers in the combustor and cyclone separator. The system was allowed to come up to pre-heated air temperature (650°F) before lighting off a fuel oil flame. The oil flow was progressively increased over a period of several hours in order to increase the bulk gas temperature in the combustor and cyclone and allow the refractory to cure.

The slagging cyclone testing was run from November 1990 through January 1991. The objective of this period was to determine the collection efficiency of the slagging cyclone separator.

An unexpected char carry-over problem developed in the primary zone when PC-firing cyclone tests commenced. Relative to previous PC tests the primary zone carbon conversion was lower by 2%. Complete discussion of this problem and how it was finally overcome is covered in Section 4.3.3.

4.3.1.2 Cyclone Performance

Despite the problems associated with the coal carry-over, several strong indications of excellent cyclone performance were obtained from the cyclone tests. First, the total slag recovery, both from the slag bucket and the cyclone bucket, through Test C1-6, was 100.6%. This measurement has some inherent inaccuracies, due to slag movement on the walls of the entire combustion system, refractory cracking at flanges that are regularly opened and small amounts of refractory dissolution. Total slag recovery before cyclone installation was typically 90%. Thus, slag collection with the cyclone is significantly greater than that obtained prior to the cyclone installation, and indicates cyclone collection efficiencies on the order of 90%.

Second, in a number of tests, a good estimate of fly ash carry-over to the downstream section was obtained from particulate samples. As previously described, unburned coal was carried over to the downstream isokinetic particle sample when enough accumulated in the cyclone bucket for

it to be re-entrained into the cyclone outlet flow. For most tests, there was a noticeably distinct fly ash layer on the particle filter. This fly ash layer was underneath the unburned coal layer. With care, relatively uncontaminated samples of each layer were obtained which allowed estimates of fly ash size and loading and overall slag collection efficiency to be made for each run. Table 4-2 shows these estimates for the tests C1-1 through C1-6.

Table 4-2

Fly Ash Loading and Overall Slag Collection Efficiency Estimates with Slagging Cyclone

Test Number	Estimated Total Slag <u>Collection</u> (%)	Estimated Exhaust Fly Ash <u>Loading</u> (ppmw)
C1-1	99.7	7
C1-2	99.6	9
C1-3	99.2	18
C1-4	97.2	64
C1-5	98.9	25
C1-6	98.4	37

For these test conditions, the NSPS emissions limit of 0.03 lb/MM Btu would correspond to approximately 15 ppmw. These estimates confirm that the cyclone is operating at approximately 90% collection efficiency and definitely shows the potential for meeting the turbine inlet particulate loading requirements and possibly the NSPS requirements.

4.3.1.3 Particle Size Distributions

Fig. 4-36 shows measured size distributions for the coal feed and for three samples of unburned coal recovered from the cyclone bucket. The top size of the cyclone bucket samples was the same as that of the coal feed, but the mean size was somewhat larger. The mass fraction contained in particles less than 10 microns in diameter was considerably smaller for the bucket samples than for the coal feed. This is consistent with by-passing the primary zone flame; coal that has been exposed briefly to a high temperature environment will be deficient in small particles, as these will have time to be oxidized completely. In addition, the cyclone separator will be less efficient at capturing the finest coal particles.

Fig. 4-37 shows measured size distributions for particle samples collected by isokinetic sampling downstream of the cyclone separator. The figure shows the size distribution of a cyclone bucket powder sample, a sample of black powder from the particle filter and a sample of fly ash removed from underneath the black powder on the same particle filter. The unburned coal carried over from the cyclone bucket to the isokinetic particle sampler is somewhat smaller than that remaining in the bucket, but is still relatively large. The fly ash collected on the filter, however, is extremely fine, with a mean size of around 3 microns. Some 90% of the fly ash is contained in particles of diameter 5 microns or less.

Fig. 4-36 Particle Size Distributions from Cyclone Bucket. Measured Size Distributions for: (1) 200 Mesh Dorchester Coal; (2) Sample from Cyclone Bucket, Test C1-1; (3) Sample No. 1 from Cyclone Bucket, Test C1-2; (4) Sample No. 2 from Cyclone Bucket, Test C1-2.

Fig. 4-37 Particle Size Distributions from Isokinetic Sampler. Measured Size Distributions for: (1) Sample No. 1 from Cyclone Bucket, Test C1-2; (2) Unburned Coal from Particle Sampler, Test C1-2; (3) Fly Ash from Particle Sampler, Test C1-2.

4.3.1.4 Material Balances for Cyclone Tests

A summary table for the slag material balance for the slagging cyclone tests is shown in Table 4-3. All tests were with Dorchester coal (6.3 to 7.0% ash) except for Test C1-8, which was with Pittsburgh No. 8 coal (7.6 to 7.9% ash). As pointed out above, the ash content of the coal appears to be variable, with Dorchester analyses showing between 6.3 and 7.0% ash and Pittsburgh No. 8 analyses showing 7.6 to 7.9% ash. An accurate assessment of the total slag collection efficiency obviously depends on accurate knowledge of the coal ash input. Allowing for the above mentioned variability in ash contents, total slag collection efficiencies of between 96.5 (assumes Dorchester ash is 7.0%, Pittsburgh No. 8 is 7.9%) and 106.9% (assumes Dorchester ash is 6.3% and Pittsburgh ash is 7.6%) were obtained. Median ash contents based on the five available Dorchester analyses and the two available Pittsburgh No. 8 analyses are 6.50% for Dorchester and 7.75% for Pittsburgh No. 8. Based on these median ash contents, the total slag collection efficiency for all slagging cyclone tests to date is 99.5%. Despite the variability of these assessments, it is obvious that the slagging cyclone performs extremely well and gives approximately 90% collection of any slag that escapes the impact separator.

Table 4-3

Slag Material Balances

Test	Coal In (lb)	Slag Collected in Slag Bucket (lb)	Slag Collected in Cyclone Bucket (lb)	Cumulative Total Slag Collection (lb)
C1-1	768	36	2.0	38.0
C1-2	1888	103	14.5	155.5
C1-3	418	N/A	5.0	N/A
C1-4	200	N/A	2.8	N/A
C1-5	203	50	1.4	214.7
C1-6	204	13	3.4	231.1
C1-7	202	17	2.6	250.7
C1-8	202	8	1.6	260.3
C1-9	189	20	1.4	281.7

4.3.2 SLAG TAP AND REVISED IMPACT SEPARATOR ADDITION

4.3.2.1 General Operation

At the conclusion of slagging cyclone testing, the combustor was torn down and installation of the revised impact separator and slag tap hardware commenced. The primary zone components were first removed from the test assembly to allow the upper housing of the old slag separator to be removed. The new slag separator upper housing was installed and aligned with the cyclone separator inlet. The primary zone components were then re-installed, along with the new slag separator nozzle. Subsequently, the new impact separator/centerbody assembly was installed. A quartz window was installed to provide a view of the top of the new separator surface. The water supply, water level controls and the pneumatically actuated slag ram were installed in the slag bucket. The cooling water system was modified to provide cooling to the new components. Additional gas and water instrumentation systems were installed and calibrated. The slag ram system was tested. Movement of the ram was relatively slow, the limitation being the airflow capacity of the actuating solenoid valve. A solenoid valve of larger airflow capacity was procured. The automatic level control system for the slag water-bath was checked and worked well.

Upon completion of the slag tap hardware installation, shakedown testing started in March 1991. Pre-heated air (650°F) was passed through the combustor for two (2) four-hour periods to dry the newly installed refractory liner. Subsequently an oil-burning test was made to cure the refractory and check out the slag bath systems. Pre-heated air was run for two hours and then the oil flame was ignited. The oil flow-rate and gas temperature were increased slowly over a four-hour period. In this test, the slag water bath systems were checked out. Thermocouples were installed to measure the outside wall temperatures of the bath above the water line, the water temperature, the gas temperature above the bath, and the bleed steam/gas temperatures exiting the quench bath. The outside temperature of the bath above the water line stabilized at approximately 150°F after one hour of oil burning. The water temperature some 6-in. below the surface stabilized at approximately 210°F (boiling point at 6 atm is 320°F) after one hour of oil burning. No operational problems were encountered during the test.

After the test, the combustor was opened for inspection. It was discovered that the water level in the slag water bath had been considerably above the design level during the test. The level switch was checked and found to be functioning properly. It was discovered that the ball valve controlling the water supply to the water bath had been leaking, leading to the overfilling of the bath. The valve was replaced. A number of other changes were made before commencing coal-burning tests. In particular, a window was added to the slag bath, so that the tap hole itself could be remotely viewed during the run.

4.3.2.2 Slag Tap Performance

The PC-firing tests with the slag tap installed began on 4/17/91. A remote video camera was used to monitor the slag tap region. Coal flow was ramped up to about 50% load. Since the wall temperature of the slag quench vessel above the waterline rose to over 500°F, the run was stopped and a water spray was installed on the outside wall of the upper part of the slag quench vessel to prevent overheating. The first successful tapping occurred on the 4/19/92 during test S1-2, which consumed 531 lbs of Dorchester coal. Of the three test coals used in this program, the Dorchester has the highest T₂₅₀.

Following this test, two more test runs were done focusing just on the tapping of slag. The video monitor viewing the slag tap showed molten slag descending from the tap and freezing as it hit the water. A slag ram was occasionally used to free frozen slag from the tap area. Once during this test series we encountered a case (S1-4) where the tap froze up. This is now believed to have been caused by the char problem, which was solved later.

