MEMBRANE WESP – A Lower Cost Technology to Reduce PM2.5, SO_3 & Hg^{+2} Emissions

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ABSTRACT

Multi-pollutant control technologies will become more important in the future. This new membrane wet electrostatic precipitator (WESP) system is ideally suited to, and very cost effective for, removing PM2.5, SO_3 and Hg^{+2} after limestone wet flue gas desulphurization (WFGD) scrubbers in the utility industry.

Several coal-fired utilities have been experiencing increased SO_3 emissions from their existing WFGD scrubbers, especially after installing a Selective Catalytic Reduction (SCR) for NOx Control. Achieving co-benefits of Hg removal by installing SCR's and WFGD systems is already becoming a key strategy for reducing mercury levels after coal fired power plants.

WESP can readily collect acid aerosol and fine particulate due to greater corona power and virtually no re-entrainment. The WESP can also enhance collection of Hg (Hg ash & Hg^{+2}). The main historical limitation associated with wet precipitators has been the higher cost of special alloys and stainless steel material used in their manufacture. This new technology WESP, based on fabric membrane for the collecting electrodes, dramatically reduces weight and cost, compared to conventional, metallic WESPs.

Cleaning of the corrosion resistant fabric membranes, is facilitated by capillary action between the fibers, providing even water distribution, & continuous flushing, which removes collected material without spraying, so the entire precipitator remains on line.

Operation of several pilot units using the membrane technology has demonstrated excellent PM removal efficiency. The first commercial size unit, collecting fine particulate and sulfuric acid mist after two boilers firing No. 6 oil with 4% sulfur, shows high SO_3 removal as well. The operation and performance of this two-module, upflow, membrane, single-field unit, along with some of the problems encountered and overcome in the start-up, will be described.

Cost estimates comparing the membrane design to conventional metal plate WESP's are presented. Recommendations are made to show how the membrane technology can be used after

utility-size, limestone WFGD scrubbers. Capital cost comparison of both vertical up-flow and horizontal flow WESP's will be made.

INTRODUCTION

Fine particulate, PM 2.5 and pseudo particulate (H_2SO_4 mist) is of concern to coal-fired utilities because it effectively scatters light, leading to increased stack opacity. Soot or condensed hydrocarbons and acid aerosols, are capable of causing significant opacity problems at concentrations as low as 10 ppm (v). Acid aerosols form when an acid (notably sulfuric acid) condenses, providing excellent condensation nuclei for water accumulation, eventually creating aerosol particles 1-2 μm in diameter. Sulfuric acid condensation nuclei are prevalent when SO_3 concentrations are high, either because of burning high sulfur coal or when selective catalytic reduction (SCR – used for NOx control) catalyst beds oxidize significant amounts of SO_2 to SO_3. SCR's are increasingly being used in coal-fired power plants for NOx control, especially in the Midwest. Most states limit opacity at the stack/scrubber outlet to around 10%.

Advantages of Wet Electrostatic Precipitators

Wet precipitators are excellent for controlling fine particulates, & sulfuric acid mist. In wet precipitators, re-entrainment is virtually nonexistent due to adhesion between the water and collected particulate. WESPs can achieve up to several times the typical corona power levels of dry precipitators, greatly enhancing collection of submicron particles[1&2]. Also the gas stream temperature is lowered to the saturation temperature, promoting condensation, and enhancing the collection of soluble acid aerosols.

DISCUSSION

Problems with Existing Wet Electrostatic Precipitators

In most wet precipitators, both tubular and flat-plate, the collection surface normally has the form of a plain, *solid, continuous* sheet of metal or plastic. Therefore, the flushing liquid (water) passing over the surface tends to "bead" due to both surface tension effects as well as the initial geometric surface imperfections ("hills and valleys") (Figure 1). Because the flushing liquid cannot be uniformly distributed over the surface, this beading can lead to channeling and formation of "dry spots" of collected particles. The resulting build-up of collected material causes the precipitator electrical performance to degrade. As a result, current flow is inhibited, which results in increased emissions from that section of the electrostatic precipitator.

