ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

DE-AC22-95PC95143--14

TECHNICAL PROGRESS REPORT NO. 14
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ABSTRACT

A High Performance Power System (HIPPS) is being developed. This system is a coal-fired, combined cycle plant with indirect heating of gas turbine air. Foster Wheeler Development Corporation and a team consisting of Foster Wheeler Energy Corporation, Bechtel Corporation, University of Tennessee Space Institute and Westinghouse Electric Corporation are developing this system. In Phase 1 of the project, a conceptual design of a commercial plant was developed. Technical and economic analyses indicated that the plant would meet the goals of the project which include a 47 percent efficiency (HHV) and a 10 percent lower cost of electricity than an equivalent size PC plant.

The concept uses a pyrolysis process to convert coal into fuel gas and char. The char is fired in a High Temperature Advanced Furnace (HITAF). The HITAF is a pulverized fuel-fired boiler/air heater where steam is generated and gas turbine air is indirectly heated. The fuel gas generated in the pyrolyzer is then used to heat the gas turbine air further before it enters the gas turbine.

The project is currently in Phase 2 which includes engineering analysis, laboratory testing and pilot plant testing. Research and development is being done on the HIPPS systems that are not commercial or being developed on other projects. Pilot plant testing of the pyrolyzer subsystem and the char combustion subsystem are being done separately, and after each experimental program has been completed, a larger scale pyrolyzer will be tested at the Power Systems Development Facility (PSDF) in Wilsonville, AL. The facility is equipped with a gas turbine and a topping combustor, and as such, will provide an opportunity to evaluate integrated pyrolyzer and turbine operation.

This report addresses the areas of technical progress for this quarter. A general arrangement drawing of the char transfer system was forwarded to SCS for their review. Structural steel drawings were used to generate a three-dimensional model of the char transfer system including all pressure vessels and major piping components. Experimental testing at the Combustion and Environmental Test Facility continued during this quarter. Performance of the char burner, as benchmarked by flame stability and low NOx, has been exceptional. The burner was operated successfully both without natural gas and supplemental pulverized coal.

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EXECUTIVE SUMMARY

The High Performance Power System is a coal-fired, combined cycle power generating system that will have an efficiency of greater than 47 percent (HHV) with NO_x and SO_x less than 0.025 Kg/GJ (0.06 lb/MMBtu). This performance is achieved by combining a coal pyrolyzation process with a High Temperature Advanced Furnace (HITAF). The pyrolyzation process consists of a pressurized fluidized bed reactor which is operated at about 926^{o}C (1700^{o}F) at substoichiometric conditions. This process converts the coal into a low-Btu fuel gas and char. These products are then separated.

The char is fired in the HITAF where heat is transferred to the gas turbine compressed air and to the steam cycle. The HITAF is fired at atmospheric pressure with pulverized fuel burners. The combustion air is from the gas turbine exhaust stream. The fuel gas from the pyrolyzation process is fired in a Multi-Annular Swirl Burner (MASB) where it further heats the gas turbine air leaving the HITAF. This type of system results in very high efficiency with coal as the only fuel.

We are currently in Phase 2 of the project. In Phase 1, a conceptual plant design was developed and analyzed both technically and economically. The design was found to meet the project goals. The purpose of the Phase 2 work is to develop the information needed to design a prototype plant which would be built in Phase 3. In addition to engineering analysis and laboratory testing, the subsystems that are not commercial or being developed on other projects will be tested at pilot plant scale. The FWDC Second-Generation PFB pilot plant in Livingston, NJ, has been modified to test the pyrolyzer subsystem. The FWDC Combustion and Environmental Test Facility (CETF) in Dansville, NY, has been modified to test the char combustion system. Integrated operation of a larger scale pyrolyzer and a commercial gas turbine are planned for the PSDF in Wilsonville, AL.

A more detailed design of the char transfer system has been completed for the PSDF in Wilsonville, AL. Structural steel drawings were received from SCS and used to generate a three-dimensional model of the pressure vessels and major process piping. The transfer system was designed to support the technical requirements of both the HIPPS and PFB projects. Although the total mass flow of char is the same under both test programs, the particle size distribution of the char is quite different. The system was initially designed to provide an isolation boundary between the oxidizing and reducing environments. In order to maintain this isolation boundary, a three hopper design was proposed. SCS is in the process of reviewing this arrangement and will comment with respect to overall cost, safety, and physical layout.

In an effort to expedite the char combustion tests at the CETF, a data analysis program was written to assess on-line heat and material balance closure. The HIPPS char burner test program utilizes flue gas recycle to simulate gas turbine exhaust, and as such, introduces some complexity to the more typical “once through” data analysis. The on-line heat and material balance continually checks all process parameters (pressures, flows, temperatures) and verifies steady state setpoint periods. During this period the ball mill was operated successfully, after some minor repair, and produced a consistent and even char particle size distribution. The char burner operated with a stable flame and low overall NOx without the support of natural gas or supplemental pulverized coal.

Slag samples were removed from the furnace in an effort to determine its effect on overall water wall heat transfer. The thermal properties of the slag can be used to define the boundary conditions for future CFD analysis.

INTRODUCTION

In Phase 1 of the project, a conceptual design of a coal-fired high performance power system was developed, and small scale R&D was done in critical areas of the design. The current Phase of the project includes development through the pilot plant stage, and design of a prototype plant that would be built in Phase 3.

Foster Wheeler Development Corporation (FWDC) is leading a team of companies in this effort. These companies are:

- Foster Wheeler Energy Corporation (FWEC)
- Bechtel Corporation
- University of Tennessee Space Institute (UTSI)
- Westinghouse Electric Corporation

The power generating system being developed in this project will be an improvement over current coal-fired systems. Goals have been identified that relate to the efficiency, emissions, costs and general operation of the system. These goals are:

- Total station efficiency of at least 47 percent on a higher heating value basis.
- Emissions:

  NO_x < 0.06 lb/MMBtu
  SO_x < 0.06 lb/MMBtu
  Particulates < 0.003 lb/MMBtu

- All solid wastes must be benign with regard to disposal.
- Over 95 percent of the total heat input is ultimately from coal, with initial systems capable of using coal for at least 65 percent of the heat input.

The base case arrangement of the HIPPS cycle is shown in Figure 1. It is a combined cycle plant. This arrangement is referred to as the All Coal HIPPS because it does not require any other fuels for normal operation. A fluidized bed, air blown pyrolyzer converts coal into fuel gas and char. The char is fired in a high temperature advanced furnace (HITAF) which heats both air for a gas turbine and steam for a steam turbine. The air is heated up to 760°C (1400°F) in the HITAF, and the tube banks for heating the air are constructed of alloy tubes. The fuel gas from the pyrolyzer goes to a topping combustor where it is used to raise the air entering the gas turbine to 1288°C (2350°F). In addition to the HITAF, steam duty is achieved with a heat recovery steam generator (HRSG) in the gas turbine exhaust stream and economizers in the HITAF flue gas exhaust stream.

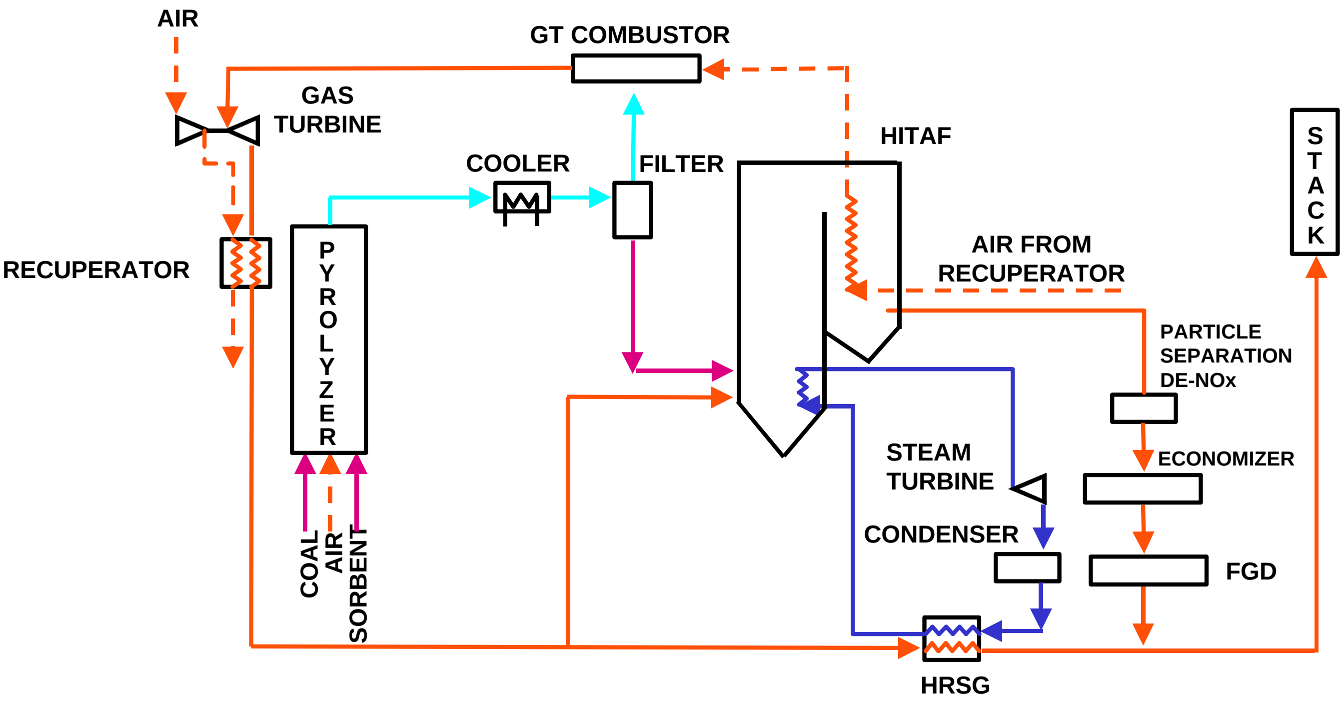

Figure 1 All Coal Fired HIPPS

MT81026a

An alternative HIPPS cycle is shown in Figure 2. This arrangement uses a ceramic air heater to heat the air to temperatures above what can be achieved with alloy tubes. This arrangement is referred to as the 35 percent natural gas HIPPS, and a schematic is shown in Figure 2. A pyrolyzer is used as in the base case HIPPS, but the fuel gas generated is fired upstream of the ceramic air heater instead of in the topping combustor. Gas turbine air is heated to 760^oC (1400^oF) in alloy tubes the same as in the All Coal HIPPS. This air then goes to the ceramic air heater where it is heated further before going to the topping combustor. The temperature of the air leaving the ceramic air heater will depend on technological developments in that component. An air exit temperature of 982^oC (1800^o F) will result in 35 percent of the heat input from natural gas.

A simplified version of the HIPPS arrangement can be applied to existing boilers. Figure 3 outlines the potential application of the HIPPS technology for repowering existing pulverized coal fired plants. In the repowering application, the gas turbine exhaust stream provides the oxidant for co-fired combustion of char and coal. The existing boiler and steam turbine infrastructure remain intact. The pyrolyzer, ceramic barrier filter, gas turbine, and gas turbine combustor are integrated with the existing boiler to improve overall plant efficiency and increase generating capacity.

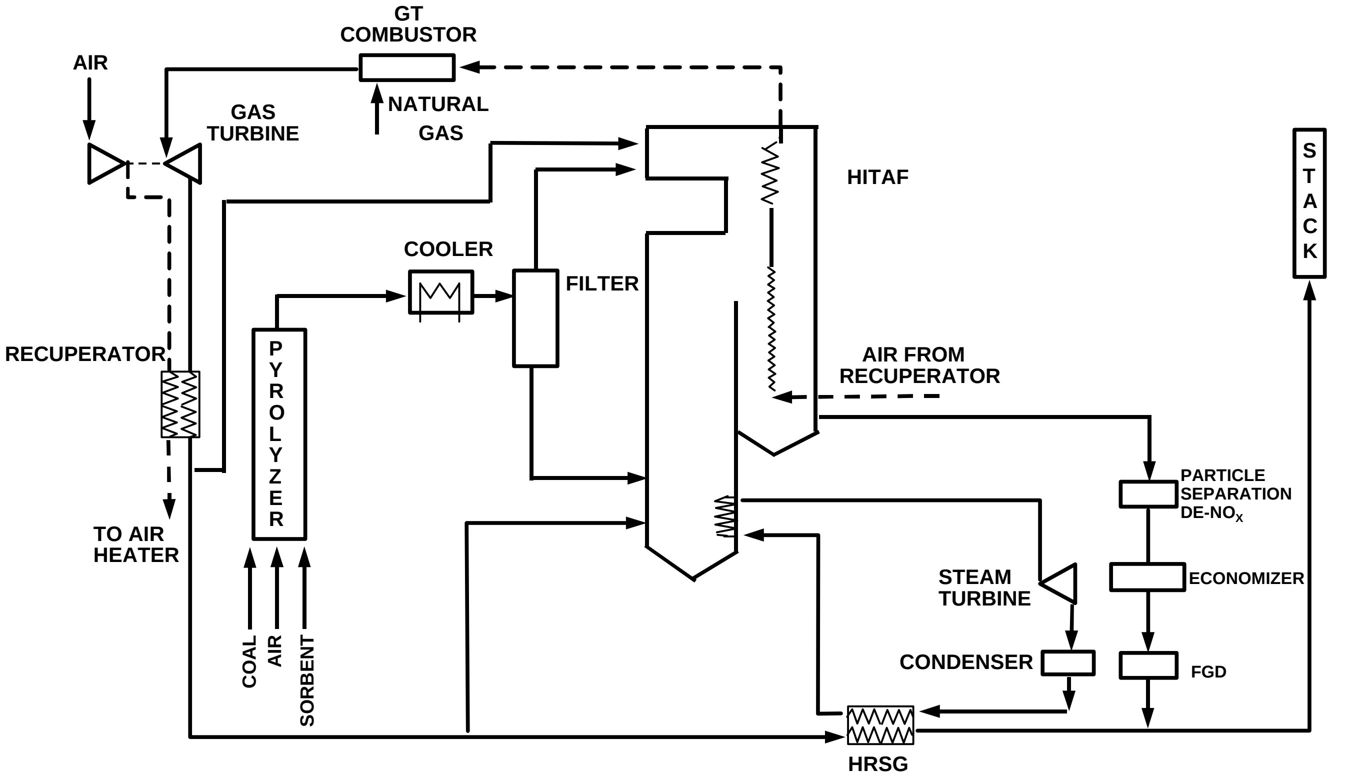

Figure 2   35-Percent Natural Gas HIPPS

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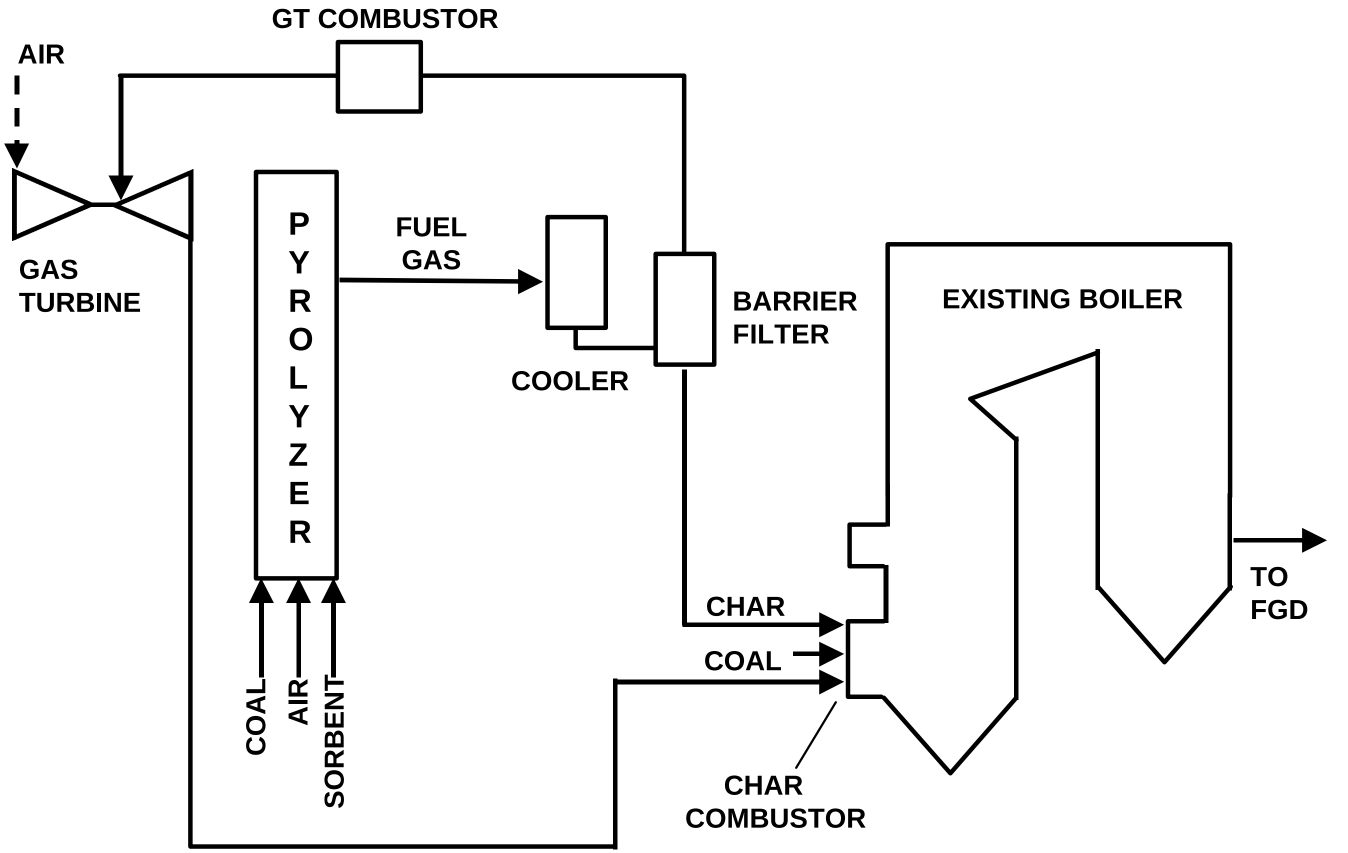


Figure 3 Simplified HIPPS Repowering Process Flow Diagram

TECHNICAL PROGRESS

Task 1 - Project Planning and Management

Work is proceeding in accordance with the Project Plan.

