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Task 3 Deliverable Report

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Pilot-Scale Testing of Coal and Biomass as Reburn Fuels

Task 3: Pilot Scale Tests

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ABSTRACT

The objective of this task is to validate the results of small-scale combustion tests that have shown significant reductions of NOx and moderate reduction of mercury emissions as a result of reburning feedlot biomass (FB) and coal: FB blends. Pilot scale tests were performed over 2.5 days during May 24, 25 and 30, 2007 in the Combustion Research Facility (CRF) at Southern Research Institute (SRI), Environment and Energy Department, 2000 9th Ave South, Birmingham, AL 35205 in order to confirm the small-scale experiments performed at Texas A&M University Mechanical Engineering (TAMU/MENG) Department. The one mega watt (1 MW_{th}, thermal) pilot scale facility simulates the flue-gas path from the burner through the particulate collection devices, including a temperature-time profile that matches that of full-scale coal-fired power plants. The CRF has been designed to simulate the major boiler types in service today–specifically, wall-fired, tangentially-fired, tangentially-fired with overfire air, and low-NOx burner types. The NOx emissions were measured by continuous-emission monitors (CEMs), while the mercury speciation measurements were performed using a state-of-the-art semi continuous emission monitor, with an advanced spike and recovery system only featured at Southern Research Institute. The first set of data ever obtained from a facility simulating boiler burners indicated problems with modification of a large facility for safe injection of reburn fuel (FB and coal:FB blends) and operations. Thus the injection and operational parameters differed from those of small scale tests. Particularly the main burner operated near stoichimetry almost simulating a low NOx burner (LNB) instead of operating at 5% excess air as performed in small scale experiments. The preliminary data from SRI tests indicated NO_x reduction of about 75% for each of the different reburn fuel types, including the raw manure (LAFB-Raw or LA-RM) and low ash partially composted manure (LAFB-PC or LAPC) and almost independent of firing conditions tested so far. The NOx reduction of 75% is attributed due to almost staged combustion like behavior of the main burner and the reburner. The fuel used for the main burner is Galatia coal, which had very low mercury content but somewhat higher Cl level compared with Wyoming Powder River Basin (PRB) coal used in the TAMU small-scale tests. The SRI results indicated negligible elemental Hg was emitted for most of the tests due to high Cl in the main burner and reburn fuel. The pilot scale tests demonstrated the difficulties in incorporating the changes in a large scale utility boiler and valuable experience was gained from these preliminary tests. It also indicated differences in performance using different baseline coal supply. As a result, the test procedure, operating conditions and injection geometry will be improved for the future pilot scale tests to be performed with DOE funding.

1 INTRODUCTION

The ultimate objective of this interdisciplinary and system-oriented research project involving professors across Texas Engineering Experiment Station (Mechanical Engineering) and Texas Agricultural Experiment Station (Biological and Agricultural Engineering) of the Texas A&M University System (TAMUS) is to develop environmentally benign and economically viable thermo-chemical and biological conversion technologies to convert low–value inventories of livestock biomass into renewable energy. The new enabling technologies will minimize the need for wastewater treatment lagoons and land applications, reduce reliance on high-rate land application of phosphorus-rich manure, and also provide new options for the disposal of livestock mortality. One of the objectives is energy conversion from animal wastes through co-firing, reburn and gasification in order to identify the best approach for energy conversion and reduction of emissions in coal fired systems.

Extensive research has been conducted by TAMUS on energy conversion from coal and animal waste over last two decades. With support from the DOE-NETL-Pittsburg, the TCFA, the USDA, the USDOE-Golden Field Office and the TCEQ, the reburn tests conducted with FB as reburn fuel (without overfire air) for reduction on NOx revealed significant reductions for NOx under certain operating conditions and injection methods. Subsequently limited tests have been performed at 500,000 BTU/hr DOE-NETL-Pittsburg facility which confirmed TAMU data [US Patent # 6,973,883; TAMUS Disclosure # TAMUS Disclosure # 1997, 2003]. Typically the heat rate contribution from the reburn fuel to the plant's total heat requirement ranges from 6-20%. In addition to NOx capture, the FB could also be used to reduce Hg emissions. Appendix A presents a brief overview of current literature and the Hg tasks proposed under TCEQ grant. It is apparent from review that the current Hg capture technique involves the use of powdered activated (PAC) carbon either in pure form or halogenated PAC (HPAC) for the capture of Hg. Further the presence of Cl in fuel enhances the Hg capture as $HgCl_2$ which could be dissolved in water or wet scrubbers.

The chlorine contained in animal waste derived biomass fuel (called as AWDBF) may produce $HgCl_2$ (called oxidized form of Hg) particularly from low rank coals and hence capture the compound using water spray, chemical scrubbers or ESP. The method is ideally suitable for plants installed with wet scrubbers which capture SO2. The sludge from scrubbers is used for making Gypsum board. None of the existing methods presented thus far involve the use of trace amounts of Animal Waste Derived Biomass Fuels (AWDBF).

The small scale TAMU tests (TCEQ task Report on reburn by Annamalai et al, 2006) show a reduction of Hg by almost 60 % when a blend of Coal:FB (80:20) was fired as reburn fuel. The pilot scale tests are useful in providing additional data on NOx and Hg reduction and validating small scale test data.

2 PILOT SCALE FACILITY SELECTION

Numerous issues arose during the selection of suitable pilot scale test facility. 1) Due to the untimely death of an experienced senior PhD graduate student who was responsible for a part of Task 2 (small scale TAMU tests) dealing with Hg experiments, the generation of Hg data from the TAMU facility was delayed. 2) Furthermore, the investigators were working with DOE and TAMUS contract personnel in satisfying all required formalities in setting up the new DOE Grant in Oct 2005 to provide co-funding with the TCEQ. The set up of new grant caused further delay. 3) According to the original proposal, Task 3 dealt with pilot scale studies using the DOE-NETL facility at Pittsburgh, PA. A meeting was arranged on July 15, 2005, at the NETL facility in Pittsburgh, PA., to discuss the modalities of the pilot scale testing either to be conducted at NETL or a site to be recommended by DOE-NETL. John Sweeten and Kalyan Annamalai visited the DOE-NETL and met with DOE officials to discuss the pilot scale tests. Mr. Mark Freeman of DOE-NETL presented an overview of previous pilot tests on co-firing and reburn with AWDBF and KA made a presentation on the status of current research on AWDBF. Dr. Sweeten presented his work on biofuel properties of feedlot manure/biomass. After the presentations, Mr. Mark Freeman informed us that they did not get the required funding to hire sub-contractors for running the DOE-NETL pilot scale facility and hence recommended other vendors. 4) Based on recommendations from DOE-NETL, Dr. John Sweeten and Dr. Kalyan Annamalai then made trips to two of the suggested facilities (Vendors I and II) prior to possible selection of the site for pilot scale experiments. Vendor I's coal-fired unit (visited on June 29-30, 2006) is rated at 1 million BTU/hr (300 kW) vs. 100,000 BTU/hr (29 kW) for the lab-scale pilot plant in TAMU/MENG Department. Vendor I Energy Group has experience with several types of biomass fuels including sewage sludge/biosolids. However the Vendor I mentioned that they have a backlog of pilot scale test and informed us that the facilities would not be available until fall 2006. There is no doubt Vendor I could have conducted the pilot plant tests while TEES specified test conditions for combustion or reburn protocols. However, the administration of Vendor I waived off a non-disclosure agreement (NDA). So, the PIs and the personnel of Vendor I were circumspect in presentations, careful to stick to published or open literature material. Dr. Kalyan Annamalai outlined an ambitious test schedule. Vendor I said they could conduct some of the requested experiments, but would have to leave out many of the requested tests to have any hope of completing before the TCEQ grant expiration (including the final report date of Dec. 31, 2006). Further, Vendor I saw nothing in the presentations that was compelling enough for an NDA. Apparently, a NDA was expected to be a drawn out process with Vendor I and TAMUS administration and thus would likely cause further delays and uncertainty. 5) The PIs visited with Vendor II (Southern Research Institute) in July 19 and 20, 2006 and discussed the pilot scale tests. Vendor II had a facility rated at 3.5 million BTU/hr (thermal; 1.025 MW_{th}). The SRI Energy Group had experience with several types of fuels: such as coal, switch grass, etc. The facility was available for fall testing in fall 2006. The cost quoted by Vendor II was approximately $80,000 for one week (5 working days) of testing and report preparation. Vendor II was advised that feedlot biomass (FB) was unlikely to cause odor concerns, because when dried to less than 10% moisture, decomposition is very slow, and odor would be no more than Wal-Mart grade bagged compost. TAMUS mentioned that they required a 2-

way NDA (Non-disclosure agreement). SRI agreed to sign the NDA (Non Disclosure Agreement).

