Healy Clean Coal Project: 1998 Combustor and Spray Dryer Absorber Characterization Testing

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The Healy Clean Coal Project (HCCP), selected by the U.S. Department of Energy under Round III of the Clean Coal Technology Program, is currently in its test operations phase. After more than five years of planning, design engineering and permitting activities, the project celebrated its ground-breaking ceremony at Healy, Alaska on May 30, 1995. Most of the major plant equipment was delivered to the Healy site 250 miles north of Anchorage, Alaska in 1996. Construction of the plant was completed in November 1997, with coal-fired operations starting in January 1998. The project status, its participants, description of the HCCP technology, and the 1998 operational performance of the combustion system and flue gas clean-up system are presented in this paper.

The TRW Clean Coal Combustion System is designed to minimize NO_x *emissions, achieve very high carbon burnout, and remove the majority of flyash from the flue gas prior to the boiler. The TRW system also provides the first step of a three-step process for controlling* SO_2 *by converting limestone to flash calcined lime that subsequently absorbs* SO_2 *within the boiler. The majority of* SO_2 *is removed downstream of the boiler, using Babcock & Wilcox's (B&W's) activated spray-dryer absorber (SDA) system, which utilizes the flash calcined material (flash calcined lime + flyash) produced by the TRW system. Since most of the coal ash is removed by the combustors, the flash calcined material is rich enough in calcium content such that the SDA can be operated solely on recycled lime, eliminating the need to purchase or manufacture lime for the backend scrubbing system.*

HCCP is the first utility-scale demonstration of the TRW clean coal combustion technology. During 1998, approximately 5,000 hours of plant thermal operation were accumulated, with approximately 4,500 hours of coal-fired operating time. Both run-of-mine (ROM) and ROM/Waste coal blends were tested in the combustion system. For the majority of the testing, the coal combustors were operated in conjunction with B&W's activated recycle spray dryer absorber system. To date testing has shown:

- *ability to achieve low NOx emissions simultaneously with low CO emissions and high carbon burnout*
- *good combustion efficiency and high slag removal prior to the furnace*
- *good limestone calcination efficiency*
- *consistent achievement of* SO_2 *emissions less than 0.10 lb / MMBtu.*

This paper presents the results of coal-fired test operations from June 12 through December 21, 1998. During this period of time, approximately 3300 hours of plant thermal operation was accumulated, with approximately 3200 hours of coal-fired operation. The majority of test operations were at full load, 50 MW_e. The emission data presented includes all coal-fired operations during this period of time, including, in most cases, start-up and shutdown operations. Not included herein is emission data during: 1) January through June 11, 1998, which primarily consisted of coal-firing start-up and shake down activities and was prior to certification of the Continuous Emissions Monitoring System (CEMS) and, 2) oil-fired only operation. The emission levels of NO_x, CO, and SO_2, were lower than permitted emission limits. From June through December 1998, the demonstrated environmental performance while burning ROM or ROM/Waste Coal Blends was as follows:

NOx Emissions:	*0.208 to 0.278 lb NO_x / MMBtu (0.245 average)*
SO2 Emissions:	*0.01 to 0.09 lb SO_2 / MMBtu (0.036 average)*
Ca/S Ratio:	*1.0 to 3.0 (typically less than 2.0)*
CO Emissions:	*0.01 to 0.13 lb CO / MMBtu (0.038 average)*
Ash Removal:	*80 to 90% (including less than 5% bottom ash)*

If published data from the Continuous Emission Monitoring system is used, which includes oil-fired only data during start-up and shutdown, the average NO_x emissions over this time period is 0.25 lb NO_x / MMBtu versus the 0.245 average shown in the table above. The NO_x emission levels presented above were achieved prior to any optimization of furnace air staging or furnace O_2 levels. In general, the lowest NO_x emission levels at full load were achieved at lower furnace O_2 levels (3.0-3.5%), without any significant increase in plant CO emissions. The CO emissions were measured by a CO analyzer located at the furnace exit. This analyzer is not part of the Continuous Emission Monitoring System.

Demonstration Test operations are continuing during 1999. The focus of the 90-day Demonstration Testing planned for 1999 will be to accumulate data on availability and sustained operations. On-going preparations for long duration operation include addressing some previously identified plant operational and/or hardware durability problems, and includes such items as improving mill exhauster fan erosion resistance, mitigating slag/ash falls from the furnace hopper slope, and selecting optimal flame scanner locations. In addition, fine-tuning of the control system will be performed in order to improve system response time to load changes.

The $242 Million project is owned and financed by the Alaska Industrial Development and Export Authority (AIDEA), and is cofunded 48% by the U.S. Department of Energy (DOE). Golden Valley Electric Association of Fairbanks, Alaska will be the contract operator and provided the plant operators for the testing. Usibelli Coal Mine of Healy Alaska provided the Run-of-Mine and Waste coals fired during the combustor characterization testing.

I. BACKGROUND

The multistage coal combustion technology demonstrated at the Healy Clean Coal Project (HCCP) power plant started at TRW with Low-NO_x utility oil burners in the 1970s and with pressurized magnetohydrodynamic (MHD) coal combustors in the early 1980s. Initial tests at TRW of an atmospheric pressure coal combustor at 10 MMBtu/hr in 1982 were followed by testing of a 40 MMBtu/hr industrial size combustor using a wide variety of coals to obtain extensive data on combustion, slag removal, NO_x and SO_2 emission and particulate carry over. A retrofit demonstration at a Cleveland, Ohio manufacturing plant was started in 1984 and over 10,000 hours of operation were accumulated while providing plant steam at high availability. Fifteen different coals with a wide range of physical properties were tested in this industrial-size coal combustor:

Moisture	1.36 % to 31.7 %
Ash	4.39 % to 27.32 %
Volatiles (dry, ash free)	10.6 % to 60.8 %
Nitrogen (dry, ash free)	0.95 % to 1.9 %
Sulfur (dry, ash free)	0.48 % to 4.59 %
Higher Heating Value (HHV)	7,358 Btu/lb to 13,061 Btu/lb
Ash Fusion Temp. (T-250)	2,118 deg F to 2,900 deg F

During the early 1990s, a utility-scale prototype version of the Healy precombustor and a 7.5 ton/hour direct coal feed system were successfully tested at TRW's Fossil Energy Test Site as part of the Healy Clean Coal Project. More than five years of planning and permitting culminated in spring 1995 with the start of construction on the 50 MW_e (net) HCCP power generation unit. During the summer of 1995, earthwork, foundation and structural steel work began with construction and erecting of all equipment continuing through late 1997. Construction was completed in November 1997, with coal-fired operations starting in January 1998.

II. TECHNOLOGY

The Healy Clean Coal Project integrates a slagging, multi-staged coal combustor system with an innovative sorbent injection/spray dryer absorber/baghouse exhaust gas scrubbing system. Twin 350 MMBtu/lb combustors designed by TRW are used to supply hot gases to a conventional Foster Wheeler bottom-fired boiler. The flue gas cleaning equipment was supplied by Babcock & Wilcox (B&W) based on technology developed by Joy Environmental Technologies of Houston, Texas and NIRO Atomizer of Denmark.

The first step in the Healy Clean Coal Project combustion process, shown in schematic format in Figure 1, is the pulverized coal feed system which consists of coal silos, Foster Wheeler MBF 21.5 coal pulverizers and exhauster fans, and the TRW coal feed system. The purpose of this system is to ensure a steady feed of coal (over a wide range of physical properties) to both combustion stages. The second step in this process is the TRW multi-staged coal combustor which is utilizes a multi-staged combustion process to minimize the formation of nitrogen oxides while burning a wide variety of coals including "hard to burn" coals. This combustor system melts and removes most of the coal mineral contaminates as slag. Pulverized limestone is injected prior to the combustor-boiler interface to provide for SO_2 removal from the combustion gases. The limestone is converted by heat in the combustion gases to flash calcinated material (high surface area lime + ash particles, called FCM) which reacts with the SO_2 in the combustion gases and removes the SO_2 as calcium sulfate. The unreacted FCM and sulfates are captured and recycled within the B&W spray-dryer absorber system downstream of the boiler to further reduce the SO_2 content in the combustion gases prior to the exhaust stack.