Slag tapping was very effective when sorbent was being injected. At times it was difficult to distinguish with the video camera, between condensed water on the top of the slag quench chamber and the molten slag dripping through the tap. Thus, the iron oxide acts as a fluxing agent and reduces slag viscosity significantly. It is important to control the amount of fluxing agent, otherwise too much of the slag can carry over into the cyclone section.

4.3.2.3 Slag Tap/Sulfur Reduction Tests

The main focus of these tests was to acquire sulfur reduction performance data. Improved slag flow was achieved during the sulfur reduction tests by operating with a lower primary zone equivalence ratio ($1.1 < \phi < 1.2$), and burning the Pittsburgh No. 8 coal which has a higher sulfur value and a lower T₂₅₀.

4.3.2.4 NO_x Control

NO_x levels documented in Fig. 4-38 show that rich-lean quench staging effectively gives lower than NSPS values.

P6921

Fig. 4-38 Equivalence Ratio (ϕ) and NOx for Test SL1-3

4.3.2.5 CO Emissions

A nondispersive infrared CO analyzer, which measures in the ppm range, was added to the gas analysis system just prior to the non-DOE testing done for the Northern States Power Company.

Measurements taken after the lean-quench combustor, during PC-firing tests done in 10/92, show CO levels of 10 - 70 ppm for primary zone equivalence ratios varying from 1.1 to 1.6.

This further collaborates the +99% carbon combustion efficiency measured by the low carbon content in the flyash captured by the isokinetic particulate sampling probes after the lean-quench combustor.

4.3.2.6 Heat Loss and Pressure Loss

The addition of the redesigned impact separator stage with the curved centerbody lowered the heat loss about 3%. Below are listed tables for heat loss and pressure loss at a variety of equivalence ratios.

Early in slag tap testing we encountered intermittent problems with the float switch controlling the water level in the quench vessel. Because of this thermocouples were installed above and below the water line to help monitor the water level. Water is now controlled manually based on the temperature indications in the vessel.

PRESSURE LOSSES

Primary Zone ϕ	1.15	1.00	1.20	1.60	1.40
Coal	Pitt 8	Dorchester	Dorchester	Dorchester	Pitt 8
Air Injectors	3.5%	5.0%	3.8%	?	2.6%
Primary Zone Nozzle & Impact Separator	3.5%	4.4%	3.5%	?	2.3%
Slagging Cyclone	1.6%	2.0%	1.5%	1.8%	1.0%
Stage III & Exhaust Duct	0.3%	0.3%	0.3%	0.3%	0.3%
Total	8.9%	11.7%	8.5%	7.9%	6.2%
	(SL 3-2)	(	SL 3-4	)	(SL-33a)

HEAT LOSSES

Primary Zone ϕ	1.15	1.00	1.20	1.60	1.40
Coal	Pitt 8	Dorchester	Dorchester	Dorchester	Pitt 8
Primary Zone	11.2%	10.0%	9.2%	7.1%	9.5%
Impact Separator	7.8%	7.8%	6.3%	5.0	6.5%
Cyclone	14.8%	15.0%	12.5%	8.8%	10.8%
Stage III	4.0%	4.5%	4.5%	4.4%	5.0%
Exhaust Duct	15.5%	14.2%	14.5%	15.8%	17.0%
Total Less Exhaust Duct	37.7%	37.3%	32.5%	25.3%	26.8%
	(SL 3-2)	(	SL 3-4	)	

4.3.2.7 Sorbent Feed Modifications

A number of modifications were made to the sorbent feed system during March 1991. The intention was to improve the stability of the sorbent feed and to provide a method of clearing plugs in the sorbent feed nozzle at the sorbent storage tank. First, the entire sorbent hopper bottom conical section was removed and remachined so as to provide a completely smooth contraction. Then a number of pairs of one-eighth-inch holes were drilled into the nozzle along its axis. The holes were distributed along the length and periphery of the nozzle. Each pair of holes is supplied separately with high pressure nitrogen via a number of remotely operated solenoid valves. The purpose of the nitrogen jets is to provide a method of clearing plugs.

A number of sorbent feed tests were made to evaluate the blockage clearing system. The nozzle itself was of too large a diameter to give the required limestone flow rate with a reasonable tank-to-carrier line pressure difference. Given the success of the blockage clearing system, a small diameter sorbent nozzle was determined acceptable and installed. During sorbent feed tests the sorbent tank load cell indicator failed. The indicator was too old to warrant repair so it was replaced.

To further assist limestone flow, both hematite (Fe_2O_3) and magnetite (Fe_3O_4) were added as dilutents. These iron oxides, at the equivalence ratios ($1.15 < \phi < 1.25$) of interest, should not be very good sorbents; at higher equivalent ratios ($\phi > 1.4$) these would become effective sorbents. Iron oxides are also good fluxing agents which allowed good tapping of the slag.

4.3.2.8 Sulfur Reductions

Sulfur reductions at the exit to the lean/quench combustor using 325 mesh Marblewhite limestone varied from 20 up to 50%. There was general agreement in sulfur reductions measured in the exit to the primary zone and at the exit to the lean/quench combustor, see Fig. 4-39.

Fig. 4-39 Percent of Total Sulfur Present and Ca/S Molar Ratio for Test SL1-3

Results from sorbent injection experiments with the slag tap/quench are also plotted in Fig. 4-40. Although the very high captures previously observed at the exit of the primary zone were not duplicated, the sulfur capture at the exit from the lean zone (i.e. the combustor emissions reduction) has been increased dramatically. At a fuel/air equivalence ratio of 1.2 and a Ca/S molar ratio of 3, the lean-zone exit sulfur capture has been increased from 10 to 50% by adding the slag tap. This confirms that the reacted sorbent has been prevented from decomposing by removing it from the high temperature slag bucket and quenching it in water. Although this reduction is less than that required to meet the NSPS limits, these results were encouraging.

Fig. 4-40 Sulfur Capture with Pittsburgh No. 8 Coal

4.3.3 CHAR CARRY-OVER PROBLEM AND SOLUTION

As mentioned in Section 4.3.1.1, an unexpected char carry-over problem developed in the primary zone with the resumption of PC-firing with the reconfiguration of the subscale test hardware to include the cyclone separator and the slag tapping.

These physical changes required that the primary combustor be raised up about six feet higher, along with reconfiguring the primary air lines and reorienting the lean-quench combustor from a horizontal to a vertical position.

These physical changes required that the primary combustor be raised up about six feet higher, along with reconfiguring the primary air lines and reorienting the lean-quench combustor from a horizontal to a vertical position.

4.3.3.1 Attempted Solutions

Injector Modifications

The hypothesis was that a fraction of the coal is not injected properly into the upward-directed jet in the primary zone, but rather turns over and exits directly through the primary zone nozzle. This coal would have a very limited residence time in the primary zone and would travel through an oxygen depleted zone, and therefore would be at best partially pyrolyzed.

Fig. 4-41 shows the coal/air injector assembly as originally installed. The coal injector tube is located just upstream of a contraction section, which is designed to promote mixing of the coal and primary air. The contraction leads to the main injector tube, which extends to the primary zone wall. The purpose of the injector tube is to ensure that all the coal is injected towards the dome region and none is allowed to turn over and exit the primary zone.

Fig. 4-41 Coal/Air Injector Assembly as Originally Installed

Fig. 4-42 shows the coal/air injector assembly as it was during the cyclone tests to date. The main injector tube, which was uncooled, had melted back as far as the pivot joint. This had happened early on in the previous PC testing, but had not been remedied as there was no discernible effect on combustor performance. It was decided to manufacture replacement tubes in order to return the coal/air injector assembly to its original configuration so that any uncertainties about the fuel injection could be eliminated.

Fig. 4-42 Coal/Air Injector Assembly, Showing Melted Injector Tubes

While the tubes were being procured and machined, the existing injector tubes were moved toward the contraction section and positioned as specified in the original design. This produced no beneficial reduction in the char carry-over. Next the contraction section was removed and the injector tips moved in so that the coal stream was injected right at the primary zone wall. While this is not favorable from a coal/primary air mixing point of view, it eliminated the possibility of any coal impinging on the cold injector assembly walls and being injected at an excessively low velocity, with the possibility of by-passing the primary combustion zone. This also did not help.

The coal/air injector assembly was returned to its original design, but again no change was observed in the char carry-over.

Increased Primary Zone Aspect Ratio

A test was run in which the spool piece was installed in the primary zone in order to increase the aspect ratio (L/D) from 1.25 to 1.50. No significant effect was observed on the char carry-over.

Ordered New Deliveries of PC

Next we focused on the pulverized coal itself. Analytical results of the Dorchester coal indicated that there were some signs of oxidative aging of the coal. It is known that with time coal will deteriorate and lose some of its volatility and its heating value. Based on this a new shipment of coal was ordered.

Since the analysis of the char confirmed an extremely low volatility and a reduced heating value, it was believed that this supported the hypothesis that the char resulted in the by-passing of the toroidal vortex region in the primary zone.

While waiting for a new shipment of Dorchester PC, the new Pittsburgh No. 8 PC was fired. This proved that the char carry-over problem was found to be independent of the bituminous coal burned. It was decided to reconfigure the subscale combustor away from the slag tapping and back to the centerbody impact separator and the slag bucket. Upon arrival of the new coal shipment of Dorchester coal, it burned with no change in the char carry-over.

4.3.3.2 The Solution: Increase the Coal/Air Injection Velocity

Two new diagnostic tools were applied to help TDS solve the char carry-over problem: an exhaust, helium-neon laser based, extinction diagnostic and a filtered video camera viewing into the top of the primary zone.