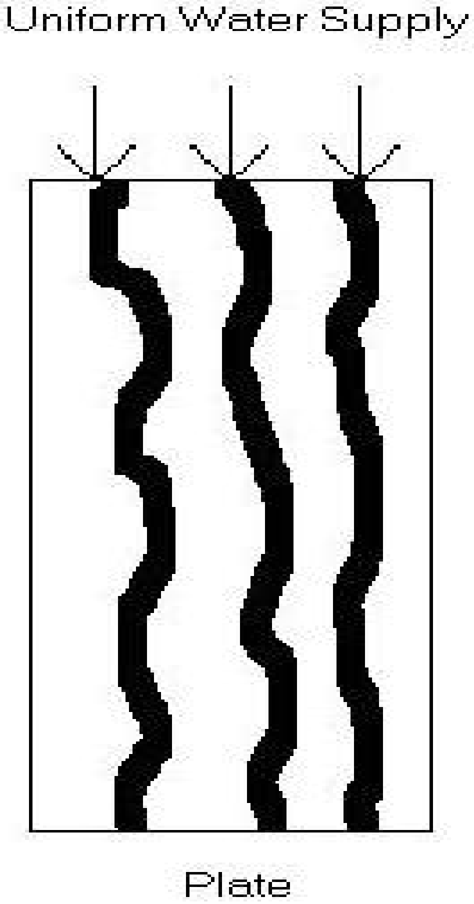

Figure 1: Water Flow in Conventional Metal Plate WESP

Most "old-design" wet precipitators employ atomization or spraying to more uniformly distribute liquid over the surface. However, any spraying into the gas stream will produce aqueous mist droplets which are highly conductive. As a result, the high voltage electric field will have a conductive path to ground, shorting out the field. To avoid this grounding, called sparkover, the field voltage is usually reduced or switched off during intermittent spraying for collector plate cleaning.

Corrosion is also a big concern of metal plate wet precipitators, so the internals must be made of expensive alloys.

Membrane Wet Electrostatic Precipitator Design Solves These Problems

Developed over the last six years, a new type of wet precipitator, in which fabric membranes replace traditional metal collecting electrodes, solves these problems. Tests indicate that membranes made from materials that transport liquid (primarily water) by capillary action are effective collection electrodes. Capillary flow promotes well-distributed water flow both vertically and horizontally which is necessary for particle collection, removal and transport (Figure 2). This solves a major historical problem in wet electrostatic precipitators, both of the wet upflow and wet horizontal flow types, which is to keep the collecting electrodes <u>continuously</u> clean.

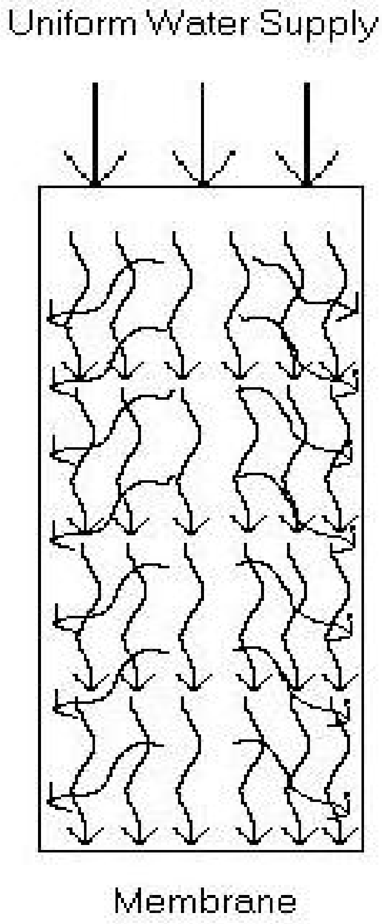

Figure 2: Water Flow in Membrane WESP

The flushing liquid can be delivered to the membrane in a number of ways. The most important design aspect is that the water is "dripped", not sprayed, over the collecting surface (Figure 3). C*apillary action* of the membrane material, along with an assist from gravity, delivers the water throughout the membrane eliminating splashing or spraying. A controlled amount of water can be delivered *through* the membrane's upper edge. The amount of water delivered and the resulting thickness of the surface liquid film can be controlled. Tests indicate that adequate flushing of collected material can be achieved with only 0.75 – 1.25 GPM per 1,000 ACFM of saturated gas.