Task 2 – Engineering Research and Development

Subtask 2.1 –Furnace Slag Analysis (Enhanced CFD Analysis)

Slag pieces (Figure 4) were taken from the CETF furnace in early June, 1998 in order to characterize the CETF wall conditions for HIPPS testing. The chemical and thermo-physical property information of the slag may be used for HIPPS test data evaluation including CFD analysis where it is applicable. Sample number one in Figure 4 was a heavy molten slag (Lab reference #98068). This sample would be found in regions where there are high temperatures. The second “fried” slag piece was divided into two samples distinguished as a sintered slag (Lab reference #980689) and a fused slag (Lab reference #980690). The “fried” slag would be found in regions of lower temperatures.

The analyses that were performed at FWDC included Fluorescent X-ray analysis, X-ray Diffraction analysis, Energy Dispersion X-ray (EDX) analysis, and ash fusion temperature analysis. The thermal conductivity of the heavy molten slag was determined at Thermophysical Properties Research Laboratory (TPRL), Inc.

Fluorescent X-ray analysis was used to indicate the different elements in their highest oxidation states that exist after the samples were heated and oxidized. As noted in Tables 1, 2, and 3, the largest oxide compounds found were silicon dioxide, aluminum oxide, and ferric oxide. X-ray Diffraction analysis determined the crystalline compounds present in the raw samples by matching the peaks of the diffracted energy at different diffraction angles. Silicon oxide and kaolinite and illite clays were present in all of the samples. Energy Dispersion X-ray (EDX) analysis was performed in order to determine the elements present in the raw samples. EDX is an elemental analysis that indicates the presence of a particular element, either in a free or compound form, by noting the intensity of the response at an element’s identifying electron volt (eV) energy level when an X-ray is directed at the sample. Elements are generally present in varying levels at different locations within a sample. Therefore, the EDX analyses were performed at surface and interior locations. The EDX analyses confirmed the results of the Fluorescent X-ray analysis by noting the presence of silicon, aluminum, and iron.

Ash fusion temperatures were determined for the three samples in reducing and oxidizing atmospheres (Table 4). The molten and fused slags have lower fusion temperatures in the reducing atmosphere than in the oxidizing atmosphere because of the larger quantities of iron that exist in the sample.

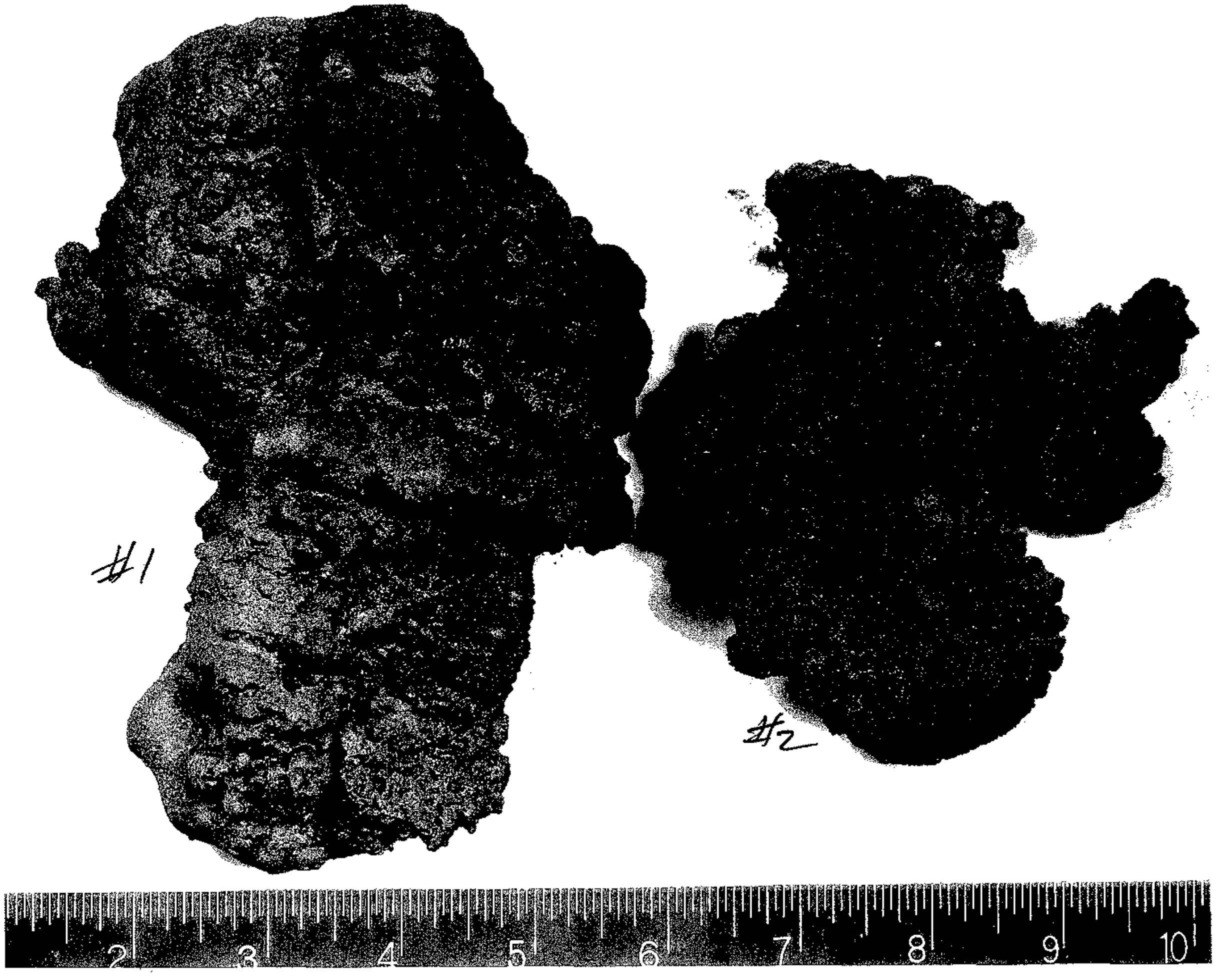
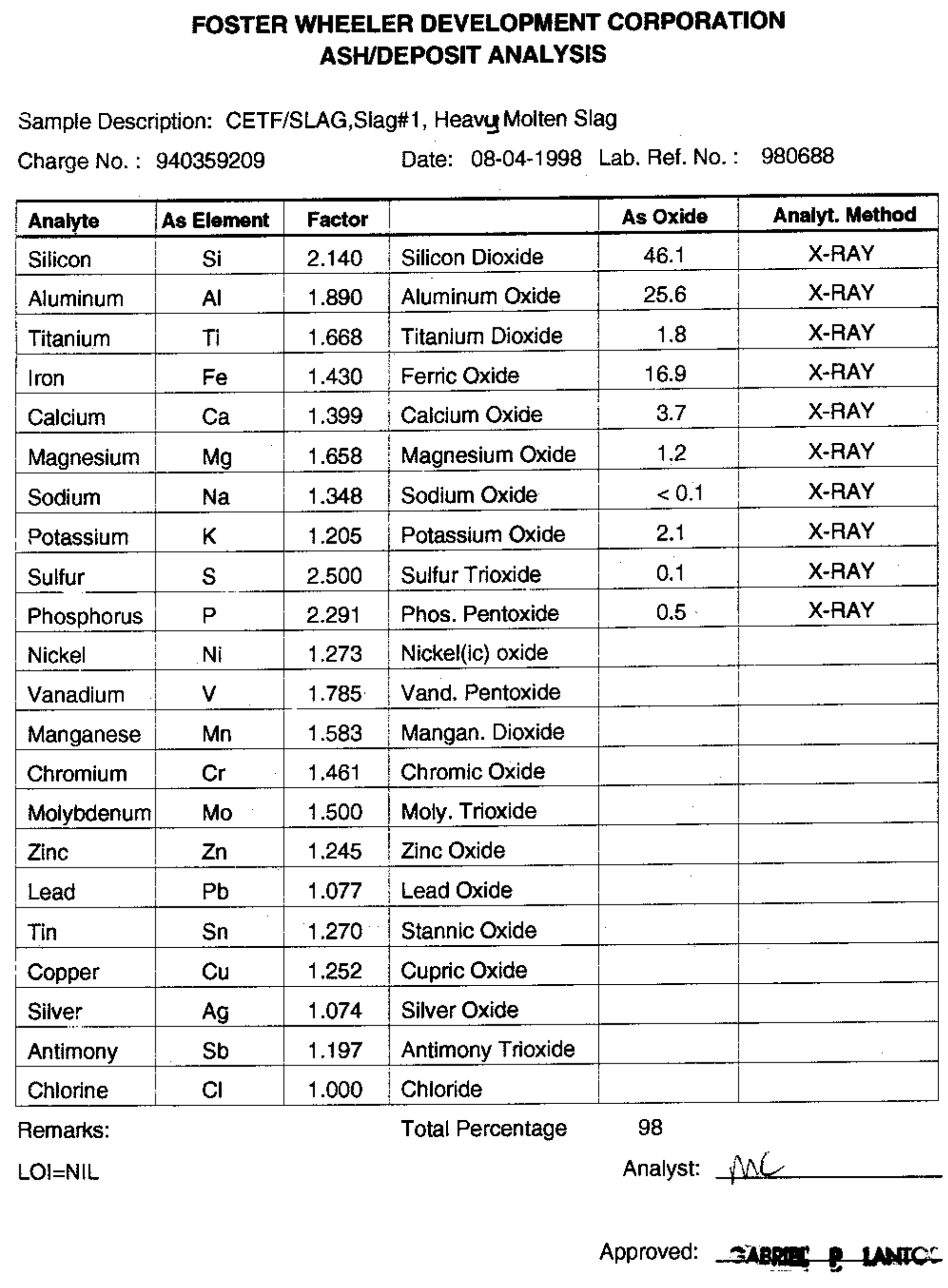


Figure 4 Slag Pieces from CETF Furnace



FOSTER WHEELER DEVELOPMENT CORPORATION
ASH/DEPOSIT ANALYSIS

Sample Description: CETF/SLAG,Slag#1, Heavy Molten Slag

Charge No. : 940359209 Date: 08-04-1998 Lab. Ref. No. : 980688

Analyte	As Element	Factor		As Oxide	Analyt. Method
Silicon	Si	2.140	Silicon Dioxide	46.1	X-RAY
Aluminum	Al	1.890	Aluminum Oxide	25.6	X-RAY
Titanium	Ti	1.668	Titanium Dioxide	1.8	X-RAY
Iron	Fe	1.430	Ferric Oxide	16.9	X-RAY
Calcium	Ca	1.399	Calcium Oxide	3.7	X-RAY
Magnesium	Mg	1.658	Magnesium Oxide	1.2	X-RAY
Sodium	Na	1.348	Sodium Oxide	< 0.1	X-RAY
Potassium	K	1.205	Potassium Oxide	2.1	X-RAY
Sulfur	S	2.500	Sulfur Trioxide	0.1	X-RAY
Phosphorus	P	2.291	Phos. Pentoxide	0.5	X-RAY
Nickel	Ni	1.273	Nickel(ic) oxide		
Vanadium	V	1.785	Vand. Pentoxide		
Manganese	Mn	1.583	Mangan. Dioxide		
Chromium	Cr	1.461	Chromic Oxide		
Molybdenum	Mo	1.500	Moly. Trioxide		
Zinc	Zn	1.245	Zinc Oxide		
Lead	Pb	1.077	Lead Oxide		
Tin	Sn	1.270	Stannic Oxide		
Copper	Cu	1.252	Cupric Oxide		
Silver	Ag	1.074	Silver Oxide		
Antimony	Sb	1.197	Antimony Trioxide		
Chlorine	Cl	1.000	Chloride		

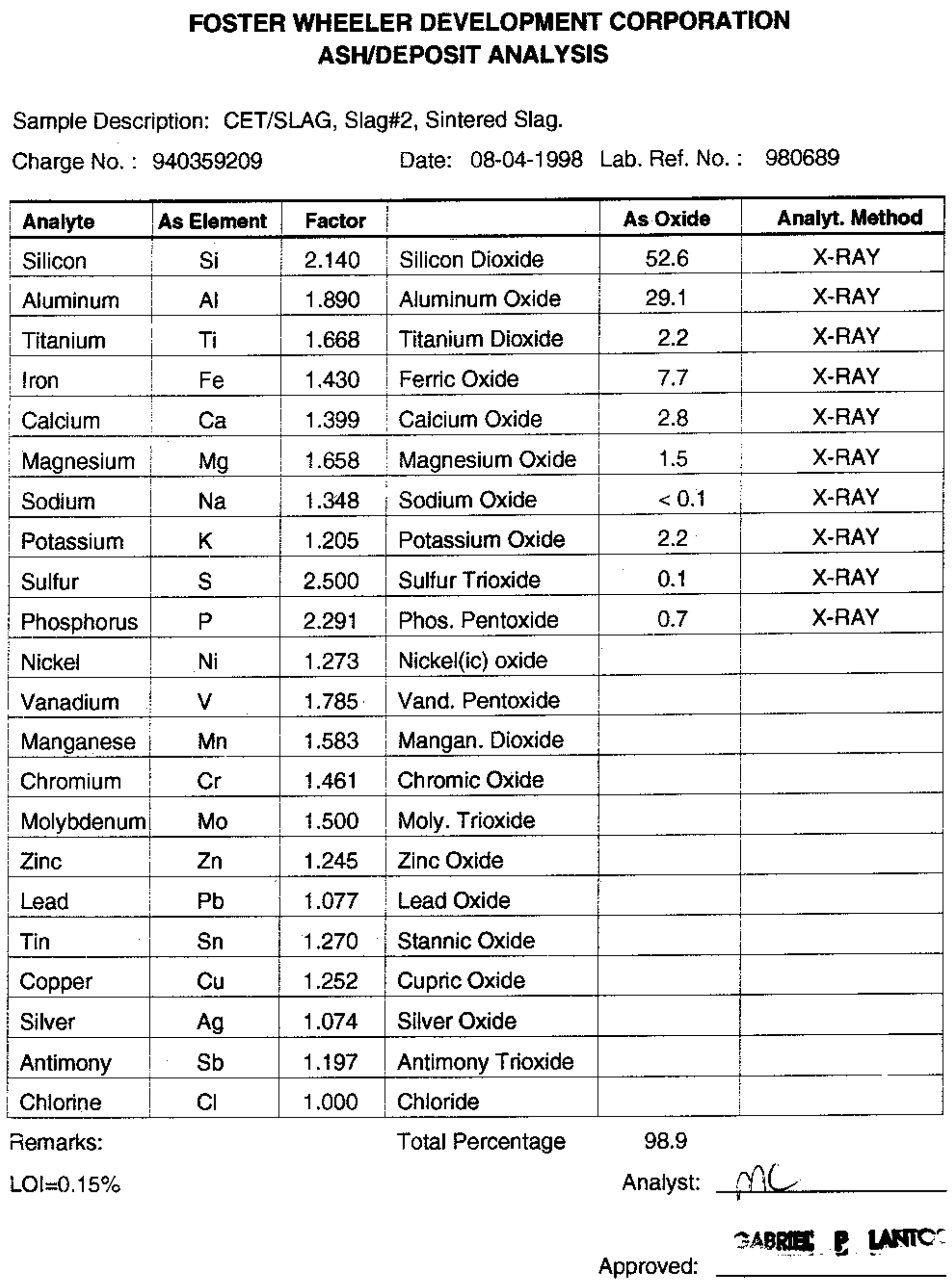
Remarks: Total Percentage 98

LOI=NIL

Analyst: MC

Approved: GABRIEL P. LANTOC

Table 1 Chemical Composition of Furnace Slag (Heavy Molten)



FOSTER WHEELER DEVELOPMENT CORPORATION
ASH/DEPOSIT ANALYSIS

Sample Description: CET/SLAG, Slag#2, Sintered Slag.

