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Ashworth Gasifier - Combustor for **Crawfordsville, Indiana Power Plant**

Thomas Hewson - CEO, ClearStack Power, LLC, Arlington, VA
William Harrington - COO, ClearStack Power, LLC, Gary, IN
Robert Ashworth - Sr. V. P. Technology, ClearStack Power, LLC, Sugar Land, TX

ABSTRACT

ClearStack's multi-pollutant reduction Ashworth Gasifier-Combustor™ is a breakthrough technique that reduces the major air pollutants associated with coal combustion in the most environmentally friendly manner ever. Limestone is added with the coal to capture sulfur, mercury and other heavy metal air toxics produced in the slag and fly ash. Further, up to 15% biomass can be fired with coal to help meet EPA Renewable Energy Standards (12.5% biomass by 2021). The Ashworth Gasifier removes a high percentage of the coal ash in the gasifier proper, reducing the rate of particulate entry into the boiler. Consequently, less particulate in the flue gas enters downstream electrostatic precipitators and thereby less particulate emissions are emitted to the atmosphere. It is a low cost multi-pollutant reduction technology that can be easily retrofitted to existing coal-fired boilers and can also be installed on new ultra-supercritical boilers to obtain high thermal efficiencies (45-46%) with high pollutant removals.

The Sterling Energy Group selected the Ashworth Gasifier-Combustor as the best technology alternative for their Crawfordsville Power Plant in Crawfordsville, Indiana. The Crawfordsville Unit has two coal stoker boilers, Unit #5 and Unit #6. Unit #5 was built in 1955 with a design capacity of 11.5 MWe and Unit #6 was built in 1965 with a design capacity of 12.65 MWe. The retrofit on Unit #5 is expected to be completed by 2015. Following successful operation of Unit #5, Unit #6 will be retrofitted.

INTRODUCTION

The ClearStack Ashworth Gasifier-Combustor™ is a three-stage pulverized coal oxidation technique that dramatically reduces the major air pollutants (NO_X, SO_2, Hg and other air metal toxics) associated with coal combustion. Its patented air-blown slagging gasifier (oxygen plant not required) design was selected by the Sterling Energy Group as the lowest cost technology alternative for their Crawfordsville coal repowering project in Indiana. This project requires a retrofit power generation technology capable of using low cost local waste coal to compete in the competitive MISO power market.

The technology was previously demonstrated at the Lincoln Developmental Center in Lincoln, Illinois with the following dramatic pollution reduction results;

- **NO_X emissions down to 0.095 lb/10^6 Btu (40.85 g/GJ) and less**

- **SO_2 reduction of 72% at a Ca/S ratio of 0.85, achieving 85% calcium utilization**

- **CO emissions from 15 to 30 ppmvd @ 3% O_2 *(the Lincoln boiler had high air leakage (~12% O_2 at boiler outlet); Alstom, for a tight boiler, calculated CO @ 7-8 ppmv (3% O_2 dry)***
- **Hg capture in slag/fly ash near 100 wt%**
  (TCLP leachate tests of slag and fly ash yielded 0 mg Hg/L in the leachate)

- **Near 100% capture of Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mo, Ni, Se, Ag, Tl, V, Zn & 80% Mn with slag and fly ash. TCLP tests showed the concentrations of Ag, As, Ba, Cd, Pb, and Se in the leachate were all well below the EPA regulatory limit for both the slag and fly ash. The slag and fly ash produced are nonhazardous to human health.**

- **26% Fluorine and 14% Chlorine capture by ash (Ca/S ratio of 0.85)**

The technology promises to be a low cost multi-pollutant reduction technique for existing pulverized coal-fired units that can also provide much greater fuel flexibility. It can handle lower grade and less expensive waste coals, raw coals with high ash content, and biomass (eligible for renewable energy credits in several state programs). In the near term, this technique will provide Crawfordsville with a low cost option to reduce acid gas and air toxic emissions from its two coal-fired units.

The Crawfordsville Power Plant (Fig. 1) is owned by the Sterling Energy Group with headquarters in Gary, Indiana. The City sold the power plant to Sterling in 2013. Historically, the plant has consumed low sulfur coal from Southern Indiana that is trucked to the plant.