Figure 3. **Top View of Water Distribution Test Stand**

Several Membrane Materials Can be Used

Because the liquid film is also the collecting surface (i.e. it conducts electricity), the membranes can be made from corrosion resistant, nonconductive materials like Polypropylene, or PPS. These materials essentially eliminate problems of corrosion, while offering a much lower cost alternative to stainless steels and expensive alloys *(See results* ***of Membrane Chemical Resistance*** *tests in Appendix A).*

In addition, the cost of installation and transportation are significantly lower due to weight reductions of as much as a 60-80%, compared to metal plate type WESP's. The membrane collecting electrode can be kept very flat with a small amount of tension.

An initial pilot-scale test run was performed to visualize the membrane's ability to remove particulate. Pictures were taken before energizing the field and a few seconds after the field was energized. The dust loading, temperature, and flow conditions were kept constant between the two displayed images of Figure 4, providing a visual indication of the effectiveness of the wetted collection membranes.

Figure 4: Dirty and Clean Stack (ten seconds after energizing field)

Particulate Collection Efficiency – Results of Tests

Testing in three pilot units has shown outstanding particulate collection efficiency comparable to, and in some cases superior to, a conventional metal plate WESP. Figure 5 shows the V-I-curve for the pilot precipitator installed on a lime kiln application. The two lines, one with air load, and the other with lime dust in gas flow, represent V-I characteristics of membrane WESP with air and lime dust. Using a Power Plus transformer-rectifier set, the membrane WESP exhibited power profiles comparable to conventional wet precipitators.

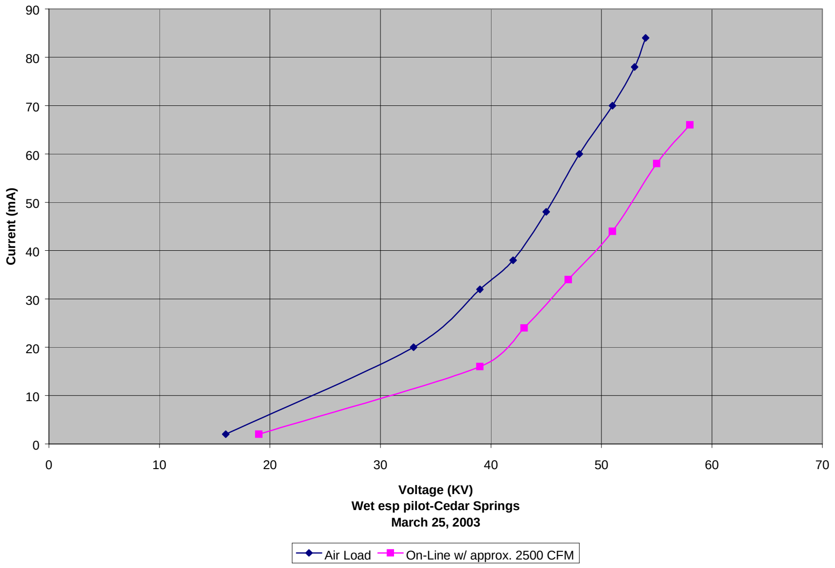

Figure 5: V-I curves for the Lime Kiln Pilot Wet Membrane Precipitator

Pilot Scale Testing

Figure 6: Lime Kiln Pilot Test Unit

Lime Kiln

Pilot Plant Results -- after 5000 hr operation:

Inlet and outlet emissions test results are shown in Table 1 and indicate that the single field unit captured 88-95% of the particulate and achieved very low outlet loading levels of 0.0015 to 0.005 Gr/ACF.

The gas velocity and the SCA goals of the pilot unit were met in that the test results were demonstrated at gas velocities of 10 –11 ft/sec. & Specific Collective Area (SCA) of ≈ 65 ft^2/1000 ACFM.

No build up of lime dust was observed. At the end of the 5,000 hour test the polypropylene membranes appeared almost “as new” (See Attachment A).

Also, Mullen Burst strength tests were run which showed that the membranes had lost less than 5% strength. This would suggest a membrane life of up to 5 years.

Utility Pilot Plant

Under partial sponsorship from the U.S. Dept. of Energy, we built a third pilot membrane WESP after an existing wet FGD system at **First Energy's Bruce Mansfield Station** in Shippingport, PA.

The goal of this project was to compare the performance of the membrane design to a "conventional" metal, tubular WESP. Under all conditions the membrane unit performed somewhat better than the metal tubular unit as seen in Table 1.