Thus a request was made to the TCEQ to extend the ending date of the contract from the original date of June 30, 2006 to May 31, 2007. After receiving approval from TCEQ on no cost extension officially in Dec 2006, bids were submitted to the Texas A&M/TEES Purchasing Office in January 2007 for processing and forwarding to two pilot scale vendors. A response was received from only one bidder. Another bidder did not respond, probably due to problems with signing non-disclosure agreements.

The selected vendor for pilot tests was Southern Research Institute, located at 2000 9th Ave South, Birmingham, AL 35205.

3 PROBLEMS AND SOLUTIONS REGARDING PILOT TEST CONDITIONS

SRI originally planned to use low chlorine Choctaw America as the baseline coal (bituminous coal, Cl of about 15 ppm) as main burner fuel (Table 3.1) and thus generate NOx by burning coal. For the main burner, the firing condition was originally set at 5% excess air at the burner (ϕ_M= 0.95), which leads to excess oxygen of approximately 1%. Estimated feed rates for main feed rates and reburn feed rate are given in Table 3.2

Table 3.1. Choctaw America Coal

	As received %
C	78.92
H	4.77
N	1.89
O	5.96
S	0.9
Moisture	1.49
Ash	5.65
HHV	13,789 BTU/lb

Table 3.2. SRI Pilot Scale Facility: Initially-estimated feed rates using Choctaw America Coal as baseline

Pilot Facility Thermal Rating	3,500,000	BTU/hr		
Reburn Thermal Rating	10	%		
Hrs of operation/day	12	hrs/day		
days operation	3	days/week		
Period of test	1	week		
FUEL for Reburn:	PRB Coal	TX Lignite	LA PC FB	LA RM
HHV,BTU/lb	7820	6145	5705	5765
Total Hrs	36	hrs		
Input through reburn	***350,000***	***BTU/hr***		
	PRB Coal	TX Lignite	LA PC FB	LA RM
Reburn Feed rate, lb/hr	**44.8**	**56.9**	**61.3**	60.7

Reburn Fuel Needed, lb	1611	2050	2209	2186
Main Burner	90	%		
Total Hrs	36	hrs		
Input through main Burner	3,150,000	BTU/hr		
	PRB Coal	TX Lignite	Choctaw	
Main Burner Feed rate, lb/hr	402.8	512.6	228.4	
Main Burner Fuel Needed, lb	14,501.3	18,454.0	8,230.0	

Prior to discussing parametric cases, feedlot biomass (FB) and equivalence ratio ϕ will be defined. For FB, terminology is as follows:
LA = low ash from paved fly-ash feedlots,
HA = high ash from soil surfaced feedlots,
PC = partially composted solids (e.g. 30-60 days), and
RM = Raw manure as-collected (i.e. not composted).

Equivalence ratio ϕ, is defined as:
ϕ = Required stoichiometric oxygen for combustion divided by the actual oxygen supplied, given a fueling rate,
ϕ = Supplied fuel flow rate divided by the maximum fuel that could be burned for a given O_2 flow rate.
Hence, $\phi>1$ implies that the mixture is fuel-rich, and as such, the supplied O_2 is less than stoichiometric for a given fuel flow rate and will be completely consumed. However, for fuel-rich mixtures, the fuel may not be burned completely to CO_2 and H_2O. Moreover, note that there are four equivalence ratios (ER) involved in reburn systems:

1) Main Buner ER: Typically ϕ_M = 0.95 to 0.9
2) Reburn Pipe ER: $\phi_{Reb\ supp}$ = 2.3 (typically estimated so that Reburn Zone Equivalence Ratio, ϕ_{RBZ}, will be approximately 1.1; see item three below).
3) Reburn Zone ER:
$$\phi_{RBZ} = \frac{O_2 \text{ required for stoichiometric combustion of reburn fuel}}{O_2 \text{ left in main combustion products} + O_2 \text{ supplied through reburn pipe}}$$
4) Overall ER:
$$\phi_{Overall} = \frac{O_2 \text{ for complete combustion both reburn and main fuel}}{\left(\begin{array}{l} O_2 \text{ supplied by over fire air} + O_2 \text{ supplied by reburn pipe} \\ \qquad + O_2 \text{ supplied by main burner} \end{array}\right)}$$
Typically $\phi_{overall}$ is 0.85 to 0.9. This is used to calculate over fire air (air fired downstream of reburners). Over fire temperatures are typically 1880 - 2240 F (1300-1500 K) to complete combustion so that stack O_2 is about 2 - 3%.

Reburn Combustion conditions: Base Case: LA-PC-FB, Equiv Ratio 1.15 (SR= 0.87), Test variables: Two types of fuels: Low Ash Raw Manure (LARM), Low Ash Partially Composted (LAPC), Blend of Coal+ LAPC (Limited Test); Reduce % heat input by manure; Equivalence ratio: 1 to 1.15 , Emissions to be tested (NOx, SOx, Hg, $HgCl_2$).

There will be a log sheet on all experimental conditions.

Problem 1: Based on the extensive parameter testing required for two different reburn fuels (FB for TCEQ and Dairy biomass, DB for DOE-Golden), the vendor's proposal estimated two weeks of testing with a budget of almost $170,000. The number of parametric studies was reduced to perform the experiment within a week ($85,000); the amount requested even for one week is approximately twice the amount of the allocated funds from TCEQ and the ongoing DOE projects combined. In order to stay within the budget, it was decided split the cost approximately on equal basis between TCEQ and the ongoing DOE-Golden projects. Thus negotiations were performed with SRI in the first week of March to reduce the number of conditions for testing so that tests could be performed within a week for both FB and DB and stay within budget. In addition there was a facility fee of over $3,000 per day by the parent Southern Company (SC) which built the facility in 1990 (so the company owns most of it) for all confidential work to be performed at the facility with clients. If Southern Company is allowed to have the report and pretest plans, then they are willing to waive the fees on this facility entirely. TEES/TAMUS requested SC to waive the use fees and we agreed to provide report to Southern Company and pre-test plans in order to reduce pilot scale test costs. Thus the contract negotiations between TAMUS-TEES and SRI continued till May 2007. Meanwhile TAES-Amarillo prepared the fuels, which were ground and shipped to SRI. Fuels prepared include PRB coal, TX lignite, LA-PC-FB, and LA-FB.

Problem 2: The pilot scale facility did not have an eductor large enough to handle the reburn fuel. A new eductor was acquired which delayed the start of experiment.

Problem 3: The pilot scale furnace is 3.5 feet in diameter, with an average upward flow of less than 10 feet/second. If the reburn fuel is injected at 50 ft/s across the furnace, it will blow the flame into the wall on the opposite side. The higher ash from FB in this facility may fall and may choke the main burner. The problem was minimized by using an opposed jet supplied with recirculated flue gases which will also aid in reducing the oxygen percentage in the reburn zone. However the selected injection configuration by SRI in order to stay within time constraint was different from the injection configuration used by TEES/TAMUS.

Problem 4: Meanwhile SRI faced a change in lab personnel, which caused delays of tests beyond May 31, 2007. Thus a conference call was scheduled on 4/26/07 with Ms Kate Williams to check whether no-cost contract extension was possible beyond May 31, 2007. TAMU and SRI were informed that the contract will end on May 31, 2007. The SRI hired/contracted new personnel in order to conduct tests within May 31st deadline. TAES shipped the experimental fuels in early May.

Problem 5: For the main burner, the desired firing condition is with 5% excess air at the burner (ϕ = 0.95) which leads to excess oxygen of approximately 1%. However pilot scale facility safety system required O_2 percentage above 1.5%. Thus the facility was modified for introduction of over fire air even for the base case.

4 OPERATING CONDITIONS

Part of the DOE funds, as well as internal funding, have been used to generate an EXCEL based program called REB-LOWNOX specifically for reburn methodology. The input data are main burner and reburn fuel properties, thermal rating of boiler, oxygen % in main burner

air and reburn gas, % heat provided by reburn fuel, main burner (ϕ_M), reburn zone (ϕ_{RBZ}) and overall ($\phi_{overall}$) equivalence ratios. The outputs are:

i) derived fuel properties: chemical formulae for both main and reburn fuels, stoichiometric oxygen for main and reburn fuel, heating values per unit stoichiometric oxygen, A:F ratio in main burner
ii) operating conditions for main burner: fuel flow rate, air flow rate, expected CO2, O2 % in main burner products
iii) operating conditions for reburn system: fuel supply rate, oxygen supply rate and reburn gas supply rate to maintain desired equivalence ratio in reburn zone (ϕ_{RBZ}), required equivalence ratio in the reburn gas supply pipe (ϕ_{RB}) for specified ϕ_{RBZ}, CO and CO2 %
iv) operating conditions for over fire air: over fire air flow rate required to maintain $\phi_{overall}$ (in order to get desired stack oxygen % in stack):

The EXCEL program can be used to generate data for real scale boiler also. Sample input and output are presented in Tables 4.1 and 4.2. Operating conditions were generated for different conditions using the REB-LOWNOX spread sheet based program. Sample conditions produced by TAMU Excel program are shown in Table 4.1 (Choctaw coal) while sample conditions calculated by SRI are shown in Appendix B.

