Advanced ESP Designs for Black Liquor Recovery Boilers

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ABSTRACT

This paper discusses advanced designs for black liquor recovery boiler ESPs. Using only commercially proven technologies such as ELEX rigid discharge electrodes and NWL's PowerPlus™ sets, it is demonstrated how a stringent stack PM emissions standard of 0.010 grains/dscf at 8% O_2, at conditions of 70% design flow through one chamber of a dual chamber ESP, can be achieved with an advanced ESP design that has 48% less collecting plate area and 21% lower installed cost than a conventional retrofit ESP. The superior PM emissions performance and lower installed costs associated with advanced ESP designs are discussed when retrofitting a new ESP and also when rebuilding an existing ESP.

INTRODUCTION

Over the past fifty years there have been several step-wise advances in electrostatic precipitator (ESP) design that have resulted in substantially lowered particulate matter (PM) emissions. Data provided in this paper will demonstrate the beneficial effect of the simultaneous application of two commercially proven technologies into the design of a recovery boiler ESP:

- Southern Environmental's customized ELEX rigid discharge electrode (RDE)
- Switch mode power supply (SMPS), which is a three-phase, high frequency power supply.

The RDE is a relatively mature technology, whereas high frequency power supplies are a more recent development.

An ESP with SMPS energization was retrofitted by Southern Environmental onto Recovery Boiler No. 1 at Canfor Pulp & Paper's mill located in Prince George, British Columbia, Canada. It consists of one casing with the following configuration: two isolatable chambers, five 12 ft long mechanical fields, 39 ft tall collecting plates, 12 inch wide gas passages, and 28 gas passages per chamber. The ESP was compliance tested in January, 2012 and, as will be demonstrated, its PM emissions performance exceeded that of a conventional, industry-typical recovery boiler ESP by a significant margin.

ELEX DISCHARGE ELECTRODES

The ELEX discharge electrode (Figures 1 and 2) has an operating history in North America dating back into the 1970's. The characteristics and performance of this RDE have been well documented in several recent technical papers [1, 2, 3]. It is widely recognized that it is among the best current distributing discharge electrodes in the air pollution control industry, and it also has the capability to promote very high current densities when compared to other types of discharge electrodes. These characteristics alone lead to better overall ESP performance, regardless of the application at hand.

An important feature of the ELEX electrode, as documented in several recent publications[1, 2, 3], is its adaptability to customization. This feature permits the designer to create an optimum set of electrostatic conditions in several different collection zones of the ESP. An example would be doubling the quantity of electrode emitter tabs in the inlet field(s) of an ESP, enabling production of higher current levels to overcome space charge effect. This can then be coupled with a corona voltage-enhancing electrode configuration installed in the ESP's downstream fields.

An additional optimization feature of the ELEX electrode is the capability to vary the tip spread of its emitter tabs. Air load tests[2] demonstrate that at wide tip spreads the electrical section's operating corona current density increases by as much as 44% when compared to pipe-and-spike type electrodes, as illustrated in Figure 3. The ability to effectively control the voltage/current relationship in each collection zone of the ESP through variation of the emitter tip spread is a feature available only with the ELEX electrode, and this is one reason for its superior performance.

Examples of two commonly used ELEX electrode customization possibilities are shown in Figures 1 and 2. It should be noted that these features have been successfully employed since the late 1990s.