UNIT	EXCEL/ SHERBORG	LIME KILN	DOE METAL	DOE MEMBRANE
Application	FRB Fired Boiler	Lime Dust	SO3, PM	SO3, PM
Description	2 Fld Upflow Metal	1 Fld Upflow Membrane	2 Fld Upflow Metal	2 Fld Upflow Membrane
Downstream of:	Rod Deck Scrubber	Rod Deck Scrubber	Wet FGD	Wet FGD
Gas Vol. ACFM	245,000	7,000	8,000 15,000	8,000 15,000
Gas Temp. ^{o}F	120-150^0 F	130^0 F	125^0 F 125^{0}F	125^0 F 125^{0}F
SCA – 1st Fld. 2nd Fld.	34 51	65	35 19	35 18 35 21
Gas Velocity thru WESP, fps	9	11	9 16.7	9 16.7
Outlet Opacity, %	<10	<5	<2 <5	<2 <5
Inlet Loading, Gr/ACF		0.04	0.054 0.05	0.046 .05
Outlet Loading Gr/ACF		0.0027	0.004 0.015	0.0017 0.01
PM Efficiency %		93	93 70	96 80
SO3 Efficiency %	N/A	N/A	88 65	93 71
Hg^{+2} Efficiency %	N/A	N/A	76 50	82 61

Table 1: Performance Comparisons of One Full-size & 3 Pilot Units

Mercury Removal

We also tested Hg removal with the Bruce Mansfield Pilot (results in Table 2 below). Tests were conducted across the existing wet scrubber and across the membrane WESP. In this plant, there is no dry precipitator, only a wet dcrubber installed after the boiler for both particulate and SO_2 control. The SCR was installed, but not operating during these tests.

The higher level of elemental Hg was somewhat surprising. However, we see that removal efficiency across the scrubber was 82% for ash Hg and 69% for Hg^{+2}. And, of course, no collection on elemental mercury. The interesting thing, though, is that the membrane WESP achieved *significant additional* collection efficiency on both the ash and oxidized mercury, 72% and 78% respectively, across just the WESP. This suggests that the membrane WESP is not only effective in both Hg ash and Hg^{+2} removal, but augments and increases the overall mercury removal across a scrubber/WESP combination. In fact, as shown in the last line of the table, the overall scrubber/WESP removal efficiency on Hg ash plus Hg^{+2} = 94%.

These results also suggest that, to the extent the Hg^0 can be converted to Hg^{+2}, the combination scrubber/WESP should be able to remove 80%-90% of the total mercury in the gas stream.

Species	%	Scrubber Inlet (µg/ m^3)	WESP Inlet/Scrubber Outlet (µg/ m^3)	Scrubber Eff. % wt.	WESP Outlet (µg/ m^3)	WESP Eff. % wt.
Ash Hg	33	4.5	0.8	82%	0.2	72%
Hg+2	44	5.8	1.8	69%	0.4	78%
Hg0	23	3	3	0%	2.7	10%
Combined		13.3	5.6	58%	3.3	41%
OVERALL: Eff. (ash + Hg^{+2}) = 94%						

Table 2: Scrubber/Membrane WESP – Mercury Removal Ontario Hydro Method

Membrane Build-Up Tests

After these tests which clearly demonstrated the membrane WESP's high performance efficiency in removing PM, SO_3 and Hg^{+2}, we decided to search for the ultimate test as far as membrane buildup was concerned. In 1995 we had installed a two-field, metal plate, up-flow WESP at Excel Energy's Sherbourne, Minnesota Station. This unit suffers from chronic calcium sulfate $CaSO_4$ buildup and is forced every six months to take the modules off-line to remove the accumulated calcium sulfate using high pressure water, and to clean the electrodes in the first field. The experiment with membranes consisted of "draping" the membranes over the metal plates, which are 4' long in direction of gas flow, and irrigating the membranes continuously with water. After six-months of continuous operation, as you can see in Figure 7, the metal plates exhibited their typical build-up to the point where neither the collecting plates nor the discharge electrodes are effective. By comparison, the eighteen "membrane" tubes in this compartment, although subjected to identical operating conditions as the metal plates, were totally free of build up after the six-month period. We believe this conclusively proves that as long as the membranes can be kept wet there will be no build up.