Figure 1. Crawfordsville Power Plant.

With its current environmental controls, the plant will be unable to meet the applicable industrial boiler MATS standards without additional investment. By retrofitting the Ashworth Gasifier-Combustor the plant will be able to burn a lower cost waste coal and meet all applicable MATS limitations.

ASHWORTH GASIFIER - COMBUSTOR TECHNOLOGY

The Ashworth Gasifier-Combustor includes two complimentary gasification-combustion techniques: 1) A two-stage gasifier-combustor technology that Florida Power Corporation (FPC) called the CAIRE (Controlled AIR Emissions) Combustor [1] reduced both sulfur and nitrogen oxide emissions. ClearStack has the rights to this technology and 2) a three-stage gasifier-combustor technology that was developed by ClearStack to achieve ultra-low NO_X emissions and to improve sulfur capture. Both of these goals were achieved in testing of the three stage technique at the Lincoln Developmental Center in Lincoln, Illinois and as a bonus mercury and other air metal toxics were captured in the slag as well. The technology is currently protected under patents worldwide. In the Ashworth Gasifier-Combustor design, modifications were made that improved sulfur capture and further reduced NO_X emissions in a demonstration at the Lincoln Developmental Center. These design changes had to do with the mode of firing, residence time in the 1st Stage, use of finer limestone, the rate and mode of secondary air firing, the residence time in the 2nd Stage and the addition of a 3rd Stage of combustion air in the boiler proper.

Sulfur Capture

Limestone is added with low alkaline ash coal to capture sulfur and air metal toxics in the slag produced. The reaction to capture sulfur is as follows: Eq. (1) $CaO + H_2S \rightarrow CaS + H_2O$. The thermochemical equilibrium for sulfur dioxide capture (oxidizing environment), and hydrogen sulfide capture in a reducing environment with calcium oxide is shown in Fig. 2. The capture of sulfur by CaO in a reducing environment as hydrogen sulfide at 2650°F (1455°C) is more favored than the capture of sulfur dioxide in an oxidizing environment at 1500 - 1600°F (816 - 871°C) using fluidized bed combustion.

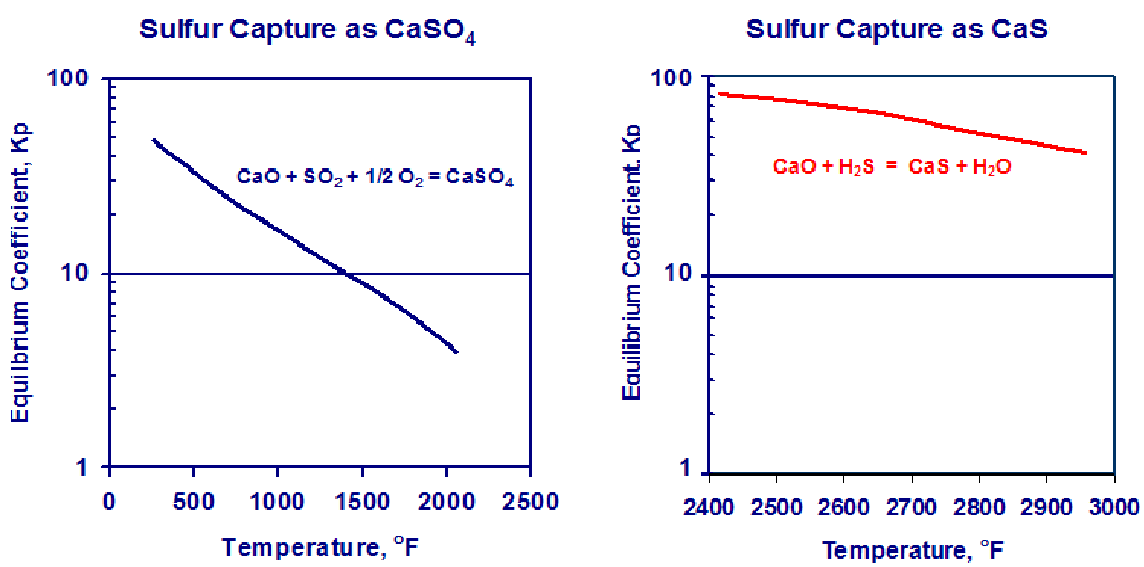

Figure 2. Equilibrium coefficients for sulfur capture in oxidizing and reducing atmospheres.