Figure 1 – Aggressive and Standard ELEX Electrode

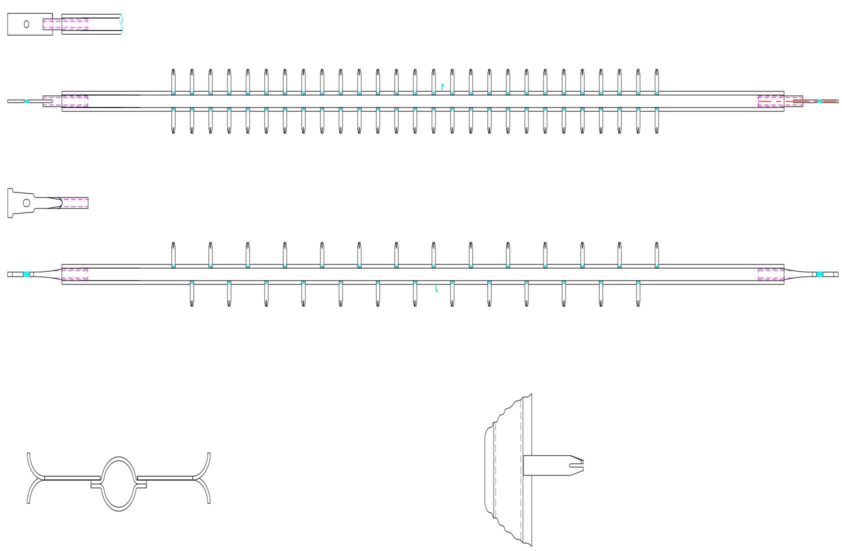
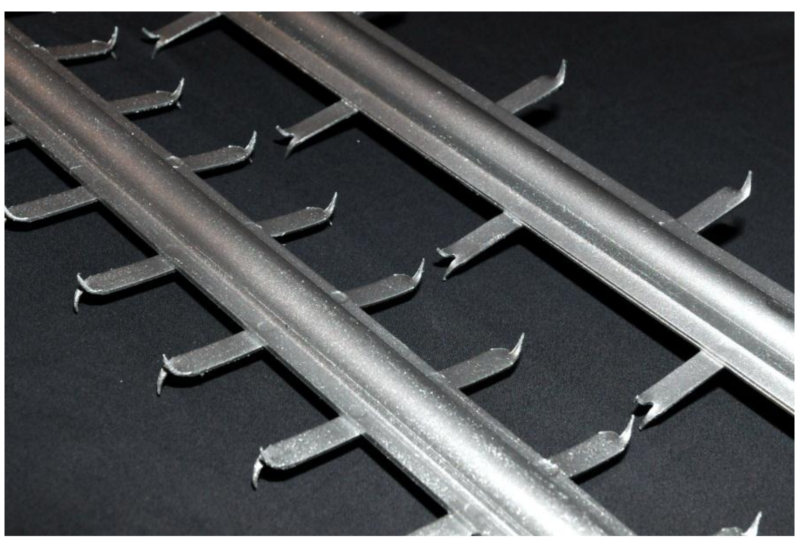


Figure 2 –Aggressive and Standard ELEX Electrode



RDE Airload V-I Curves (Field Data)