Charge No. : 940359209 Date: 08-04-1998 Lab. Ref. No. : 980689

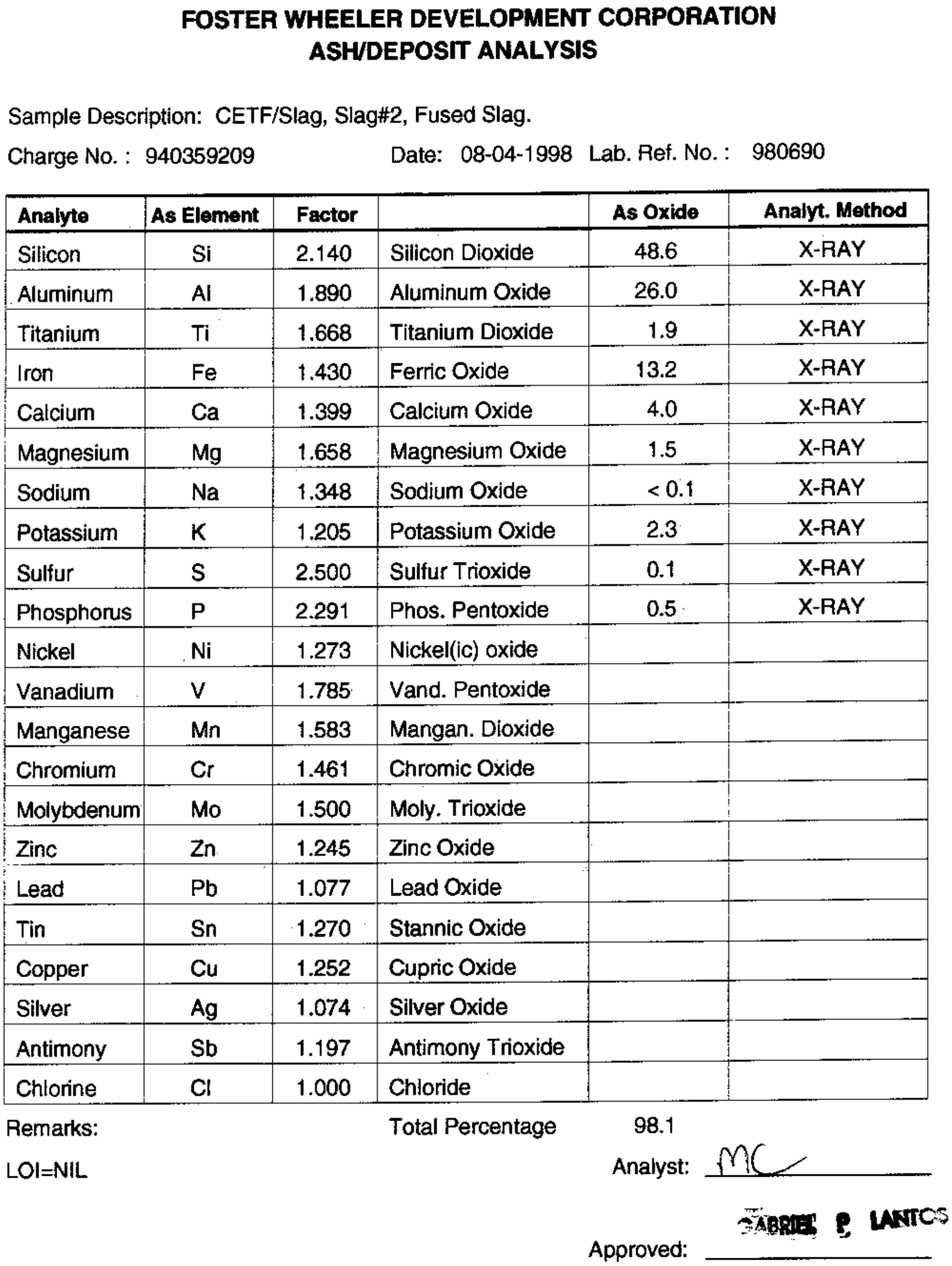
Analyte	As Element	Factor		As Oxide	Analyt. Method
Silicon	Si	2.140	Silicon Dioxide	52.6	X-RAY
Aluminum	Al	1.890	Aluminum Oxide	29.1	X-RAY
Titanium	Ti	1.668	Titanium Dioxide	2.2	X-RAY
Iron	Fe	1.430	Ferric Oxide	7.7	X-RAY
Calcium	Ca	1.399	Calcium Oxide	2.8	X-RAY
Magnesium	Mg	1.658	Magnesium Oxide	1.5	X-RAY
Sodium	Na	1.348	Sodium Oxide	< 0.1	X-RAY
Potassium	K	1.205	Potassium Oxide	2.2	X-RAY
Sulfur	S	2.500	Sulfur Trioxide	0.1	X-RAY
Phosphorus	P	2.291	Phos. Pentoxide	0.7	X-RAY
Nickel	Ni	1.273	Nickel(ic) oxide		
Vanadium	V	1.785	Vand. Pentoxide		
Manganese	Mn	1.583	Mangan. Dioxide		
Chromium	Cr	1.461	Chromic Oxide		
Molybdenum	Mo	1.500	Moly. Trioxide		
Zinc	Zn	1.245	Zinc Oxide		
Lead	Pb	1.077	Lead Oxide		
Tin	Sn	1.270	Stannic Oxide		
Copper	Cu	1.252	Cupric Oxide		
Silver	Ag	1.074	Silver Oxide		
Antimony	Sb	1.197	Antimony Trioxide		
Chlorine	Cl	1.000	Chloride		

Remarks: Total Percentage 98.9

LOI=0.15% Analyst: mC

Approved: GABRIEL P LANTC

Table 2 Chemical Composition of Furnace Slag (Sintered Slag)



FOSTER WHEELER DEVELOPMENT CORPORATION
ASH/DEPOSIT ANALYSIS

Sample Description: CETF/Slag, Slag#2, Fused Slag.

Charge No. : 940359209 Date: 08-04-1998 Lab. Ref. No. : 980690

Analyte	As Element	Factor		As Oxide	Analyt. Method
Silicon	Si	2.140	Silicon Dioxide	48.6	X-RAY
Aluminum	Al	1.890	Aluminum Oxide	26.0	X-RAY
Titanium	Ti	1.668	Titanium Dioxide	1.9	X-RAY
Iron	Fe	1.430	Ferric Oxide	13.2	X-RAY
Calcium	Ca	1.399	Calcium Oxide	4.0	X-RAY
Magnesium	Mg	1.658	Magnesium Oxide	1.5	X-RAY
Sodium	Na	1.348	Sodium Oxide	< 0.1	X-RAY
Potassium	K	1.205	Potassium Oxide	2.3	X-RAY
Sulfur	S	2.500	Sulfur Trioxide	0.1	X-RAY
Phosphorus	P	2.291	Phos. Pentoxide	0.5	X-RAY
Nickel	Ni	1.273	Nickel(ic) oxide		
Vanadium	V	1.785	Vand. Pentoxide		
Manganese	Mn	1.583	Mangan. Dioxide		
Chromium	Cr	1.461	Chromic Oxide		
Molybdenum	Mo	1.500	Moly. Trioxide		
Zinc	Zn	1.245	Zinc Oxide		
Lead	Pb	1.077	Lead Oxide		
Tin	Sn	1.270	Stannic Oxide		
Copper	Cu	1.252	Cupric Oxide		
Silver	Ag	1.074	Silver Oxide		
Antimony	Sb	1.197	Antimony Trioxide		
Chlorine	Cl	1.000	Chloride		

Remarks: Total Percentage 98.1

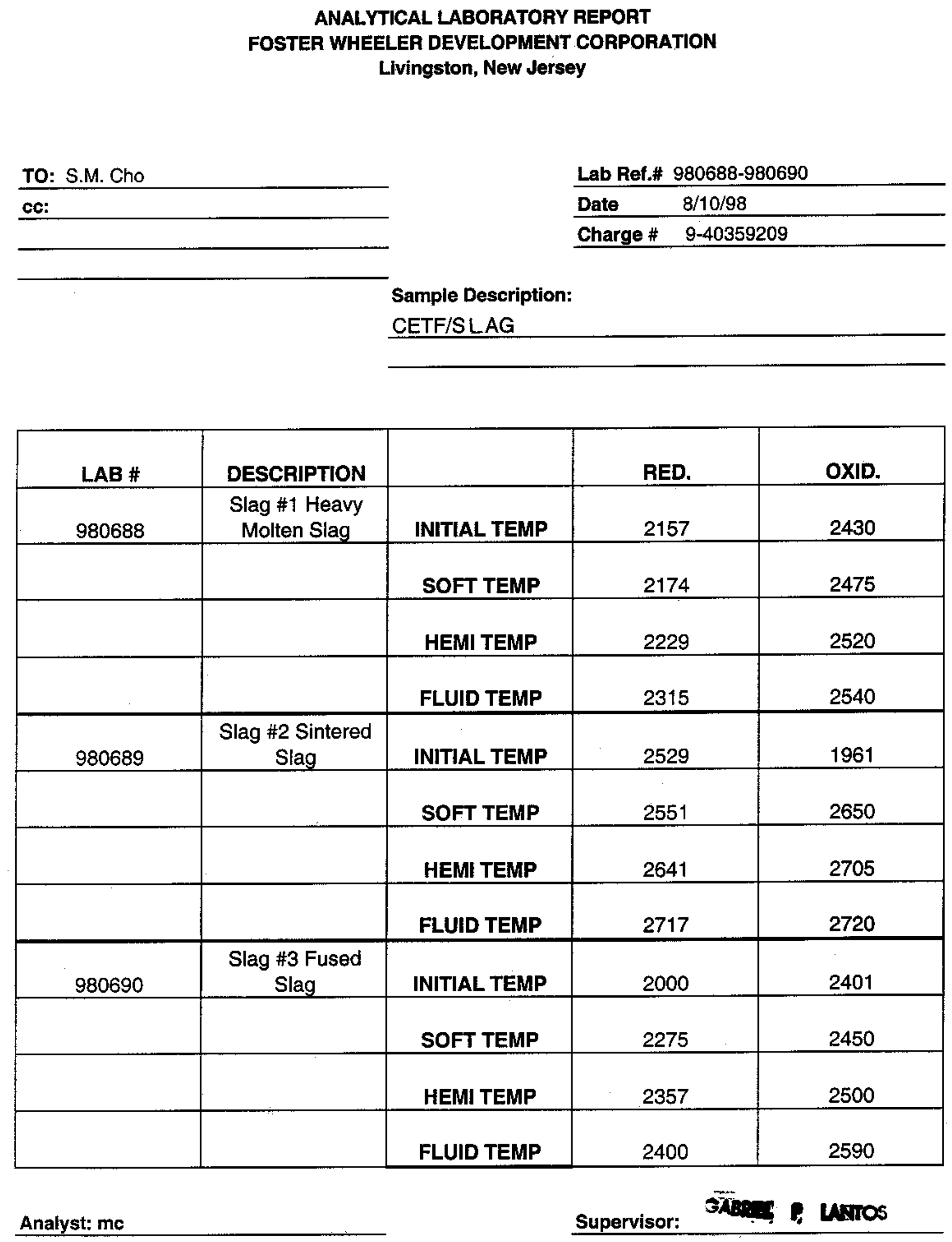
LOI=NIL

Analyst: MC

Approved: GABRIEL P LANTOS

Table 3 Chemical Composition of Furnace Slag (Fused Slag)

Finally, thermal diffusivity and specific heat properties of the molten slag sample were measured at TPRL in order to determine its thermal conductivity. Figure 5 and Figure 6 of the TPRL report indicate the differences in thermal diffusivity and specific heat as the sample is heated or cooled as well as the non-linear effect with temperature. Figure 7 is the calculated thermal conductivity of the sample. This information can be used when specifying CFD boundary conditions.



ANALYTICAL LABORATORY REPORT
FOSTER WHEELER DEVELOPMENT CORPORATION
Livingston, New Jersey

TO: S.M. Cho
cc:

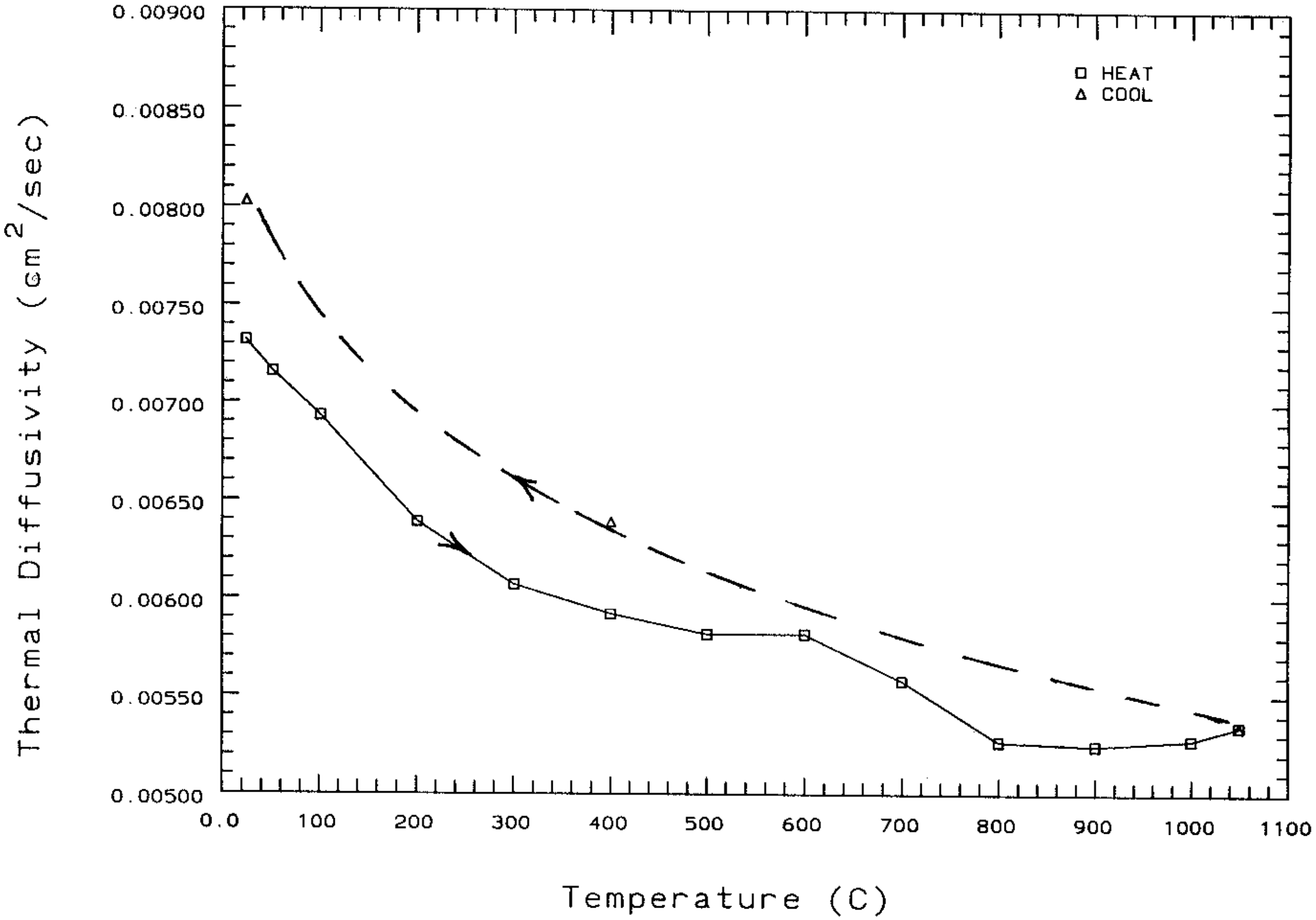
Lab Ref.# 980688-980690
Date 8/10/98
Charge # 9-40359209