NO_X Reduction Mechanisms

This three-stage oxidation technology is an improved technique for the reduction of NO_X. It precludes the formation of nitrogen oxides from fuel bound nitrogen in the 1st stage (gasifier) and is slightly reducing in the 2nd stage and is a lower temperature in the 3rd stage oxidation zone. These conditions result in reduced NO_X formation.

The 1st Stage is operated at a stoichiometric ratio (SR) of about 0.60. This SR is best for eliminating fuel bound NO_X and the NO_X precursors, ammonia (NH_3) and hydrogen cyanide (HCN). If equilibrium is achieved, which pilot plant testing showed, there is no fuel bound NO_X formed. The 1st Stage gasification zone normally has a heating value of 60 to 65 Btu/scf (2355to 2555 KJ/NM^3) at 2650ºF (1455ºC).

Fuel gas from the 1st Stage enters the furnace at a temperature of some 2650°F (1455ºC). Second stage oxidation takes place here to bring the air:fuel stoichiometric ratio up from 0.60 to 0.90. Nitric oxide (NO) formation (most prominent form of NO_X formed in pulverized coal-fired boilers) is minimized by the various reducing reactions that occur in the lower part of the furnace.

A furnace zone with an SR of 0.90 yields a concentration of around 3% by vol. CO which is a slightly reducing gas condition. This condition reduces NO_X formation and does not affect boiler waterwall tube life. Third stage air (OFA) is added in the upper furnace to complete the combustion process, increasing the SR from 0.90 up to an SR of 1.10 to 1.20. The OFA is injected at a point where the flue gas temperature is ~2400ºF (~1316ºC) to minimize the formation of thermal NO_X.

Three-stage kinetic modeling [2] was completed by GE-EER for ClearStack. A One Dimensional Flame (ODF) kinetics model was used. The ODF model has been validated from experimental data from several sources and in this case the ODF model was set up for three stages of oxidation. The 1st Stage SR_1 was held at 0.60. The 2nd Stage SR_2 was varied and the 3rd Stage SR_3 was held at a constant 1.14.

Two models were run, one that included steam addition to the 1st Stage and one that did not. In both cases, modeling predictions showed that three-stage oxidation could reduce NO_X emissions to less than 0.10 lb $NO_X/10^6$ Btu (43 g/GJ) of coal fired.

The modeling accuracy and low NO_X capability was shown during the Lincoln Demonstration. With steam addition that lowers the 2nd Stage temperature, emissions as low as 0.07 lb $NO_X/10^6$ Btu (30 g/GJ) could be achieved (Fig. 3).

Mercury Capture

The mercury present in the coal is tied up as an amalgam in the molten slag. Once an amalgam with calcium occurs, it is very difficult to separate the two elements. Evidence for this is shown by the fact that the mercury once captured, does not leach from the slag, see Eq. (2).