Table 4.1.INPUT DATA on REB-LOWNOX EXCEL based program

Equivalence Ratios (ϕ)	
Primary Burner Equiv	0.95
Reburn Zone equiv ratio	1.15
Primary Fuel gas	NO
Overall Equiv with overfire air	0.854

Primary Fuel : Input only on Atom basis

Primary Fuel	Choctaw coal
Element	% by mass
C	78.92
H	4.77
N	1.89
O	5.96
S	0.9
Moisture	1.49
Ash	5.65
HHV, BTU/lb	13790

Burner Rating	3.50E+06
Main Burner fuel	90
$x_{NO,MAINBURNER}$	400

Main AIR Properties	
Temp	78
$RH_{ambient}$	15
$O_{2,main,\ overfire,\ dry}$	20.9
P MAIN, overfire	101

Reburn Gas Properties	
$P_{ambient}$	101
Temp	78
$RH_{ambient}$	15
Preburn	101
$O_{2,\ reburn,\ dry}$	10

Reburn Fuel	3 WYPRB Subbituminous Coal
Element	% Mass
C	46.523
H	2.730
N	0.657
O	11.293
S	0.273
Ash	5.640
Moisture	32.883
TOTAL	100.000
HHV (BTU/lb)	7,823.000

A chart has been developed for any generic fuel (C-H-O) for obtaining the desired RBZ (reburn zone) equivalence ratio (See TCEQ Monthly report, March 2007). The chart is applicable to almost any fuel. Using such a chart, one can select desired ϕ_{RB}, for specified reburn zone equivalence ratio (ϕ_{RBZ}) at various heat input ratios when main burner equivalence ratio operates at $\phi_M = 0.95$ (about 5% excess air).

If desired, $\phi_{RBZ} = 1.1$, then needed reburn gas equivalence ratio is (i.e. reburn injection pipe) is 2.3 at 10% heat input (See TCEQ Monthly report, March 2007). Since reburn zone is fuel rich overfire air (air fired downstream of reburners) is used to complete combustion. Further the $\phi_{Overall}$ can be controlled by adjusting the amount of over fire air. For $\phi_{Overall} = 0.9$, the stack O_2 or furnace exit oxygen (FEO) is about 2% and $\phi_{Overall} = 0.83$, the FEO is about 3.7%.

Fuel Requirements: The Vendor 2 facility will require approximately 3,500 lb of coal per day (with 10 hrs of operation per day; 350 lb/hr). For 5 days of tests and 2 weeks of test duration, the total coal required will be approximately 35,000 lb (17.5 short tons) and 7,000 lb of FB (90:10 blends on heat basis) for cofiring applications. For reburn applications with a maximum of 30%

Table 4.2.OUTPUT for Stack O_2 = 3% for 3,500,000 BTU/hr, 10% Heat Input via Reburn, Φmain = 0.95 (5% excess air) &

Exp #	**Φove rall**	**Main Air**	**Main Fuel**	**Main O_2 Exhaust**	**RB Fuel Type**	**RB Fuel Rate**	**RB Air**	**Φ RBZ**	**Φ RBF**	**RB O2**	**RB N2**	**RB Gas (Air+N2)**	**Overfire Air**	**CO2 Stack**
0.0	0.0	SCFH	lb/hr	%	0.0	lb/hr	SCFH	0.0	0.0	%	SCFH	SCFH	SCFH	%
1.0	0.8	31861.5	228.4	1.0	WY Coal	44.7	3346.8	1.1	2.2	10.0	3012.1	6359.0	6309.7	17.0
2.0	0.8	31861.5	228.4	1.0	WY Coal	44.7	3661.7	1.1	2.0	10.0	3295.5	6957.2	6182.3	16.9
3.0	0.9	31861.5	228.4	1.0	WY Coal	44.7	3059.3	1.2	2.4	10.0	2753.4	5812.7	6424.6	17.0

heat input with coal as reburn fuel, total coal fuel sample mass should be 12,250 lb (approx 6 short tons); for reburn with FB alone the required amount jumps to 21,000 lb (10.5 tons; FB feed: 65 lb/hr due to low heart value). Since coal will be fired only for baseline studies, the required amount could be reduced to about 3.5 short tons for coal but FB should still be about 10.5 tons.

With 10% reburn heat input; the highest feed rate for any reburn fuel is 62 lbs/hr. During

Figure 1: Reburn Fuel Pallets Prepared and shipped by TAES-Amarillo/Bushland

the 3-day test, there is a maximum of 36 hours of testing. Therefore, the maximum amount of all fuels fuel that could be burnt as reburn fuel is only 2232 lbs. This is rather optimistic, given that one will not be able to do reburn all of the time since certain amount of time is required for heat up in addition to time between each fuel type to change the fuel in the feeder, etc.

Kevin Heflin (assistant to John Sweeten) prepared 800 lb of PRB coal LAPCFB; 3,150 lb LAPCFB from 2006 (samples #140-142). Texas Lignite: 2,100 lb ready; LAPCFB: 500 lb from 2005 samples and LA-Raw-FB: 500 lb from 2006 samples (Figure 1). He shipped the manure and coal in pallets on Friday, May 04, 2007. Each pallet weights ~1,200 lbs (~300 lbs/box); was shrink wrapped, and all fuels were double bagged and boxed for transportation by common freight carrier.

5 PILOT SCALE RESEARCH FACILITY

5.1 Facility

The Combustion Research Facility (CRF) at Southern Research Institute (Southern Research) in Birmingham, AL, rated at 3.5 MMBtu/hr (1,025 MW_{th}) is a semi-industrial-scale, coal-fired facility, which mimics the thermal profile of a full-scale boiler from the burner through the economizer (Figure 2). The furnace is a vertical, up fired, 28-feet high cylinder, with an inner diameter of 3.5-feet.The thermal rating is 35 times the TAMU burner capacity, the fuel could be natural gas or coal. This allows gas velocities of 10 to 20 feet per second and residence times of 1.3 to 2.5 seconds, depending upon the firing rate. The design furnace exit gas temperature is 2200 °F. The secondary air (600 F) is given a swirl motion and the primary air-coal mixture enters through a refractory quarl with a 25° angle (half angle). The CRF is well suited for NO_x and mercury emission research relative to coal-fired power plants. Southern Research has operated the CRF for over 15 years and has performed extensive mercury speciation investigations and testing of technologies to mitigate mercury and NO_x emissions. The furnace is

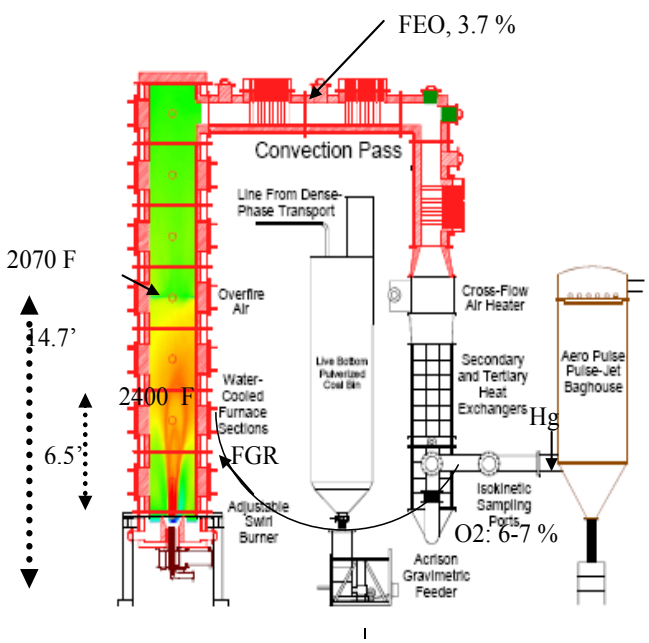

Figure 2: Combustion Research Facility (CRF) at SRI.

refractory lined to radiate heat back to the flame, simulating the radiant heat emitted from the surrounding burners in a full-scale boiler. However, water-cooled walls underneath the refractory allow steady consistent control of furnace temperatures. The refractory lining allows flame temperatures similar to those in full-scale coal-fired boilers. The overfire air port may be fixed and approximately 1 s residence time between main burner and the over fire air port.