At HCCP, the two coal combustors are installed side by side and fire the boiler from the bottom upwards. An isometric view of the boiler and combustion system used in the HCCP is shown in Figure 2. Each combustor has its own dedicated coal storage, grinding, and feed system. Crushed coal is discharged from a storage silo into a pulverizer via a coal feeder/weighing scale. The pulverized coal and pulverizer sweep air (or primary air) is boosted in pressure to 60 inches of water (gauge) (1.15 atm) by the mill exhauster fan. This pressure is necessary to overcome the pressure drop through a non-storage coal feed/splitter subsystem that enables the coal to be split and fed into the precombustor and slagging stage. The coal feed/splitter subsystem also separates a major portion of the primary air and diverts this air to NO_x ports located in the boiler furnace. This helps in reducing the amount of cold air going into the combustor, thereby increasing the temperature of the combustion gases to promote slagging conditions over the entire range of coal ash melting temperatures.

Pulverized coal is fed to both the precombustor and slagging stages of the combustor. The precombustor portion of the coal is fed directly to a coal burner located in the headend of the precombustor. The slagging stage portion of the coal is split into six parts and injected into the head-end of the slagging stage via six injection ports. From the slagging stage, the combustion gases enter the slag recovery section where the gases are directed vertically upwards into the furnace through an interface opening in the sloping bottom of the furnace. The fuel rich combustor exhaust is intercepted by the boiler NO_x port air, where final air is added to complete combustion. Optional over-fire-air can also be introduced to provide further air staging for supplemental NO_x and temperature control.

A single limestone feed subsystem services both combustors. Pulverized limestone, stored in a silo, discharges via a weigh scale feeder to a rotary air-lock and a two-way splitter. A separate air-driven eductor is used at each leg of the splitter to transport the limestone-air mixture to a single limestone injector located on the side of the slag recovery section. The limestone particles flash-calcine to highly reactive lime with high surface area. These particles remove some of the SO_2 from the combustion gases as they pass through the furnace. The FCM particles are collected and utilized by the B&W spray-dryer absorber system to remove most of the remaining SO_2 in the combustion products, typically resulting in less than 10% of the sulfur contained in the coal exiting as SO_2 with the plant stack gases. Final FCM and fly ash particulate control is accomplished in the baghouse.

Combustion System Description

Figure 3 illustrates an isometric view of one of the two 350 MMBtu/hr TRW (88 million kcal/hr) multistage slagging combustors designed for the HCCP. It consists of a precombustor, a slagging stage and a slag recovery section. The main chamber of the slagging stage is approximately 9 feet in diameter by 16 feet in length. The walls of the combustor were fabricated using tube-membrane construction, primarily with 1.5 inch SA213 T2 tubing and SA387 Grade 11 fin material. The combustors are cooled by a two-phase forced circulation system directly integrated with the boiler drum (1400 psia, 585 deg F). The twin combustors were fabricated at Foster Wheeler's facility in Dansville, NY, per TRW specification drawings and were transported to the plant in several subassemblies. The combustors are suspended from the boiler (top-supported).

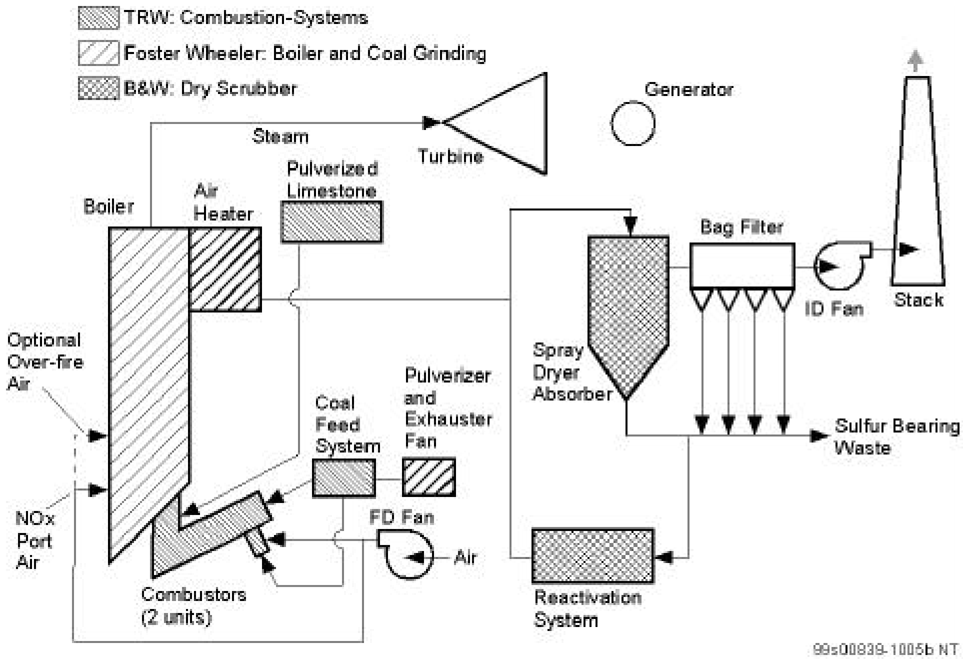

FIGURE 1 – HCCP INTEGRATED SYSTEM

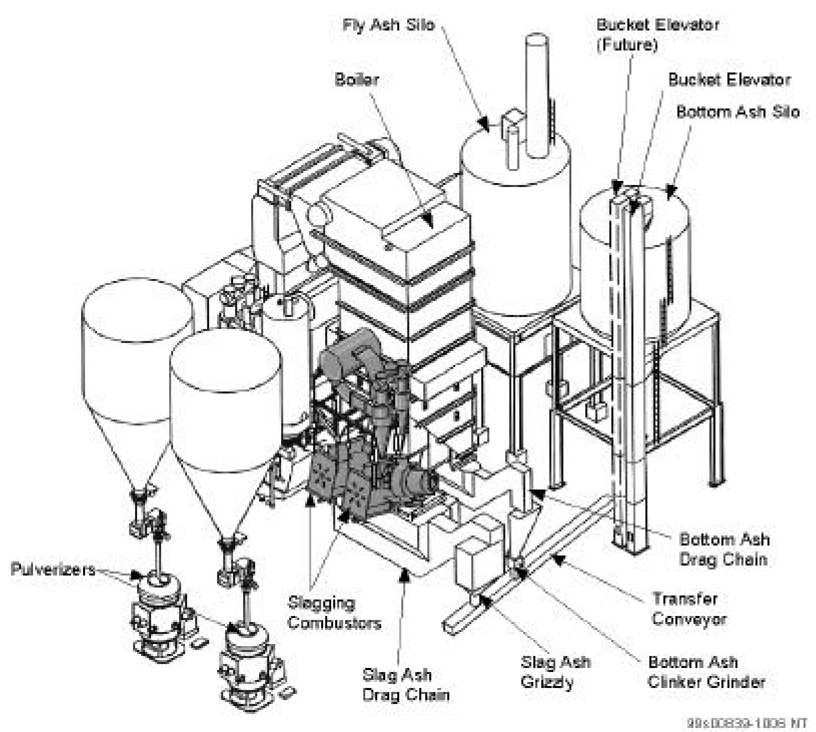

FIGURE 2 – ISOMETRIC VIEW OF HEALY BOILER ISLAND

A functional schematic of the combustion system is shown in Figure 4. Pulverized coal is injected in both the precombustor and slagging stage. The precombustor is used to boost the combustion air temperature from the air heater (from typically 500-700 deg F to 2300-3300 deg F) by burning 30 to 45% of the total pulverized coal flow rate. The precombustor is a vital component of the system because it controls the temperature and velocity of the hot combustion gases entering the slagging stage for optimum combustion and slag removal. It is designed to ensure stable, efficient combustion of a wide variety of coals, and to prevent slag freezing within the slagging stage while burning high ash fusion temperature coals under fuel rich conditions. Low volatility coals can be accommodated by firing a larger portion of the coal in the precombustor.