$$\text{Equation (2)}\quad Ca^o + Hg^o = CaHg \text{ (amalgam)}$$

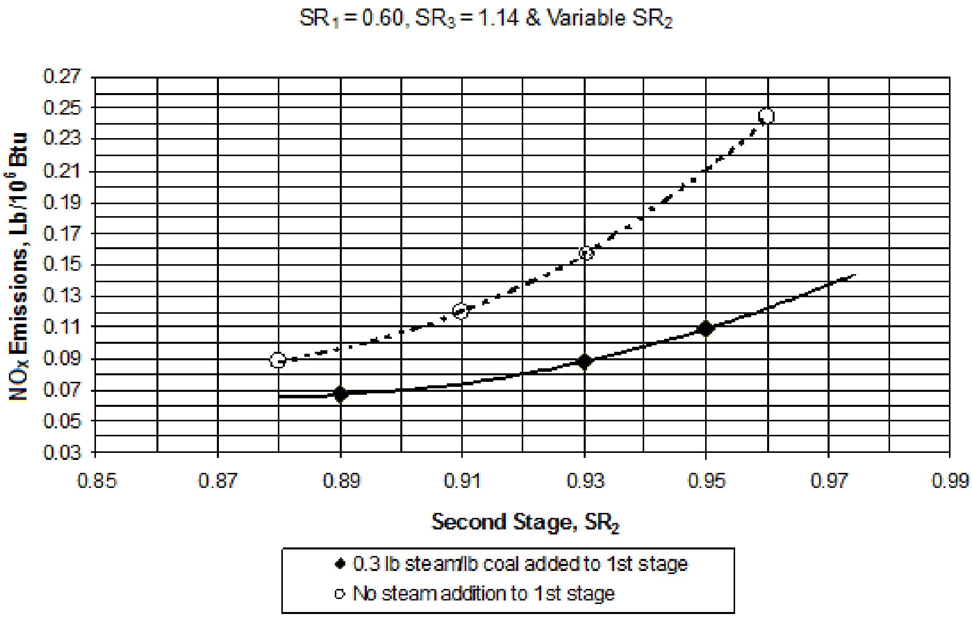

Figure 3. 3-Stage NO_X emissions.

Saleable By-Products

Since the advent of low NO_X burners, many coal-fired power plants that once sold their fly ash to the cement industry could no longer do so due to high carbon content. With the Ashworth Gasifier the high carbon conversion of the old excess air burners returns to provide a fly ash with 5-wt% carbon or less. Coal-fired cyclone boiler slag is currently being used as a wear-resistant component in surface coatings of asphalt in road paving. Finer-sized slag can be used as blasting grit and is commonly used for coating roofing shingles. The fly ash produced can be used in cement, see Fig. 4.

Figure 4. Slag and Fly Ash from Gasifier.

LINCOLN DEVELOPMENTAL CENTER DEMONSTRATION

The Ashworth Gasifier-Combustor demonstration [3] took place at the Illinois Department of Human Services, Lincoln Developmental Center in Lincoln, IL. The boiler house there consisted of three boilers, Units #1 and #3 were coal-fired stoker boilers and Unit #2 was a coal-fired stoker that had been converted to natural gas. The Center seldom used the gas-fired unit due to the high price of natural gas compared to coal at that time. Unit #2 was therefore selected as the host boiler for the retrofit (Fig. 5).

Figure 5. Ashworth (40 Million Btu/hr) Gasifier-Combustor System at Lincoln.

Test Results at Lincoln

The gasifier itself was very easy to operate after going through the typical start-up problems. One could switch from gas to coal and back to gas without any trouble. Initially, we did experience that the slag tap would sometimes plug. It was found that the 1st Stage was not hot enough at an SR of 0.60 due to the imposed limited feed throughput of coal. We found that when the 1st Stage temperature was maintained at 2600ºF (1427ºC) and up, the slag plugging problem went away. The gasifier design modifications were successful in increasing sulfur capture and reducing NO_X emissions compared to the FPC CAIRE combustor.

NO_X Emissions

Nitrogen oxides (NO_X) emissions were as low as 0.095 lb/10^6 Btu (40.8 g/GJ) with coal firing using the three-stage combustion technique. The unit was gas capable and when firing natural gas only, at similar conditions, NO_X emissions were 0.048 lb/10^6 Btu (20.6 g/GJ). A Continuous Emissions Monitor (CEMS) was also used.

SO_2 Emissions

Sulfur dioxide (SO_2) emissions were reduced to 1.70 lb/10^6 Btu (731 g/GJ) for a high sulfur Illinois coal that yields uncontrolled SO_2 emissions of 6.14 lb SO_2/10^6 Btu (2639 g/GJ) - a 72 % reduction using 80% minus 200 mesh limestone. This reduction was achieved with a limestone Ca/S ratio of 0.85 providing for 85% utilization of the calcium injected. With the use of a finer, more reactive limestone (99.6% minus 325 mesh) even greater reductions should be observed.