As shown in Figure 3, the temperature-time history is similar to that of full-scale coal-fired boilers, for the entire seven second residence time, from the burner to the particulate

collection devices. The peak flame temperatures are consistent with that of commercial boilers. The residence time in the furnace is between 2.5 and 3 seconds.

The facility is controlled and monitored by a networked combined digital control system (DCS) and data acquisition computers, managed by Yokogawa CS-1000 system software that

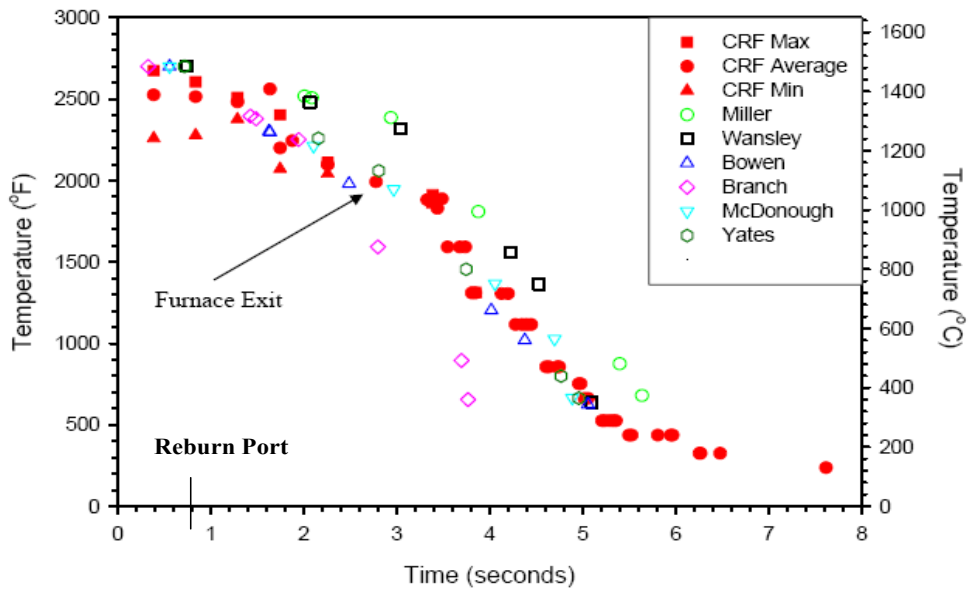

Figure 3. Temperature-time profile of the Combustion Research Facility (CRF).

runs under the Windows NT operating system. This DCS performs all process control for the facility and allows complex feed-forward and calculated variable control. This computer control also performs the safety monitoring needed for safe operation of combustion equipment, including Furnace Exit flame scanning and interlocks, automatic startup and automatic shutdown of the entire facility. Process data acquisition and storage is accomplished within the Yokogawa software.

5.2 Fuel Preparation

Fuel preparation includes on-site storage bins or open yard, rotary drum coal crusher, a CE Raymond bowl mill, and pulverized coal storage with 8 storage bins (capacity: 25 tons of solid fuel). The fuel is crushed to a size of minus 3/8 inch which is then transported to one of two 125 ft3 storage bins mounted on load cells, equipped with vibrator/bridge-breakers, and rotary lock feeders. The fuel is further ground at a rated capacity of 2 tons per hour. The air for the pulverizer is preheated with a dedicated natural-gas burner.

The primary air is maintained at 150 °F, and the secondary air enters the furnace at 600 °F. The coal mill is a refurbished and instrumented 1937 Model 352 CE-Raymond bowl mill, which has a rated capacity of 2 tons per hour. This type of mill provides representative milling simulations of the different air-swept table and roller mills normally used in power-plant service.

During start up, the pulverized coal feed is diverted to a waste bin until the particle size has been established, after which the coal is dense-phase transported over to the pulverized-coal silo and feeder. The particle size of the coal is normally maintained at 70% passing 200 mesh, but other particle size ranges are easily obtained.

5.3 Diagnostics

5.3.1 Gas Analyzers

A complete extractive continuous emissions monitoring (CEM) system is installed in the facility and is interfaced to the computer control system. A set of gas analyzers, which analyze the flue gas for concentrations of O_2, NO_x, SO_2, CO_2, and CO, receives the dry flue gas sampled from a set of three extractive lines. The Combustion Research Facility has both pilot-scale baghouses and a pilot-scale ESP that may be used to extract the ash from the flue gas. Each of these devices has been designed and constructed to represent the full-scale baghouse and ESP devices in use today.

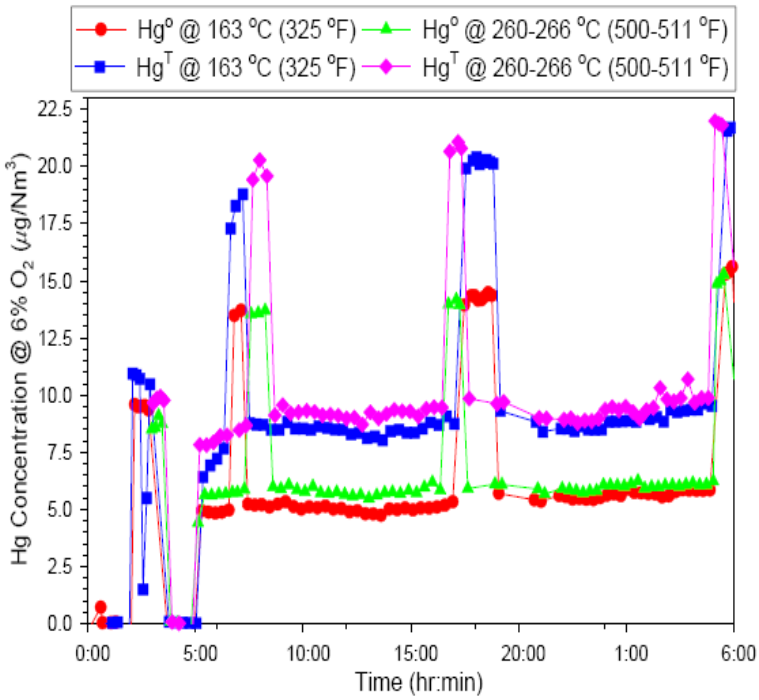

Figure 4. Mercury speciation data with spike and recovery.

5.3.2 Hg

Mercury monitoring was performed with an advanced and customized mercury monitoring system, including a state-of-the-art gold-trap analyzer and an APOGEE Scientific QSIS probe for sampling from dust-laden flue gas. Southern Research also developed an advanced *spike and recovery* system to establish the validity of the mercury-speciation measurements. Because of these and other advancements, mercury speciation measurements within an uncertainty of ±5% are possible. This *continuous spike and recovery* system allows spiking at the tip of the APOGEE Scientific QSIS probe. The spike of mercury is introduced into the tip of the APOGEE Scientific QSIS probe far enough downstream from the inlet to prevent losses to the duct and far enough upstream of the porous annulus (coated with a monolayer of glass to inert the probe) to allow complete mixing before the sampled gas is pulled through the porous frit. A relatively small quantity of air is used to carry the mercury spike to the probe. Therefore, dilution is insignificant, and the general flue-gas composition is undisturbed. The main impact of the spike is simply to increase the concentration of mercury in the sampled gas. This is significant, since mercury-oxidation processes that interfere with speciation measurements can involve three and four component interactions of flue-gas species on catalytic ash sites.

Figure 4 illustrates the use of the *continuous spike and recovery system* for establishing total and oxidized mercury concentrations in the flue gas, while first burning natural gas (time 0:00 to 5:00) and then Black Thunder, a Powder River Basin (PRB) coal. As shown, the *spike recoveries* are observed on top of the measured initial mercury concentrations for both fuels. The concentration of mercury in the spike stream is generated by controlling the flow rate, pressures, and temperatures of air in and through a mercury-loaded support-packed flexible tube and the reservoir in which the tubing is enclosed. High-precision mass-flow controllers are used to obtain the precise metering needed for high-certainty calibrated spikes. The proper use of *spike and recovery* provides a greater level of confidence in the resulting mercury speciation measurements than other methods currently in use.