The high temperature, oxygen-rich combustion gases from the precombustor enter the slagging stage tangentially, generating a high velocity, high temperature confined vortex flow. The balance of the pulverized coal (55 to 70% of total) is injected through a multi-port injector at the head end of the slagging stage. The high gas temperature produced by the precombustor promotes a hot slagged surface on the interior of the slagging stage, which combined with the strong recirculation patterns, ensures stable ignition and combustion. The multi-port injector helps distribute the coal evenly for better coal/air mixing and combustion. The slagging stage is operated at fuel rich conditions at stoichiometric ratios typically in the range 0.7 to 0.9. Carbon conversion to combustion gases is maximized and NO_x emissions are minimized by controlling the temperature, gases and solids mixing and stoichiometric conditions in the slagging stage.

The precombustor, slagging stage and the slag recovery section are operated in a slagging mode, i.e., the coal ash melts to form a molten slag layer which coats the inside surfaces. The coal particles are combusted at a high enough temperature to melt the residual coal ash contained within each particle. Slag droplets are produced, which are centrifuged to the walls of the combustor, forming a self-replenishing slag layer. This slag layer is molten on the gas-side surface and frozen at the tubewall interface. The frozen slag layer protects the water-cooled metal body of the combustor from erosion, abrasion and corrosion, and also reduces the heat transferred to the water in the combustor body. The molten slag is transported along the walls by shear and gravity forces. The molten slag flows through a key slot, along the bottom to the slag tap opening located in the slag recovery section. Up to 90% of the slag is discharged through the slag tap by gravity. A dipper skirt arrangement is used to provide a water seal for the system. The molten slag drops into the water, where it shatters upon contact and is rapidly quenched, yielding a granular glass-like product. The slag is removed from the slag tank by a drag chain conveyor.

Only 10 to 25% of the original coal ash enters the boiler. Because of the aerodynamics of the cyclonic slagging stage, the majority of this entrained slag will be molten droplets of less than 10 microns in size. As the fine slag droplets solidify at lower temperatures in the furnace, spherical shaped particles are formed that are expected to have lower fouling and erosion characteristics than conventional flyash particles, potentially increasing the life of the furnace and its convective tubes.

Emissions Control

Figure 5a presents typical Healy Clean Coal Project combustion side gases and solids flows when each combustor unit is operated at a firing rate of 315 MMBtu/hr on a Usibelli ROM and

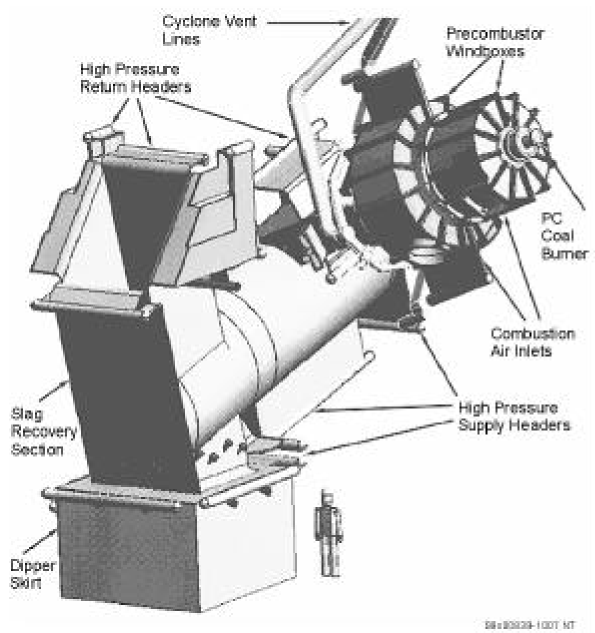

FIGURE 3 – ISOMETRIC VIEW OF ONE OF THE TWO 350 MMBTU/HR TRW SLAGGING COMBUSTORS

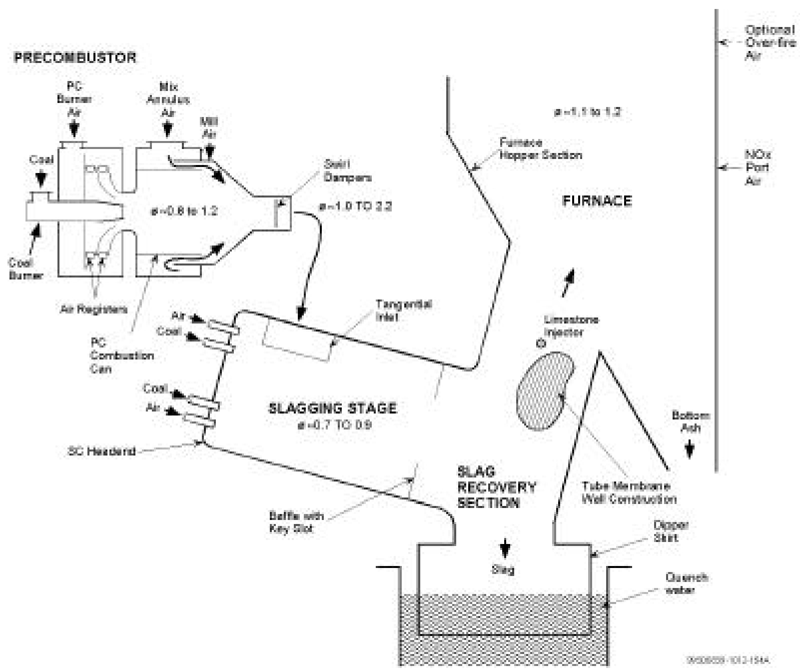

FIGURE 4 – FUNCTIONAL SCHEMATIC OF TRW COMBUSTION SYSTEM

waste coal blend. The flow rates presented in Figure 5a are for the total plant, which includes two coal feed systems, one pulverized limestone feed system and two coal combustor systems. The coal feed system provides coal and a portion of the mill air directly to the precombustor and slagging combustor stages with the remaining mill air sent to the boiler NO_x ports. The warm combustion air from the air heater section is delivered to the boiler NO_x and over-fire air (OFA) ports and to both coal combustion stages. Low NO_x emissions are achieved when the slagging combustor gases are fuel rich / high temperature and the furnace combustion gases are fuel lean / low temperature.

In the slagging stage, a high flame temperature is achieved by preheating the combustion air in the air heater to as high a value as possible, and the stoichiometry is reduced to as low a level as possible without compromising on slagging and carbon conversion. As the combustion gases enter the furnace, the stoichiometry is still less than unity. The remaining air is added in the furnace either at the NO_x ports (as is done at HCCP) or at the OFA ports to complete the combustion at an overall stoichiometry of 1.1 to 1.2 (10 to 20% excess air). In the furnace, the addition of final air is delayed until the gas temperature is reduced by radiative cooling to the walls; this reduces the peak temperatures in the furnace. Also, excess air in the range of 10 to 20% is maintained not only to reduce NO_x but also to complete the combustion of any unburned carbon in the gases.

For mitigation of SO_2 emissions, the combustor offers the advantage of *in-situ* calcination of pulverized limestone ($CaCO_3$), which is injected in the upper region of the slag recovery section. The limestone particles are calcined in the furnace to highly reactive flash-calcined lime (CaO) particles. By the time these lime particles mix and move with the combustion products to the exit of the boiler, a portion of the SO_2 is absorbed to form calcium sulfate ($CaSO_4$). In the HCCP, the utilization of these flash-calcined lime particles is further enhanced by the back end flue gas desulfurization system specifically supplied by B&W/Joy/Niro. For the HCCP, when firing low sulfur coal, approximately 5 to 20% sulfur capture takes place in the furnace when injecting pulverized limestone at a calcium-to-sulfur (Ca/S) molar ratio < 2.

The flue gas desulfurization system, shown schematically in Figure 5b, is comprised primarily of a spray dryer absorber and pulse-jet baghouse. Auxiliary systems include a reagent (FCM) storage, preparation and feed system and an ash conveying system. Use of the FCM as the sole SO_2 scrubbing reagent is a unique feature of the process, resulting in significant cost savings over the conventional use of pebble lime as the reagent, which is typical for most dry flue gas desulfurization systems.