Helium-Neon Laser Diagnostic

A He-Ne laser extinction diagnostic was installed in the exhaust duct downstream of the lean-quench combustor. This diagnostic provided a real-time measure of exhaust duct particle loading by monitoring the decrease in the power of a low power He-Ne laser beam passed through the exhaust gas stream (normal to the exhaust gas flow direction). The laser beam entered and exited the exhaust duct via optical windows. The exit beam power was measured via a photo diode detector. Reference power levels were acquired before and after the coal combustion segment of a test run. During coal combustion, the laser beam power monitored by the photo diode decreased due to light scattering by the particles present in the exhaust gas stream. The natural logarithm of the ratio of the decreased laser beam power (when scattering occurs) to the reference power level (no scattering occurring) provided a measure of the number density of particles in the exhaust gas stream, which can be correlated with exhaust gas particle loading (i.e., mass flow rate of particles in the exhaust gas stream).

Since the extinction diagnostic has a frequency response of order 10 kHz, this diagnostic was installed primarily to determine if exhaust char was being produced on a continuous basis or whether there existed some periodic structure to char production. Periodic, unsteady char production suggested that the coal/air injection jets in the primary zone may have been oscillating spatially. If this occurred, the coal/air jets may have been bending down toward the exit of the primary zone, thereby sending coal directly to the exit of the primary zone, rather than upward into the toroidal vortex in the dome of the primary zone. The decrease in burn-out time due to this phenomena could cause char production. If steady-state char production was detected, other types of phenomena had to be considered that could result in the production of char, such as biased coal injection. Biased coal injection occurs when the coal flow rates supplied to each of the four primary zone coal/air injectors differ. This can cause different regions of the primary zone to have different stoichiometries, thus producing char locally. It was important, therefore, to determine if the char production was steady or unsteady in order to begin isolating the source of the problem.

The extinction diagnostic served several other purposes also, making this diagnostic a valuable asset. If it is assumed that the particle size distribution of the particles in the exhaust stream are very close from test run to test run, then a direct measure of the relative change in particle loading from one run to the next can be easily determined. In fact, the extinction diagnostic can be calibrated based on the exhaust particle loadings derived from data from the particle collection probe sampling the exhaust gas stream. Thus, if a particle probe filter breaks during a run, exit particle loading data can still be acquired by information derived from the extinction diagnostic. It also supplies a real-time technique for determining whether operating parameter changes affected char production. It was then possible to see the effects of stoichiometry, coal carrier gas flow rate, etc., on char production.

Primary Zone Combustion Monitoring

A video camera was positioned so that it viewed the combustion at the top of the primary zone. Review of the tapes could provide an indication if unstable combustion was occurring in the primary zone.

Problem Uncovered

During test CR1-6, the four coal injector delivery tubes were repositioned inside each coal/air injector passage to see if this had an effect on char production. The coal carrier line from the coal tank to the four-way coal splitter was elevated before beginning test CR1-6 in order to see if changes in splitter elevation could affect coal delivery behavior. (It should be noted that the entire combustor, including the coal splitter, was elevated by nominally 30 in. when the cyclone was installed and that the char problem appeared after installation of the cyclone.) Repositioning the coal delivery tubes in the coal/air injectors and raising/lowering the coal carrier line between the coal tank and splitter did not change char production rates during CR1-6. However, every time a coal delivery system element was moved, a noticeable change in coal flow rate was observed. This observation implied that the stability of the coal delivery system may have been marginal, if not unstable. It was thought that this instability was responsible for the unstable combustion observed in the primary zone combustion video, and was possibly leading to the char production.

As a result of an internal TDS meeting on 9/16/92, it was decided to change the coal delivery system in such a way as to improve coal flow stability. After determining the actual flow velocities in the lines conveying the pulverized coal from the coal tank to the coal/air injectors, it was concluded that these velocities were low relative to those needed to produce very stable two-phase flow. These velocities were increased to the desired levels by replacing all hoses on the coal delivery system with smaller ID hoses. Increasing carrier line velocities this way assumed that the carrier air and coal mass flow rates could be kept constant.

It was recognized that keeping the carrier air flow rate constant may not be possible, because of the supply pressure limitation of the carrier air compressor. A small change in hose ID could significantly increase the pressure drop over the delivery system lines. The first option considered was to rent a higher pressure compressor to ensure that sufficient pressure would be available to achieve the carrier air flow rates desired. Since it would have taken time to acquire and install a rental compressor system, it was decided to modify the coal delivery system hoses to experimentally determine what coal delivery flow conditions could be achieved with the resident carrier air compressor.

Results from test SL2-2 demonstrated that the resident carrier air compressor could not supply the pressure head needed to maintain proper carrier air flow. Either a higher pressure compressor system or a high pressure air tube trailer would need to be rented. A permanent higher pressure carrier air supply would not be installed until it had been demonstrated that this approach would correct the char problem.

Arrangements were made to lease an air tube trailer which could be regulated down to nominally 150-180 psig and used as an air source for the coal carrier air. Since it would take two weeks to in place of air could negatively affect the combustion in the primary zone, but could give some insight to the effects of this approach.

Although it took almost the entire run to stabilize the desired coal flow rate of 14 lb/min, the He-Ne diagnostic was indicating that the particulate loading in the exhaust gases was down by 40% from previous runs. Post-test system breakdown revealed that the cyclone bucket contained less char than observed in previous runs conducted after installation of the slagging cyclone. These results suggested that the system elements influencing char production may have been identified, and that steps being taken to correct the problem were effective.

Solution

Basically the char carry-over problem was a result of low carrier air flow rates yielding unstable two phase flow and flow pulsations. Reducing the coal to carrier-air loading ratio by increasing carrier mass flow rate eliminated the char problem plaguing this system since installing the slagging cyclone. The additional decoupling of the carrier air from the primary air supply also assists in improving the combustion stability.

4.3.4 AMES ALKALI MEASUREMENTS

During two subscale combustion tests run in October 92, exhaust alkali measurements (vapor phase and solids bound) were made using the Ames Alkali Monitor by Dr. Dave Eckels, Ames National Laboratory. During the first test the sampling probe was facing into the flue gas flow and operated isokinetically. Eckels indicated that ingested solids tends to effect the stability of the flow rate through his instrument. He said that it would take sometime to remove the effects of flow variation, but would have results by 12/31/92. The vapor phase alkali concentrations in the exhaust of the slagging combustor were nominally 20-30 ppbw sodium and much less for potassium. The solid bound alkali levels, as measured by the Ames monitor were orders of magnitude higher.

During the second test the sampling probe for the Ames monitor was installed facing downwind and was not operating isokinetically. The Ames monitor worked well during this test. Hence, only the vapor phase alkali levels were quantifiable. This should be satisfactory since it is the vapor alkali that troubles gas turbine components. The solid bound alkali can be determined via chemical analysis of the collected flyash.

Dr. Eckels' report concluded that during coal combustion the sodium vapor phase levels varied between 20 and 25 ppbw and the potassium vapor levels between 8 and 20 ppbw. Eckels believes the accuracy of these measurements should be taken as one-half order of magnitude.

The vapor alkali levels measured when using the slagging cyclone separator are very encouraging, since acceptable vapor alkali levels for gas turbines are considered by Westinghouse to be 20 ppbw. This implies that no further alkali polishing would be required for the Westinghouse Direct Coal-Fired Gas Turbine System (DCFGT).

4.3.5 DISCUSSION OF TEST RESULTS FOR CURRENT COMBUSTOR CONFIGURATION

The TDS Toroidal Vortex Combustor used as the primary combustor in Westinghouse's proposed DCFGT system has proved to be reliable and effective during the subscale testing. The latest configuration has proven out that slag tapping can be accomplished successfully while effecting high carbon gasification levels in the primary zone. Measured CO levels at the exit to the lean-quench combustor have varied between 10 - 70 ppm at $1.1 \geq \phi \leq 1.6$. NO_x levels are controllable to $\leq 0.2 \text{ lb/MM Btu}$ level at $\phi \geq 1.05$, which is significantly below current NSPS.

Inclusion of the slagging cyclone separator has reduced emission levels significantly so that turbine blade erosion is unlikely, plus the alkali levels may not produce significant corrosion.

The particulate loading levels at the turbine inlet will still be above the NSPS limits of 0.03 lb/MM Btu , but this could be handled by back end cleanup.

Sulfur capture results have only been mildly encouraging. With the introduction of the slag tapping system, it has been possible to increase sulfur reductions to 50% at a Ca/S molar ratio of three with 325 mesh limestone.

In the last year of this project, the tendency has been to consider more fuel rich conditions in the primary zone ($\phi > 1.4$) so as to increase the caloric value of the low Btu gas being burned in the lean-quench combustor. This would tend to lead in the direction of the iron oxide sorbents which are more effective at lower flame temperatures and higher H_2S concentrations. One of the last experimental runs on the subscale combustor verified that up to 70% sulfur capture could be obtained at higher Fe/S molar ratios. The iron oxides produce a stable iron oxysulfide matte which is stable and soluble in the molten slag. Since iron oxides are also fluxing agents this may be the direction to go if in combustor sulfur capture is required. To meet the new EPA sulfur requirements it will take additional sulfur capture to get to the 90 to 95% needed for the future. It is believed by TDS that the introduction of a scrubber after the Westinghouse 501D turbine could control both the SO_x and the particulate emissions to the required levels.