5.4 Reburning Configuration

Reburning took place at port two (Figure 2 and Figure 3), approximately 0.8 seconds above the burner tip. An Acrison feeder was used to feed the reburn fuel into an eductor funnel at the rate desired. The eductor motive gas was in some cases pure nitrogen and in others house air, depending on the oxygen concentration desired in the reburn gas. Even when nitrogen was used for the motive gas, a significant amount of air (hence oxygen) was sucked into the transport gas through the funnel, with the reburn fuel. The sum of motive gas and aspirated air is called reburn gas. The O_2 percentage in reburn gas ranged from 7-21% O_2. In order to approach the oxygen concentrations desired for the transport gas, it was necessary to mix the transport gas for the reburn fuel with recycled flue gas. The recycled flue gas extracted downstream of heat exchanger had some oxygen in it, between 6 and 7% (Figure 5). Mixing was accomplished in the furnace; using opposed jets of transport reburn gas and recycled flue gas. The recycled flue gas was taken just downstream from the last heat exchanger (Figure 5) pulling from a long pipe inserted axially along the duct, through an elbow, to minimize the recycle of fly ash. The flue-gas source was at 325 °F but was allowed to cool down some before being pulled through a blower and fired back into the furnace, opposite the reburn injection. The blower speed was controlled with a variac, and the flow was determined using a sonic orifice. In addition to providing greater control of the

reburn-gas oxygen concentration, independent of the furnace oxygen concentration, the opposed-

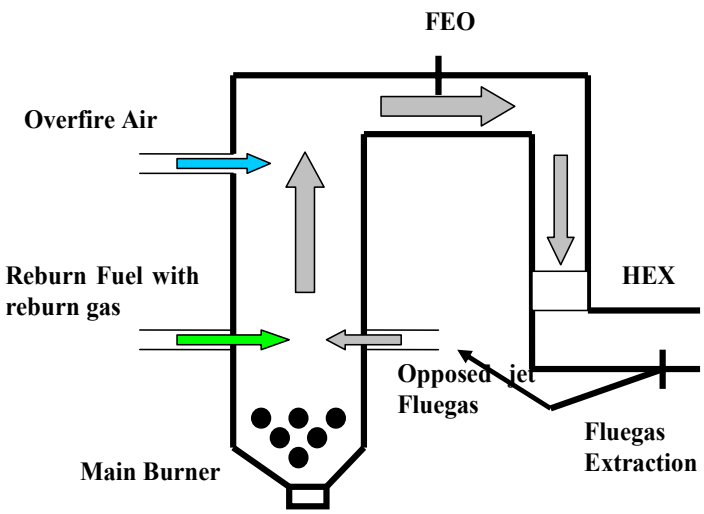

Figure 5: Schematic of the Pilot Scale Facility. FEO: furnace exit Oxygen, typically 3.7 %

jet flow induced greater mixing of the reburn fuel and gas in the furnace. Further it also prevented reburn fuel flame impinging on the opposite wall.

5.5 Furnace Firing Parameters

SRI switched the baseline coal from Choctaw American coal to more readily available Galatia coal (see fuel analysis in Table 6.1. The Galatia coal feed rate was 282 +/- 4 lbs/hr in the main burner at full load. See Table 5.1 for main burner operating condition. At this condition, without overfire air and 3.7% Furnace Exit Oxygen (FEO), approximately 400 ppmv (actual) of NO_x were produced (this was approximately 555 ppmv of NOx corrected to 3.0% O_2 in the flue gas). After this full-load NO_x level was established, the coal feed rate was reduced to 90% of full load. From then on, the Galatia coal feed rate to the main burner was 253 +/- 5 lbs/hr, and the secondary air was adjusted to provide 5% excess air at the main burner. The one exception to this was Condition 14, where 15% of the fuel was replaced with reburn fuel, and the coal feed rate was ~240 lbs/hr. Independent of the reburner, the overfire air (OFA) was adjusted for each test condition, to produce 3.7% FEO, thus matching that of the baseline condition. The primary and secondary air flows in the main burner were 120 SCFM and 452 SCFM, respectively, for all tests conducted, except condition 14.

The secondary air valve had problems sticking before and during the test. Consequently, the actual amount of secondary air was much higher than originally indicated by the readout. Hence, the flow settings for the main burner were obtained by adjusting the secondary air until

the furnace exit oxygen reached the consistency with the desired amount of air in the main burner.

Table 5.1. SRI 1 MWth Pilot Scale Facility and Furnace Firing Parameters Main Burner, baseline firing conditions

MAIN BURNER	SRI		
Swirl #	0.6		
Thermal Power, BTU/hr	3.50E+06		
Thermal Power, kW	1,025		
Coal	Galatia (see table 6.1)		
HHV, BTU/lb as is	12,694		
HHV, kJ/kg as is	29,526		
HHV-DAF, kJ/kg	33,434		
HHVO2, kJ/kg of O2	12,460		
HHVO2, BTU/lb of O2	5,589		
Main Burner Load	**100%**	**90%**	**85%**
Thermal Rating, MWth	**1,025**	**923**	**830**
Fuel Firing rate: lb/hr	282	254	240
Fuel Firing rate: lb/min	4.70	4.23	4
Fuel Fire rate, kg/min	2.13	1.920	1.814
O2 stoich rate kg/min	4.936	4.442	3.998
O2 stoich rate SCFM	127.720	114.948	103.453
Prim air, lb/min	9.256	9.256	9.256
Sec air(1), lb/min	34.863	30.451	28.245
Total main burner air(1),,lb/min	44.118	39.70648562	37.50056976
Prim air, SCFM	120	120	120
Sec air(1),, SCFM	452	394.8	366.2
Total main burner air(1),,SCFM	572	514.8	486.2
FEO (furnace ext Oxygen)	3.70%		
Estimated Overall Equiv ratio at 100 % load by main burner	0.826		
Stoich A:F	10.30		
Overall A:F include overfire	12.56		
Stoich airflow , lb/m	46.39	46.01633333	43.48
Req Air flow lb/m	56.09	55.626	52.56

(1): Set flow; however Sec. Air valve some time get stuck and hence the table values may be inaccurate; air flow estimated from FEO (See Appendix C) from its neighboring injector. In addition, the injectors were positioned with a 10° angle away from horizontal injection, to provide some swirl.

In order to do this for the desired 5% excess air in the main burner, it was necessary to have the over fire air (OFA) on, because otherwise the furnace exit oxygen would drop down below 1.5%

FEO, which would cause a furnace interlock to shut off the flame. Unfortunately, the secondary air valve did not remain at the same *stuck setting*. Soon after the test started, the actual secondary air flow decreased somewhat, indicated by the amount of OFA necessary to obtain the FEO levels needed. Midway through the test plan, the flow to the main burner was readjusted, and the OFA required decreased. However, it appears that once the furnace was adjusted to the desired operating condition, the secondary air closed somewhat. The difficulty in adjusting the secondary air correctly, using the OFA and FEO, independent from the secondary air flow reading, was confounded by the fact that the OFA and secondary air originate from the same duct and are controlled by a damper between the two. The effect on the test was that instead of the main burner being continually fired at 5% excess air, it was more often near stoichiometric. More discussion is presented in the results section.

6 RESULTS

6.1 Fuel Properties

6.1.1 Main Burner Fuel

In order to reduce time for conducting pilot scale tests, the SRI selected readily available Galatia sub-bituminous Coal to produce 90 % of heat rate instead of Choctaw coal. Remaining 10 % of heat rate is provided by reburn fuel. Main burner fuel properties are presented in Table 6.1.

Table 6.1. Galatia HvB Bituminous coal analysis (from coal feeder discharge).

Proximate		Ultimate, DAF	
% Moisture	5.10	% Carbon	82.60
% Ash	6.59	% Hydrogen	5.19
% Volatiles	31.70	% Nitrogen	1.90
% Fixed C	56.62	% Sulfur	1.48
HHV (Btu/lb)	12694	% Oxygen	8.83
HHV (kJ/kg)	29,526		
		Hg (µg/g)	0.107+/-0.001
		Cl (%)	0.4396 +/-0.0047
Chemical Formulae, DAF	$C_{6.877}H_{5.149}N_{0.136}O_{0.552}S_{0.0466}$		
St. O2, kg of O2/kg as received	2.37		

6.1.2 Reburn Fuel

Table 6.2 presents the reburn fuel properties

Table 6.2. Properties of Reburn Fuels.