Combustion gases discharged from the air heater outlet of the unit is directed to a dedicated 100% capacity spray dryer absorber (SDA) and PulseFlo® pulse-jet baghouse system wherein SO_2 removal and particulate collection takes place.

The combustion gases enter the SDA module via the roof gas disperser, which distributes the incoming flue gas symmetrically around the rotary atomizer. The roof gas disperser promotes mixing (i.e. gas liquid contact) of the combustion gases and reagent slurry to promote drying, maximize SO_2 removal and minimize solids deposition inside the SDA. The SDA utilizes a NIRO F-350 rotary atomizer to atomize the feed slurry (i.e. a mixture of FCM, reaction products, flyash and water) into a fine spray and inject it into the incoming combustion gases.

The finely atomized feed slurry mixes with the combustion gases, resulting in the evaporation

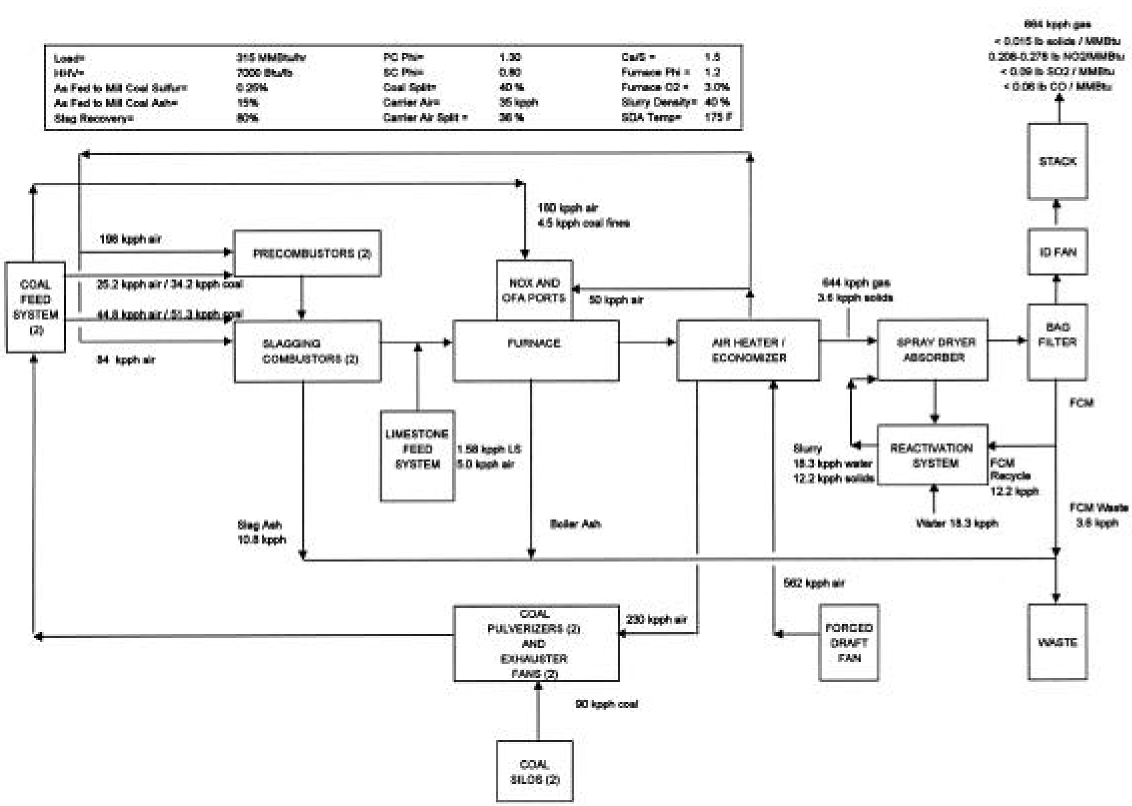

FIGURE 5A – HEALY CLEAN COAL PROJECT COMBUSTION SIDE FLOWS

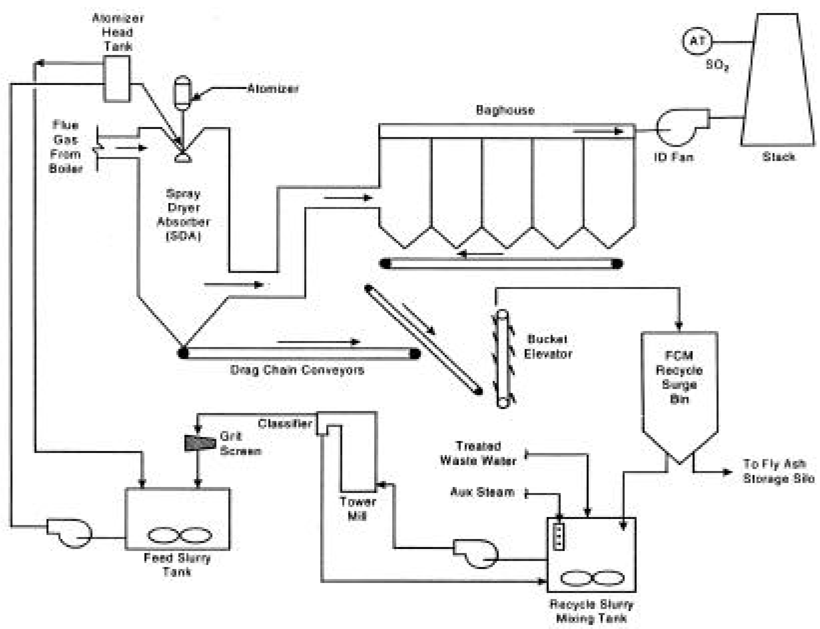

FIGURE 5B – FLUE GAS DESULFURIZATION SYSTEM of water and the removal of SO_2 via chemical reaction with the hydrated lime component of the slurry. The chemical reactions that occur as the hydrated lime ($Ca(OH)_2$) component of the FCM feed slurry reacts with the SO_2 produces reaction products in the form of calcium sulfite ($CaSO_3$ - ½ H_20) and calcium sulfate ($CaSO_4$ - $2H_20$).

As the flue gas and feed slurry mixture pass through the spray dryer absorber, the concentration of the SO_2 is reduced substantially and the spray drying of the reagent slurry and reaction products is completed.

The combustion gases and entrained particles of calcium sulfite, calcium sulfate, unreacted reagent and flyash exit the SDA module into the PulseFlo® pulse-jet baghouse wherein the final step of the SO_2 and particulate removal processes takes place. The PulseFlo® pulse-jet baghouse removes >99.9% of the boilers exhaust solids, reaction products and recycled FCM before discharging the combustion gases to the stack.

Depending on percent ash removal in the combustor, coal sulfur content and Ca/S ratio, approximately 60-90% of the solids (i.e. reaction products, unreacted reagent, inerts, and flyash) collected in both the SDA module hopper and the pulse-jet baghouse hoppers is conveyed by the ash transport system to the flue gas cleaning system's FCM recycle surge bin. The remaining solids are rejected as waste.

Overall SO_2 removal efficiencies greater than 90% have been demonstrated when operating at furnace calcium to sulfur ratios in the range of 1.1 to 1.8.

III. OPERATION AND PERFORMANCE RESULTS

Operation Summary

The 1998 Healy Demonstration Test Program consisted of several test activities, including Coal Firing Start-up Activities, Compliance Testing, Combustion System Characterization Testing, SDA Technology Characterization Testing, and Coal Blend Testing. The first 4 months of the Demonstration Test Program were dedicated to coal-firing start-up operations and focused on slowly bringing all plant systems on line while burning ROM coal at part-load operation. The plant reached full load for the first time in March 1998. Combustion System Characterization Testing was initiated in May 1998, concurrent with the initial firing of waste coal blends. The focus of the Combustion System Characterization Testing was to map the combustor performance characteristics over a broad range of operating conditions and hardware configurations. Shutdowns were incorporated into the test planning activities in order to inspect the combustor internal slagging characteristics as a function of the various hardware configurations and test conditions evaluated.