Sample Description:
CETF/SLAG

LAB #	DESCRIPTION		RED.	OXID.
980688	Slag #1 Heavy Molten Slag	**INITIAL TEMP**	2157	2430
		SOFT TEMP	2174	2475
		HEMI TEMP	2229	2520
		FLUID TEMP	2315	2540
980689	Slag #2 Sintered Slag	**INITIAL TEMP**	2529	1961
		SOFT TEMP	2551	2650
		HEMI TEMP	2641	2705
		FLUID TEMP	2717	2720
980690	Slag #3 Fused Slag	**INITIAL TEMP**	2000	2401
		SOFT TEMP	2275	2450
		HEMI TEMP	2357	2500
		FLUID TEMP	2400	2590

Analyst: mc
Supervisor: GABRIEL P. LANTOS

Table 4 Furnace Slag Softening Characteristics



Plot 1 Thermal Diffusivity

Figure 5 Thermal Diffusivity of Furnace Slag

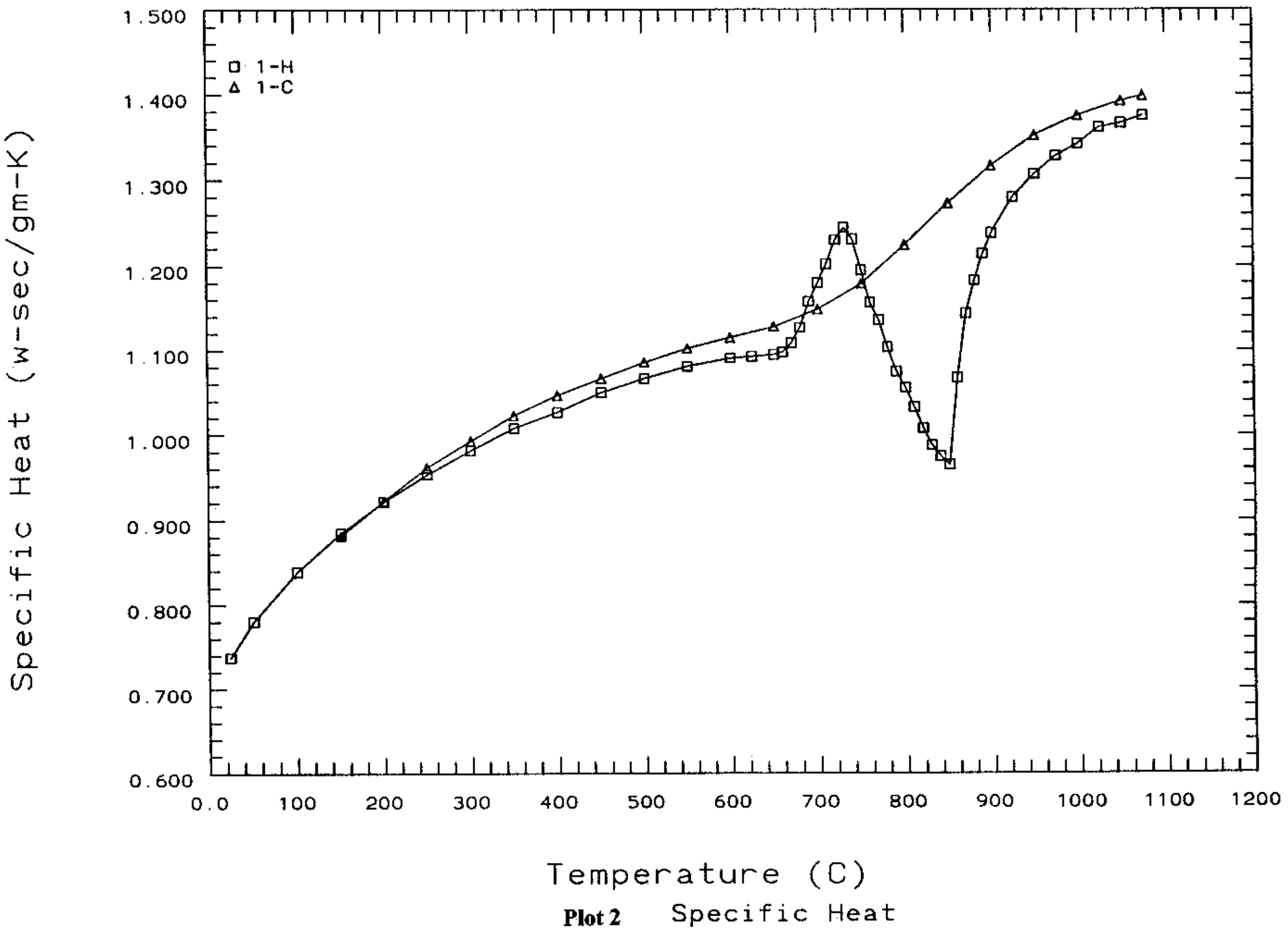
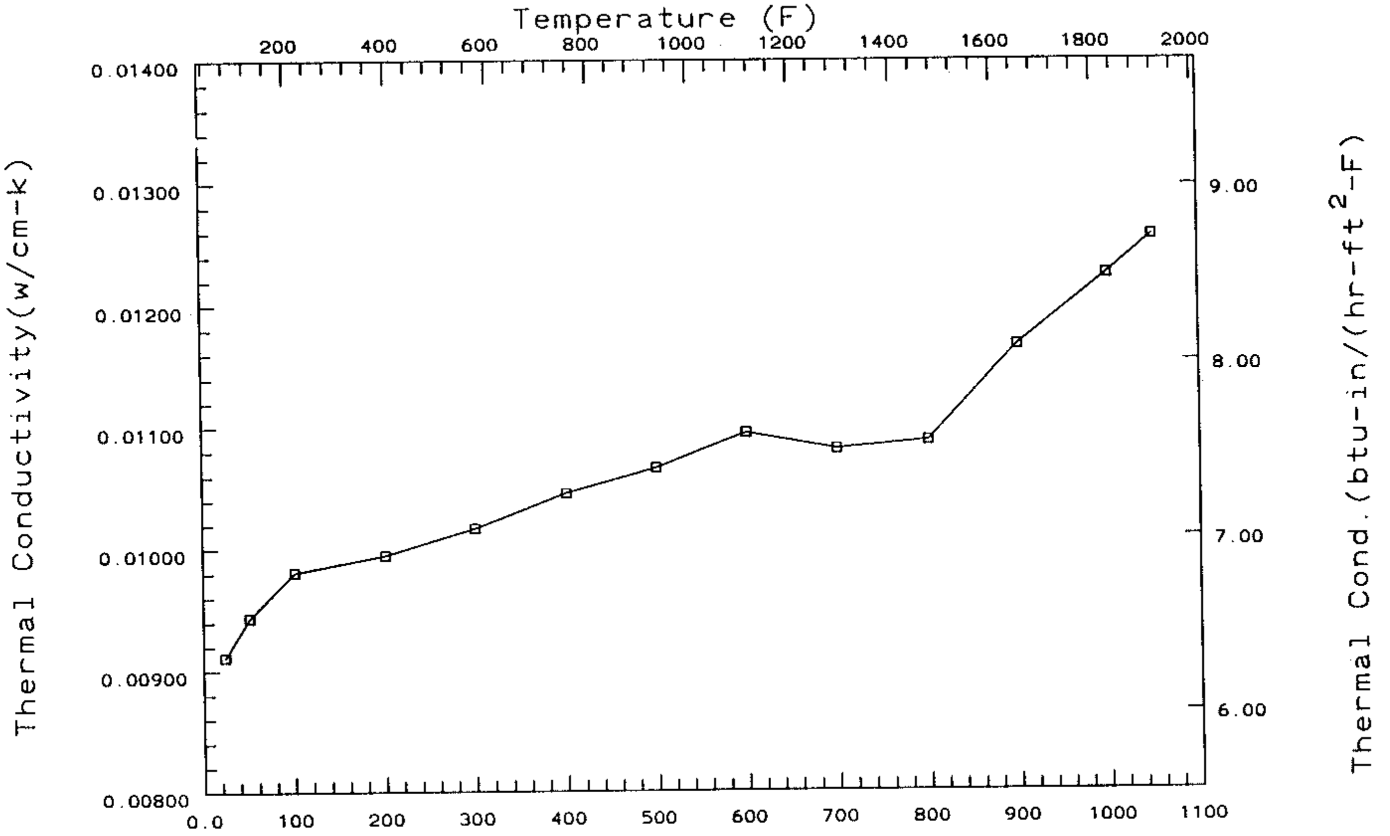


Figure 6 Specific Heat of Furnace Slag



Temperature (C)

Plot 3 Thermal Conductivity

Figure 7 Thermal Conductivity of Furnace Slag

Task 3 - Subsystem Test Unit Design

Subtask 3.3 – Wilsonville Pilot Plant Design

The Power Systems Development Facility (PSDF) in Wilsonville, Alabama is to be used to support the objectives of both the PFB and HIPPS programs. A modified char transfer system has been designed to replace the existing N-Valve arrangement currently installed. During this quarter a general arrangement of a lock hopper system was developed as an alternative to the N-Valve. The following process assumptions were made:

1. Maximum Char Flowrate = 2,500 lbs./hr.
2. Char Bulk Density = 20 lbs./ft3.
3. Maximum Syngas Cooler Outlet Temperature = 1300 Deg. F.
4. Feed Hopper Outlet Temperature = < 500 Deg. F.
5. Lock/Surge Hopper Cycle Time = 30 minutes
6. Vessel Design Criteria = 300 psig @ 650 Deg. F.
7. Complete isolation of oxidizing and reducing environments.

Figure 8 depicts the plan and elevation layout of the proposed char transfer system. Under HIPPS operating conditions, the cyclone and bed overflow nozzles are removed, and all of the generated char is carried over into the candle filter. Assuming a nominal char generation rate of 2,500 lbs./hr., this solids loading defined the design basis for the candle filter system. Under PFB operation only half of the generated char exits the cyclone and enters the candle filter. The candle filter was designed with a “candle catcher” system to provide a means to remove broken candles on-line. The candle catcher is comprised of a small section of pipe immediately under the filter vessel. Under normal operation this section of pipe would be filled with fine char material and fluidized to develop a uniform pressure drop. Any broken candle fragments falling into this section of pipe would displace the char material, altering its pressure drop profile, and thus signaling the presence of broken candle pieces.

The design of the char transfer system was established to provide complete isolation between the oxidizing and reducing environments. In order to accomplish this separation between the two environments, a series of three lock hoppers needed to be installed. The pressure of the lower feed hopper is independently controlled to follow the pressure of the PFB. The intermediate lock hoppers for the candle filter drain and the cyclone and overflow drain are used to convey the material from the higher pressure of the pyrolyzer system to the lower pressure of the feed hopper. It should be noted that the operation of the lower feed hopper is different between the HIPPS and PFB programs. Under HIPPS operation, the generated char feedstock is very fine (appx. 80% thru 200 mesh) and needs to be fluidized in order to effectively fill the rotary valve. The HIPPS feed hopper incorporates a flat bottom fluidized design. Under PFB operation, due to the coarser particle size distribution, a packed bed will be maintained with a conical bottom.

In addition to the char transfer system, a number of other modifications will need to be made to the facility in support of the HIPPS program. A sand feed injection system will need to be installed. Modifications will also need to be made to the existing coal and limestone feed systems to improve their performance with feeding pulverized feedstocks (70% thru 200 mesh).

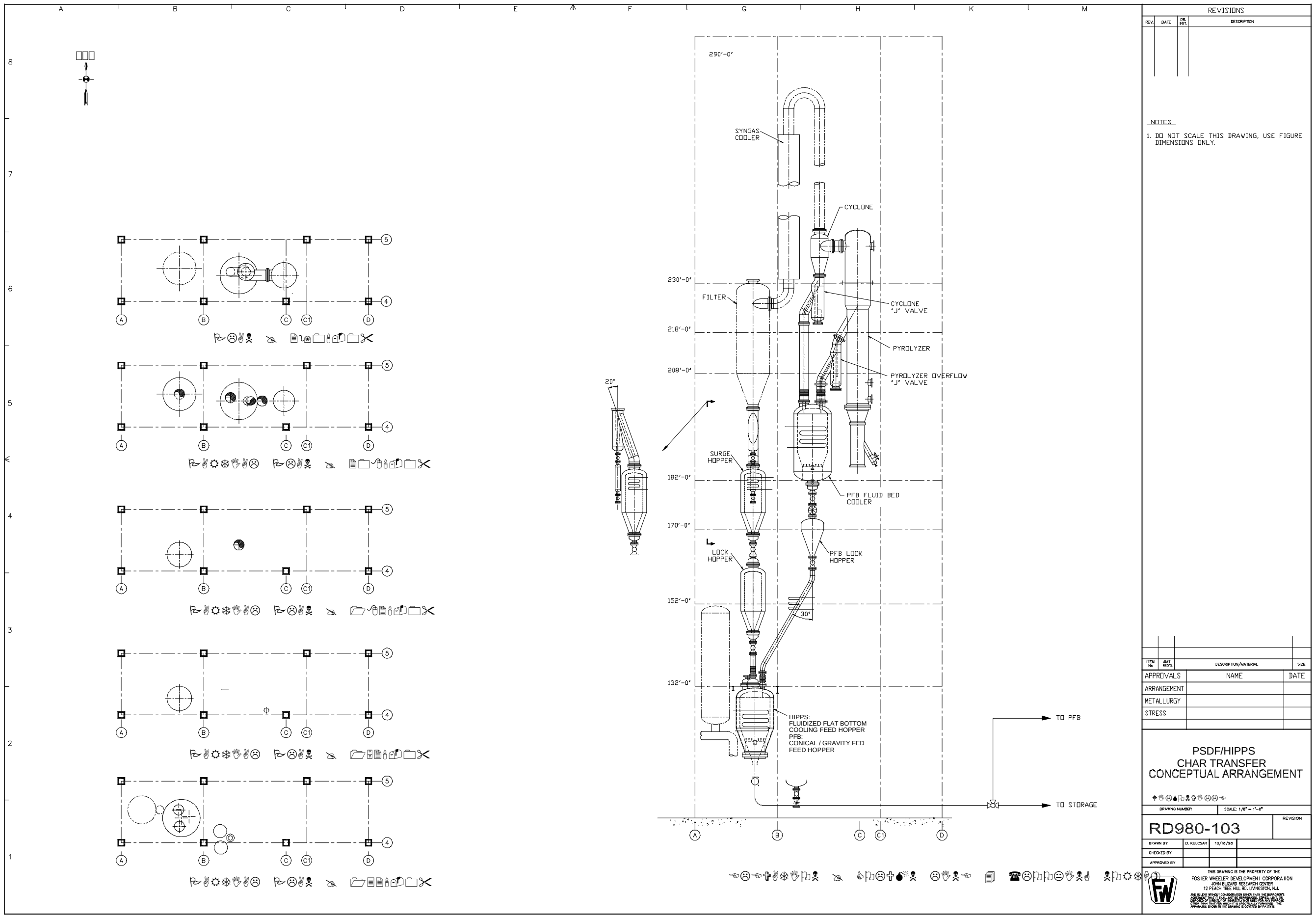


Figure 8 General Arrangement Drawing (Wilsonville – Plan & Elevation)

Task 4 - Subsystem Test Unit Construction

No work was performed under this task for this quarter.