CO Emissions

With coal firing only, carbon monoxide (CO) emissions were 15 - 30 ppmv @ 3 vol % O_2 dry compared to natural gas firing at similar conditions of 10 - 20 ppmv @ 3 vol % O_2 dry. These levels are much higher than would be expected for most coal unit applications. The Lincoln boiler had a lot of air leakage, around 12% O_2 at the boiler outlet. Alstom boiler models projected for a tighter typical coal boiler, CO levels at 3% O_2 dry should be roughly 7-8 ppmv, which is similar to exhaled human breath.

Carbon Conversion

The carbon conversion achieved was 99 wt. %. Carbon in the gasifier slag was 0.1 to 0.2 wt. % and carbon in the fly ash was less than 5 wt. %, making it suitable for use in cement manufacturing. With such high carbon conversion and significant mercury reduction without the need for activated carbon injection, the Ashworth Gasifier design avoids high loss on ignition (LOI) levels and carbon carryover problems that can be created by low NO_X burners and/or activated carbon injection for mercury.

Mercury Reduction

The Detroit Edison Fuel laboratory analyzed all of the solids streams entering and exiting the Ashworth Gasifier-Combustor system. Mercury reduction was surprisingly high (93 to 100%) based on solids analyses. In addition, what was also impressive is that the mercury that was captured did not leach.

Other Air Toxics and Halides Reductions

From trace element analyses of other metal toxics in the slag and fly ash nearly all of the antimony, arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, lead, molybdenum, nickel, selenium, silver and vanadium were captured and around 80% of the manganese was captured. The Toxicity Characteristic Leaching Procedure (TCLP) tests showed the regulated concentrations of Ag, As, Ba, Cd, Cr, Hg, Pb, and Se in the leachate were all well below the EPA regulatory limit for both the fly ash and slag. Leachate testing was completed by Detroit Edison, as shown in Table I.

Table I. Fly Ash and Bottom Ash Toxicity Characterization Leaching Procedure Tests

Metal Toxic	Fly Ash mg/l	Bottom Ash mg/l	Regulatory Limit mg/l
Ag	0.0000	0.0002	**5**
As	0.0334	0.0005	**5**
Ba	0.5460	0.1750	**100**
Cd	0.4842	0.0002	**1**
Cr	0.1201	0.6335	**5**
Hg	**0.0000**	**0.0000**	**0.2**
Pb	0.0276	0.0080	**5**
Se	-0.0113	-0.0008	**1**

Testing also showed 26% fluoride capture and 14% chloride capture by the fly ash with a Ca/S ratio of 0.85. With a higher Ca/S ratio and finer limestone (discussed later), halide capture should increase.

Renewable Energy Use

With this technology if biomass is available and conventional coal is used (less than 10 wt% moisture) it could replace some 10 -15% of the coal, thus conserving our fossil fuel resources and help a utility meet imposed renewable energy standards.

ECONOMIC COMPARISON W/SCR PLUS WET SCRUBBER PLUS HG REMOVAL

The ClearStack Technology is well suited for either a new plant application or as a retrofit technology to provide additional environmental controls and/or renewable power credits. Below are retrofit cost comparisons of the Ashworth Gasifier-Combustor with Wet Scrubbing (WS) to remove SO_2 and Hg plus Selective Catalytic Reduction (SCR) for NO_X Control. The SCR + WS was designed to match the environmental performance of the Ashworth Gasifier-Combustor.

A 200 MWe coal-fired boiler firing run of mine bituminous coal was used as the basis for the retrofits. See Table II. For calculation of operating costs, an 80% capacity factor was used. The capital and operating costs are based on $2015 U.S. dollars.

Table II. 200 MWe Application Cost Comparison

Technology	Capital Cost, $	$/kWe	Added Operating Cost, $/Yr	¢/kWhr
Ashworth Gasifier - Combustor	**$29,000,000**	**$145**	**$6,500,000**	**0.46¢**
SCR + WS:				
Selective Catalytic Reduction	$36,700,000	$183.5	$7,800,000	0.56¢
Wet Scrubber	$38,900,000	$194.5	$10,200,000	0.73¢
	============	======	============	======
TOTAL	**$75,600,000**	**$378**	**$18,000,000**	**1.29¢**

The multi-pollutant reducing Ashworth Gasifier-Combustor is seen to be some 38% of the capital cost and 36% of the operating cost compared to the SCR + WS technologies. The analysis does not include any credit for other air metal toxics (80-100%) that are removed by the gasifier.