ANCILLARY STUDIES

5.1 COLD-FLOW CYCLONE TESTS

The inclusion of a high efficiency cyclone separator in the second combustor stage was proposed during the conception of this project to enhance the possibility of meeting the NSPS particulate emissions requirements at the combustor exit. The proposed cyclone would have to operate at high temperature (2000°K) and high pressure. Particulates in the gas would be in the form of fine molten fly ash particles. Because of the lack of experience with cyclones at these conditions, operation of the cyclone at this high gas temperature posed uncertainties and risks.

5.1.1 SCALING OF CYCLONE FLOWS

To obtain information on cyclone operation and performance at the novel operating conditions involved, laboratory scale cold-flow cyclone modeling experiments were performed.

The cold-flow experimental results had to be scalable to the subscale combustor conditions in order to allow an assessment of predicted performance at those conditions. This was accomplished by modeling of the following principal non-dimensional parameters in the laboratory scale experiments:

$$\text{Reynolds Number} \quad Re = \frac{\rho u D}{\mu}$$

$$\text{Stokes Number} \quad Stk = \frac{\rho_p u d_p^2}{18 \mu D}$$

$$\text{Weber Number} \quad We = \frac{\rho u L^2}{\sigma}$$

$$\text{Swirl Number} \quad Sw = \frac{G_\phi}{R G_x} = \frac{\pi D_e D}{4ab}$$

where ρ is the gas density, u is the inlet velocity, D is the cyclone barrel diameter, μ is the gas viscosity, ρ_p is the particle density, d_p is the mass median diameter of the inlet particle flux, L is a characteristic length of the liquid layer, σ is the liquid surface tension, D_e is the cyclone exit diameter, a is the cyclone inlet height, b is the cyclone inlet width, R is a characteristic radius, and G_ϕ and G_x are the tangential and axial momentum fluxes, respectively. Re-entrainment effects are correlated by the liquid layer Reynolds Number Re_L , expressed as

$$Re_L = \frac{4Q_L}{v_L a}$$

where Q_L is the liquid volume flow rate and v_L is the liquid kinematic viscosity.

Aerosols of glycerine were generated in the inlet gas stream to simulate molten ash particle viscosity and surface tension in the subscale combustor model cyclone, as the values at ambient conditions are comparable to those of molten ash at gas turbine combustor conditions. Comparative values are presented in Table 5-1.

Table 5-1

**Comparison of Properties of Glycerine at Ambient Conditions
and Coal Ash at Combustor Conditions**

Coal Ash at 1700-2000°K

Viscosity	3 - 5	Poise
Surface Tension	0.05	N/m

Glycerine at 288°K

Viscosity	100 weight percent	23.4	Poise
	88 weight percent*	1.95	Poise
	60 weight percent*	0.15	Poise
Surface Tension (100 - 60 weight percent)		0.06	N/m

*Glycerine-Water Solutions

5.1.2 EXPERIMENTAL ARRANGEMENT

5.1.2.1 Test Hardware

A schematic diagram of the experimental apparatus is shown in Fig. 5-1. The dimensions of the model cyclone, fabricated from Plexiglas, are given in Fig. 5-2. Air from the main facility compressor provided the test gas. The mass flow rate was controlled by flow regulating valves, and measured using a standard sharp-edged orifice plate. A heat exchanger was installed to lower the 260°F air temperature from the compressor to 70°F.

An aerosol was generated by atomization of glycerine using an air-blast atomizer which produced droplets up to several hundred microns in diameter. In order to determine overall cyclone collection efficiencies, the cyclone exit flow was filtered allowing measurement of glycerine passed through the cyclone. The filter material used was rated at 95 to 98% collection for particles above 0.2 microns. The larger aerosol particles were removed by an impact separator before the glycerine droplet-laden test gas entered the cyclone model.

Nominal test conditions and the range of variation of test parameters are given in Table 5-2. Test conditions were selected to give correct similarity between experiment and projected subscale combustor conditions.

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1 & 2 are locations for measurements of gas velocity, pressure, temperature, and particle distribution

Fig. 5-1 Cyclone Separator Experimental Arrangement

CYCLONE MODEL DIMENSIONS

BARREL DIAMETER $D = 0.26 \text{ m}$

a/D	0.49
b/D	0.25
S/D	0.74
h/D	2.66
H/D	3.96
D_e/D	0.41
B/D	0.59

M9449

Fig. 5-2 Model Cyclone Dimensions

Table 5-2

Design Conditions for Cyclone Modeling Experiments

<u>Test Parameter</u>	<u>Nominal Value</u>	<u>Variation</u>
Cyclone Diameter (m)	0.26	--
Test Gas	Air	--
Pressure	Atm	--
Temperature	Ambient	--
Gas Flow Rate (kg/s)	0.16	0.08 - 0.24
Inlet Velocity (m/s)	20	10 - 30
Particulate Size Range (micron)	1 - 20	--
Particulate Viscosity (Poise)	23	0.2 - 23
Particulate Surface Tension (N/m)	0.06	--
Particulate Flow Rate (gm/s)	3	--
Outlet Geometry	Conventional	Advanced

The two cyclone outlet geometries tested are shown schematically in Fig. 5-3. The conventional exit geometry has a vortex finder, a simple open-ended tube, whereas in the advanced exit geometry, the exit tube has a longitudinal slit through which the gas exits. The bottom of the tube was sealed. Therefore, the inlet to the exit tube provided a degree of controlled diffusion as the gas left the cyclone barrel by flowing tangentially into the exit tube through the slit. The objective of the advanced exit geometry was to provide a linearly distributed sink in the cyclone barrel, as opposed to the strong local sink produced by the conventional vortex finder exit. This was expected to eliminate large radially inward velocities in the vicinity of the exit, and hence improve separation performance. The advanced exit geometry was expected to produce a significantly lower pressure drop than the conventional exit.

Fig. 5-3 Model Cyclone Exit Geometries

5.1.2.2 Instrumentation

The velocity of the test gas at the cyclone inlet (inlet tangential velocity) and at the cyclone exit were measured using pitot tubes. Gas pressures and the pressure drop across the cyclone were measured using standard inclined manometers. The size distribution and concentration of particles in the gas were measured in situ using a Malvern laser diffraction particle sizer. The cyclone performance was obtained from both the size distribution and concentration measurements and also from weighing the glycerine tank, impact separator tank, and cyclone collection tank before and after a test.

5.1.3 TEST RESULTS

5.1.3.1 Conventional Vortex Finder Exit

The cleanup performance of the cyclone was determined by measuring the droplet size distribution at the cyclone outlet. (Mean inlet size distribution is given in Fig. 5-4.) Some difficulties were experienced in obtaining a high enough concentration of particles at the cyclone outlet in order to obtain an accurate Malvern reading. These difficulties were overcome by installing much larger spray nozzles in order to increase the inlet loading. Outlet size distributions for tests with a conventional vortex finder exit are shown in Fig. 5-5. At 50% of the design inlet velocity (10 m/s), all the particles in the outlet stream were below 9 microns in diameter. At the design inlet velocity (20 m/s), all particles above approximately 3 microns in diameter were removed. At 140% of the design inlet velocity, all particles above approximately 2 microns in diameter were removed.

The overall collection efficiency was determined by filtering the outlet flow and measuring the weight change in the cyclone itself and in the filter. Results from these tests are shown in Fig. 5-6 for the vortex finder exit, and also for the slot exit, discussed later. The overall collection efficiency was dependent upon the inlet size distribution. The overall efficiency increased with inlet velocity, reaching 85% at 140% inlet velocity.

Fig. 5-4 Mean Inlet Particle Size Distribution

Fig. 5-5 Outlet Size Particle Distributions - Vortex Finder Exit

Fig. 5-6 Overall Collection Efficiency - Vortex Finder Exit and Slot Exit

Fig. 5-7 Grade Efficiency - Vortex Finder Exit

A more useful assessment of cyclone separator performance can be obtained by determining the grade efficiency curve for the separator. The grade efficiency is the fraction of particles of a given size which are collected by the cyclone. This curve is shown in Fig. 5-7, for the vortex finder outlet. At 50% of the design velocity, a 50% cut diameter (d_{50} , the particle diameter at which 50% collection is obtained) of around 2 microns was indicated. At 100% and 140% design velocity, a d_{50} of around 1 micron was indicated.

5.1.3.2 Slot Exit

Overall collection efficiencies for the slot exit are shown in Fig. 5-6. Unlike the corresponding results for the conventional exit, the overall efficiency peaked around 70% at the design inlet velocity. The outlet size distribution for the slot exit is shown in Fig. 5-8, and the grade efficiency curve for the slot exit is shown in Fig. 5-9. Indicated d_{50} 's are essentially the same as for the conventional exit (around 2 microns at 50% of design velocity and around 1 micron at higher velocities), but the performance is slightly worse than for the conventional exit.

5.1.3.3 Pressure Drop

In determining the total pressure drop across the cyclone, it was assumed that none of the outlet kinetic energy was recovered. Therefore, the pressure drop is simply the difference between the inlet total pressure and atmospheric pressure. Pressure drop results are plotted in non-dimensional form in Fig. 5-10. As expected, the slot exit geometry produced a lower pressure drop than the vortex finder exit. This was attributed to the degree of controlled diffusion present in the slot exit flow. The vortex finder exit pressure drop corresponds to approximately 10 inlet dynamic heads, whereas the slot exit pressure drop corresponds to approximately 8 inlet dynamic heads. The slot exit, therefore, produced a 20% reduction in pressure loss.