RB Fuel Element	WY Subbituminous Coal % Mass	TX Lignite Coal % Mass	LA PC FB % Mass	LA RM FB % Mass
C	46.52	37.18	33.79	34.98
H	2.73	2.12	3.65	4.16
N	0.66	0.68	1.97	2.36
O	11.29	9.61	23.94	19.03
S	0.27	0.61	0.51	0.38
Mercury, Hg	0.00017	0.00014	0.00006	
Chlorine, Cl	0.010	0.009	0.73	0.85
Ash	5.64	11.46	16.50	9.57
Moisture	32.88	38.34	19.64	29.52
HHV (BTU/lb)	7,823	6,143	5,703	2,444
HHV (BTU/lb, DAF)			8,499	

6.2 Operating conditions

The baseline coal firing conditions were shown in Table 5.1. The reburn fuels include PRB coal, LAPCFB, LARMFB, and Texas lignite (TXL). The firing rates were adjusted to provide 10 % heat input. The required flow rates of reburn gas (9-28 SCFM) and opposed jet flue gas (24-79 SCFM), corresponding O_2 concentrations and overfire air flow rates for the various test runs were adjusted to yield FEO of 3.7 %. The injections include both lateral and 45 incline. The O2 % in reburn gas ranged from 7-21% while the % in flue gas ranged from 6-7 %.

Since equivalence ratio of main burner ϕ_M during operation is not exactly known, an analysis has been conducted to determine the oxygen input in the main burner using oxygen mass balance between main burner and the mass flow at furnace exit where O2 % is known.

From the combustion textbook by Annamalai and Puri (CRC Press, 2006), for any fuel operating with excess air, the equivalence ratio of a furnace can be given as:

$$\phi_{overall} = \frac{1}{SR} = 1 - 4.76 * \left(\frac{FEO\%}{100} \right)$$

And

$$Excess\ \%\ air = \{SR - 1\} * 100$$

Where $\phi_{overall}$ the equivalence ratio and SR is is the stoichiometric ratio. If FEO % =3.7 and as such $\phi_{overall}$ = 0.826, SR= 1.21 and excess air including over fire air is 21%. However, the present furnace is supplied with air, N_2 and flue gas; thus ϕ_M= 0.826 is only approximate. Thus even this approximate result is very close to exact values from 0.81 to 0.83. Figure 6 shows the estimated equivalence ratio of main burner from the knowledge of reburn gas, opposed jet gas flow O_2 percentage in reburn and opposed jet gas and FEO. Once the ϕ_M is known, the reburn equivalence ratio can be estimated without overfire air (Figure 6). Also from the knowledge of

O_2 percentage in reburn gas and opposed jet gas and type of reburn fuel fired, the ϕ_{RBZ} was estimated (Figure 7).

6.3 Emission Results

6.3.1 NOx and SO2

Table 6.3 shows a summary of results on emission of NOx, and SO2 along with measured values of CO2. Using more detailed set of data and Figure 7, the % NOx reduction was plotted vs. estimated ϕ_{RBZ} for the three different reburn fuels (Figure 8). LA-RM-FB indicated

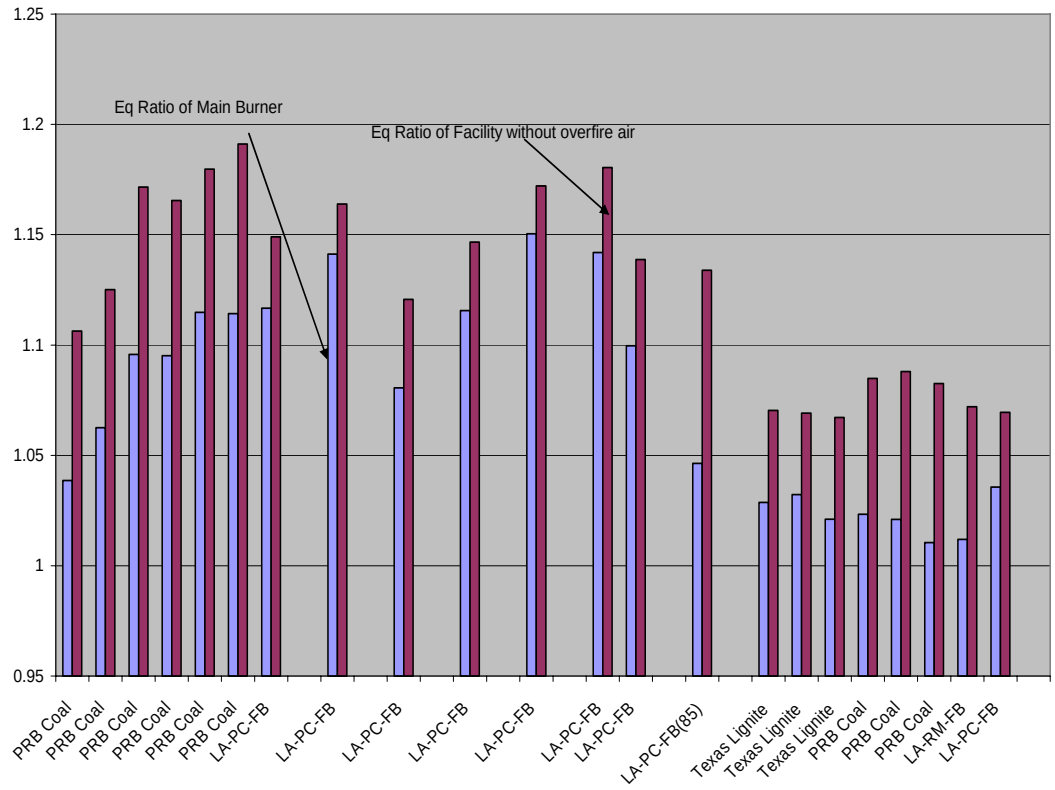

Figure 6 Estimated Equivalence Ratio (ϕ) of main burner and Equivalence Ratio the facility without over fire air; ϕ>1 implies that gas is oxygen deficient or mixture is rich; FEO: 3.7 % (with over fire air)

similar results (67 % not shown) as that of LA-PC-FB. The % reduction was calculated for baseline NOx of 555 ppmv for 3% FEO; this does not include the effect of lowering of NOx due to use of flue gas which supplies additional NOx in the reburn zone. The uncertainty in each measurement is much higher, illustrated by the difference in a few of the repeat condition results. The NO_x measurements for example, differ by as much as 40 ppmv for some of the test conditions. The carbon monoxide levels at furnace exit did not significantly increase during any of the test conditions.

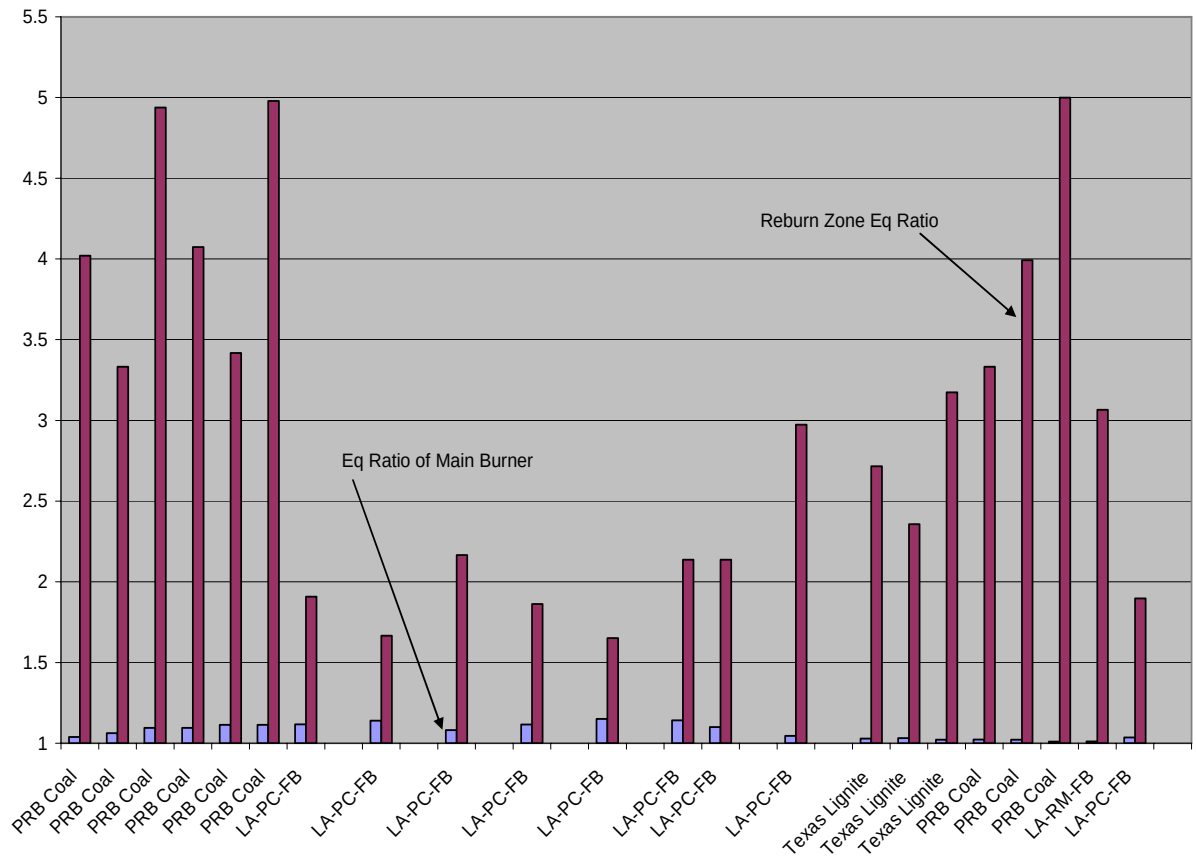

Figure 7. Estimated Equivalence Ratio of Main Burner and Reburn Zone Equivalence Ratio: Note: there is no O_2 supply from main burner; FEO: 3.7 %; Standard Flow at 60 F (376 SCF per lb mole)