The Ashworth Gasifier-Combustor allows a utility to sell its fly ash and slag; carbon in fly ash is low and metal toxics won't leach from either the fly ash or the slag.

CRAWFORDSVILLE RETROFIT APPLICATION

The boiler to be retrofitted first is Crawfordsville Boiler Unit #5, a Riley boiler with a Riley Stoker spreader stoker. The gasifier will be placed on the front of the boiler and will replace the spreader stoker feeders shown in Fig. 6.

Figure 6. Unit #5 - Travelling grate stoker.

The system will be sized to fire 158 Million Btu/hr of feed coal, and will consist of installing a refractory lined water tube gasifier, a second stage partial oxidization unit and an overfire air system.

A coal feed system that includes two pulverizers (one operating, one spare), a limestone storage and feed system, a slag quench and removal system will be used. An existing air preheater and an ESP will also be used. A control system will be installed for the gasification and combustion system, and a monitoring system will be used to measure SO_2, NO_X, and CO. Pulverized waste pond fines coal (70% minus 200 mesh) and limestone (99.6% minus 325 mesh) will be fired into the slagging gasifier at an air rate to maintain a SR of 0.60 to 0.70. The slag will flow from the gasifier to a water quench tank. The ash will be de-watered and then conveyed to storage and then to a conventional landfill or will be sold.

The second stage air will be added to the hot fuel gas from the gasifier as it enters the boiler furnace to bring the stoichiometric ratio up to 0.90. In the upper furnace, overfire air (OFA) will be added to complete the combustion process. Flue gas from the boiler will flow through an air heater to an electrostatic precipitator for particulate removal and then to an atmospheric stack.

DESIGN IMPROVEMENTS FOR CRAWFORDSVILLE

Finer Size Limestone

After more detailed evaluation of sulfur capture removal versus limestone particle size, it is expected that using a 99.6% minus 325 mesh limestone will achieve near 100% removal of sulfur in the gasifier rather than the 72% capture experienced at Lincoln. The smaller size limestone is also readliy available at near to the cost of the minus 200 mesh limestone.

The average particle size of commericially available 99.6% minus 325 mesh is equivalent to 9 microns and the 80% minus 200 mesh limestone used at Lincoln had an average particle size of around 30 microns. The surface area of the -325 mesh limestone is about eleven times more than the limestone used at the Lincoln Developmental Center Demonstration; as size decreases, surface area increases and reaction rates are faster.

This same size phenomena was experienced by Natec when using Nahcolite (sodium bicarbonate) to spray into flue gas at the Public Service of Colorado Cherokee Power Plant to remove SO_2 as $Na_2(SO_3)$/ $Na_2(SO_4)$. With a Nahcolite average particle size of 44 microns, Natec removed 65-70% SO_2 and with a 9 micron Nahcolite they removed 100% of the SO_2. The LIFAC Sorbent Injection Project [4] stated that at a given Ca/S molar ratio, SO_2 removal efficiency was found to be significantly higher for a fine limestone grind (80% minus 325 mesh) than for a coarser limestone grind (80% minus 200 mesh).

A smaller size limestone was used at Lincoln than was used at the Foster Wheeler Development Center (FWDC) for this reason, and greater sulfur removal was seen. A very good trendline power curve data fit for average particle size of limestone versus sulfur capture (Trendline $R^2 = 0.993$) is seen in Fig. 7; an R^2 of 1.0 is a perfect data fit.