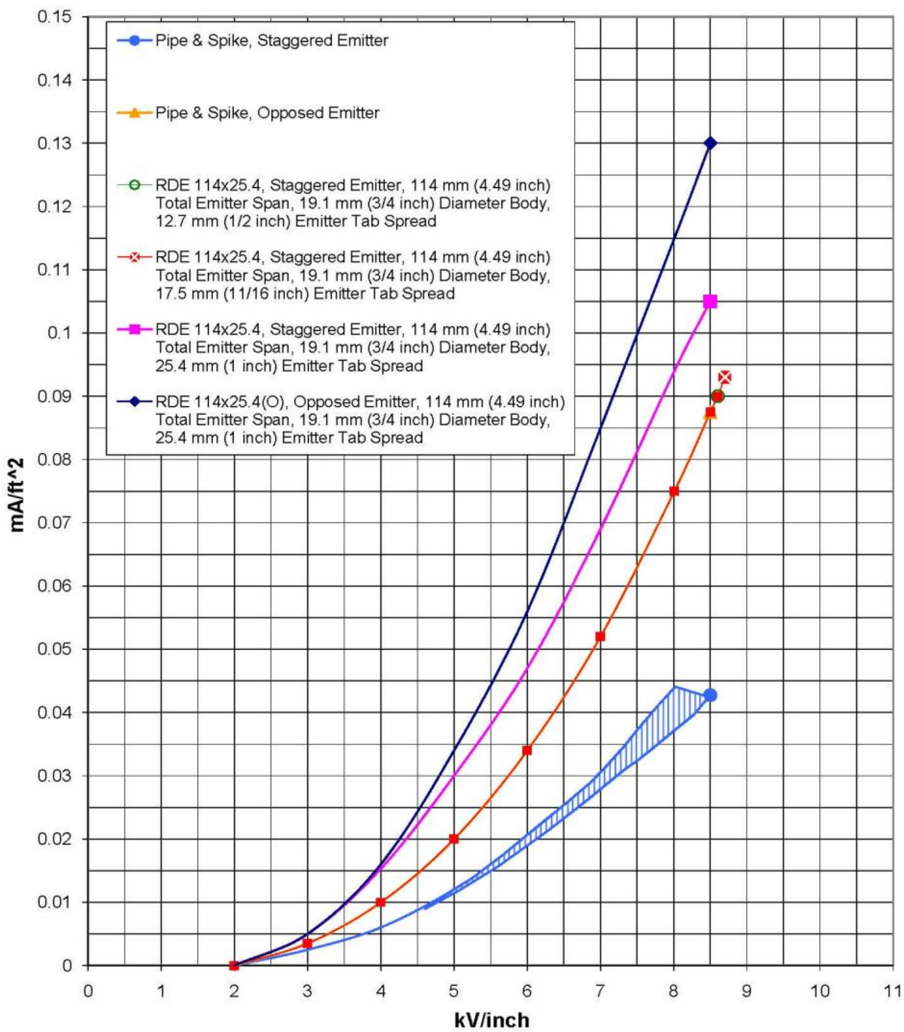


Figure 3

In the 1980's ELEX AG carried out extensive laboratory testing to compare various types of RDEs with respect to their ability to provide a uniform distribution of corona current on the collecting electrode surface.[(1)] These tests demonstrated that the ELEX electrode was (and still is) the best commercially-available discharge electrode for uniformly distributing corona current onto adjacent collecting plates.

Over the past twenty years approximately forty recovery boiler ESPs have been placed into operation in North America incorporating ELEX electrodes. Other ELEX electrode applications in the pulp & paper industry include hogged fuel boilers, combined coal & wastewood boilers, and lime kilns.

SWITCHMODE POWER SUPPLIES

Figure 4 – Switchmode Power Supplies

A recent advancement in ESP technology is the use of SMPS in lieu of conventional 60 Hertz transformer-rectifier sets. Various forms of this technology have been developed over the past two decades. One product, NWL's PowerPlus™ power supply, has gained significant operating time and has become widely accepted throughout the electric utility industry.

An SMPS set consists of four modules; An AC/DC module that takes three-phase input and rectifies and filters it to create a fairly smooth DC bus of approximately 650 volts DC. The next module is a DC/AC block that consists of an integrated gate bipolar transistor (IGBT) full bridge circuit, which converts the DC bus into a high frequency AC waveform. A resonant tank module, combined with the last AC/DC module, steps up the high frequency AC, rectifies it, and thus delivers high voltage DC to the ESP. This block, which is oil-filled, is the high frequency equivalent to a conventional 60 Hz transformer-rectifier set. Several examples of various SMPS configurations are pictured in Figure 4 above.

Because the AC input voltage is rectified, filtered, and then switched very quickly (25 kHz) in small packets of energy, the ripple voltage is only 3-5% of the DC voltage level as compared to 35-45% for linear 60 Hertz power supplies.[4]

The three-phase input also results in a much higher power factor (0.94 vs. 0.63) and lower power consumed per kilowatt of power delivered to the ESP.

In summary the major advantages in electrical performance of SMPS over a conventional transformer-rectifier set are:

- Increased secondary voltage and secondary current

- More efficient delivery of power to the ESP.

These effects have been observed and applied on numerous occasions over the past decade or so, such that a clear trend of performance enhancement when using SMPS in conjunction with ELEX electrodes has been established.

In the electric utility industry many ESPs employing SMPS in conjunction with ELEX electrodes have entered into commercial operation over the past decade, all with very favorable results. And presently, with the recovery boiler ESP operating at Canfor's Prince George Mill, the pulp & paper industry has also benefited from this development.

SMPS OPERATING EXPERIENCE

SMPS has significant operating experience in across the board ESP applications, including the following:

- Pulp and Paper ESP Applications = 53 units
- Total all ESP Applications = 1,636 units
- Total of Southern Environmental SMPS units deployed = 343 units

Southern Environmental has been integrating the SMPS technology in its ESP solutions since 2002.