Overall in 1998, a total of 50 operational runs were conducted, accumulating 4,471 hours of cumulative coal burn time (not including oil-fired only start-up and shutdown time) on the Healy Coal Combustors. Of this total, 1,938 hours were on Run of Mine (ROM) coal and 2,533 hours were on ROM and waste coal blends. ROM coal was used primarily during: 1) plant coal firing start-up tests in the January to April, 1998 time frame, 2) emissions source testing in June 1998, and 3) when waste coal was not available from UCM in August and September 1998. The longest continuous run with ROM coal, conducted with both combustors at full load, was 431 hours (18 days). The longest continuous run with a blended coal, conducted primarily at part load with only one combustor in operation at full load, was 581 hours (24 days). During this test, the second combustor was shutdown following approximately 24 hours of coal-fired operation due to a vibration alarm on the mill Exhauster Fan as a result of non-uniform erosion of the fan blades.

In general, the composition of the ROM coal was fairly consistent from test-to-test, however, the blended coal composition varied significantly depending on the coal mining technique, the coal seam, and the type of coal blending technique used. Daily coal samples were taken by Golden Valley during loading operations, and were subsequently analyzed by Usibelli Coal Mine

The overall range of coal properties tested from May through December, 1998, compared to the range of coal properties listed in the Design Specification, is as follows:

	Design Basis			
	Run of Mine	Performance	55/45 Blend	1998 Actuals (avg) (May – Dec 1998)
Higher Heating Value, (Btu/lb)	7815	6969	6874	6196 to 8271 (7507)
Vol. Matter, (%)	34.6	30.8	30.4	25.0 to 37.5 (35.1)
Fixed Carbon, (%)	30.9	27.5	27.2	24.1 to 30.9 (27.9)
Moisture, (%)	26.4	25.1	25.0	22.5 to 29.4 (25.9)
Ash, (%)	8.20	16.6	17.4	5.7 to 24.0 (11.1)
Sulfur, (%)	0.17	0.15	0.15	0.11 to 0.36 (0.18)
T_{250} (Deg F)	2228	2750	2800	2270 to 2900

As shown in the above table, the actual ranges in coal properties tested in 1998 were broader than the range indicated by the three different coal types listed in the Design Specification: Run-of-Mine, and two waste coal blends: 50% Waste / 50% ROM (also called "Performance Coal") and 55 % Waste / 45 % ROM.

Performance Results

This paper presents the results of coal-fired test operations from June 12 through December 21, 1998. During this period of time, approximately 3300 hours of plant thermal operation was accumulated, with approximately 3200 hours of coal-fired operation. The majority of test operations were at full load, 50 MW_e. The emission data presented includes all coal-fired operations during this period of time, including, in most cases, start-up and shutdown operations. Not included herein is emission data during: 1) January through June 11, 1998, which primarily consisted of plant start-up and shake down activities and was prior to certification of the Continuous Emissions Monitoring System (CEMS) and, 2) during oil-fired only operation.

Table 1 presents a summary of the Coal Combustion System and SDA performance goals, New Source Performance Standards (NSPS), and HCCP Air Quality Permit requirements compared to the performance results demonstrated during coal-fired test operations from June 12 through

TABLE 1 – HCCP PERFORMANCE GOALS AND RESULTS

PARAMETER	New Source Performance Standards (NSPS) [1]	HCCP AIR QUALITY PERMIT	CONTRACT GOALS	DEMONSTRATED IN 1998 (June - December, 1998)	
				RANGE	TYPICAL
NOX	0.5 lb/MMBtu (prior to 7/97) 0.15 lb/MMBtu (modified after 7/97) 1.6 lb/MWhr (new plant after 7/97)	0.350 lb/MMBtu (30 day rolling average)	< 0.35 lb/MMBtu	0.208-0.278 lb/MMBtu 30-day rolling ave. [9], [10]	0.245 lb/MMBtu 30-day rolling ave. [9], [11]
CO	Dependent on ambient CO levels in local region (Title V of 1990 CAAA)	0.20 lb/MMBtu, (hourly average) (202 ppm CO @ 3.0% O2)	< 200 ppm (dry basis) at 3.5% O2 (dry basis) [2] (<206 ppm CO @ 3.0% O2)	<130 ppm at 3.0% O2 [6], [8]	30-40 ppm at 3.0% O2 0.036 lb/MMBtu [5], [8]
SO2	90 % removal and less than 1.2 lb/MMBtu 70% removal when emissions are less than 0.60 lb/MMBtu	0.096 lb/MMBtu, (annual average) 0.10 lb/MMBtu, (3-hour average) 65.8 lb/hr max, (3-hour average)	70 % Removal (minimum) 79.6 lb/hr SO2 (maximum)	< 0.09 lb/MMBtu (<35 ppm @ 3% O2) [6], [8]	0.038 lb/MMBtu (15 ppm @ 3% O2) (25 lb/hr) [5], [8]
OPACITY	20% Opacity (6 min. average)	20% Opacity, (3 min average) 27% Opacity (one 6 min period per hour)	20% Opacity, 3 min average	<10 % Opacity [6]	5.6% Opacity (Jun - Dec 1998) [5],[15] 2.3% Opacity (1999) [15]
PARTICULATE MATTER	0.03 lb/MMBtu	0.02 lb/MMBtu, (hourly average)	0.015 lb/MMBtu		0.0047 lb/MMBtu (1999) [14], [15]
CARBON BURNOUT	NA	NA	> 99% at 100% MCR for Perf., ROM, and 55/45 Blend [3] >98% at 100% MCR for Waste Coal	NA	99.7% [4]
SLAG RECOVERY	NA	NA	> 70% at 100% MCR for all coals [3]	76-87% [7]	83% [7]
NET POWER PRODUCTION	NA	NA	50 MWe for all coals	NA	50-55 MWe [12],[13]

NOTES
[1] From 40CFR60.40a - 40CFR60.49a; New NOx Standards based on 62 FR 36948
[2] From minimum to 100% MCR (Maximum Continuous Firing Rate)
[3] 100% MCR for Performance Coal is 315 MMBtu/Hr, ROM Coal is 306 MMBtu/Hr, Waste Coal is 322 MMBtu/Hr, 55/45 Waste/ROM Coal is 316 MMBtu/Hr
[4] Measured for one test based upon slag and flyash carbon contents
[5] Average of available 30 min. (average) test data, June 12,1998 to December 21, 1998 (total of 3100 hours of run time)
[6] 95% of CO, SO2, and opacity data are observed to be less than these reported value (using available 30 min average test data)
[7] Slag weight corrected for 6% moisture content.
[8] Data corrected to 3% O2
[9] 30-day rolling average determined from available 30 min (average) test data, June 12, 1998 to December 21, 1998, total of 3100 hours (5480 data points).
30-day rolling average only includes days in which power was generated.
[10] Represents minimum and maximum of 30-day rolling average data described in Note [9]
[11] Represents the average of 30-day rolling average data described in Note [9]
[12] Nominal power set point from April through September, 1998 was 60-62 MWe (gross), 53-55 MWe (net);
[13] Nominal power set point in November and December, 1998 was 57 MWe (gross), 50 MWe (net)
[14] Based on independent particulate matter testing performed on March 10-11, 1999 by Haas, Morgan & Hudson
[15] Opacity and particulate matter emissions during 1998 were higher than expected due to a problem with premature baghouse filter bag failure, which was corrected in 1999

December 21, 1998. As noted above, the emission data presented in the table includes all coal fired operations during June 12 through December 21, 1998, including in most cases, coal-fired start-up and shutdown operations, but does not include oil-fired only operations. The average values for NO_x, SO_2, CO, and Opacity listed in Table 1 were determined by averaging the emission data recorded on the plant data recording system (referred to as ODMS) during the approximately 3200 hours of coal-fired operation from June 12,1998 through December 21,1998. The NO_x emission data presented in the table is based on a 30-day rolling average, whereas the SO_2, CO, and opacity data averages are based on 30-minute averages. As shown, the performance results for NO_x, SO_2, and CO demonstrated during coal-fired operations from June 12 through December 21, 1998, met or exceeded all performance goals. As noted in the table, during 1998, the opacity and particulate matter were higher than anticipated due to a problem with the baghouse. Following modification of the baghouse in December 1998, the opacity and particulate matter emissions are meeting performance goals.