Fig. 5-8 Outlet Size Distribution - Slot Exit

Fig. 5-9 Grade Efficiency - Slot Exit

Fig. 5-10 Measured Pressure Drop of Vortex Finder and Slot Cyclones

For both geometries, all particles below 2 microns in diameter were removed at 140% of design velocity. Collection efficiencies with the slot exit were slightly lower than those obtained with the conventional vortex finder exit. However, the expected improvement in pressure drop was observed.

Though care was taken to perform experiments which realistically simulated the expected high pressure, and high temperature conditions in a hot-flow slagging cyclone separator, several points should be noted:

- Inlet droplet loading in the plastic model test was an order of magnitude higher than that expected in the hot-flow cyclone. (A number of workers have reported increased separation efficiency at high inlet loadings.)
- Appearance of the separated glycerine on the wall and the manner in which it flowed was at variance to that observed on slag coated walls. The total ash loading in the first two stages of the subscale slagging combustor is on the order of 6,000 to 9,000 ppm, depending on the coal ash percentage and the stoichiometry. (This loading compares with approximately 15,000 ppm in the cyclone modeling experiments.)
- Experiments were performed under isothermal conditions. (Slag viscosity is extremely temperature dependent, and strong temperature gradients will exist under high pressure and high temperature conditions.)

In Fig. 5-11, the model grade efficiencies at 50% and 100% of design inlet velocity are compared with those of three different pressurized fluidized bed cyclone applications: the Exxon miniplant; the CURL PFBC; and, the Grimethorpe PFBC. Operating conditions for the PFBC cyclone separators are listed in Table 5-3. All grade efficiency curves were scaled to the nominal test conditions in the subscale combustor cyclone separator using the Stokes Number, based on barrel diameter and inlet tangential velocity, as the scaling parameter. The data for the three PFBC cyclones collapse remarkably well, given the difference in operating conditions. The PFBC data indicate a grade efficiency which is not quite as good as the model performance at 100% inlet velocity.

The cyclone collection efficiency required in order to meet the NSPS requirements upstream of the turbine will be a function of the ash content of the coal, the sorbent loading, and the collection efficiency of the impact separator. Based on the measured combustor fly ash loadings and size distributions with the original subscale combustor configuration and the cyclone grade efficiency curves obtained in the model tests, it is possible to estimate the fly ash loadings and size distributions at the cyclone exit. These estimates are illustrated in Fig. 5-12, for two coals (Dorchester 6% ash, 1% sulfur) and Pittsburgh No. 8 (7.6% ash, 2.4% sulfur), with and without sorbent and for two cyclone inlet velocities (50% and 100% of design velocity). Except for one case (Pittsburgh No. 8 with sorbent at 50% velocity), there are predicted to be no particles present in the exhaust which are greater than 5 microns in diameter. Indications are that at the design velocity, the NSPS limit can be met, particularly for the lower ash, low sulfur coal. The current industry limit consensus is sketched in Fig. 5-12.

In order for the high pressure, high temperature cyclone to reproduce the high efficiencies measured in the bench scale experiments, the inlet gas stream must be at a high enough temperature for the mineral matter to be molten and the cyclone walls must be maintained at a high temperature in order to obtain good separated slag flow. The fluxing effects of iron oxides noted above in Section 6.11 may well be of great benefit in ensuring highly efficient slagging cyclone separation.

Results from the bench scale experiments indicated that a slagging cyclone, operated at subscale slagging combustor conditions, would provide sufficient cleanup to meet the turbine requirements, and provide sufficient cleanup to meet the NSPS goals for some coals, provided that the mineral matter to be separated is molten and sticky at the inlet.

Fig. 5-11 Grade Efficiency Comparisons

Table 5-3

Experimental Conditions For Cyclone Tests

	<u>Exxon Miniplant (Tertiary)</u>	<u>CURL PFBC (Secondary)</u>	<u>Grimethorpe PFBC (Primary)</u>
Temperature (°K)	908	1055	910 - 1180
Pressure (atm)	7.0	6.2	5.9 - 11.9
Inlet (m/s)	36	30	16.3 - 27.4
Diameter (m)	0.15	0.15	1.2

Fig. 5-12 Predicted Cyclone Exit Particulate Size Distributions;
The Present Industry Consensus is That Expander Gas
Should Meet the Criterion of Being in the Region Beneath
the Curve Defined by the Dashed Line (Arrows)

5.2 SUBSCALE CASCADE DESIGN

A critical factor in the successful development of a direct coal-fuel gas turbine is the delivery of a suitably clean combustion product gas that is compatible with the turbine components. Under the original contract the second phase of the Basic Program included evaluating the effect of combustor exit gas on turbine materials. Two 30-hour subscale combustor tests were to be conducted at the TDS facility to determine turbine vane erosion, corrosion, and deposition trends. A sketch of how the cascade was to be installed is illustrated in Fig. 5-13. A new set of turbine vanes would have been installed for each test. The vanes and the test rig conditions were designed to simulate the conditions within the first stage of the Westinghouse W501 engine.

A subscale cascade test rig was designed by Westinghouse. This apparatus, ready to be manufactured, was placed on hold by METC on April 6, 1989 until other portions of the Base Program could be further evaluated.

5.2.1 DESCRIPTION OF DESIGN

Sectional views of the subscale cascade rig design are shown in Figs. 5-14 and 5-15. Fig. 5-14 is a top view, which clearly shows the five vanes of the test cascade. Fig. 5-15 is a vertical section of the inlet and cascade only. It shows the contraction in the area leading to the vanes. This construction generates the high velocity needed to simulate the engine.

In the cascade, as designed, exhaust gas flow from the lean-burn stage of the TDS combustor passes into the left end of the cascade rig, a 10.75-in. I.D. water cooled circular duct. It then transitions from the circular cross section to rectangular, in an air-cooled sheet metal section. Flow leaves the sheet metal section at approximately 550 ft/s and enters five (5) air-cooled vanes. It expands through a pressure ratio of two in the vanes, passes through a short diffuser, and then will be quenched to 400°F by an array of wide-angle water spray nozzles. Two sheet metal curved ducts return the flow to the original centerline, where it passes to the let-down valve and exhaust stack.

Fig. 5-13 Sketch of Cascade Rig for Installation in Exhaust of Slagging Combustor at TDS's, Haverhill Facility (Elevation)

Fig. 5-14 Section of Subscale Cascade Rig (Plan View)

Fig. 5-15 Section View of Upstream Portions of Subscale Cascade Rig (Vertical Section)

Upstream of the cascade, internal pressure is retained by the water-cooled circular duct. For the cascade itself, and the downstream ductwork, the pressure containment is by a heavy, insulated rectangular box with removable top and bottom. These covers make it possible to access the cascade assembly between tests, and remove it for inspection or replacement.

5.2.2 DESIGN CHARACTERISTICS

The cascade vanes were designed, assuming a total of five (5) airfoils across the transition mouth, with the W501 geometry modified to fit the rectangular rig. A W501 vane, reduced 50% in height, results in the following vane dimensions:

<u>Vane</u>	<u>In.</u>
Pitch	2.12
Chord	3.31
Gaging	0.86
Cascade Inlet (Total Width)	8.48
Cascade Height	2.61

Vane cooling was designed to maintain surface metal temperatures at the W501 level, with airfoil boundary conditions scaled from the original W501 calculations. Allowance was made for differences in Reynolds Number, size, and fluid properties. Calculations showed that sufficient cooling would be achieved using a series of spanwise holes drilled through the airfoil. There are eight holes on the camber line. A total of 0.5 lb/s of air is consumed when all five (5) vanes are added together. The cascade design conditions are contained in Table 5-4.

5.2.3 INSTRUMENTATION

The subscale cascade rig is fully instrumented for protection and safety, and analysis. The instrumentation is designed to assure that the cascade will be subjected to known, and planned, exhaust gas conditions over the duration of each 30-hour run. Locations of the sensors are denoted on Figs. 5-14 and 5-15. Planned instrumentation is listed in Table 5-5.

In addition to the instrumentation cited in Table 5-5, sensors to verify water flow to the water jacket and exit spray nozzles were to be monitored to assure that no overheating occurred.

Table 5-4

Design Specifications for Subscale Cascade Rig

Flow rate, combustion gases to cascade	7 lb/s
Total pressure, inlet to cascade	75 psia
Total temperature, inlet to cascade	1850°F
Velocity approaching cascade	550 fps
Minimum design pressure for test rig	140 psia (See Note 1)
Test rig cooling medium	water
Gas path cooling medium, upstream of vanes	air (See Note 2)
Gas path cooling medium, downstream of vanes	water
Number of vanes in cascade	5
Type of vane	Scaled W501
Design cascade pressure ratio	2
Vane cooling medium	air
Cooling air, available flow rate	2 pps (See Note 2)
Cooling air, available total pressure	105 psia
Cooling air, temperature	750°F
Number and duration of tests	(2) 30-hour tests
Number of vane sets	2

- Notes: 1. Maximum output of facility air compressor.
2. Regenerative cooling; spent cooling air passes into third stage of combustor.

Table 5-5

List Of Subscale Cascade Rig Instrumentation

A. Analytical Instrumentation

1. Inlet Pressure Taps
2. Inlet Temperature Probe Rakes
3. Inlet Particulate Sampling Probe
4. Cascade Approach Static Pressure Taps
5. Cascade Vane Metal Temperature Thermocouples
6. Cascade Downstream Static Pressure Taps
7. Rig Exit Static Pressure Taps

B. Supervisory Instrumentation

1. Cascade Air-Cooled Approach Section Metal Temperatures
2. Cooling Air Inlet and Outlet Pressure
3. Containment Vessel Metal Temperatures
4. Cascade Discharge Section Metal Temperatures
5. Exit Duct Metal Temperatures

5.3 ANCILLARY SULFUR STUDIES

During this program, two parallel experimental programs were conducted at TDS in addition to the main subscale slagging combustor program. These efforts, neither of which spanned more than a fraction of a year, were Subtask 9.0, Spent Sorbent Stability in Molten Slag, and Subtask 11.0, Basic Sulfur Capture Studies.