Figure 7: Picture of Membrane Build-up Test

First Commercial Installation

The first commercial application of the membrane WESP technology is at Smurfit Stone Container Corporation's, Stevenson, AL Plant. This system, shown in figure 8, is a two-module, upflow, single field, membrane WESP installed on two boilers burning No. 6 fuel oil with 4% sulfur content. The vanadium in the oil converts a significant portion of the SO_2 to SO_3 (about 20 PPM inlet to the WESP) so the goal of this wet unit was to remove fine particulate and SO_3 mist after an existing sodium hydroxide scrubber.

Figure 8: Picture of SSCC Stevenson Membrane WESP

The design parameters of this system are as shown below. Started up in March 2005, the membrane WESP has achieved the 0.05 lbs mm/BTU particulate and sulfuric acid (combined), outlet emission requirement at volumes slightly lower than the design volume of 125,000 ACFM. Problems which developed during early operation have been solved and the unit now has operated essentially trouble free for the last ten (10) months.

Design Parameters for New Installation

2 Boilers - WESP downstream of Na scrubber

Total Boilers Max. Firing Rate, MMBtu/hr	445
Gas Volume to WESP, ACFM	125,000
Gas Temperature, oF	135
Fuel Type, Oil	#6 Bunker C
Fuel Sulfur Content Max.	4% wt.
Inlet loading to WESP, lb./MMBtu	0.13
Inlet loading, lb./hr	60
H_2SO_4 inlet concentration, ppmv	20 approx.
Outlet Emission Rate, lb./MMBtu	0.05
Outlet Emission Rate, lb./hr	22
Outlet Emission, Gr/ACF	0.02
Removal Efficiency (PM & H2SO4)	62%

Materials of Construction

The WESP casing is fabricated using 1/8th" thick 316L Stainless Steel with 304 Stainless Steel stiffeners. The support system for the discharge electrode is 904L and the discharge electrodes themselves are Hasteloy C2000 (at the customer's request). The membranes are felted polypropylene.

Condensing Wet Precipitator Advantage

One other interesting aspect of the membrane design is its ability to act as a heat exchanger and cool the saturated gas stream by several degrees, condensing additional water out of the gas stream in the process. As seen in Figure 9 at the operation in Stevenson we are able to reduce the saturated gas temperature through the modules approximately 10^0 F, This temperature reduction condenses sufficient moisture from the gas stream to virtually eliminate the need for make-up water to irrigate the membranes.