Figure 6 plots the key plant parameters (power, boiler $\%O_2$) and stack emissions (NO_x, SO_2) as a function of time for 13 days of an 18-day continuous run conducted with both combustors at full load burning ROM coal from June 8 though June 26, 1998 (remaining data from test run not available). Figure 7 shows the same parameters for a 24-day continuous test run from September 27 to October 21, 1998 on a waste coal blend conducted primarily at part load with only one combustor in operation. The key statistics from these extended test runs are provided below:

	Run of Mine	**Waste Coal Blends**
Test Period	6/12/98 – 6/25/98	9/27/98 – 10/21/98
Test Hours	312 hours	580 hours
Average NO_x in Exhaust	0.233 lb/MM Btu	0.204 lb/MMBtu
Average SO_2 in Exhaust	0.030 lb/MM Btu	0.035 lb/MMBtu
Average O_2 in Boiler	3.50 %	6.75 %
Average Gross MW_e	59.9 MW_e	29.8 MW_e
	(2 combustors at full load)	(1 Combustor at full load)

During the continuous runs, the plant produced 58-62 MW_e with two combustors in service and 28-30 MW_e with only one combustor in service. As illustrated by the stack emission trends indicated in Figure 6, the emission levels of NO_x, and SO_2 were very consistent during the steady-state portion of the test. No problems were experienced with the Run of Mine coals or with any of the coal blends in the slagging combustor stage. In early testing with waste coal blends with heating values below 7400 Btu/lb in combination with wide coal property variations (particularly heating value, ash content, ash T_{250}), slag freezing in specific areas of one or both of the two operating precombustors would occur over a period of several days. Several secondary air injection modifications were evaluated in order to minimize this slag freezing phenomena: 1) Improve secondary air mixing by injecting the air into the core flow of the precombustor combustion products through high velocity discrete air jets, and 2) Relocating a portion of the Secondary Air from the precombustor to the headend of the slagging stage. Ultimately, precombustor slag freezing was minimized by relocating the secondary air injection to the slagging stage and by transferring the excess mill air (i.e., the additional mill air not required for coal transport) to the boiler after start up. These changes not only eliminated the mixing of air downstream of the precombustor combustion chamber, but it also effectively increased the precombustor operating temperature to the 3200-3500 deg F level. During 1999, additional adjustments to the precombustor coal burner configuration (e.g., adjustment of coal fines injection velocity and inner and outer air register settings) were made in order to broaden

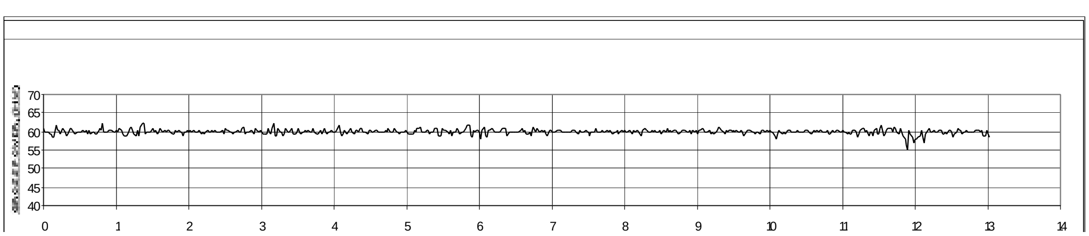

FIGURE 6 - HCCP EMISSIONS DURING 13 DAYS OF CONTINUOUS OPERATION WITH RUN OF MINE COAL (BOILER AT FULL LOAD – 2 COMBUSTORS), JUNE 12, 1998 TO JUNE 25, 1998

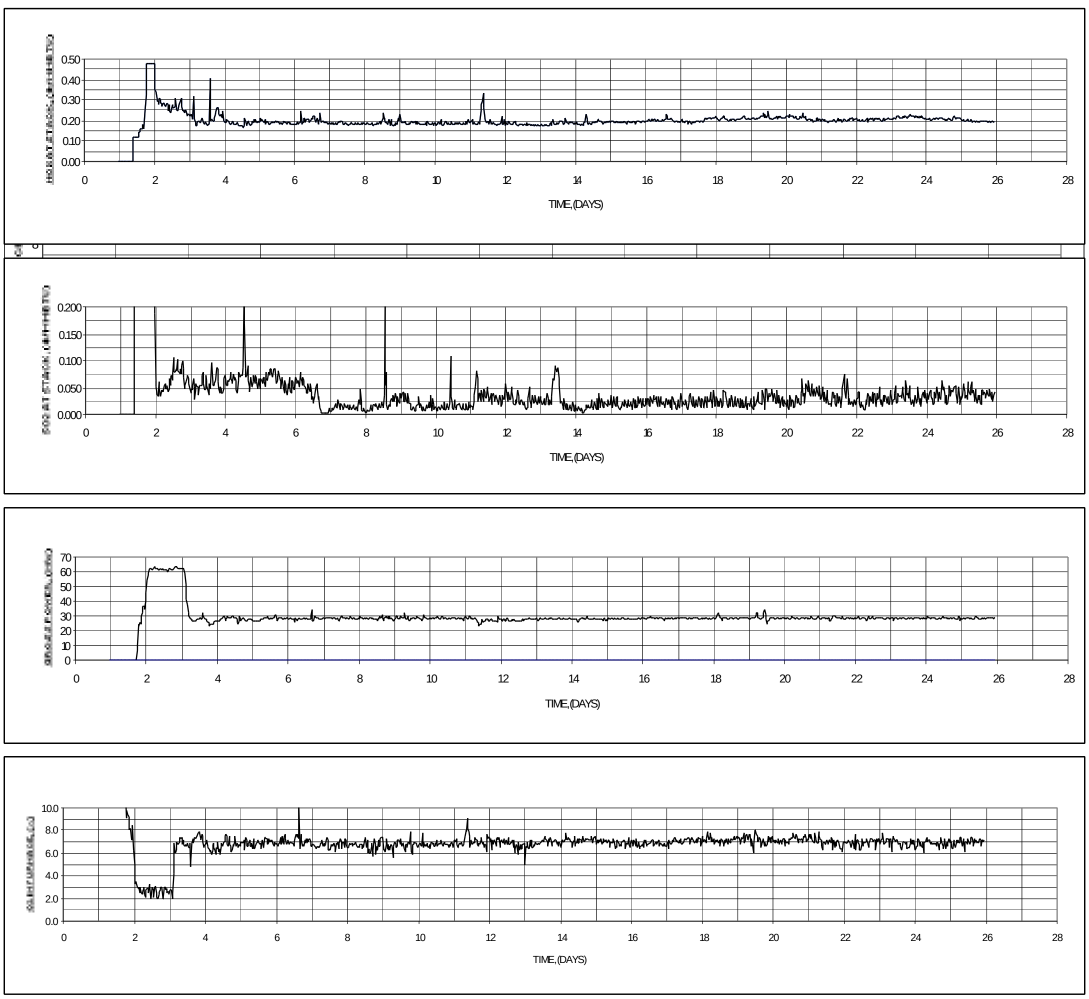

FIGURE 7 – HCCP EMISSIONS DURING 24 DAYS OF CONTINUOUS OPERATION WITH WASTE COAL BLEND (BOILER AT PART LOAD – 1 COMBUSTOR), SEPT. 27, 1998 TO OCT. 21, 1998

the operating envelope when burning ROM/Waste blend coal.

As the Demonstration Test Program continues, additional emission data will be collected to characterize the integrated HCCP performance over longer operational periods. Longer-term operation planned for 1999 will provide the opportunity to evaluate and optimize the HCCP emission performance over a wider range of ROM/Waste blend coals and limestone characteristics as a function of boiler load and boiler excess air. This will enable a more accurate projection of the expected HCCP performance during future long-term commercial operations.