Task 5 – Subsystem Test Unit Testing

Subtask 5.2 – Char Combustion System Testing

During the last quarter, phase one of the system shakedown at the Combustion and Environmental Test Facility (CETF) was completed, which included calibration and checkout of system instrumentation. With this task completed, system components were started up and tested during this quarter. Systems tested this quarter include the following:

1. Furnace Fans and Main Gas Igniter
2. Furnace Safety Interlocks and Integrated Operation
3. Duct Burner
4. Char Milling System
5. Char Storage and Delivery System
6. Pulverized Coal Delivery System
7. Flue Gas Reheat Burner
8. Data Analysis

Subtask 5.2.1 – Furnace Fans and Main Gas Igniter

The furnace Forced Draft (F.D.) and Induced Draft (I.D.) fans were tested and airflow through the furnace was established. The required airflow for testing was attained and the various dampers that divert air from the windbox were tested through their respective ranges. The airflows diverted from the windbox include; Burner Air, Tertiary Air, Over Fire Air, Igniter Air, Lower Windbox Upper Air Wall, Lower Windbox Middle Air Wall, and Lower Windbox Lower Air Wall.

The main gas igniter was fired, and no problems were found with this system. The igniter output was varied from ~5 MMBtu/hr to ~20 MMBtu/hr.

Subtask 5.2.2 – Furnace Safety Interlocks and Integrated Operation

During this phase of shakedown, the Master Fuel Trip (MFT) was tested to verify proper configuration of the Distributed Control System (DCS). The MFT is configured to shut off all fuel to the furnace in the event of flame loss or other dangerous furnace conditions. Coupled with the MFT, is built in logic in the DCS that prevents some systems from operating without other systems in operation. For instance, the Char Feed System can not start without the Main Igniter in service. These interlocks were also tested during shakedown this quarter.

For ease of operation, several of the motors and fans that compose many of the subsystems have integrated start/stop functions programmed into the DCS. These subsystems include the Char Feed System, Coal Feed System and the Main Igniter System, as well as other systems which were tested during this phase of shakedown.

Subtask 5.2.3 – Duct Burner

During this second phase of shakedown testing, we were able to ramp the Duct Burner up to a temperature of 800ºF in the windbox, and successfully maintain this setpoint. This is critical for achieving conditions similar to that of turbine exhaust gas in the windbox. Figure 9[a] shows a "snapshot" of the firing of the duct burner from data recorded during this period.

A temperature gradient between the upper and lower sections of the windbox was detected and additional thermocouples were employed to compensate flow measurement to these areas of the windbox.

Note: [a] – refer to Attachment 2

Subtask 5.2.4 – Char Milling System

Some concern was raised over the relatively low bulk density of the char and how the Foster Wheeler Model D2A Ball Mill located at the CETF would operate. During this quarter, small batches of char were milled successfully to support shakedown of the Char Storage and Delivery System. Figure 10[a] shows the operation of the mill from data recorded during one of these runs.

Iso-kinetic fineness measurements from these small batches indicated the target fineness of 85% < 200 mesh (75 μm) was attainable. Minor problems were detected with feeding the char from the mill storage silo to the mill. To eliminate these feeding problems, modifications were made on the mill weighfeeder to accommodate the lower density char. The manufacturer of the feeder was brought in to troubleshoot this problem and the modifications included side skirts and a compaction plate.

Note: [a] – refer to Attachment 2

Subtask 5.2.5 – Char Storage and Delivery System

The char was successfully pneumatically transported from the ball mill to the Char Silo and from the silo to the Char Burner. The Char Silo Baghouse operated as designed, pulsing when fuel is entering or leaving the silo, and prevented any fine material from exhausting the silo. A minor leak was detected on the roof of the silo around a pressure relief hatch during silo filling. The manufacturer was contacted and a stronger spring was installed on the relief hatch.

The char weighfeeder feed rate was ramped from 0 – 3000 #/hr, with 3000 #/hr being the target feed rate for testing. The feeder operated fine and the supporting rotary air locks, that deliver the fuel to the feeder from the silo, and from the feeder to the transport line, were able to support this flow rate.

The transport blower that delivers the char to the Char Burner also proved adequate at supplying the required amount of head to transport the fuel the required distance.

During one of these shakedown tests, the char fed to the furnace was burned unsupported. This was done to test the combustion performance of the char. The conditions in the furnace allowed the flame to be stable, however, a test of long duration wasn't achieved as char flow ran out before much data could be gathered. Figure 11[a] shows some of the data recorded for this test.

Note: [a] – refer to Attachment 2

Subtask 5.2.6 – Pulverized Coal Delivery System

This system takes pulverized coal from a one ton super sack and pneumatically transports it to the burner. The feed auger and rotary air lock that deliver the fuel from the feed hopper to the transport line operated correctly, and were able to supply coal steadily at all speeds. The transport blower was capable of transporting the fuel pneumatically to the Char Burner.

Subtask 5.2.7 – Flue Gas Reheat Burner

A concern during testing is the dew point of the fluegas entering the baghouse. A Flue Gas Reheat Burner was designed to keep the baghouse above the dew point during testing. The burner was tested this quarter and was able to keep the baghouse above the dew point during furnace start up and shut down.

Subtask 5.2.8 – Data Analysis

The characterization of the burner and combustion equipment performance versus load and excess air is the goal of the testing to be done at the CETF. To accomplish this, a methodology of test data analysis was devised. System heat and material balances are performed as well as emissions reporting and mill performance calculations. Attachment 1 outlines the data reduction analysis being performed for the HIPPS Burner testing.

The program interfaces with the data historian, which collects and stores all instrument inputs from the plant every second. Attachment 2 identifies and explains all the major analog inputs monitored for this program. The operator enters the test point criteria and the program displays damper settings, air flow splits, vane positions, etc. that are required for the test.

Constantly monitoring the plant conditions, the program alerts the operator when a parameter is out of the specified range for the test point. Once the test is completed, a test summary is printed out which gives a quick description of the test to allow the operators and test engineers to decide which direction testing should proceed in.

Matrix testing will commence next quarter to characterize the performance of the Char Burner.

Attachment 1

Data Analysis

DATA REDUCTION for HIPPS TEST at CETF

INTRODUCTION

Any combustion test has to result in the characterization of the burner/combustion equipment performance (stability and emissions) vs. load and excess air. This performance is critical both for commercial and environmental reasons. To this end, a methodology of test data analysis shall minimize the effect of measurements' errors on the outcome of the test and has to provide a means to alert the investigator in case any significant (unacceptable) discrepancies have occurred. That is why, good and typical combustion test methodology involves direct calculations of the combustion material balance supplemented by a reverse calculation, based on flue gas and fly/bottom ash chemical analysis. For example, assume that we know all fuel constituencies and the mass of the air, required for complete combustion of 1 Lb. of fuel or theoretical air (L_{TH}). Then, for measured fuel rate (M_f) and total combustion air (Q_{TA}), supplied to a combustion chamber, one may obtain an excess air , which we refer to as "a excess air by direct measurements":

$$X_S^{DIR} = \left(\frac{Q_{TA}}{M_f L_{TH}} - 1 \right) \times 100 \quad \%, \quad Eq.(1)$$

On the other hand, the excess air may be obtained by the gas analysis data. This analysis is typically performed on dry basis in terms of <u>volumetric concentrations of the gaseous combustion products.</u> (Analysis on the dry basis excludes some uncertainty related to variable moisture sources).
Assuming a complete fuel burn out (for simplicity of the example only), we may calculated Xs based on oxygen concentration in flue gas [O2 % vd] recommended by B&W [1]:

$$X_S^{GA} = \left[\frac{N_2}{N_2 - 3.76 \times O_{2,vd}} - 1 \right] \times 100 \quad \%, \quad Eq.(2)$$

Where:

N_2 - is the volume concentration of nitrogen in dry air.

If the difference between values of excess air, determined by two independent measurements is in a reasonably good agreement, then the particular test data are deemed to be reliable. The same general approach for HIPPS test data reduction shall be used in order to attain a high confidence level of the test results. All necessary calculations and procedures are described hereafter.

1.1. Oxygen Requirements for Complete Combustion

<u>A. Oxygen balance</u>. Based on the ultimate char and coal analysis the number of Lb.-moles of oxygen, required for complete combustion of one (1) pound of fuel is determined by the following expression:

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[1] This formula applies for the isochoric reactions only, such as carbon combustion in the air and assumes no unburned fuel. For any solid or liquid hydrocarbon fuel a combustion reaction and material balance on the dry basis (i.e. as measured by analyzers) might be written as follows:

$C_nH_mO_k$+(n+m/4−k/2)*[O_2+3.76*N_2]+X_s*[O_2+3.76*N_2] = n CO2 +Xs*O2 +(n+m/4)*(1+Xs) *3.76*N2
4.76*(**n+m/4-k/2+Xs)** moles 4.76*(n+m/4-k/2+Xs)-m/4, mole (on the dry basis)
Here Xs is a fraction of total mole of air required by fuel combustion stoichiometry. In cases of char or low volatile fuel combustion, moisture in the flue gases approaches to minimum (lim $\mathbf{m} \rightarrow 0$), and thus Eq. (2) becomes more accurate.

$$M_{O_2} = \sum_{i=1}^{n} \frac{[C_i]}{\mu_i} \times A_{st,i} = \left(\frac{[C]}{12.011} + 0.5 \times \frac{[H_2]}{2.016} + \frac{[S]}{32.066} - \frac{[O_{2,f}]}{31.999} \right) \quad \text{,Eq. (3)}$$

where:

i=1,…,n - an **i**-th component of the coal analysis;

[Ci], μi - mass concentration and molecular weight of the **i**-th component in fuel (brackets [ ] indicate mass concentration)

Ast,i - stoichiometric coefficient for **i**-th component.

When sorbent for SO_2 reduction is introduced into the furnace, some additional moles of oxygen will be required, regardless of the type of sorbent ($CaCO_3$, $NaHCO_3$ or CaO):

$$\Delta M_{O2}^{SORB} = 0.5 * \frac{[S_2]}{32.066}, \quad \text{Eq. (3a)}$$

From Eq.(3) and (3A) one may derive to the number Lb.-mole of air or other oxidizing medium, such as vitiated air, required for complete combustion of fuel:

$$M_{ox} = \frac{M_{O_2} + \Delta M_{O_2}^{SORB}}{O_{2\,ox}} \quad , \quad \text{Eq. (4).}$$

Here O_{2ox} - is the volume concentration of oxygen in the oxidizing media (air or vitiated air). This equation allows us to obtain required theoretical mass of a given oxidizing media for the complete fuel burn out

$$L_{TH,i} = 394 \times \rho_0 \times M_{ox,}, \quad \text{Lbs/Lb} \qquad \text{Eq. (5)}$$

Where:

394 – volume of one mole of gaseous substance at 77 F and 14.695 PSIA, also known as Avagadro Number (22.4 m^3/kg-mole).

ρ_o – density of air or other oxidizing media at standard conditions determines by equation

$$\rho_o = \left(\sum_{i=1}^{n} C_i * \mu_i \right) / 394 \,, Eq.(6)$$

i=1,…n – an ***i***-th constituent of the vitiated air;

C_i, μ_i – volume concentration and molecular weight of the ***i***-th vitiated air constituent

Natural gas combustion is widely used in the current program to generate an oxidizing media. Thus, we also need a formula similar to Eq. (3) to obtain number of Lb-moles of oxygen required for complete combustion of one pound of natural gas, based on mass concentration of hydrocarbons [CnHm] and other combustibles found in it:

$$M_{O_2} = \sum_{i=1}^{k} \frac{[C_n H_m]_i}{\mu_i} \times (n_i + \frac{m_i}{4}) + 0.5 \times \left(\frac{[CO]}{28.010} + \frac{[H_2]}{2.016} \right) + 1.5 \times \frac{[H_2 S]}{34.082} - \frac{[O_{2,f}]}{31.999}, \quad \text{Eq. (7),}$$

where stoichiometric coefficients for hydrocarbons reactions of oxidation are expressed as

$$\left(n_i + \frac{m_i}{4} \right)$$

As we can see from expression (6), the vitiated air density presents an additional process variable. Indeed, we control oxygen content and temperature of the vitiated air by means of air and flue gas mixing and complementary natural gas firing. Other concentrations of components in the oxidizing media depend on the actual unit performance, in particular, O_2 in the flue gas, moisture in the air and fuel, as well as moisture evaporated from the bottom ash pit and temperature of the flue gas leaving unit. Thus, we need to develop some specific and detailed procedures to account for stream component balances in order to verify stoichiometric conditions of a particular test.

1.2. Material Balance of Combustion

The HIPPS-CETFflow diagram is shown in Figure 12. As it shows, we have several means to determine the components of the vitiated air :

a. Multi-point measurements of the volumetric concentrations of components by mass-spectrometer (wet basis).
b. CEMs multi-point measurements of the volumetric concentrations on the dry basis.
c. In-situ analyzers which include 1) single point measurements in the upper and lower windboxes of the wet oxygen $\{O_{2,UPW}, O_{2,LWW}\}$, 2) multi-point carbon dioxide probe $\{CO_{2,\ W}\}$after in-duct burner, 3) single point measurements of the wet oxygen and carbon dioxide $\{O_{2,W\text{-}S}, CO_{2,W\text{-}S}\}$in the flue gas before leaving unit (in stack and before stack).

Some major conventions regarding notations for flows measured, calculated and obtained through reverse calculations are presented below. For *other notations* not shown hereafter see Attachment 2.

m_i^{TH} -any theoretical flow obtain by calculations;

Q_i^* -measured flow with the density compensation due to variable constituencies;

Q_i -measured flow with the standard density compensation (pressure, temperature);

$\overline{m}_i$ -calculated flow

$\tilde{m}_i$ -flow obtained by back or reverse calculations

1.2.1. Combustion Material Balance Based on Mass-Spectrometry

Mass-spectrometry provides all concentrations of the vitiated air components, as well as ones for flue gas constituencies after gas-cooler and before entering stack. Thus, by exploiting Eq. (4) and Eq. (6) for measured vitiated air constituencies, we obtain a theoretical mass flow of vitiated air for complete char and coal combustion:

$$m_{VA}^{TH} = \frac{394 \times \rho_{0,2} \times \left(B_{CH} M_{O2}^{CH} + B_C M_{O2}^{C}\right)}{O_{2,W}^{VA}}, \qquad \text{Eq. (8)}$$

Here $\rho_{0,2}$, $O_{2,W}^{VA}$ - are vitiated air density and average oxygen volume concentration after duct burner[2].

All air flow measurements at CETF are based on differential pressure ΔP and involve typical pressure, temperature and humidity (through air density) compensation as shown in the equation below

$$Q_i = 3600 \times k \times A \times \sqrt{2g \times \Delta P \times r_{o,i} \times \frac{To * (P_B + P_1)}{T_1 * Po}}, Eq.(9)$$

Where:

k – flow sensor correction factor (equal 1 for “Air Monitor” Volu-Probe)

A – area of flow in the cross section where device is installed

T,P – temperature and pressure correspondingly. Indexes “0” and “1” denotes standard and actual flow conditions

As mentioned above, the major flows measured under the HIPPS project at the CETF are mostly mixtures of air and flue gas, or so called vitiated air. Thus, in additon to typical pressure, temperature and moisture compensation, these measurements require correction due to variable flow constituencies (e.g. density) and shall employ Eq.(6). In some cases, where direct measurements of components are not available some calculations were implemented as shown below.