RECOVERY BOILER ESPs

Pulp & paper mills use ESPs to remove saltcake PM carried by the effluent gases from black liquor recovery boilers. Saltcake PM emanating from recovery boilers is extremely fine and hygroscopic, comprised primarily of sodium sulfate and sodium carbonate, along with small quantities of sodium chloride, sulfide and sulfite. The particle size distribution is fine, typically varying from 0.4 to 4.0 in mass median diameter. Particulate density is low; typically 9 lb/cu ft unpacked and 30 lb/cu ft when compacted. Gases emanating from recovery boilers have moisture contents of from 20% to 40% by volume; as such, saltcake PM has moderate electrical resistivity, and so high corona current densities are typically attainable.

A recovery boiler ESP's inlet PM concentration can be high when compared to other ESP applications, ranging up to 9 gn/acf. This high PM loading, coupled with the fineness of the PM, gives rise to space charge and corona suppression in the ESP's inlet fields. Corona suppression refers to high corona voltages coupled with very low corona current flow, and it is caused by a failure to electrically charge the fine saltcake particles.

However, once particle charging has successfully taken place in the ESP's inlet fields, the ESP's downstream fields operate at high corona power levels due to the PM's moderate electrical resistivity. Space charge can be overcome in ESP inlet fields by use of aggressive, high current-producing discharge electrodes. Another complementary approach is to increase the number of independent electrical fields in the direction of gas flow; this is commonly referred to as increasing the ESP's electrical sectionalization.

Saltcake particles also tend to be very sticky, tenaciously clinging to ductwork vanes, collecting plates and discharge electrodes. This problem can be overcome with installation of effective ESP rapping systems on both collecting plates and discharge electrode frames. Also, the ESP's inlet ductwork and inlet plenum must be carefully configured to avoid areas of saltcake buildup. Lastly, ESP and ductwork thermal insulation must be the appropriate material and thickness for the site's ambient conditions, and it must be properly field-applied.

FIELD TEST PROGRAMS

Two recently installed recovery boiler ESPs were the subject of extensive field testing, and these test results form the basis of the data analyses and conclusions to follow:

- Site A–an ESP with ELEX electrodes on 12-inch plate spacing, energized by conventional 60 Hz transformer-rectifier sets
- Site B–an ESP with ELEX electrodes on 12-inch plate spacing, energized by SMPS sets (Canfor's Prince George Mill).

At each site a total of four, multiple-run, concurrent ESP inlet loading and stack emissions tests were conducted. Each test evaluated a unique configuration of online electrical fields. For certain tests the inlet electrical fields, those populated with charging electrodes, were de-energized. During other tests one or two of the ESP's center fields were de-energized. No tests were conducted with an outlet field de-energized, as this practice would bias the test results due to increased fine particle re-entrainment.

TEST DATA ANALYSIS

The goal was to provide insight into the effect on ESP performance of:

- Industry-typical electrical sectionalization in the direction of gas flow as compared to superior electrical sectionalization
- Installation of charging electrodes in the first field of the ESP
- SMPS as compared to conventional 60 Hertz transformer-rectifier sets.

It is a common practice in the industry to split downstream mechanical fields into two electrical fields in the direction of gas flow while leaving one or two of the inlet mechanical fields electrically intact. For this investigation, "superior electrical sectionalization" is defined as all of the ESP's mechanical fields split into two electrical fields in the direction of gas flow, whereas "industry average electrical sectionalization" implies that one or two of the ESP's upstream mechanical fields are not electrically split.

Table 1 lists the six scenarios examined. Three of the scenarios were evaluated directly from field test data, while three scenarios were extrapolated from field test data, and as such are identified on Table 1as "theoretical." For each scenario the ESP's size (the ESP's Specific Collection Area or SCA) was determined to achieve a stack PM emissions concentration of 0.010 grains/dscf at 8% O_2.

Table 1
Required ESP Size for 0.010 grains/dscf at 8% O_2

Scenario	Data Source	Type Electrical Energization	Quality of Electrical Sectionalization	Effective Charging Electrodes?	Nominal Collecting Plate Spacing (in)	Required SCA Normalized to 12-inch Spacing (sq ft/kacfm)	SCA Ratio
A	**Field Test**	T-R	Average	Yes	12	545	1.00
B	**Field Test**	SMPS	Average	No	12	542	0.99
C	**Theoretical**	T-R	Superior	Yes	12	505	0.93
D	**Field Test**	SMPS	Average	Yes	12	433	0.79
E	**Theoretical**	SMPS	Superior	Yes	12	389	0.71
F	**Theoretical**	SMPS	Superior	Yes	12 & 16	351	0.64

Scenario A–This scenario is typical of the majority of ESPs currently operating on recovery boilers in the United States, and it is considered the baseline scenario.