Analytical Model Comparisons

During May 1998 (prior to certification of the continuous emission monitoring equipment), parametric tests were performed in order to: 1) determine the boundaries for key operating variables (e.g., slagging combustor stoichiometry) and 2) provide a basis for comparison to analytical model predictions of the HCCP combustor performance. Although this data was not presented in the previous section, which discusses emission performance results, it is presented in this section in order to show a comparison between "predicted" performance and "actual" performance.

Figure 8 presents the TRW NO_x model predictions for the Healy combustor as a function of slagging combustor stage stoichiometry. Superimposed on the model are data points from tests conducted at Healy with a ROM/Waste blend coal during May 1998 when the slagging stage stoichiometry was varied in order to map NO_x as a function of stoichiometry. In general, good agreement was obtained between model predictions and actual test results. The combustor stoichiometry was observed to be the most important combustor operating parameter for NO_x control, while changes to the combustor coal split and air split had secondary effects. Most of the full load tests were conducted at combustor air / fuel stoichiometries between 0.80 and 0.85. This stoichiometric range was selected since it yielded low NO_x emissions while still maintaining high slag recovery, high carbon burnout and low CO emissions. According to the model, it may be possible to further reduce NO_x through additional optimization of the combustor operating conditions. NO_x data obtained during 1998 also indicated that the furnace O_2 may have been higher than optimal (typical range was 3.5% to 4.5%) for minimum NO_x formation.

Figure 9 presents the TRW model for in-situ sulfur capture in the furnace as a function of Ca/S ratio and coal sulfur content. Superimposed on the model are data points from tests conducted at Healy with a waste blend coal with 0.3% sulfur coal and 74 micron median size limestone injection, during May 1998. During this period of time, the limestone feeder was not accurately calibrated, and, therefore, the limestone flowrate was determined based on several grab samples taken during the test These grab samples were used to develop a correlation between limestone feeder belt speed and limestone flowrate. The sulfur reduction shown for the Healy test data was determined by comparing the baseline SO_2 emissions at the furnace exit without any limestone flowrate to the SO_2 emissions at the furnace exit with limestone flowrate at various Ca/S ratios. Also included in Figure 9, for reference, is the data from the industrial size combustor tests in Cleveland and CTS where fine sized (7-25 micron) limestone was used with high sulfur coals (~3%). Due to use of low sulfur coal at Healy, the combustors and furnace are primarily being used for calcination of the limestone and only a relatively low level of sulfur

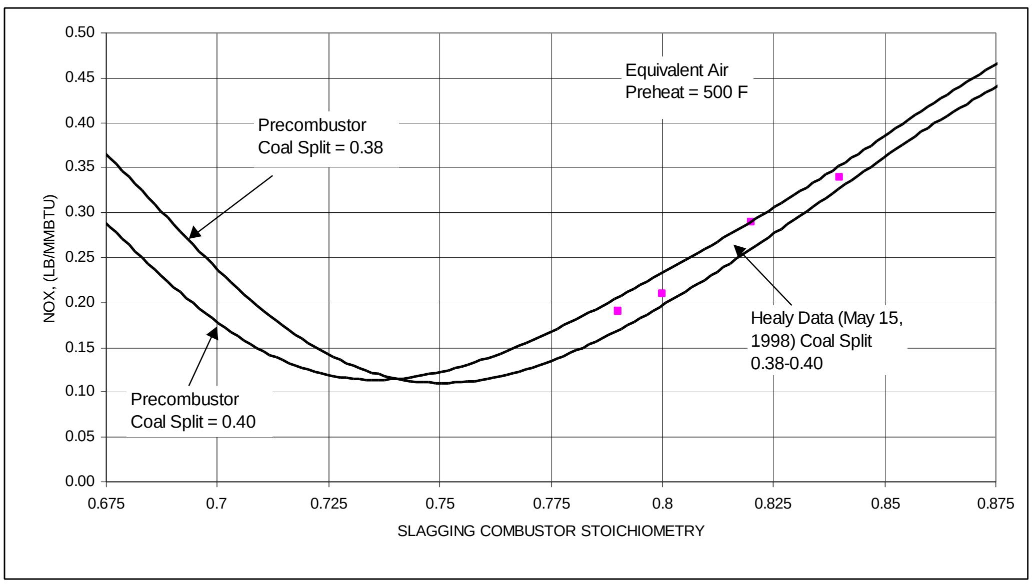

FIGURE 8 – COMPARISON OF HEALY NO_X DATA WITH TRW NO_X MODEL (300 MMBTU/HR)

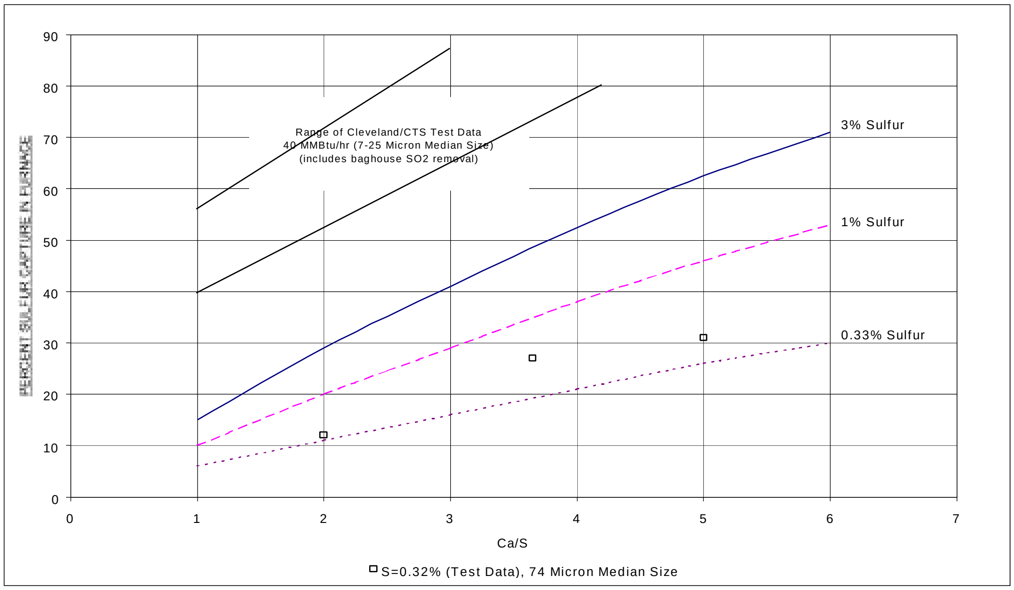

FIGURE 9 – COMPARISON OF HEALY FURNACE SULFUR CAPTURE WITH TRW SULFUR CAPTURE MODEL PREDICTIONS

capture occurs in the furnace. At HCCP, the utilization of the in-situ flash-calcined lime particles is further enhanced by the back end flue gas desulfurization system and baghouse, which results in up to 99% sulfur capture. However, based on the data from the industrial size combustor tests, during operation with higher sulfur coals, additional sulfur capture within the furnace is expected for a given Ca/S ratio.

Figure 10 presents preliminary slag recovery data. A "total" slag recovery value was determined for a cumulative test period covering 45 days, during which 4 tests were conducted (including 4 start-up and shutdown periods). Slag recovery was determined to be approximately 80-85% over this 45-day period, based on ash hopper load cell measurements. This value includes bottom ash, which is estimated to contribute less than 5% to the total ash capture. This reduction in the quantity of coal ash entering the furnace has several benefits, including: 1) reduction in ash loading through the boiler convective pass, 2) reduction in ash loading on the baghouse bags, and 3) reduction in total ash loading to the SDA which reduces the limestone flow requirements.

IV. FUTURE

HCCP Improvements

During the 1998 HCCP Demonstration Test Program, some site-specific integrated plant operational and/or hardware durability problem areas were identified and are currently being addressed. The following table summarizes the site-specific issues identified and the planned resolutions being implemented.