Initial mixing of flue gas recirculation and pure air occurs in the airheater, before the secondary air duct flow measuring device. In order to provide the variable components correction for this mass flow measurement, we have to consider material balance of oxygen between airheater and downstream of duct burner. Thus we may write a system of equations based on mass oxygen concentrations[3]:

$$Q_R^* \times \left[O_{2,W}^{FG}\right] + \bar{m}_{air} \times \left[O_{2,W}^{AIR}\right] - Q_{NG} \times L_{O2,NG}^{TH} = Q_{VA}^* \times \left[O_{2,W}^{VA}\right] \text{, Eq.(10)}$$

$$Q_{VA}^* = Q_R^* + \bar{m}_{air} + Q_{NG}, \text{ Eq.(11)}$$

By substitution of the vitiated air mass in Eq. (10) from (11) we obtain a mass flow of air that entered the unit

$$\bar{m}_{air} = \frac{Q_R^* \times ([O_{2,W}^{VA}] - [O_{2,W}^{FG}]) + Q_{NG} \times (L_{O2,NG}^{TH} + [O_{2,W}^{VA}])}{\left([O_{2,W}^{AIR}] - [O_{2,W}^{VA}]\right)}, \text{ Eq.(12)}$$

This calculated flow along with measured recirculation flow is used to determine actual vitiated air density before in-duct burner. Density of the pure air is also corrected by moisture content in the air based on the current relative humidity and pressure.

$$r_{0,1} = \frac{r_R \times Q_R^* + r_{air} \times \bar{m}_{air}}{Q_R^* + \bar{m}_{air}}, \text{ Eq.(13)}$$

Applying this density to the mass flow measuremets in the secondary air duct we obtain the total mass of vitiated air (Q_{VA}^*) introduced into boiler by using Eq. (9). The accuracy of above calculation may be verified by means of back calculated recirculation mass flow:

$$\tilde{m}_R = Q_{VA}^* - \bar{m}_{air},$$

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[2] Due to natural fluctuation of the vitiated air oxygen concentration in the lower and upper windboxes its average represents a weighted average of correspondent oxygen analyzer readings and measured flow split.

[3] Oxygen mass concentrations in the following equations presented in rectangular brackets and obtained through correspondent volumetric measurements.

Eq.(14)

If difference between air flows accounted by equations (14) and measured flue gas recirculation is in reasonable agreement, then all related measurements are correct.

Having all significant components accounted for, we then may correct measured re-circulation flow by its density, exploiting Eq. (7) and (9). Following the routine defined above by Eq.(10) through (12), we derive the air flow rate introduced into unit. As before, we may verify the pure air flow introduced into unit by using Eq.(12) and Eq.(14).

It should be also mentioned, that another alternative exists to verify either pure air flow rate introduced into unit or heat release in the air duct, by accounting for a heat balance of the vitiated air flow before and after duct burner:

$$\tilde{m}_{NG} \times LHV = T_{V,\Sigma} \times \dot{M}_{VA} \times \sum_{I=1}^{n} [Ci] \times c_{p,i}(T_{V,\Sigma}) - T_{VA,1} \times \left\{ \begin{array}{l} \dot{M}_{R} \times \sum_{I=1}^{n} [Ci] \times c_{p,i}(T_{VA,1}) + \\ + \dot{M}_{A} \times \sum_{j=1}^{k} [Cj] \times c_{p,i}(T_{VA,1}) \end{array} \right\}, Eq.(14a)$$

Triple verification assures not only actual rates of stream introduced into the unit, but some related measurements, such as natural gas flows, that as previous CETF experience shows, hold potential sources of errors. If difference between measured natural gas flow and calculated by above equation is in a reasonably good agreement, then all measurements are correct. Based on verified natural gas flow, we now may obtain the density of the actual vitiated air entering the windbox, since it will be affected by the duct burner.

For all flows inside lower and upper windboxes and for recirculation flow we have all necessary data for correction by variable density and may account for actual flows by equations, that are structured as Eq.(9)[4]. Based on available measurements and the above calculations we will be able to obtain excess air defined mostly by direct measuremants similar to Eq.(1):

$$X_{S}^{DIR} = \left\{ \frac{Q_{R}^{*} + \bar{m}_{air} + Q_{NG} + \left(Q_{CH}^{TR} + Q_{CL}^{TR} + Q_{SRB}^{TR} + Q_{PLANT}\right) \times \frac{[O_{2,W}^{air}]}{[O_{2,W}^{VA}]}}{M_{VA}^{TH}} - 1 \right\} \times 100\ \%,\ Eq.(15)$$

Or based on oxygen balance for available mass flow measurements

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[4] All correction factors (k) for all ΔP based flow measurements calculated based on STD air density (P_o=29.92 in Hg, T_o=77°F and relative humidity RH_o=60%)

$$X_S^{DIR} = \left\{ \frac{\left(Q_R^* + \bar{m}_{air} + Q_{NG}\right)\times\frac{\left[O_{2,W}^{VA}\right]}{100} + \left(Q_{CH}^{TR} + Q_{CL}^{TR} + Q_{SRB}^{TR} + Q_{PLANT}\right)\times 0.232}{31.9988 * \left(B_{CH}\times M_{O2,CH}^{TH} + B_{CL}\times M_{O2,CL}^{TH}\right)} - 1 \right\}\times 100\%, Eq.(15a)$$

To ensure reliability of the test result, the data reduction incorporates the direct excess air verification by means of comparison with the one obtained through flue gas analysis data.

1.2.2. Excess Air Based on Mass-Spectrometry Analysis

All concentrations reported by the Mass Spectrometer are measured on a wet basis. For a given barometric pressure and relative humidity the mass/volume ratio of oxygen and nitrogen is determined. Since all nitrogen introduced into process is not undergoing any significant changes, it typically serves as a basis to determine actual excess air in the process. By definition, the excess air is a ratio of an actual (V^{AC}_{air}) and theoretical (V^{TH}_{air}) air required for complete fuel combustion. If one assumes no significant effects of the atmospheric nitrogen conversion into oxides or fuel nitrogen, then the following excess air expression is true:

$$Xs = \frac{V_{air}^{AC}}{V_{air}^{TH}} = \frac{N_2}{N_2^{TH}}, Eq.(16)$$

In case of combustion <u>in regular air</u> one may express the theoretical nitrogen as a difference $N_2^{TH} = N_2 - N_{2,Xs}$, and N_2 through its equivalent oxygen $^{79}/_{21}*O_2$, we obtain familiar Eq.(1) (See Introduction to this chapter):

$$Xs = \left[\frac{N_{2,d}}{N_{2,d} - 3.76\cdot O_{2,d}^{GA}} - 1\right]\times 100\,\% = \left[\left(1 - 3.76\cdot\frac{O_{2,d}^{GA}}{N_{2,d}}\right)^{-1} - 1\right]\times 100\,\%,\ Eq.(17)\,.$$

Notice, that nitrogen-to-oxygen ratio in the vitiated air is a variable, then above equation must be used in the most generic form:

$$Xs = \left[\left(1 - \frac{N_{2,d}^{VA}}{O_{2,d}^{VA}}\cdot\frac{O_{2,d}^{GA}}{N_{2,d}}\right)^{-1} - 1\right]\times 100\,\%, \qquad \text{Eq.(17A)}$$

The major idea of the Eq.(17) is to express the oxygen concentration in the flue gas as a fraction of invariable nitrogen in pure air. Since nitrogen volume (concentration) in flue gas differs from pure air it shall be adjusted and for complete combustion might be presented as follows

$$N_{2,w} = 100\,\% - (O_2 + CO_2 + SO_2 + H_2O)$$

Thus, in case of complete combustion we may rewrite Eq (17A) and substitute measured concentrations on wet basis by correspondent dry values as

$$Xs = \left[\left(1 - m\cdot\frac{O_{2,d}^{GA}}{100 - O_{2,d}^{GA} - CO_{2,d}^{GA} - SO_{2,d}^{GA}}\right)^{-1} - 1\right]\times 100\,\%, \quad \text{Eq.(17B)}$$

Where:
$m=N_2^{VA}/O_2^{VA}$- major characteristics of the vitiated air expressed as the volume percent on the dry basis.

Since combustion of char and coal practically is never complete, presence of the incomplete combustion products will result in seemingly higher excess air accounted by Eq.(17B) vs. the one suggested by a direct flow measurements accounted by Eq.(15). It is obvious, that for different burner settings and equal fuel and air flows, an oxygen analyzer in the flue gas will see "higher" $O^{GA}_{2,d}$, due to lesser oxygen consumption. Indeed, the presence of the incomplete combustion products suggests an oxygen increase, which is directly proportional to concentrations of the incomplete combustion products and stoichiometry coefficients of their oxidation reactions. Thus, difference between air excess expressed as oxygen concentrations in the flue gas for complete ($O_{2,ga}^{comp}$) and incomplete ($O_{2,ga}^{incomp}$) combustion always satisfies a relation

$$O_{2,ga} = O_{2,Xs} + \Delta O_{2,CO} + \Delta O_{2,CH4} + \Delta O_{2,UBC} > O_{2,ga}^{comp} = O_{2,Xs}$$ [5].

To compensate $O_{2,ga}$ measured by analyzer we shall express concentrations of incomplete combustion products through their $O_{2,i}$ equivalent[6]:

$$X_S^{GA} = \left\{ \left[1 - m \times \frac{O_{2,ga} - 0.5 \cdot (CO_d^{GA} + H_{2,d}^{GA}) - 2CH_{4,d}^{GA} - \Delta O_{2,d}^{UBC}}{100 - CO_{2,d}^{GA} - SO_{2,d}^{GA} - CO_d^{GA} - CH_{4,d}^{GA} - O_{2,d}^{GA}} \right]^{-1} - 1 \right\} \cdot 100\%, \text{ (Eq. 17,C)}$$

where:

$$0.5 \times CO, ppm \times 10^{-4} = \Delta O_{2,CO}, \%$$

$$0.5 \times H_2, ppm \times 10^{-4} = \Delta O_{2,H2}, \%$$

$$2 \times CH_4, ppm \times 10^{-4} = \Delta O_{2,CH4}, \%$$

$$\Delta O_{2,d}^{UBC}, \% = \frac{394 \times \frac{UBC^*}{12.011}}{V_{prod,vd}}$$

$$UBC^* = (A \times UBC^*_{FLY} + B \times UBC^*_{BOT}) / 100$$

$$UBC^* i = ubc_{measured} \times \frac{Ash + r_{SORBENT} * FuelRate}{100 - ubc_{measured}}$$

A,B – weight fraction of fly and bottom ash correspondingly, established on the empirical basis.

$V_{prod,vd}$ - is the volume of the dry combustion products ($V_{prod,vd}$) per 1 lb. of char at standard

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[5] LIKEWISE, UBC considered as pure carbon, incomplete products in organic form deem to be methane only.

[6] We will ignore effect of fuel nitrogen on volume concentrations of the flue gas for two reasons: first it is extremely small, and, second, to a big extent it converts to fuel NOx. Thus, presence of thermal and fuel NOx will negate their effect on atmospheric nitrogen variation

conditions may written assuming that all UBC and sulfur captured applied to char only:

$$\mathbf{V}_{\mathbf{prod,vd}} = \frac{1}{r_0^{PROD} \times B_{CH}} \times \left\{ \begin{array}{l} \dfrac{Q_{VA}^{*}}{1+H_2O^{VA}} + \dfrac{\sum Q_i^{TA} + Q_{PLANT}}{1+H_2O^{AIR}} + B_{CH} \times \left(1 - \dfrac{Ash + Moist + UBC \times \dfrac{HHV}{14{,}544} + r_C \times [S]_{AVG}}{100} \right) \\ + B_C \times \left(1 - \dfrac{Ash + Moist}{100} \right) \end{array} \right\}, Eq.(18)$$

where:

r_C – mass fraction of sulfur captured

ρ_0^{PROD} -is the density of the dry flue gas after gas cooler accounted by Eq. (6)

$[S]_{AVG}$ – are mass averaged concentrations of the carbon and sulfur in char and coal.

Note, that for UBC,% expressed in terms of LOI, the percent or weight of the refuse per Lb of fuel shall account for the sulfur sorbent injection:

$$\mathrm{M_{ref}} = \frac{[\mathrm{Ash\%}]_{\mathrm{AVG}} + \mathrm{UBC} \times \dfrac{\mathrm{HHV}}{14{,}544} + m_{SORB} \times [S]_{AVG} + 32.066 \times r_C \times [S]_{AVG}}{100}$$

The above procedure eventually allows us a comparison of the excess air by Eq.(15) and Eq.(17C) in order to verify reliability of the particular test results. When significant discrepancy is found, then a thorough analysis of its causes is necessary.

1.2.3. Combustion Material Balance Based on the Combine Dry and Wet Volume Gas Analysis Measurements (CEMs and Individual in-situ monitors).

The difference in previous and described hereafter methodology relates to availability of specific measurements. We do not have direct moisture content measurements available, but it will be critical for all measurements including air and flue gas flows [see Eq. (7) and (9)]. To account for water content in the flue gas we may use a simple relation between dry and wet oxygen concentration in the stack:

$$\frac{O_{2,d}^{stack}}{O_{2,w}^{stack}} = \frac{100}{100 - H_2O^{FG}}, thus \Rightarrow H_2O^{FG} = 100 \times \left(1 - \frac{O_{2,w}^{stack}}{O_{2,d}^{stack}} \right), Eq.(18)$$

At the same time, we have all necessary measurements and data to perform the moisture balance in the flues from all sources:

1. Moisture due to coal combustion and surface moisture

$$M_{H2O}^{C} = 8.937 \times [H2] + \frac{SM_{COAL}\%}{100}, [lbs/lb], Eq.(19)$$

2. Moisture due to char combustion and surface moisture

$$M_{H2O}^{CH} = 8.937 \times [H2] + \frac{SM_{CHAR}\%}{100}, [lbs/lb], Eq.(19a)$$

3. Moisture due to natural gas combustion in the vitiated air duct

$$M_{NG,H2O}^{VA} = 18.015 \times \left\{ \sum_{i=1}^{k} \frac{m}{2} \times \frac{[CnHm]i}{m_i} + \frac{[H2]}{2.016} + \frac{[H2S]}{34.082} \right\}, [lbs/lb], -Eq.(20)$$

4. Moisture due to combustion of natural gas in the reheat burner

$$M_{NG,H2O}^{RB} = 18.015 \times \left\{ \sum_{i=1}^{k} \frac{m}{2} \times \frac{[CnHm]i}{m_i} + \frac{[H2]}{2.016} + \frac{[H2S]}{34.082} \right\}, [lbs/lb], -Eq.(20a)$$

5. Moisture evaporated from the pit (bottom ash conveyor)

$$M_{H2O}^{PIT} = \frac{M_{PIT}}{M_{CH}}, [lbs/lb-char], Eq.(21)$$

6. Moisture introduced with atmospheric and transport air

$$M_{H2O}^{AIR} = 0.622 \times \left[\frac{P_B}{0.01 \times RH \times P_{DRY}^{SAT}} - 1 \right]^{-1}, [lbs/lbair], -Eq.(21)$$

7. Moisture due to SOx reduction (only if $NaHCO_3$ used)
   Then, each pound of char or coal will generate moisture proportional to sorbent rate, which we express using sulfur content in a fuel and sorbent-to-sulfur ratio $\mathbf{m}_{SORB}$

$$M_{H2O}^{SOx} = 0.562 \times m_{SORB} \times [S]_X, [lbs/lb-\ fuel], -Eq.(22)$$

Data above allows us to check the moisture content in the flue gas determined by Eq.(18). As soon as moisture content in the flue gas and air has been established, all further procedures are similar to the ones obtained on the wet basis. As before, we assume six significant components in the flue gas, and thus accounting for $N_{2,W-S}$ by difference

$$N_{2,W-S} = 100\% - (O_{2,W-S} + CO_{2,W-S} + CO_{W-S} + SO_{2,W-S} + H_2O_{,W-S})$$

required for the reverse calculations by Eq. (17C) for a verification of the test results.

Based on verified natural gas flow, we now may obtain density of the actual vitiated air entering windbox, since it will be affected by the duct burner. A relation for moisture and SO_2 content increase in the vitiated air may be written correspondingly for water vapor

$$[H_2O]^{VA} = \frac{H_2O^R \times \frac{18.015}{m_R} \times \overset{*}{Q}_R + Q_{NG} \times M_{NG,H2O}^{VA}}{\overset{*}{Q}_R + \overline{m}_{air} + \overset{*}{Q}_{NG}}, Eq.(23)$$

Where : $M^{VA}_{NG,H2O}$ - defined by Eq. (20)

and sulfur dioxide

$$[SO_2]^{VA} = \frac{SO_2^R \times \frac{64.065}{m_R} \times \overset{*}{Q}_R + Q_{NG} \times \Delta SO_2}{\overset{*}{Q}_R + \overline{m}_{air} + \overset{*}{Q}_{NG}} Eq.(23a)$$

Where: ΔSO_2 - is a calculated mass of the SO_2 component per one pound of natural gas, Lbs/lb.