Scenario B – It is doubtful that there are any ESPs operating today with this particular configuration. The first mechanical field was de-energized for this test, leaving an electrically undivided second mechanical field, without charging electrodes, left to perform as the inlet field of the ESP. This scenario can be directly compared to Scenario D, which had benefit of inlet field charging electrodes. Scenario D requires 20.1% less collecting plate area than Scenario B to achieve the same stack emissions of 0.010 grains/dscf at 8% O_2.

Scenario C – This scenario can be directly compared to Scenario A, and it demonstrates the beneficial effect of superior sectionalization when transformer-rectifier sets are utilized. Scenario C requires 7.3% less collecting plate area than Scenario A to achieve the same stack emissions of 0.010 grains/dscf at 8% O_2.

Scenario D – SMPS energization promotes operation at higher secondary voltages and current flow, and its beneficial effect on recovery boiler ESP performance can be readily appreciated by comparing Scenario D to Scenario A. Scenario D requires 20.6% less collecting plate area than Scenario A to achieve the same stack emissions of 0.010 grains/dscf at 8% O_2.

Scenario E – SMPS energization promotes operation at higher secondary voltages and current flow, and superior ESP sectionalization also contributes to that end. Combining these two practices in Scenario E, we see a significant beneficial effect on ESP performance. Scenario E requires 28.6% less collecting plate area than Scenario A to achieve the same stack emissions of 0.010 grains/dscf at 8% O_2.

Scenario F – When comparing 16-inch collecting plate spacing to 12-inch collecting spacing, there are significantly higher secondary voltages developed at the wider plate spacing. Higher secondary voltages promote an overall increase in particle migration velocity and ESP collection efficiency; however, in a recovery boiler ESP's inlet field, where a high concentration of fine saltcake particles must be electrically charged, the successful abatement of space charge is incompatible with use of 16-inch collecting plate spacing. Comparing 16-inch to 12-inch plate spacing, each discharge electrode is forced to charge 33.3% more saltcake particles at 16-inch plate spacing, and the result is that particle charging becomes less efficient and so a higher quantity of uncharged and partially charged particles enter into the downstream fields of the ESP.

Hence, Scenario F retains 12-inch collecting plate spacing in the first field, which is also populated with current–producing charging electrodes, while employing 16-inch plate spacing in all downstream fields. This hybrid approach has a significant beneficial effect on ESP performance: Scenario F requires 48% less collecting plate area than Scenario A when achieving a stack PM emissions of 0.010 grains/dscf at 8% O_2.