5.3.1 SPENT SORBENT STABILITY IN MOLTEN SLAG

Since work during the basic program had indicated a significant part of the sulfur removal problem was actually a sulfur retention problem, a small parallel effort was undertaken in this area which was designated Task 9.0, Spent Sorbent Stability in Molten Slag. The objective of this task was to support the subscale component development being performed under Task 3.1, by characterizing the chemical kinetics related to the release of sulfur oxides from spent sorbent in slag. A letter report describing the complete Task 9.0 effort was submitted to METC for review on 11/12/89. The study concluded that retention of the sulfur in the slag would be adequate, provided the slag residence time in the impact separator, is one minute or less.

If sorbent can be removed with the slag quickly enough, there will be too little time for the sulfur to escape back into the exhaust stream. It was felt necessary to quantify the rate at which captured sulfur is evolved from hot sorbent/slag mixtures. A series of experiments were performed by TDS using a small apparatus, in which sulfur-containing sorbent was immersed in molten slag, and the evolved gases measured as a function of time.

Fig. 5-16 shows the apparatus schematically. The key results are summarized in Fig. 5-17 for spent sorbent by itself, a sorbent/slag mixture, and spent sorbent injected into molten slag. This latter case is the most realistic, and shows the quickest evolution of sulfur. However, even in this last case, it appeared to take nearly 6 minutes for all the sulfur to escape. If the sorbent/slag mixture can be separated from the combustor gas stream completely in some small fraction of 5 minutes, much improved permanent sulfur capture should result.

Fig. 5-16 Schematic of Sorbent/Slag Kinetics Experimental Apparatus

Fig. 5-17 Time History of Spent Sorbent Decomposition in Bench-Scale Apparatus

5.3.2 BASIC SULFUR CAPTURE STUDY

As a parallel effort to the subscale slagging combustor studies a hot flow rig was assembled and used for sulfur capture studies. The overall objective of this study was to understand the effects of operating variables (temperature, residence time, sorbent type, and sorbent feed rate) on sulfur capture from a gas mixture which simulates coal combustion products. This was undertaken in order to improve sulfur capture in the subscale slagging combustor.

Fig. 5-18 is a schematic of the Hot Flow Facility used for these tests. It is a small heat input apparatus installed at TDS' Haverhill facility for the purpose of intensively studying the sulfur capture process alone, without operating the entire subscale slagging combustor. The Hot Flow Facility nominal heat input is small (150,000 Btu/hr) compared to the subscale slagging combustor (12 MM Btu/hr). Although small in heat input, the apparatus is not small. It rises 15 ft above the laboratory floor.

The facility is provided with four (4) gas sampling ports, and a particulate sampling port, as shown in Fig. 5-18. Each gas sampling line consists of a water-cooled sampling probe, Balston filter, and Permapure drier. A dual Western Research H₂S/SO₂ analyzer, a Thermoelectron gas conditioning unit, and a Hewlett-Packard chart recorder are installed in the test cell. Teflon lines run between the facility and the main gas analysis room in order to utilize the CO, CO₂, O₂, dual H₂S/SO₂ and total sulfur analyzers normally used to analyze gas samples from the slagging combustor. Thus, the laboratory has the capability to monitor real-time sulfur species compositions at three locations simultaneously during a test.

P6899

Fig. 5-18 Schematic of the Hot Flow Facility

The sorbent delivery system consists of a Metalfab screw feeder which supplies particles via a funnel into an eductor. Nitrogen carrier gas is supplied to one end of the eductor. The sorbent is entrained from the funnel and carried into the 0.50-inch outlet tube. Since the eductor will not operate with even a small back pressure, the sorbent is injected into the facility via two 0.50-inch stainless steel tubes at 45 degrees. Testing and calibration of the Metalfab feeder has given the relationship between screw speed and sorbent rate (which is linear) between 0.4 and 1.6 lb/hr flow rates. Particulate sampling was made using a 0.375-in. water-cooled probe, followed by filter, temperature transducers, pressure transducers, flowmeter, and vacuum pump.

The overall sulfur capture measured in the Hot Flow Facility was considerably below the levels achieved in the subscale combustor. The reason for the discrepancy between sulfur capture from the two units was traced to difficulties in achieving a high heating rate and temperature for the limestone particles. The low particle heating rates and temperatures were due to high heat losses from the small (3-in. I.D.) flow reactor, and an excess of sorbent carrier gas required to maintain a continuous flow of sorbent to the reactor. However, the measured sulfur captures are consistent with the actual thermal history of the limestone particles. These experimental difficulties emphasized the sensitivity of the transient capture processes to the combustor operating conditions.

Limestone, magnetite, and a mixture of limestone and magnetite were used as sorbents. Within the limitations of the experimental conditions, the following conclusions were made:

- Limestone and the mixtures of limestone and magnetite resulted in higher sulfur captures than magnetite.
- In limestone tests, a peak in sulfur capture was detected in the time interval 20-40 ms.
- Limestone is a more efficient sorbent for sulfur dioxide (SO₂) than for hydrogen sulfide (H₂S).
- The spent sorbent sulfur species were calcium sulfate and calcium sulfite. Calcium sulfide was not detected.

It is recommended that the limestone/magnetite sorbent mixture be tested in the subscale combustor. Although magnetite by itself is a poor sulfur getter under combustor conditions, it will reduce the slag viscosity and improve the impact separator efficiency. This is especially true at flame stoichiometries greater than 1.4 where the slag viscosity is high, due to the lower flame temperatures and the presence of lime. The presence of iron in the slag might also help stabilize the reacted lime in the very stable iron/calcium oxysulfide matte. The reduced slag viscosity should permit faster slag tapping which would help retain the high transient sulfur captures obtained in the first stage. Captured sulfur is presently being lost before the third stage, due to re-evolution of sulfur from the sorbent product.

5.4 SUBBITUMINOUS COAL TESTING FOR NORTHERN STATES POWER COMPANY

Subbituminous coal testing at TDS' Haverhill facility was done as a cooperative activity between Northern States Power (NSP), Westinghouse and Textron; this was independent of the work sponsored by DOE/METC. NSP provided two different Wyoming subbituminous coals, which were burned in the pressurized slagging combustor over a series of seven test runs.

The Antelope and Rochelle seam coals were found to burn easily and completely. Carbon burnouts based on the amount of carbon in the quenched slag and the flyash were $\geq 99.99\%$. Lean-zone CO levels were found to be between 60 -70 ppm at a primary zone fuel to air equivalence ratio (ϕ) equal to 1.2.

NO_x emissions were controlled to < 0.2 lb/MMBtu, which is significantly below the 0.6 lb/MMBtu NSPS limit, by staging combustion and running the primary zone $\phi \geq 1.1$.

The limestone sorbent injected seemed to have little effect on sulfur capture. With or without sorbent addition the sulfur capture in the primary zone was 45 to 65%; the lean-quench emissions levels showed only a 30% reduction. It appears that the inherent Ca found in these coals is causing the sulfur capture.

Although particulate emissions exceeded NSP limits of 0.03 lb/MMBtu, the mean size of the particles passed through the slagging cyclone separator was 2 microns with a top size ≤ 5 microns. Based on these results, it appears that the loading of particulates, although greater than NSPS levels, are quite small in size and unlikely to cause erosion damage to the turbine blades.

Westinghouse's alkali probe measurements were taken during each run and gave vapor alkali levels < 100 ppb_w. Ames alkali probe measurements, taken on only one run, indicated that the vapor alkali had an upper limit of 100 ppb_w.

5.4.1 TEST OBJECTIVES

The objectives of the test series with the Rochelle and Antelope seam subbituminous coals were to:

- Demonstration of high combustion efficiencies
- Determine particulate and particle size distributions of gases exiting the lean-quench combustor
- Determine vapor and particulate alkali concentrations in the gases exiting the lean-quench combustor using a Westinghouse alkali probe
- Assess the emissions of particulates, sulfur dioxide and oxides of nitrogen at the exit to the lean-quench combustor
- Assess the slag removal characteristics
- Determine the gas composition and the Btu value of the fuel rich gas exiting the primary combustor.

5.4.2 OPERATING EXPERIENCE

Nominal NSP test conditions for the subscale combustor tests in Table 5-6 are given in Table 5-7; note that TDS expresses the stoichiometry in terms of a fuel to air equivalence ratio (ϕ) which is the reciprocal of the normal utility boiler equivalence ratio. From the outset of NSP combustor testing a stable, flowing slag layer was formed on the primary zone dome walls. No obstruction or fouling of any of the primary zone coal/air injectors or of the relative small diameter primary zone exit nozzle with slag was observed. The combustor has demonstrated stable and intense combustion, excellent carbon conversion, very low NO_x emissions, efficient slag capture, retention of most of the alkali in the slag and low pressure and heat losses.

5.4.3 FUEL SPECIFICATIONS

Table 5-8 and 5-9 give the coal and ash analysis of the Rochelle and Antelope coals which were provided by NSP for the test program. Along with these coals are also included the analyses for the previous coals studied in the DOE work.