From above procedures we will be able to account for excess air as before by Eq.(15) and (17C) in order to verify the accuracy of the particular test data.

1.3. Emissions Measurements

Not all emissions measured at the reference point (downstream of gas cooler) will represent ones generated by combustion in the furnace. Depending on the rate of flue gas re-circulation and vitiated air temperature upstream of the duct burner, we will see significantly variable emissions concentrations in the vitiated air. It is obvious that this information is critical for the evaluation of the unit performance[7]. That is why we have to establish procedures for the measured emissions adjustment, in order to evaluate ones pertinent to combustion in the furnace. However, we have to make a major assumption, that presence of these emissions in the vitiated air will not affect equilibrium concentrations of the hazardous species, and thus, considering them as additives will be reasonably accurate.

1.3.1. Measured Emission adjustment based on Mass-Spectrometry

For this methodology and any emission components of interest we have measured concentrations both in the vitiated air (E_i^{VA}) and at the reference point after gas cooler (E_i^{MEAS}). Then, an adjusted volume concentrations of a given emission component (E_i^{adj}) in “ppm vd” may be written as :

$$E_i^{adj} = \left(E_i^{MEAS} - E_i^{VA} \times \frac{V_{VA}}{V_{prod}} \right), Eq.(24)$$

A total volume of the dry vitiated air (V_{VA}) per LB of fuel introduced into furnace might be determined from Eq.(11) and (7). To account for combustion products volume ($V_{prod,}$) on the wet basis we have to modify Eq.(17D) and Eq.(17E) shown in section 2.2:

$$\mathrm{V}_{\mathrm{prod,\,W}} = \frac{1}{r_{0,w}^{PROD} \times B_{CH}} \times \left\{ \begin{array}{l} \overset{*}{Q}_{VA} + \sum TA_I + B_{CH} \times \left(1 - \dfrac{Ash + UBC \times \dfrac{HHV}{14{,}544} + r_C \times S}{100} \right) \\ + B_C \times \left(1 - \dfrac{Ash}{100} \right) \end{array} \right\}, Eq.24a$$

Or

$$V_{prod,W} = 394 \times \left\{ \begin{array}{l} \dfrac{[C]_{AVG} - UBC \times \dfrac{HHV}{14{,}544}}{12.011} + \dfrac{[H]_{AVG}}{2.016} + \dfrac{[Moist]_{AVG}}{18.015} + \dfrac{M_{NG,H2O}^{VA} + M_{H2O}^{PIT}}{18.015 \times (B_{CH} + B_C)} + \\ \dfrac{[S]_{AVG}}{32.066} \times (1 - r_C) + M_{VA}^{TH} \times \left[\left(N_{2,d}^{FG} + m_{VA} \times \dfrac{M_{H2O}^{VA}}{18.015} \right) \times \left(1 + \dfrac{X_S}{100} \right) + O_{2,d}^{FG} \times \dfrac{X_S}{100} \right] \end{array} \right\}, Eq.24B$$

In order to convert PPM NOx to pounds of NO_2 per MMBtu, the FWEC’s standard recommended analytical expression (Sect. 224-II, pg.22) should be substituted by an appropriate one:

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[7] Unfortunately, when mass spectrometer data is not available, increase in CO and NOx will be based on estimates related to the previous measurements by mass-spectrometer.

$$\text{NOx as NO}_2 = \frac{m_{NO_2}}{394} \times NO^{adj}_{X,PPM} \times 10^{-6} \times \frac{Vprod,w}{HHV} \times 10^{6} \times \frac{O^{VA}_{2,W} - 3 \times \frac{100 - H_2O^{FG}}{100}}{O^{VA}_{2,W} - O^{GA}_{2,W}}, Eq.(25)$$

1.3.2. Measured Emission Adjustment Based on Gas Analysis Data on Dry Basis

Based on the data reduction presented in Sect. 1.2.2. and Sect. 1.2.3., we may obtain the background concentrations of the emission components (CO, SO_2, NO_x) in the actual vitiated air entering windbox corrected by molecular weight. For any component of emmisions we may write an expression for volume concentration:

$$E_i^{VA} = \frac{m_{VA}}{m_i} \times \frac{E_i^{R} \times \frac{m_i}{m_R} \times \dot{Q}_R + \Delta E_i \times \dot{Q}_{NG}}{\overset{*}{Q}_R + \overset{*}{\overline{m}}_{air} + \overset{*}{Q}_{NG}}, Eq.(26)$$

Where: ΔE_I - is a measured or evaluated mass of the *i*-th emission component per one pound of natural gas, Lbs/lb.

Then as before find an adjusted emission concentrations according to following relation

$$E_i^{adj} = \left(E^{MEAS}_{i,vd} - E^{VA}_{i,vd} \times \frac{V_{VA,\,vd}}{V_{prod,\,vd}} \right)$$

As soon as adjusted concentrations are determined, we may use NO^{adj}x,ppm to perform a conversion to Lbs/MMBtu[8]

$$\text{NOx as NO}_2 = \frac{m_{NO_2}}{394} * NO^{adj}_{X,PPM} \times 10^{-6} * \frac{Vprod,vd}{HHV} \times 10^{6} \times \frac{O^{VA}_{2,d} - 3}{O^{VA}_{2,d} - O^{GA}_{2,vd}}, Eq.(25a)$$

This equation (Eq.25a) will be the main one to report the HIPPS burner performance, while Eq.(25) is for the purpose of the wet and dry gas results comparison.

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[8] Typical EPA methodology requires adjustment of measured NOx to 3% oxygen in the flue gas on the dry basis.

Attachment 2

Analog Input Description

TABLE 1. CETF-HIPPS: MAJOR ANALOG MEASUREMENTS

TAG No	**VALUE MEASURED / UNITS**	**NOTES**	**Notation**
A. CHAR FLOW and RELATED MEASUREMENTS			
FI-1007	Mass flow of crude char to the ball mill, Lbs./Hr	Weight belt feeder	$\mathbf{B_{CH,1}}$
FI-1617	Mass flow of pulverized char to burner, Lbs./Hr	Weight belt feeder	$\mathbf{B_{CH}}$
FI-1620	Pulverized Char Transport Air (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	$\mathbf{TA_{CH}}$
FI-2003	Primary Air to the Ball Mill (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	**PA**
FI-2008	Primary Air to the Ball Mill Drive End (Venturi), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	$\mathbf{PA_{D}}$
FI-2009	Primary Air to the Ball Mill Opposite Drive End (Venturi), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	$\mathbf{PA_{OD}}$
FI-2021	Auxiliary Air to the Exhauster (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	$\mathbf{A_{UX}}$
TI-2027	Pulverized Char, Primary and Auxiliary air Temperature, F	Temperature is used for iso-kinetic pulverized material sampling	$\mathbf{T_{ISO}}$
PCIS	Pulverized Char (Material) Iso-kinetic Sampling, g/sample	Measures pulverized char fineness before storage – expressed as % through mesh 200	$\#200_{CH}$
CCS	Coarse Char Sampling System	Base data for major fuel combustion and grinding characteristics	
B. PULVERIZED COAL and RELATED MEASUREMENTS			
FI-1212	Pulverized coal supplied to burner, Lbs./Hr	Volumetric feeder –- calibrated Lbs./RPM	$\mathbf{B_{C}}$
FI-1204	Pulverized Coal Transport Air (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	$\mathbf{TA_{C}}$
PCS	Pulverized Coal Sampling, g/sample	Measures pulverized coal fineness before burner – expressed as % through mesh 200	$\#200_{C}$
C. SORBENT FLOW and RELATED MEASUREMENTS			
FI-1419	Pulverized Sorbent Mass Flow to the burner , Lbs./Hr	Weight belt feeder	$\mathbf{B_{S}}$
FI-1422	Pulverized Sorbent Transport Air (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement	
PCS	Pulverized Sorbent Sampling, g/sample	Measures pulverized sorbent fineness before burner – expressed as % through mesh 200	$\#200_{SOR}$
D. PLANT AIR and RELATED MEASUREMENTS			
FI-6002	Total Purge Air to auxiliary equipment , SCFM	Measures compressed air for ignitor, scanners. Shall be corrected by a current plant air pressure	$\mathbf{MA_{PLNT}}$
E. VITIATED AIR FLOW			
TI-3068	Ambient Air Temperature, F	Temperature of air entering unit. Used as the dry bulb temperature for moisture content in air and heat balance calculations	$\mathbf{T_{A,0}}$

TABLE 1. CETF-HIPPS: MAJOR ANALOG MEASUREMENTS (CONTINUED)

TAG No	VALUE MEASURED	NOTES	Notation
AI-3521	Relative Humidity of the Ambient Air, %	Used for moisture content in air and heat balance calculations	**RH**
TI-3006	Vitiated Air Temperature after Air Heater, F	Temperature of the vitiated air before Duct burner – affects duct burner load	$\mathbf{T_{VA,1}}$
FI-3007	Vitiated Air flow after Air Heater (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement (requires final correction by molecular weight)[9]	$\mathbf{Q_{VA,1}}$
FI-2003	Gas flow to the duct burner, SCFH	Maintains oxygen content and temperature of the vitiated air	$\mathbf{B_{VA}}$
TI-3008 – TI-3016	Temperature distribution after duct burner, F	Indicates vitiated air mass average temperature after duct burner	$\mathbf{T_{V,}}$
MASS SPECTROMETER	Mass concentrations of the vitiated air constituencies, % vol.wet, ppm vw	Provides mass concentrations of the vitiated air constituencies– used for alternative calculation of the vitiated air molecular weight and mass flow correction	$\mathbf{C_{I,\ M\text{-}W}}$
AI-3120	Oxygen content in the vitiated air entering upper wind-box, % vol.wet	Provides O_2,wet in the vitiated air – used in calculation for establishing Vitiated air molecular weight and mass flow correction	$\mathbf{O_{2,UPW}}$
AI-3074	Carbon dioxide content in the vitiated air entering upper wind-box, % vol.wet	Provides CO_2,wet in the vitiated air – used in calculation for establishing Vitiated air molecular weight and mass flow correction	$\mathbf{CO_{2,UPW}}$
FI-3024	Tertiary Air Flow to the burner (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement (requires final correction by molecular weight)[1]	$\mathbf{Q_{TA}}$
FI-3021	Purge Air to the arch wall penetrations (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement (requires final correction by molecular weight)[1]	$\mathbf{Q_{PA}}$
PI-3020	Pressure in the upper wind-box (arch), in WC	Used as the pressure correction for flow measurements inside the upper wind-box.	$\mathbf{P_{ARCH}}$
PI-3098	Furnace pressure under arch near the burner outlet, in WC	Reported for CFD analysis.	$\mathbf{P_{BR,OUT}}$
FI-3027	Vitiated Air to the lower wind-box compartment (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement (requires final correction by molecular weight)	$\mathbf{Q_{VA,LW}}$
AI-3115	Oxygen content in the vitiated air entering lower wind-box, % vol. wet	Provides O_2,wet in the vitiated air – used in calculation for establishing Vitiated air molecular weight and mass flow correction	$\mathbf{O_{2,LW}}$
AI-3121	Carbon dioxide content in the vitiated air entering lower wind-box, % vol.wet	Provides CO_2,wet in the vitiated air – used in calculation for establishing Vitiated air molecular weight and mass flow correction	$\mathbf{CO_{2,LW}}$
PI-3028	Pressure in the lower wind-box (air-wall) , in WC	Used analysis of the air flow distribution in the lower wind-box.	$\mathbf{P_{LW,1}}$
PI-3030	Pressure in the lower wind-box (air-wall)	Used for analysis of the air flow distribution in the lower wind-box.	$\mathbf{P_{LW,2}}$

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[9] Vitiated air constituencies vary depending on actual test set points and unit performance. Due to related density changes this effect may introduce an error of the total flow measurements in excess of 5%.

TABLE 1. CETF-HIPPS: MAJOR ANALOG MEASUREMENTS (CONTINUED)

TAG No	**VALUE MEASURED**	**NOTES**	**Notation**
F. OVERFIRE AIR			
FI-3017	Vitiated Air to Overfire Air Ports (Air Monitor), Lbs./Hr	Pressure, Temperature and Moisture compensated flow measurement (requires final correction by molecular weight)[10]	**$Q_{VA,OF}$**
E. IGNITOR GAS FLOW			
FI-3046	Natural Gas flow to the ignitor, SCFH	Measures natural gas flow. Shall be corrected by an actual pressure	**B_{NG}**
H. BACK-END			
PI-3056	Lower Furnace Pressure, in WC	Used for furnace pressure control	**P_{FUR}**
TI-3114	Furnace exit gas temperature, F	Used for CFD analysis. Measured by a suction pyrometer at four (4) points	**FEGT**
PI-3113	Furnace pressure under arch, in WC	Used for CFD analysis	**P_{FEG}**
TI-3071	Furnace exit gas temperature, F	Used for CFD analysis. Measured by an optical system. (Applied Synergistics)	**T_{FEG}**
MASS SPECTROMETER	Mass concentrations of the flue gas constituencies (incl. moisture), leaving gas cooler, % vol. wet, ppmvw	Provides volume concentrations of the exit flue gas; used as alternative measurements for combustion material balance calculations.	**$C_{I, W}$**
CEMS	Volume concentrations of the flue gas constituencies, leaving gas cooler, % vd	Provides multi-point volume dry concentrations of the exit flue gas; registers emissions and provides basic data for combustion material balance.	**$C_{I, D}$**
AI-3000	Single point reading of oxygen (wet) concentrations in the exit flue gas, % vw	Used for control purposes as "O_2-Trim". Also provides base for calculations of moisture content in flues.	**$O_{2,W}$**
TI-3058	Flue gas temperature entering Air Heater.	Used for "short" heat balance of the unit to verify actual fuel burnt.	**$T_{G,2}$**
LOI-extractive	Fly ash extractive sampling, %	Provides ash sampling for UBC/LOI evaluation at the lab**.**	**UBC**
TI-4011	Flue gas temperature in the stock, F	Used for temperature compensation of the flue gas flow through stock	**$T_{G,4}$**
LOI-Camrac	Fly ash extractive sampling, %	Provides automated fly ash sampling and on-line UBC/LOI evaluation.	**UBC_A**
FI-4011	Flue Gas flow leaving stock, Lbs./Hr	Measures pressure and temperature compensated flue gas flow leaving stock (shall be corrected by flues density as well)	**B_{FG}**
MASS SPECTROMETER	Concentrations of the flue gas constituencies (including moisture), leaving stock, %vol.wet, ppm vw	Provides volume concentrations of the flue gas the stock; used as CEMS alternative measurements and combustion material balance calculations.	**$C_{I, M-S}$**
AI-4018	Measures wet oxygen concentration at the stock	Provides basis for transition from wet to dry concentrations	**$o_{2, W-S}$**
CEMS	Volume concentrations of the flue gas pollutants, leaving stock, % vd	Provides volume dry concentrations of the pollutants (O_2,CO,SO_2, NO_x) required by NY state. Also provides an alternative data for material balance of combustion.	**$C_{I, C-S}$**

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[10] Vitiated air constituencies vary depending on actual test set points and unit performance. Due to related density changes this effect may introduce an error of the total flow measurements in excess of 5%.