It is clear from Figure 8 that, the NO_x emissions were considerably lower (by as much as 75%) than the baseline test condition. However, it was also clear from the test that some of the NO_x reduction was simply due to staging. ***Nevertheless, the difference between the NO_x concentrations in the flue gas while at the condition (i.e., temperatures and gas flow rates were all stable at the given condition) but with the reburn fuel OFF, were consistently twice as high as when the reburn fuel was ON.***

It is noted that ϕ_{RBZ} is very rich due to operation of main burner near stoichiometry and as such as the temperature of reburn zone is affected due to incomplete combustion (i.e. not all reburn fuel is burnt in reburn zone). Most of the fuels seem to complete combustion near the overfire zone. However the ϕ_{RBZ} used in TAMU tests is considerably higher but still rich producing CO, CO_2, etc but there is enough O_2 to gasify all the reburn fuels to CO, CO_2 and H2O. Thus the reburn zone mixture temperatures are conducive for NOx reduction reactions.

Table 6.3. Results on Flue Gas Composition

Run Nos.	Reburn Fuel	NOx ppmv	CO_2 ppmv	SO_2 ppmv
#1 - #6	PRB Coal	189.667 +/- 7.257	17.500 +/- 0.957	955.833 +/- 56.993
#7 - #14	LA PC FB	188.286 +/- 18.566	16.143 +/- 0.253	862.429 +/- 24.837
#15	LAPCFB/PRB	168	15.7	835
#16-#18	TX Lignite	165.000 +/- 6.245	16.1 +/- 0.100	937.000 +/- 18.248
#19 - #21	PRB Coal	177.8.083	NA	800-960
#22	LA RM FB	183	NA	800-960
#23	LA PC FB	163	NA	800-960

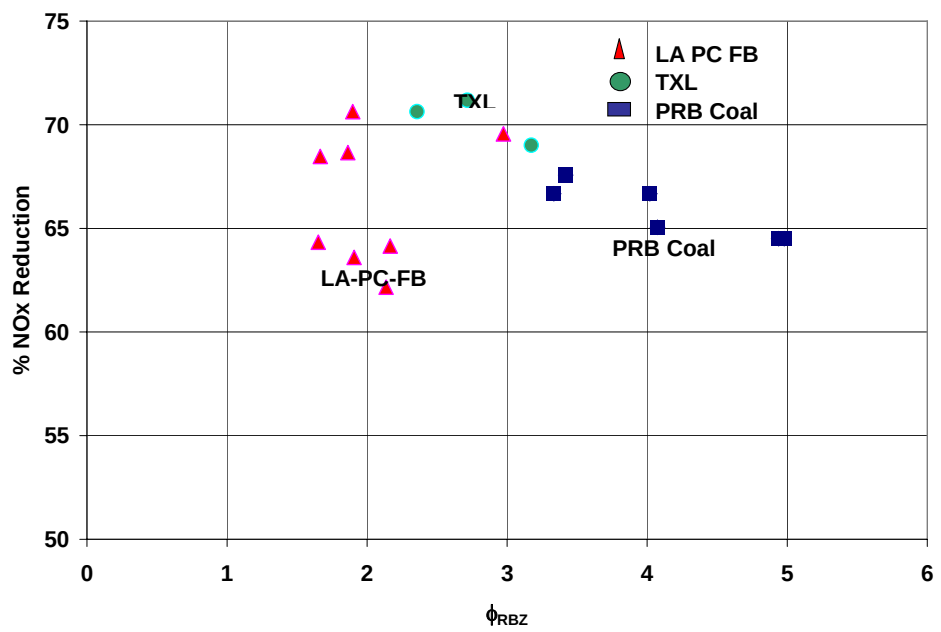

Figure 8. % NOx reduction vs. estimated Reburn Zone Equivalence ratio ϕ_{RBZ} using Galatia baseline coal at SRI preliminary tests

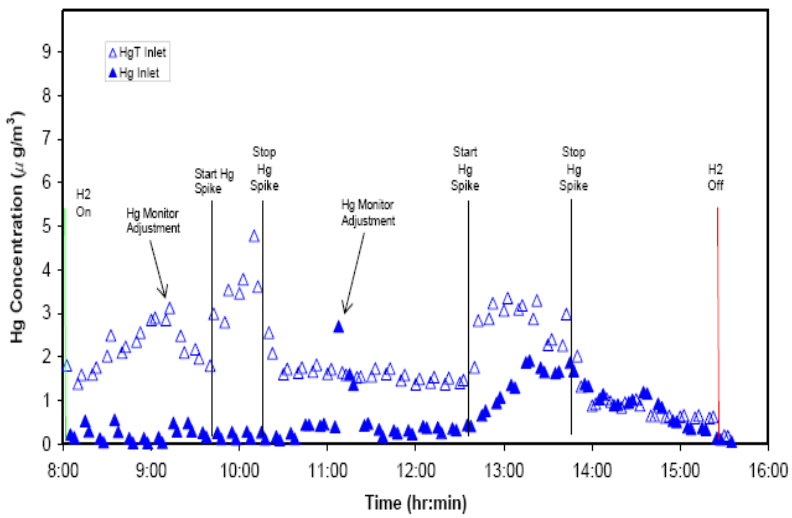

Figure 9. Mercury speciation data for the ESP inlet, taken Wednesday, May 30th.

6.3.2 Hg

As a result of the urgency of the test and the circumstances under which it was conducted, mercury data were only obtained on days two and three of the test campaign, and only at the ESP inlet. Figure 9 and Figure 10 contain the elemental and total vapor-phase mercury measurements obtained on day two and day three of the test campaign, respectively. As illustrated in the figures, the total mercury concentration in the flue gas was very low, and the oxidation was high. This is consistent with the coal type that was burned, which had very low mercury content. Galatia coal produces about 250 ppmv of HCl in the flue gas, along with a fairly high unburned carbon concentration in the ash, the combination of which tends to yield extensive mercury oxidation.

The spike intervals are for QA/QC, and data regarding the reburn test cannot be extracted during these times. It appears that the total mercury concentration rose and fell with reburn injection. Perhaps because the main-burner coal had so little mercury in it, the addition of the mercury from the reburn fuel was significant enough to increase the total by a small amount. It is impossible to extract more information from these mercury data at this time, because each condition was very short, sometimes less than 15 minutes. Normally it takes at least 4 hours (and sometimes much more) for a condition to become stable in terms of total mercury and mercury oxidation state, given that mercury capture and oxidation is highly dependent on equilibrium conditions of low-temperature fly ash composition, temperature changes, and adsorption/desorption onto and off of fly ash, duct surfaces, and even the sampling systems. Further HCl+ Hg does not react fast enough; unburned C will provide chlorinated C sites for Hg absorption.

7 SUMMARY AND CONCLUSIONS

The reburn tests at SRI were conducted as parametric experiments involving different operating conditions and reburn fuels, which included WY-PRB coal, TX lignite, low ash/partially composted feedlot biomass, and low ash raw feedlot biomass. The conditions of the tests did not satisfactorily approximate the prior conditions for small scale TEES/TAMUS tests.

1. It is believed that the SRI/CRF facility seems to have operated as staged combustion facility with main burner with 90% heat input operating slightly rich or stoichiometric and that reburn fuel with 10% heat input operating extremely rich lowering NOx emission. The over fire is used to complete combustion.
2. Hence the reburning results indicated similar NOx reduction for each of the different reburn fuel types, including the low-ash raw FB and partially composted manure (LA-PC-FB).
3. The small scale TAMU tests used 30% of heat as reburn input while the present pilot scale used only 10% as heat input and as such i) there may not enough NH3 to reduce NOx from the main or ii) the extremely rich reburn zone did not have enough temperature to proceed with reactions.