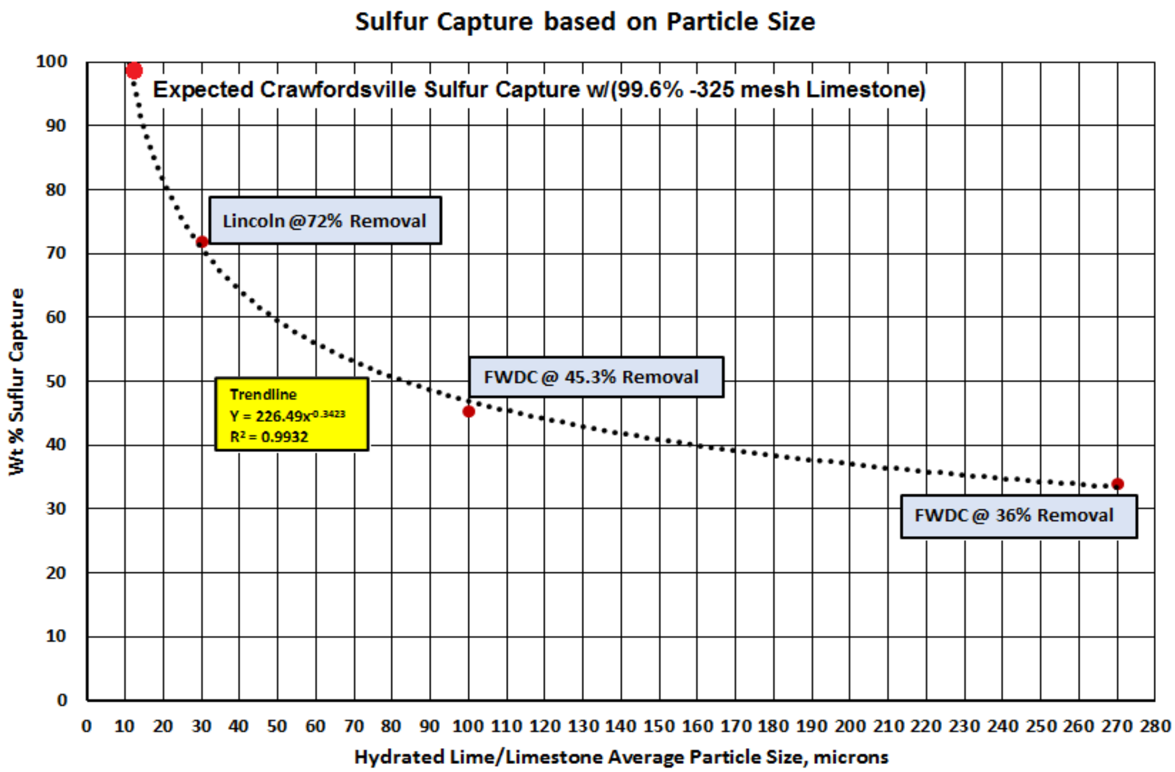

Figure 7. Limestone particle size effect on sulfur capture.

Gasifier Design

The gasifier will be designed with a top exit; this will result in more slag capture in the gasifier proper, so less fly ash will enter the boiler. At Lincoln, a side exit was used. A simplified process flow diagram for the Crawfordsville retrofit is shown in Fig. 8.