TABLE 1. CETF-HIPPS: MAJOR ANALOG MEASUREMENTS (CONTINUED)

TAG No	**VALUE MEASURED**	**NOTES**	**Notation**
FI-4020	Rate of Flue Gas re-circulation back to unit, Lbs./Hr	Measures pressure and temperature compensated flue gas flow leaving stock (shall be corrected by flues density as well)[11]	$\mathbf{B_{RE}}$
AI-4025	Oxygen content in the flue gas leaving unit, % vol. wet	Provides in-situ O_2 , (wet basis) in the flue gas at the stock – used for re-circulation and vitiated air molecular weight calculation and for material balance of combustion	$\mathbf{O_{2,W\text{-}S}}$
AI-4026	Carbon dioxide content in flue gas leaving unit, % vol. wet	Provides in-situ CO_2 , (wet basis) in the flue gas at the stock – used for re-circulation and vitiated air molecular weight calculation and for material balance of combustion	$\mathbf{CO_{2,W\text{-}S}}$
J. WATER FLOWS CIRCUITRY			
TI-5401	Water Temperature at the inlet to unit, F	Used as an initial temperature for the waterside duty calculations.	$\mathbf{T_{W1}}$
FI-6419	Water flow to B.I.T.C.H. cooler Lbs./HR	Used for the waterside duty calculations.	$\mathbf{F_{WB}}$
FI-6404	Water flow to gas cooler , Lbs./HR	Used for the waterside duty calculations.	$\mathbf{F_{WG}}$
TI-6405	Water Temperature at the gas cooler outlet, F	Used for the waterside duty calculations.	$\mathbf{T_{WG}}$
FI-6406	Water flow to gas cooler , Lbs./Hr	Used for the waterside duty calculations and measurements of the furnace incident flux.	$\mathbf{F_{WS}}$
TI-6407	Water Temperature at the slag panel outlet, Lbs./hr	Used for the water side duty calculations and measurements of the furnace incident flux	$\mathbf{T_{WS}}$
FI-3122	Water flow to bottom ash conveyor	Used for material and heat balance calculations	**Mpit**

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[11] Vitiated air constituencies vary depending on actual test set points and unit performance. Due to related density changes this effect may introduce an error of the total flow measurements in excess of 5%.

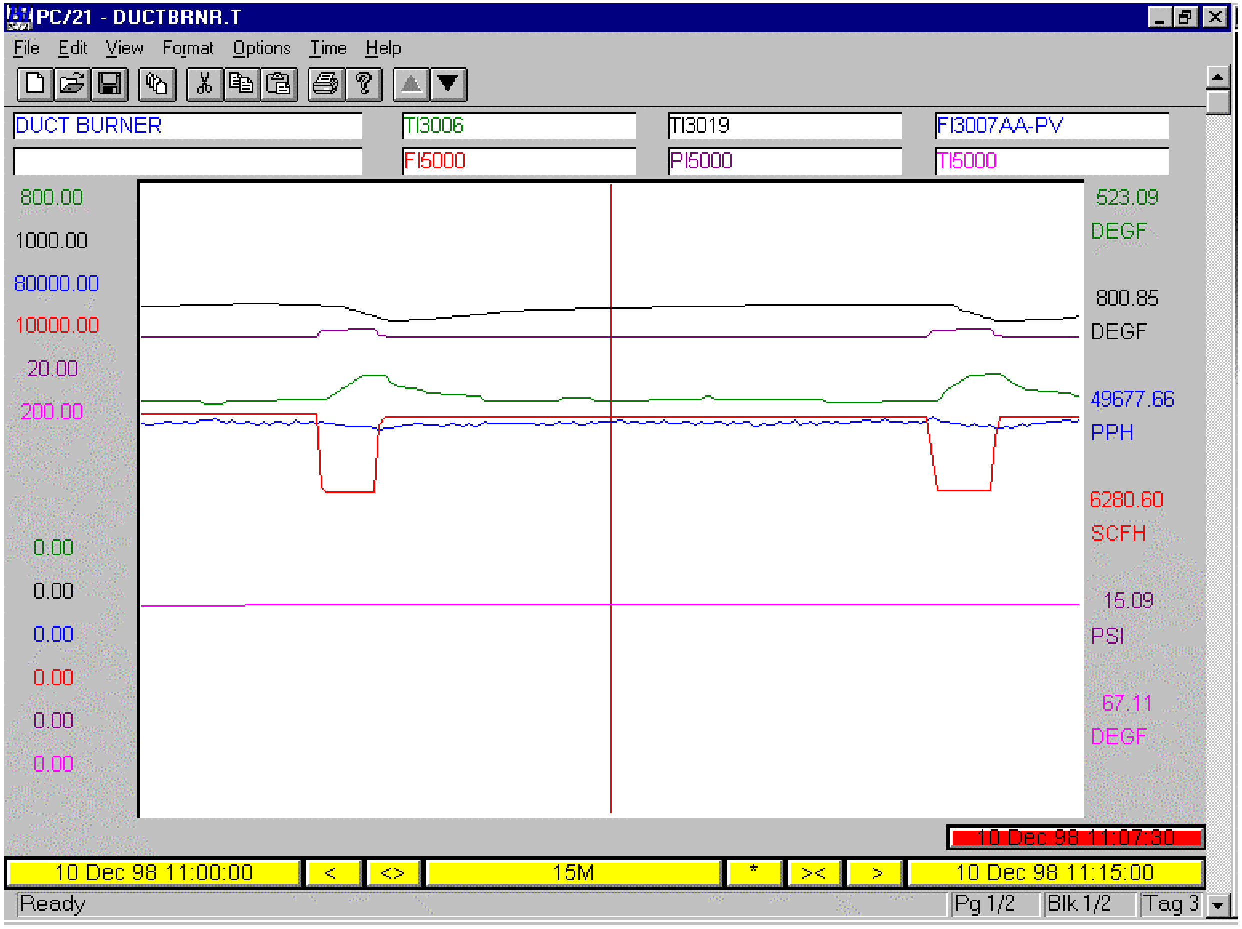

Figure 9 CETF Duct Burner Performance

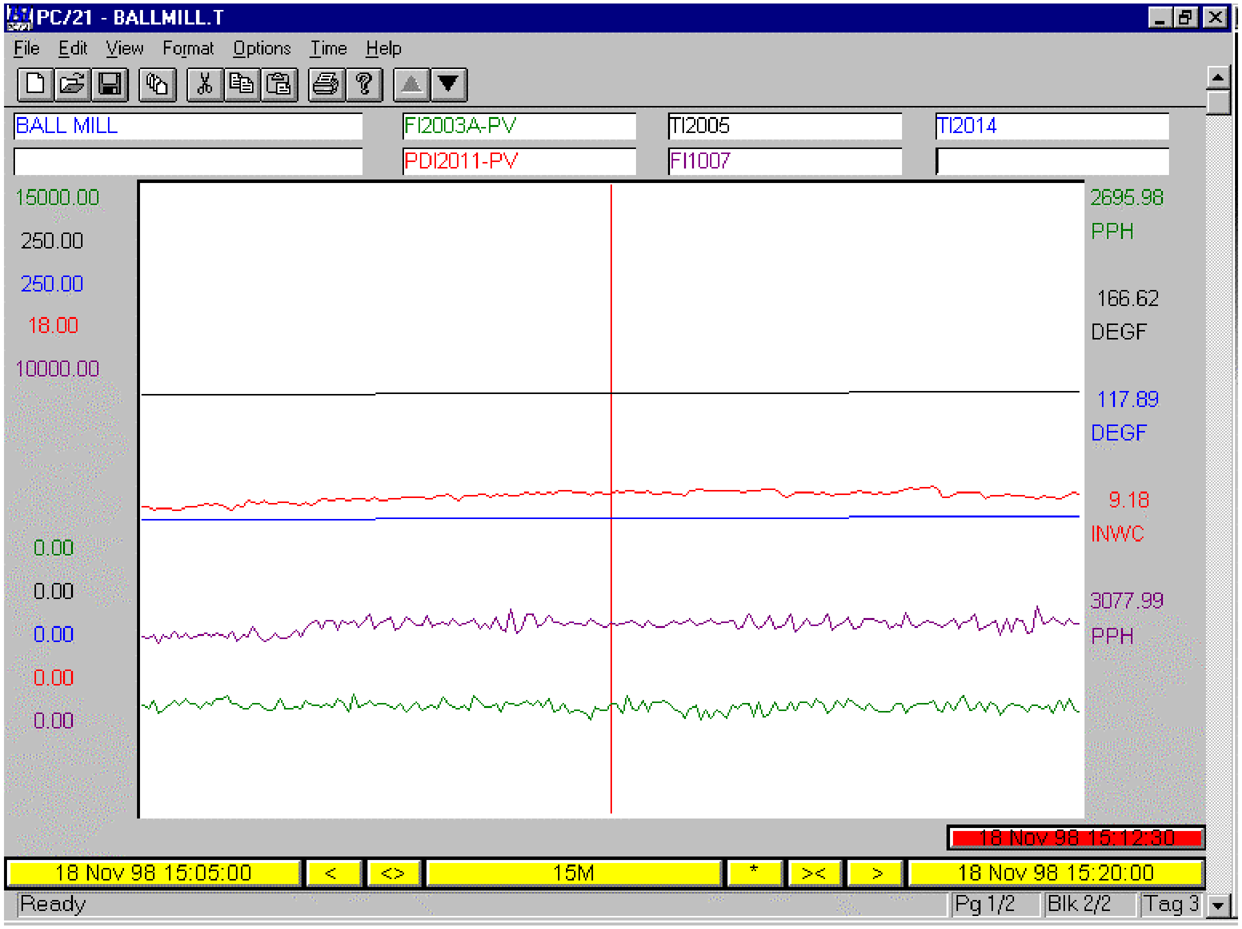

Figure 10 CETF Ball Mill Performance

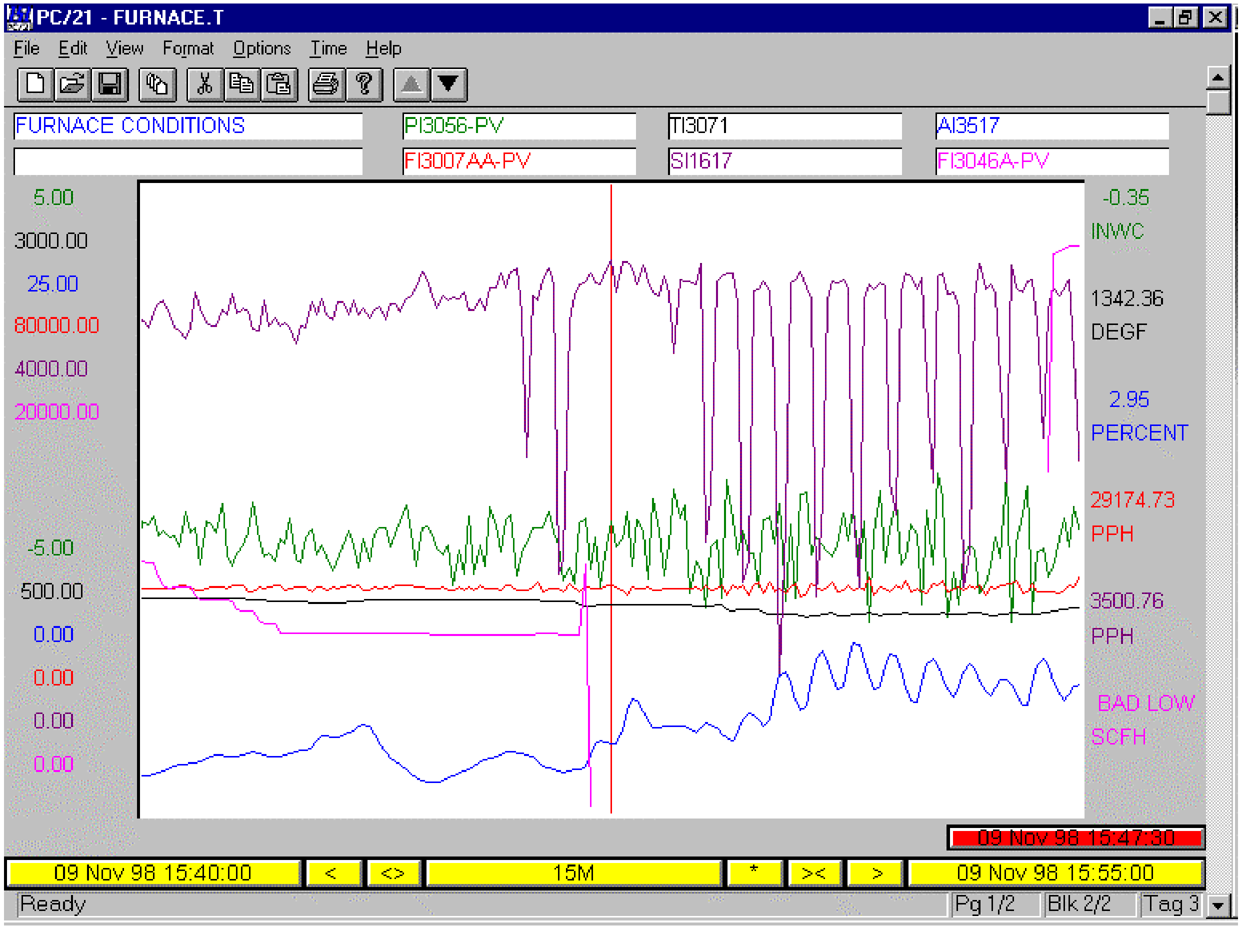

Figure 11 CETF Unsupported Char Firing

HIPPS: CETF DIAGRAM and MAJOR I/O for PERFORMANCE DATA ANALYSIS

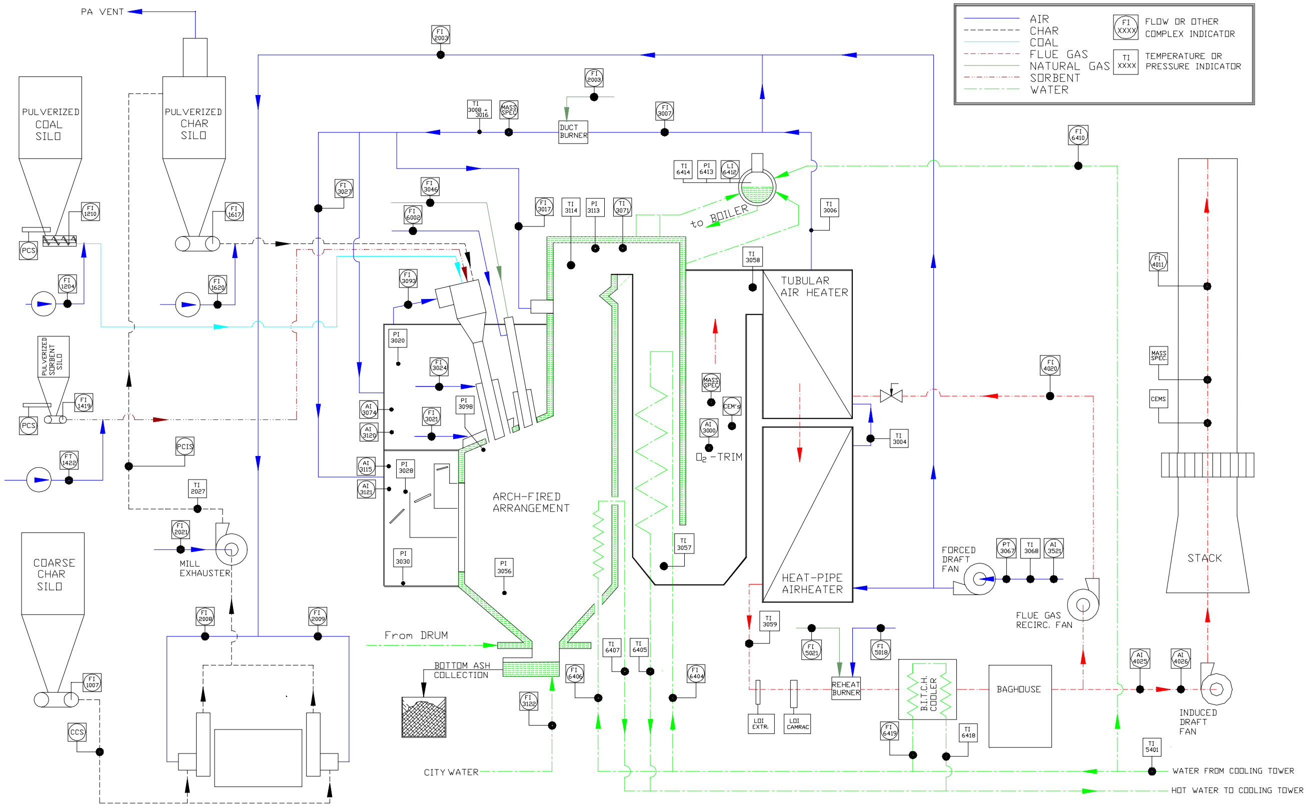

Figure 12