RETROFIT ESP

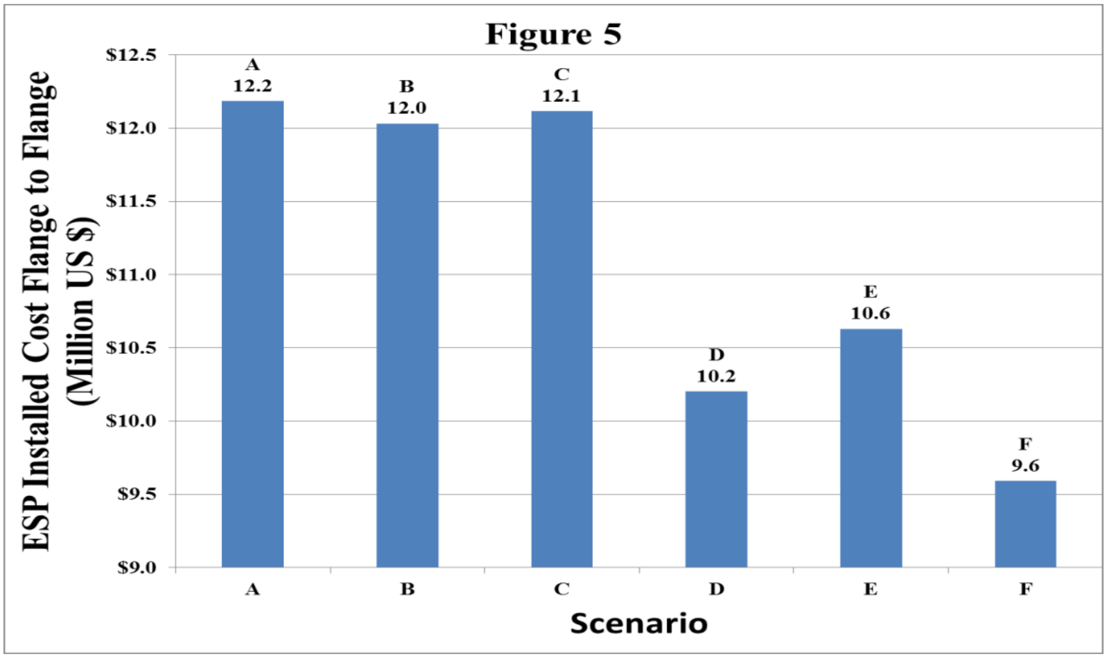
A typical requirement of recovery boiler ESP specifications is the capability to achieve the PM emissions standard (which in this example is 0.010 grains/dscf at 8% O_2) at conditions of 70% of design flow through one online chamber of a dual chamber ESP. Using the Table 1 data, dual chamber ESP sizes were determined for each scenario, as shown on Table 2 below:

Table 2
Retrofit ESP Size - Two Chambers, with 70% Flow through One Online Chamber

Scenario	Type Electrical Energization	No. Chambers	Plate Spacing (in)	No. Mechanical Fields	Charging Electrodes in 1st & 2nd EF?	No. Electrical Fields	No. GP per Chamber	ESP Total Plate Area (sq ft)	ESP SCA Normalized to 12-inch Spacing (sq ft/kacfm)
A	T-R	2	12	5	Yes	8	39	381,420	763
B	SMPS	2	12	5	No	8	39	379,080	758
C	T-R	2	12	5	Yes	10	39	353,340	707
D	SMPS	2	12	4	Yes	6	39	303,264	607
E	SMPS	2	12	4	Yes	8	40	272,640	545
F	SMPS	2	12 & 16	4	Yes	8	40	199,680	492

All of the above dual chamber ESPs can achieve 0.010 grains/dscf at 8% O_2 with 70% of design flow through one online chamber. Hence these ESPs can be directly compared on an installed cost basis.

As shown in Figure 5, ESP flange-to-flange installed cost (materials plus erection) varies from $12.2 million for Scenario A, the baseline case, down to $9.6 million for Scenario F, which is the most advanced ESP design. This represents an installed cost reduction of slightly over 21%.



Installed cost estimates for each of the scenarios include the basic EPC project construction cost of the flange-to-flange ESP proper, including all internal components, starting from the hopper steel stub column, slide plates on upward. Field installation costs include mechanical, electrical and thermal insulation & aluminum lagging. The basic scope of engineering, procurement and construction consists of the following components: downflow inlet nozzle (including turning vanes and perforated plates) ESP casing and support girders, hot roof, cold roof, penthouse design with heated purge air units, flat bottom hoppers, and a horizontal flow outlet nozzle (including a perforated plate). Also included are all ESP required accessories including SMPS or transformer-rectifier sets and their controllers, all rappers and controls, and hopper side-exit drag conveyors. Costs excluded from these estimates are: foundations, structural support steel below slide plates, electrical switchgear, ductwork, expansion joints, and dampers.

ESP REBUILD

When considering the rebuild of an existing ESP, sometimes referred to as a "gut and stuff," the advanced ESP designs have both lower installed cost and lower PM emissions. As shown on Table 3, Scenario G has been selected as the baseline case. Scenario G is a moderately-sized ESP with first field charging electrodes, conventional 60 Hertz energization, and industry typical electrical sectionalization. Scenario H is an in-kind rebuild but with superior sectionalization and the retrofit of high frequency energization.

Scenario I is similar to Scenario H in every respect except the previously discussed hybrid approach to collecting plate spacing is utilized.