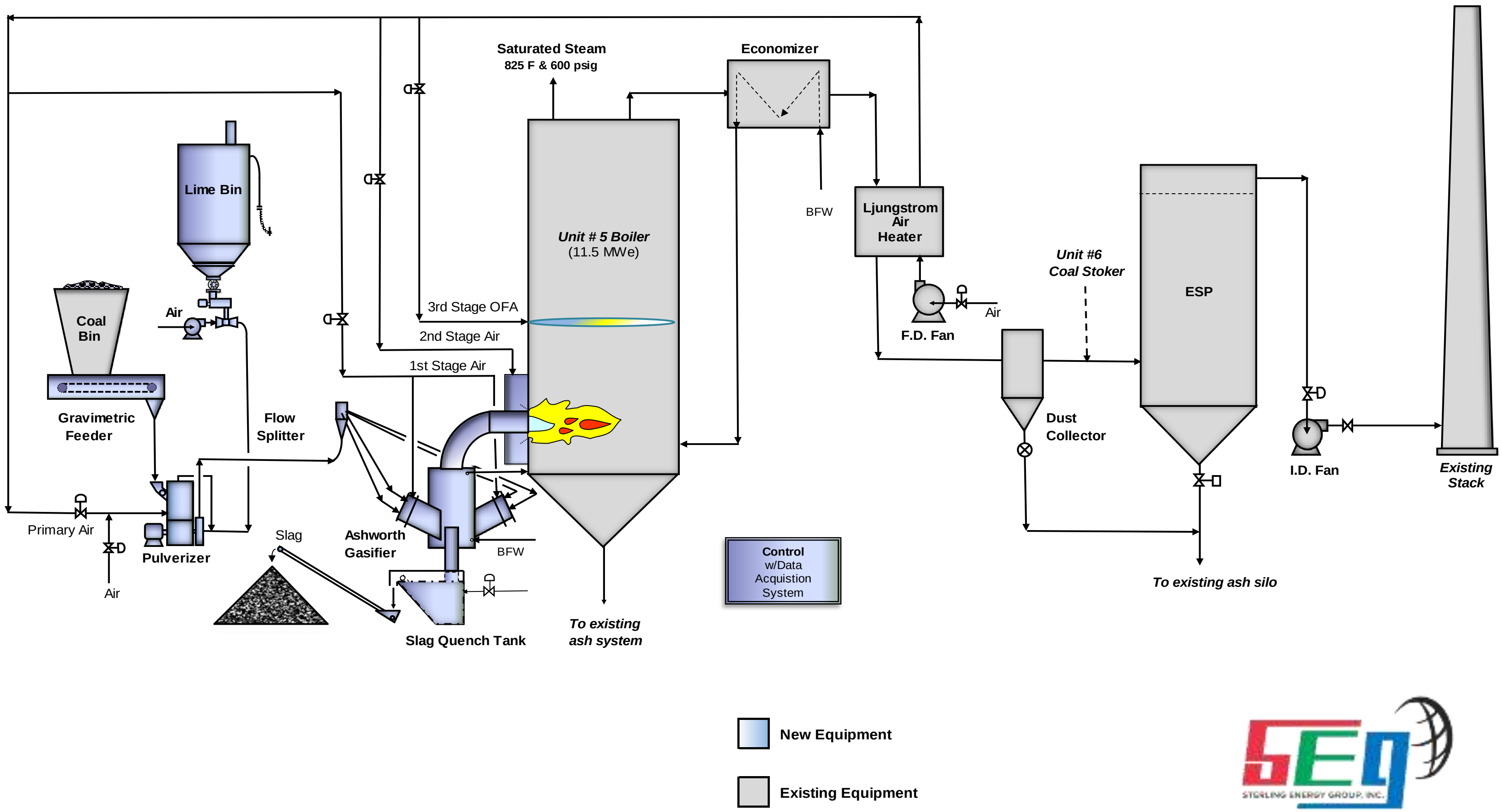

Figure 8. Simplified process flow diagram of Ashworth Gasifier-Combustor for Crawfordsville Boiler #5.

CONCLUSION

The Ashworth Gasifier-Combustor is a clean "green coal" technology because it reduces the pollutants (NO_X, SO_2, Hg, halides and other air toxics) associated with coal combustion. It allows much greater fuel flexibility, from waste coal to high ash coal to co-firing with biomass and is easy to retrofit to existing boilers. Unlike SCR, the Ashworth Gasifier-Combustor reduces rather than increases sulfur trioxide (SO_3) emissions that create opacity (bluish-white haze). It also does not require noxious chemicals (NH_3), as does SCR. There are also no vapor plumes as seen with wet scrubbers. It takes a much smaller equipment footprint than backend techniques and does not increase the net heat rate of the unit like SCR and wet scrubbers do because of the increased auxiliary power required due to increased pressure drop through the flue gas system. The ClearStack slag and fly ash products are also non-hazardous.

In the long term, applied to new ultra-supercritical boilers [5] that currently achieve 45-46% overall thermal efficiency, the Ashworth Gasifier can be more efficient than a coal-based integrated gasifier combined cycle (IGCC) power plant. It also requires less space and is less expensive to install and operate.

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Contact Information:

Thomas Hewson, CEO: Cell: 703-963-2676
William Harrington, COO: Cell: 219-712-4764
ClearStack Power, LLC
6100 Dutchman's Lane
9th Floor, Suite 900
Louisville, KY 40205
www.clearstack.com

Robert Ashworth, Senior VP Technology: Cell: 281-777-0151
ClearStack Power, LLC
19901 Southwest Freeway
Suite 228
Sugar Land, TX 77479
Office: 281-207-5482
www.clearstack.com