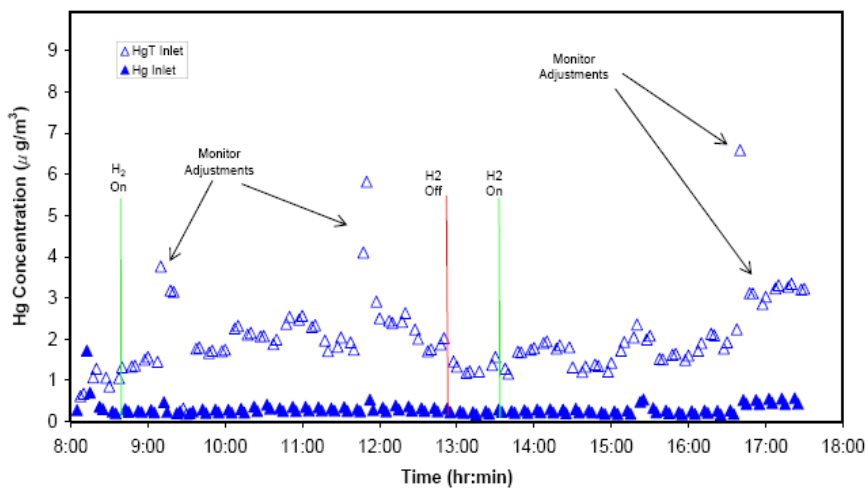

Figure 10. Mercury speciation data for the ESP inlet, taken Friday, May 25th.

4. The operational condition of reburn zone was different from TAMU tests, where larger NOx reductions from FB reburning were measured.
5. Further for same ϕ_{RBZ}, and heat % input by reburn fuel, the O2 flow in reburn system should not vary when fuel is switched from coal to FB since HHV_{O2} is roughly constant. However when PRB coal was fired as reburn fuel, the O_2 supply 2.5 SCFM for Cond #3

instead of 5.9 for same RBZ; as such the ϕ_{RBZ} increased for coal. In other words, reburn zone equivalence ratio is twice higher for coal compared to FB. As such coals operated under extremely rich conditions while FB operated under less rich conditions; still FB had the same reduction as coal indicating that FB is more effective even under less rich conditions.

6. Differences in NOx results can be attributed to difference in injection geometry of TEES/TAMUS and SRI. Depending on reburn gas jet velocity and opposed jet velocity, the reburn fuel may not have been uniformly spread across the cross section of the burner. Future work under DOE-Golden project funding will attempt to simulate TEES/TAMUS's geometry.
7. The secondary air valve had problems sticking before and during the test resulting in operation of main burner. The effect on the test was that instead of the main burner being continually fired at 5% excess air, it was more often near stoichiometric.
8. Most of the Hg seems to be oxidized since very little elemental Hg was detected. The oxidation is believed to be due to high Cl of Galatia coal, since introduction of PRB or TX lignite did not affect elemental Hg emissions validating the hypothesis that high Cl content in fuels decrease elemental Hg. Future tests must use low-Cl coal as main burner fuel in order differentiate the effect of Cl in LAPCFB on Hg oxidation. Further tests must be performed first with coals as reburn fuels followed by FB nut not in other sequence.
9. The duration of each test was short (e.g. ~10-15 min each); while NOx results may be reasonable, Hg results could be affected. In the future test, fewer test conditions and longer duration per test must be adopted.
10. When biomass fuels are used as reburn fuels, emissions of do-oxins/furans (EPA method 23) , and trace heavy metals (EPA 29 method) must also be measured

8 ACKNWOLDGEMENTS

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10 APPENDIX

10.1 Appendix A: Overview of Hg emissions, Hg Capture and Pilot Scale Testing

The 1165 coal fired utilities produce about 48 tons of Mercury (Hg) every year [Feeley III et al, 2005]. EPA's Clean Air Mercury Rule (CAMR) calls for reduction of Hg emissions in two phases: from 48 tons/yr to 38 tons/yr in Phase I and to 15 tons/yr in Phase II [EPA Website]. The Phase I control begins in 2010 with 38 Tons/yr as the cap while Phase II begins in 2018. Phase I is based on co-benefit reductions of Hg through conventional Air Pollution Control Devices (APCD) for reduction of SO2 (e.g. wet scrubbers), particulate matter (PM) emissions from coal fired flue gases required under Clean Air Interstate Rule (CAIR). For example, the Selective Catalytic Reduction (SCR) used for NOx control can also oxidize elemental Hg.

Typically the Hg in coal (Lignites: 10-350 parts per billion or ppb; Sub-Bituminous 10-440 ppb; Bituminous: 20-820 ppb) is vaporized as elemental Hg, yielding Hg^o vapor while the Hg in the flue gas exists in three different forms: elemental Hg^o (elemental) and Hg^{2+} (oxidized form, e.g. $HgCl_2$) [Linak, 2001] and Hg in particulates. The elemental Hg^o does not dissolve in water and is not usually captured in APCD while the Hg in particulates is captured in particulate control devices (PCD) (Electro static precipitator {ESP} or fabric filter {FF}, other appropriate devices). The oxidized form dissolves in water and can be captured with water spray or in flue gas desulphurization (FGD) unit. In fact the relative solubilities of Hg^o and Hg^{2+} are 1 and 1,400,000 respectively [Wilhelm, 1999]. The oxidized mercury compounds are also known to form complexes with fly ash aerosols. The particles are captured using either ESP to capture the particulate containing carbon along with Hg compounds or using wet scrubbers. In order to form oxidized Hg, Chlorine (Cl) is required.

The Cl content in Bituminous coals ranges from 200 to 2000 ppm (dry basis) while for low rank coals (sub-bituminous and lignite) Cl ranges from 20 to 200 ppm an order of magnitude lower. Typically elemental Hg content in coal is inversely proportional to Cl content of coal. Thus the low rank Sub-bituminous and lignite coals reveal lower Hg capture (3-72 %) in "co-benefit" systems than higher rank bituminous coal (9-98 %) [Feeley III et al, 2005]. Hg removal plotted against coal chlorine content reveals increasing Hg capture with Cl due to $HgCl_2$ formation [Senior and Alfonso, 2001]. Typically, when Cl concentration exceeds 200 ppm, Hg is captured primarily in the particulate phase. TXU Energy uses Texas Lignite and the Texas Municipal Power Agency (TMPA) near College Station uses Wyoming sub-bituminous coal as fuel. As Cl is low in sub-bituminous and lignite coals, the Hg exists primarily as elemental Hg, which is difficult to capture.

It is apparent that apart from "co-benefit" method (phase I) , other methods are required to meet the CAMR Phase II regulations; a few of the methods under development are as follows: i) Blended Coals: a blend of high Cl and low Cl coals, ii) Activated Carbon Injection (ACI): powdered activated carbon (PAC) injected down stream of the air preheated and upstream of APCD and capture of Hg along with fly ash in APCD , and iii) patented "thief process" by DOE where small % (< 1 %) of partially burnt char is captured near the coal burner and then injected downstream of the boiler to capture Hg . Recent experimental data indicate that the patented Activated Carbon Injection technique removes almost 90 % of Hg.

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10.2 APPENDIX B: Sample Operating Conditions: Prepared by SRI: Reburn Zone Oxygen Supply rate

The Choctaw feedrate is 259 lbs/hour at full load. The makeup air to obtain these FEO (furnace exhaust oxygen) levels at the furnace exit while reburning will be made up by putting air through the OFA (over fire air) ports. Since the CRF is operated by adjusting the split between the OFA and Secondary Air, the total air to the burner will have to be increased and the splits changed accordingly. The air splits for each of the test conditions are given below.

For TX Lignite:

Reburn Fuel = 10% heat content (Reburn Fuel Feed Rate = 58 lbs/hr), with 10% O2 in reburn transport gas:

ϕ= 1.05

Air Split = 18% Primary Air, 68.8% Secondary Air, and 13.1% Tertiary Air, with FEO = 3.0%.

The Reburn gas flow rate = 45.5 SCFM (w/10% O2 in the mix).

ϕ= 1.1

Air Split = 18% Primary Air, 68.5% Secondary Air, and 13.5% Tertiary Air, with FEO = 3.0%.

The Reburn gas flow rate = 39.5 SCFM (w/10% O2 in the mix).

The highest feed rate for any fuel is 62 lbs/hr.

These equivalence ratios and required reburn gas flow rates are estimated assuming that main burner provides “excess oxygen” in products to reburn zone