Problem Area	**Planned Resolution**
Ash/slag accumulation on the Furnace Hopper Slope; Ash/slag fall into the water-filled slag hopper results in trips on high Furnace pressure	Installation of a water lance on the Furnace Hopper Slope to mitigate ash accumulation in this region
Slag on internal surfaces occasionally obscuring flame scanner view angle	Integrate slag rodding capability on all flame scanner ports; provide additional scanner locations to ensure continuous flame monitoring
Erosion of blades and outer casing on mill exhauster fans	Incorporate improved erosion resistant materials on blades and outer casing; establish inspection program and provide spare materials

Future Tests

In order to further validate combustor scaling methodology and TRW-developed computer models for NO_x emissions and in-furnace sulfur capture, it would be useful to test the Utility-scale TRW Coal Combustion System with (1) high sulfur coal (2-3%) to fully validate the TRW in-furnace SO_2 capture model shown in Figure 9 and (2) ammonia (or urea) injection in the combustion stage to attempt to demonstrate the capability of this coal combustion system to meet the latest NSPS NO_x requirements (1.60 lb NO_x / MWh for new plants, 0.15 lb/MMBtu for modifications) as predicted by the TRW model presented in Figure 11. This analytical model of the NO_x reduction process was developed by TRW and is anchored to available experimental data. As shown, at the utility-scale, NO_x reductions down to the 0.10 to 0.15 lb/MMBtu level appear to be achievable at a NH_3:NO molar ratio of 2 to 3.

Future Design Improvements

In addition to the operational demonstration and the demonstration of the ability to control emissions of NO_x, SO_2, CO, and particulate matter, experience gained at the utility size will lead to significant design and cost reduction improvements. The Healy Clean Coal Combustion System was conservatively designed in many areas because of its first-of-a-kind status and site-specific requirements. Some of the system design changes planned for the next generation coal combustion systems are:

Current System Design	**Future Design Improvements**
High pressure coolant circulation pumps	Natural circulation coolant system
Coal mill exhauster fans	Direct coal feed from pressurized Mill
Multi-stage air injection in the precombustor (eliminated December 1998)	Single stage air injection in the precombustor

The above design changes and basic improvements in combustor system design will lead to lower system costs, increased reliability, and more economic operation. The coal combustor is designed using standard boiler design technology and procedures/processes. It was estimated by the boilermakers doing the actual Healy coal combustor fabrication that the costs would be halved on the next units produced. TRW is now in the process of updating these costs using the knowledge gained in manufacturing the Healy system, experience and data from the 1998 testing and better estimates from future hardware manufacturers and component suppliers.

Commercial Applications

The TRW Coal Combustion System offers the capability of using a wide variety of coals (including hard to burn coals) because of its multistage operating flexibility and combustion process control. A reduction in size and a life extension of boilers that incorporates the TRW Coal Combustor occurs because of the high carbon conversion and reduced solids loading in the combustion gases entering the boiler. The TRW Coal Combustor provides the capability of converting oil and gas fired boilers to coal and to eliminate oil or gas co-firing used with certain hard to burn coals. In parts of the world, the TRW Coal Combustor is attractive based on its ability to burn low grade local coals with low NO_x and particulates emissions while removing 50% of the SO_2 in the furnace and baghouse. The scrubbing of the remaining SO_2 could be added at a later time after the system is on line generating revenue. This system can be used to retrofit a wide variety of existing size boilers and the precombustor and slagging stage head end could be installed on existing cyclone furnaces to bring them into NO_x compliance and allow them to also burn local high sulfur coals.

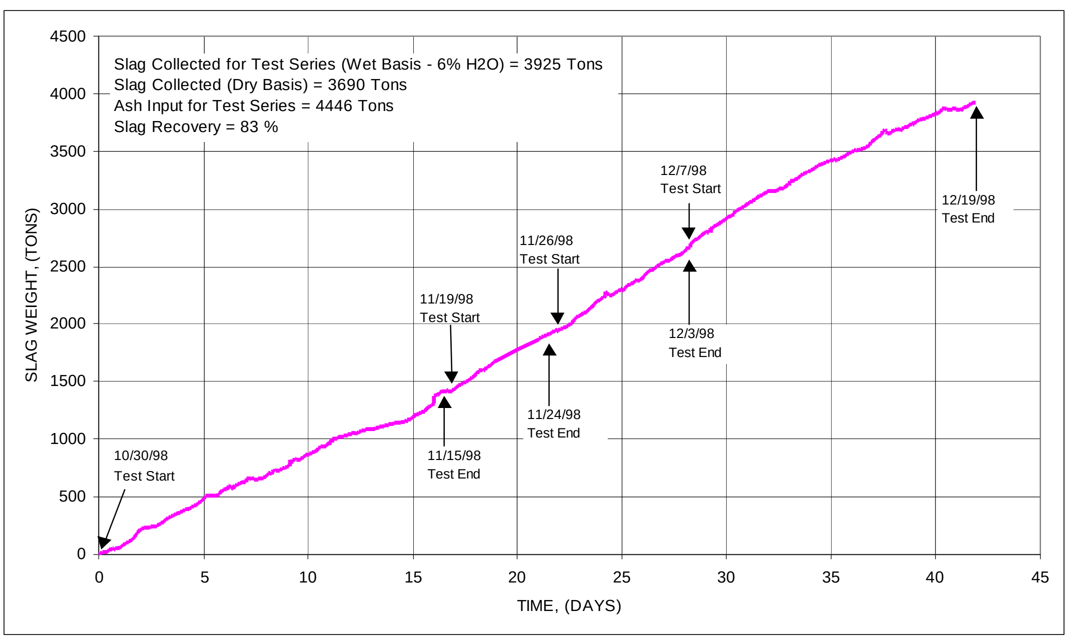

FIGURE 10 – DEMONSTRATION OF SLAG COLLECTION OVER 4 TESTS OVER A 42 DAY PERIOD BASED ON SLAG ASH HOPPER LOAD CELL READINGS

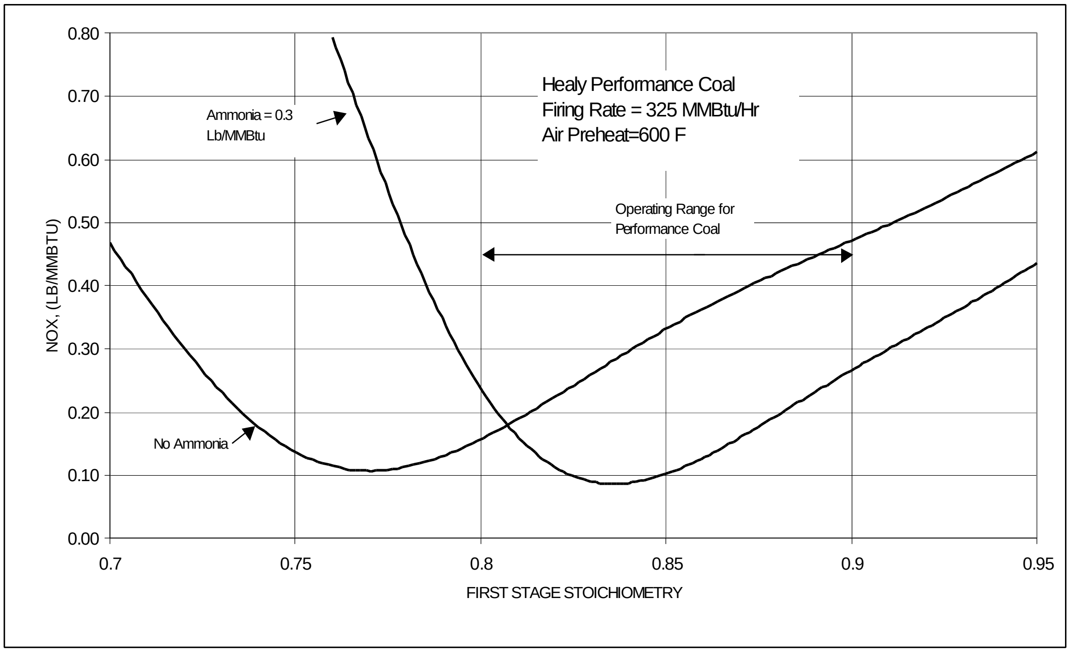

FIGURE 11 – PREDICTED NOX LEVELS IN HEALY COMBUSTOR WITH AND WITHOUT AMMONIA INJECTION

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