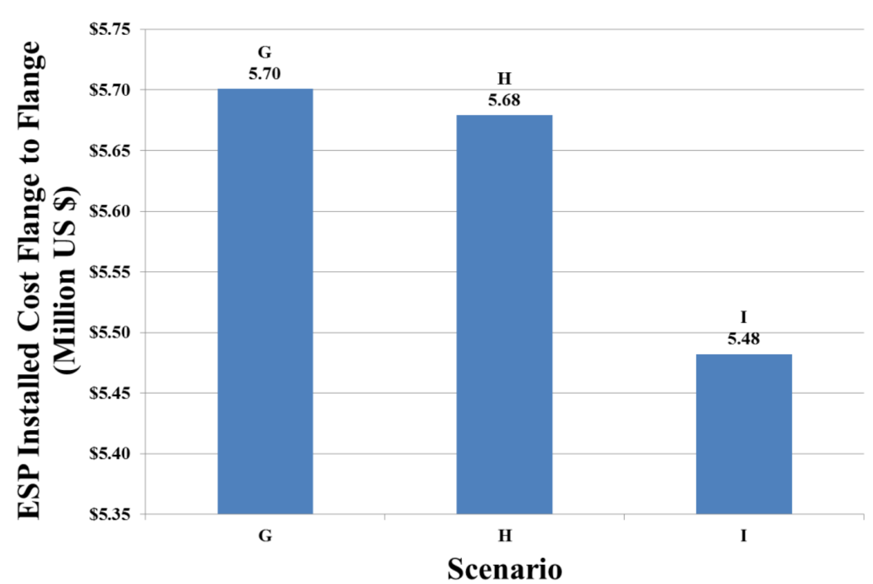
Table 3
Rebuild ESP Size - Two Chambers, with 70% Flow through One Online Chamber

Scenario	Type Electrical Energization	Plate Spacing (in)	No. Mechanical Fields	Charging Electrodes in 1st & 2nd EF?	No. Electrical Fields	ESP Total Plate Area (sq ft)	ESP SCA Normalized to 12-inch Spacing (sq ft/kacfm)	PM Emissions (gns/dscf @ 8% O2) 100% Flow - 2CH	70% Flow - 1 CH
G	T-R	12	4	Yes	6	272,640	545	0.011	0.039
H	SMPS	12	4	Yes	8	272,640	545	0.002	0.010
I	SMPS	12 & 16	4	Yes	8	221,520	545	0.001	0.006

If the baseline case is simply rebuilt in kind, the rebuilt ESP can achieve 0.039 grains/dscf at 8% O_2 with 70% of design flow through one online chamber. Scenario H reduces PM emissions to 0.010 grains/dscf at 8% O_2 with 70% of design flow through one online chamber, which is a borderline situation. The most advanced ESP configuration, Scenario I, can achieve 0.006 grains/dscf at 8% O_2 with 70% of design flow through one online chamber, which is 40% below the targeted PM emissions standard of 0.010 grains/dscf at 8% O_2.

The most advanced ESP rebuild design also has a slightly lower installed cost, as shown in Figure 6 below.

Figure 6



CONCLUSIONS

When two commercially proven technologies – customized ELEX rigid discharge electrodes and SMPS – are incorporated into the design of a recovery boiler ESP, then that ESP becomes a more efficient collector of saltcake PM.

If two additional practices are then employed – superior electrical sectionalization and use of 16-inch plate spacing in downstream mechanical fields – that ESP becomes significantly more efficient as well as more economical on an installed cost basis.

For the owner/operator, the advanced ESP technology discussed in this paper has the potential to realize multiple benefits:

- When a new recovery boiler ESP is retrofitted at an existing site, that ESP will be smaller, lower in installed cost, and take up less site real estate
- If an existing recovery boiler ESP is in need of rebuild, the rebuilt ESP will always be capable of achieving lower PM emissions without the need for additional fields or increased collecting plate height
- If the site's PM emissions standards have become more challenging, then a rebuilt ESP may be able to address these new standards, thus avoiding the cost penalty of a retrofitted ESP system
- If the site's PM emissions standards have remained unchanged, then a rebuilt ESP of advanced design will provide the operator with significantly more redundancy and reliability during day to day operation.

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