Table 5-6**Northern States Power Coal Test Matrix**

<u>Run No.</u>	<u>Date</u>	<u>Coal</u>	<u>Sorbent</u>	<u>Ca/S Ratio</u>
R-001A	12/23/91	Rochelle	Linwood	2;4
R-001B	1/03/92	Rochelle	Linwood	2;4
R-002	1/14/92	Rochelle	Linwood	2;4
A-001	2/06/92	Antelope	Linwood	2;4
A-002	2/14/92	Antelope	Linwood	2;4
R-O	IRAD test	Rochelle	none	
A-O	IRAD test	Antelope	none	

Table 5-7**Nominal Test Conditions**

Coal Thermal Input	12 MMBtu/hr
Coal Feed	95% < 200 mesh PC
Oxidizer	650 °F (620 °K)
Primary Zone Equivalence Ratio (ϕ)	1.2 to 1.4
Total Mass Flow Rate	7 lb/s (3.2 kg/s)
Exit Temperature	2000 °F
Pressure	6 atm
Sorbent	-325 mesh limestone
Sorbent Molar Ratio	Ca/S = 2;6

Table 5-8
Analyses for Coals Tested

	<u>Dorchester,</u> <u>Va</u>	<u>Pittsburgh,</u> <u>WVa</u>	<u>Hanna,</u> <u>WY</u>	<u>Antelope,</u> <u>WY</u>	<u>Rochelle,</u> <u>WY</u>
High Heating Value (Btu/lb)	14,234	13,822	11,784	9,515	9,456
Proximate Analysis (wt %)					
Moisture	1.0	1.5	9.1	20.2	21.8
Ash	6.2	7.6	5.4	4.9	5.2
Ultimate Analysis (wt %)					
Carbon	80.4	76.7	67.1	56.4	56.0
Hydrogen	4.8	5.2	5.1	3.9	3.7
Nitrogen	1.7	1.3	1.4	0.9	0.8
Oxygen	4.8	5.2	11.3	13.5	12.2
Sulfur	1.0	2.4	0.57	0.30	0.40
Size	95% thru 200 mesh				

Table 5-9
Ash Analysis and T-250s

<u>Ash Properties</u>	<u>Dorchester, Va</u>	<u>Pittsburgh, WVa</u>	<u>Hanna, WY</u>	<u>Antelope, WY</u>	<u>Rochelle, WY</u>
SiO ₂	44.78	39.40	31.46	20.09	30.20
Al ₂ O ₃	20.89	21.80	15.92	11.17	14.09
Fe ₂ O ₃	22.65	22.79	8.97	9.25	5.87
CaO	4.40	6.55	24.86	13.87	9.32
MgO	1.20	2.10	8.86	6.37	5.97
Na ₂ O	0.51	1.45	1.38	1.90	1.91
K ₂ O	1.85	1.51	1.02	0.30	0.33
TiO ₂	1.51	1.27	0.74	1.72	2.06
P ₂ O ₅	0.52	0.40	0.58	N/A	N/A
T-250 °F	2340	2295	2190	2195	2215

5.4.4 CARBON BURNOUT AND COMBUSTION EFFICIENCY

Isokinetic particulate samples collected from the exit to the lean-quench combustor and slag samples collected from the water quench tank were chemically analyzed. Based on the carbon composition in these samples the carbon burnout/carbon combustion efficiency was determined. Table 5-10 shows the results of these analyses to be $\geq 99.99\%$.

Table 5-10
Carbon Burnout and Combustion Efficiency

<u>Test Number</u>	<u>Carbon Burnout (%)</u>	
	<u>Quenched Slag</u>	<u>Fly ash</u>
Rochelle Coal		
RO	99.990	99.990
R001A	99.994	99.998
R001B	99.993	99.995
R002	99.994	99.999
Antelope Coal		
A0	99.981	99.999
A001	99.989	99.999
A002	99.989	99.999

In Fig. 5-19, plots for the measured carbon conversion after the rich-zone combustor for the Antelope and Rochelle coals along with previous carbon conversion results from the DOE testing are displayed. It should be noted that the DOE results are based on gas analysis, while the NSP coals are based on the actual carbon content in the quenched slag.

Textron installed a CO analyzer which could measure in the ppm level. This was used on the last NSP test run (A002) for monitoring lean-zone levels. CO levels were found to be between 60 - 70 ppm at $\phi = 1.2$.

All of the above results imply that the NSP pulverized coals (95% thru 200 mesh) can be effectively burned in the pressurized slagging combustor.

5.4.5 NO_x EMISSIONS

The NSP coals evaluated in this testing contained from 0.85 to 1.6% nitrogen. If all of this nitrogen was converted to NO_x there would be exhaust emissions in the pounds per million Btu level. However, by staging the combustion the NO_x levels with the slagging combustor were minimized to ≤ 0.2 lb/MMBtu.

Fig. 5-19 Measured Primary Zone Carbon Conversions

It is known that the main source of NO in the combustion of coal is fuel-bound nitrogen. Part of the fuel nitrogen is released with the volatiles in the early stages of combustion, while the remainder is released with subsequent char oxidation. NO formation from fuel-bound nitrogen is very sensitive to the combustion stoichiometry; depending on the available O₂, the HCN and NH₃ volatilized can be oxidized to NO or can react with NO to form harmless N₂. For staged combustion to be effective we must not carry over volatile or char nitrogen to the final lean-quench zone, where they could be converted to NO. The intense and rapid mixing caused by the toroidal vortex design leads to rapid devolatilization of the coal, homogeneous combustion conditions and efficient oxidation of the char to fuel-rich gases in the primary zone. These conditions favor conversion of fuel-bound nitrogen to N₂ and minimizes the carry-over of volatile or char nitrogen to the lean-quench combustor.

Previously, TDS determined that the bulk of the NO is generated in the primary zone from the fuel-bound nitrogen. This was verified (at a $\phi = 1.2$), comparing the primary zone NO_x analyzer (~200 ppm) versus the exhaust NO_x analyzer (50 - 60 ppm). Remembering that 2/3 of the air is added in the lean-quench combustor zone; thus, if the primary zone NO formation was the only source of NO_x then this value would be reduced to 1/3 its value by dilution.

Fig. 5-20 gives a plot of NO_x emissions as a function of the rich-zone equivalence ratio (ϕ) for the NSP tests and for the pulverized coal DOE tests.

As long as the $\phi > 1.0$ the NO_x values are below the NSPS requirements of 0.6 lb MM Btu. With $\phi \geq 1.1$ the NO_x levels are < 0.2 lb/MMBtu.

Fig. 5-20 NO_x Exhaust Emissions

5.4.6 PARTICULATE EMISSIONS

Isokinetic samples collected at the exit to the lean-quench combustor were used to determine the particulate emissions levels. These fly ash samples were sent for a total quantitative analysis so as to determine the carbon burnout and the alkali concentration in the particulates.

Table 5-11 gives the emissions levels after the lean-quench combustor and also gives the collection efficiency of all particulate collection systems.

Table 5-11**Particulate Emissions Levels and Collection Efficiencies**

<u>Test Number</u>	<u>Collection Efficiency (%)</u>	<u>Emissions Levels</u>	
		<u>ppmw</u>	<u>lb/MMBtu</u>
RO	95	131	0.27
R001A	97	80	0.18
R001B	97	150	0.33
R002	99	70	0.15
A0	97	66	0.14
A001	98	115	0.25
A002	99	61	0.13

The particle size distributions of the fly ash samples were determined qualitatively by a scanning electron microscope (SEM) and quantitatively by the Malvern analyzer. From the SEM's it appears that the bulk of the particles are < 1 micron. A typical particle size distribution given by the Malvern analyzer showed a mean size around 2 microns and the top size of about 5 microns.

Based on these results, it appears that the loading of particulates, although greater than NSPS levels, are quite small in size and unlikely to cause erosion damage to the turbine blades.

5.4.7 ALKALI LEVELS

During the Rochelle test runs, a Westinghouse alkali probe was placed in the downward duct section after the lean-quench combustor and just before the orifice plate. The temperatures here were around 1200° to 1500°F. It was suggested that we might be condensing some alkali at these temperatures. During the Antelope test runs, the probe was placed just after the lean-quench combustor, where it would experience higher temperatures. After some troubleshooting, the problem was traced to a faulty regulator in the alkali probe flow control system.

The Westinghouse probe was used to determine the vapor alkali levels in the exhaust gases. The particulate alkali levels were determined by chemical analysis of the isokinetic collected fly ash. Table 5-12 gives the results of these studies.

TABLE 5- 12**Alkali Levels**

<u>Test No</u>	<u>Vapor Alkali</u> <u>ppbw</u>	<u>Particulate Alkali</u> <u>ppbw</u>
R0	11	5270
R001A	34	3420
R001B	18	9170
R002	9	7000
A0	61	5210
A001	74	9630
A002	209	7030

Except for the A002 test, all vapor alkali values measured by the Westinghouse probe were below 100 ppbw. Although not quantitative because of shakedown problems, the Ames alkali probe measurements, taken during Test A002, gave indications that the vapor alkali had an upper limit of 100 ppbw. Based on the Ames results and the short duration of sampling before apparent plugging of the Westinghouse probe, the 209 ppbw is probably not correct. In fact, all the Antelope vapor alkali results are questionable due to the apparent plugging problems experienced after short sampling periods. At best, the vapor alkali results indicate lower than expected levels which was very encouraging.

5.4.8 SO_x EMISSIONS AND SULFUR CAPTURE

A limestone sorbent was fed into the primary combustor for sulfur capture during five of the tests. The sorbent Ca/S molar ratio was run at 2 and 6. The subbituminous coals tested had a significant amount of Ca inherent with the coal; it varied from $1 < \text{Ca/S} < 2$.

Since the sulfur content of either coal was $\leq 0.4\%$ it was necessary to dilute the limestone with fly ash to allow us to feed the sorbents with any degree of accuracy. Unfortunately the fly ash contained $\sim 0.5\%$ sulfur; however, this was accounted for in analyzing the test data.

It should be noted that of the five (5) sorbent runs made, it was only possible to get meaningful data from two of them. Fortunately, there was a good sorbent run on each of the coals tested. This was not uncommon in our experience on the DOE work. It is caused by difficulty in maintaining a steady sorbent feed and in difficulty of measuring SO₂ and H₂S accurately in the limited number of experiments performed.

Unlike the DOE sponsored work at a $\phi = 1.2$ on the eastern bituminous coals, where SO₂ was the dominant sulfur specie, these tests on the NSP western subbituminous coals showed the H₂S to be the dominant specie. Although surprising, it can be understood by the fact that the peak flame temperatures in the primary zone should be significantly lower with these western coals with

high moisture content. Thermochemical equilibrium calculations tell us that as the flame temperatures decrease we should expect more H₂S to be present.

Interestingly, the sorbent injected seemed to have little effect on sulfur capture. With or without sorbent addition the sulfur capture in the primary zone was 45 to 65% and the lean/quench emissions levels showed a 30% reduction.

This is not very surprising because as the sulfur gas composition decreases in the gas phase, it becomes more difficult for it to react with the limestone; plus previous nonequilibrium sulfur capture work showed lower captures with H₂S than with SO₂.

It appeared that the inherent Ca found in these coals was causing the sulfur capture. The resulting concentration of the H₂S seems to be too low to allow for further significant reaction with the limestone sorbent fed.

Previous DOE sponsored sulfur capture work was done with the Pittsburgh seam coal which contained 7.2% ash with a 6.6% CaO content. It can only be speculated that the remaining sulfur gases are so low that the sorbent does not effectively capture it.

5.4.9 HEAT LOSS AND PRESSURE LOSS

Since the pressurized slagging combustor is water cooled, we are able to measure changes in the cooling water temperatures and thus determine the heat loss from the various stages of the system as seen in Table 5-13.

Table 5-13

Heat Loss Data

	<u>Equivalence Ratios (ϕ)</u>	
	<u>1.2</u>	<u>1.4</u>
Heat Loss in:		
Primary Zone	10%	8%
Impact Separator	7%	5%
Slagging Cyclone	11%	8%
Lean-Quench Zone	4%	5%

Transducers were used to monitor the pressure changes in the system for each of the components. Table 5-14 lists the typical pressure drops seen during the NSP testing. The total pressure drop through the lean-quench combustor was 7.9%.

Table 5-14

Combustor Subsystem Pressure Losses

<u>Component</u>	<u>Percent Pressure Loss (%)</u>
Primary Zone Air Injector	2.7
Primary Zone Nozzle & Impact Separator	2.6
Slagging Cyclone Separator	2.2
Lean-Quench Combustor	0.4

**5.4.10 COMPOSITION AND HEATING VALUE FOR FUEL-RICH
GASES PRIOR TO THE LEAN-QUENCH COMBUSTOR**

Gas samples were taken from the primary zone and from the impact separator exit. These samples were analyzed by a gas chromatograph (GC) for hydrogen, nitrogen, carbon monoxide and carbon dioxide concentrations. Table 5-15 gives these concentrations on a mole percent dry basis as measured by the GC and as a mole percent wet basis, where we have calculated the water concentration based on thermochemical equilibrium calculations at the equivalence ratio set experimentally. It should be noted that this gas obviously contains water vapor and sulfur gases. The sulfur gases are in the ppm levels and should not significantly effect the heating value calculation of the gases.

Table 5-15**Composition of Fuel-Rich Gases**

<u>Species</u>	<u>At Equivalence Ratio of 1.2</u>	
	<u>Mole (% dry)</u>	<u>Mole (% wet)</u>
H ₂	1.49	1.28
N ₂	77.39	66.64
CO	5.67	4.88
CO ₂	15.46	13.31
H ₂ O	0.0	13.89

<u>Species</u>	<u>At Equivalence Ratio of 1.25</u>	
	<u>Mole (% dry)</u>	<u>Mole (% wet)</u>
H ₂	1.55	1.32
N ₂	77.28	66.10
CO	5.91	5.06
CO ₂	15.26	13.05
H ₂ O	0.0	13.61

<u>Species</u>	<u>At Equivalence Ratio of 1.45</u>	
	<u>Mole (% dry)</u>	<u>Mole (% wet)</u>
H ₂	5.10	4.45
N ₂	70.69	61.73
CO	13.64	11.91
CO ₂	10.57	9.23
H ₂ O	0.0	12.68

Conversion of the above results to heating value results was done considering the heating values of only hydrogen and carbon monoxide. The resulting fuel heating values for the fuel-rich gases are given below in Table 5-16 as a function of the equivalence ratio. ✓

Table 5-16**Fuel Heating Values**

<u>Equivalence Ratio</u>	<u>LHV (Btu/lb)</u>	<u>Btu/SCE</u>
1.2 - 1.3	250 - 350	42 - 58
1.4	700	117

CONCLUSIONS

The subscale 12 MM Btu/hr toroidal vortex combustor has demonstrated excellent coal-fired operation at atm. All three coal fuel types have been burned successfully. As a result of this active testing the following conclusions may be drawn:

- It was possible to achieve the full design thermal capacity of 12 MM Btu/hr with the subscale slagging combustor, while burning 100% pulverized coal and operating at the design pressure of 6 atm.
- Because of the separate-chamber, rich-lean design of the subscale slagging combustor, NO_x emissions that easily meet the NSPS limits are readily achieved.
- The TDS toroidal-vortex design, subscale slagging combustor readily achieves in excess of 99% carbon burnout efficiency when 100% coal-fired.
- Ninety percent of the ash can be separated as slag in the impact separator, and 98 to 99% removed with the addition of a slagging cyclone separator.
- Objectives for third-stage exit temperature (1850°F), and exit temperature pattern factor (14%) were readily achieved.
- Overall pressure loss is 5 to 6% without cyclone separator and 7.9% with the cyclone.
- Feeding pulverized coal or sorbent into the combustor against 6 atm pressure was achieved successfully.
- Sulfur reductions in the third stage exhaust of up to 50% have been achieved.
- Vapor alkali measurements done with the Ames alkali monitor indicate that slagging cyclone separator reduces the vapor Na and K levels down to 20 - 50 ppbw.

APPENDIX A
TEST MATRIX

Table 1-A

Proposed Text Matrix for Subscale Combustor

COAL FUEL			FUEL S-CONTENT		TEST DURATION		TEST CONDITIONS
Test	Bit. PC	Bit. CWM	Subbit. PC	1%	2%	2 hrs.	5 hrs.
1	x			x		x	Baseline; varying equivalence ratio from 1.5 to 1.3 to 1.1; to determine optimum f/a for NO _x control.
2	x			x		x	Focus on optimum f/a determined from Test #1; vary f/a slightly around f/a optimum.
3	x			x		x	Par. var. injection angle to 55°.
4	x			x		x	Par. var. injector tangential angle from 0° to 10°; this adds swirl.
5	x			x		x	Par. var. sorbent feed: vary Ca/S ratio.
6	x			x		x	Par. var. sorbent injection point.
7	x				x	x	Par. var. sorbent type.
8a	x				x	x	Baseline with high sulfur coal.
8b	x				x	x	Par. var. sorbent feed: vary Ca/S ratio.
10	x			x		x	Par. var. coal feed particle size: 70% - 200 mesh.
14	x			x			Optimized conditions from prior tests.
15	x				x		Optimized conditions from prior tests.
17a			x				Baseline with subbituminous coal.
17b			x			x	Par. var. sorb. feed with subbit.; vary Ca/S ratio.

Table 1-A

Proposed Test Matrix for Subscale Combustor

COAL FUEL			FUEL S-CONTENT		TEST DURATION		TEST CONDITIONS
Test	Bit. PC	Bit. CWM	Subbit. PC	1%	2%	2 hrs.	5 hrs.
18		x		x		x	Baseline; vary equiv. ratio to opt. NO _x with CWM.
19		x		x		x	Focus on optimum f/a with CWM.
20		x		x		x	Para. var. inj. angle with CWM.
22		x		x		x	Para. var. sorbent type with CWM.
24		x		x		x	Para. var. sorbent type with CWM.
25a		x			x	x	Baseline high sulfur CWM.
25b		x			x	x	Par. var. sorb. feed with high 5 CWM; vary Ca/S ratio.
26		x			x	x	Par. var. air preheat temp. (800+°F).
27		x			x	x	Par var. coal feed part. size with CWM: 70% thru 200 mesh.
28		x			x	x	Par var.: residence time with CWM.
31		x		x			Optimized conditions from prior tests with CWM.
32		x			x		Optimized conditions from prior tests with CWM.
34a			x			x	Baseline, subbit. CWM.
34b			x			x	Var. sorbent feed to subbit. CWM.

Table 1-A	
Proposed Text Matrix for Subscale Combustor	
Additions to Test Matrix	Slagging Cyclone Separator Testing
	Slag Tapping Testing
	Char Carryover Testing
	Sulfur Capture While Slag Tapping
	Alkali Measurements with/without Sulfur Capture
CL Series	
SL Series	
CR1 Series	
SL1 Series	
SL2 Series	
SL3 Series	

END

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