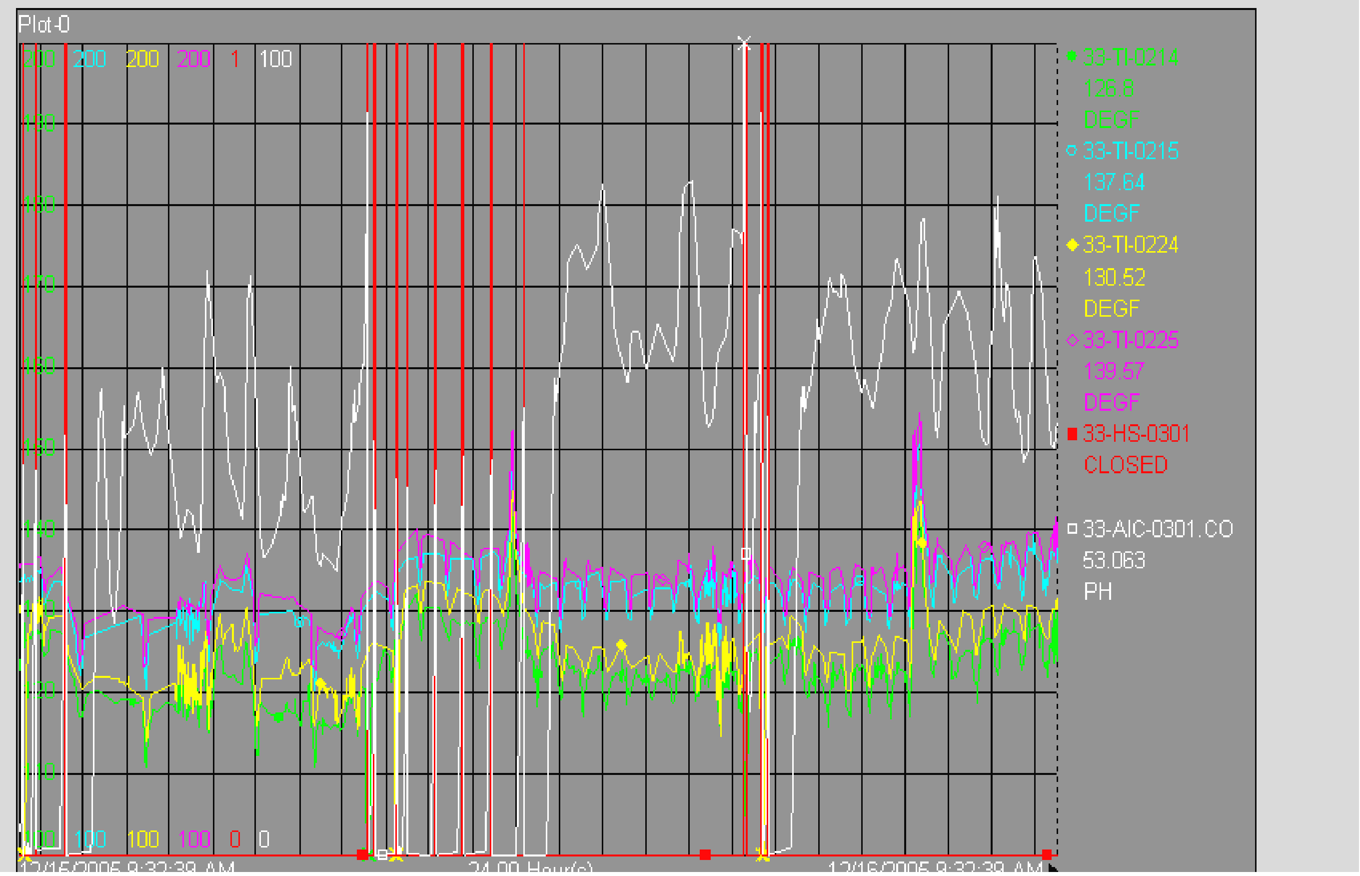

Figure 9: Snapshot of Temperature Drop across WESP System at SSCC, Stevenson

In a full size utility type unit, this could have a very beneficial effect. By eliminating the need for make-up, one could assume to operate the WESP with no (or very low) chlorides in the recycle loop. The only chlorides would be those coming over from the scrubber, which we estimate to be no more than 1 to 3 ppm (communication with Babcock Power). This means that the recycle loop could be operated with no more than 100 ppm chlorides which suggest that 316L Stainless Steel could confidently be used as the material for casing fabrication.

This offers the potential for significant savings compared to some specifications which have required 317 LMN, 904L and even C276 Hasteloy to be used for the WESP casing construction.

Reduced Costs for a Membrane WESP

Generally with "conventional" wet, upflow units such as the SEI metal–plate unit at Excel/Sherborg, the WESP must be designed with an "extra" field which can be out of service during cleaning, substantially increasing cost. Because the membranes can be continuously flushed, the possibility exists to design the unit with several fields to efficiently collect fine particulate and SO_3 mist. Obviously this will significantly reduce the overall system costs.

Costs of Metal-Plate vs. Membrane WESP's

We believe the maximum ultimate savings to be achieved with the membrane WESP will be to locate a 2 or 3-field, upflow membrane unit on top of a WFGD scrubber. Today, however, the trend is toward grade-mounted, stand-alone WESPs after the WFGD scrubber. With this in mind the following comparisons can be made:

WESP System	Cost/kW
3-field upflow membrane WESP- sitting on top of FGD scrubber	Approx. $20-25/kW
3-filed horizontal flow membrane WESP- sitting on the grade	Approx. $30-35/kW
3-field horizontal flow WESP-sitting on the grade	Approx. $40-45/kW

This cost comparison is based on following assumptions:

1. Using SS 316 for material of construction.
2. Erection cost is not included.
3. Ductwork is not included for the grade mounted unit WESP system.

Potential Applications of Membrane Wet Precipitation

The main applications envisioned for the membrane WESP are to collect fine particulate and acid aerosols, after scrubbers:

- After WFGD scrubbers in the utility industry.
- After upstream particulate scrubbers in industrial applications.

CONCLUSIONS AND RECOMMENDATIONS

These operational advantages and cost savings truly change the perception of wet electrostatic precipitators to the point where they can be considered a *cost effective* emissions control device for PM2.5, SO_3 & Hg^{+2}**.**

Continuing tests will help refine the capability and lower cost of this improvement in WESP technology.

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Attachment A

Internals of Lime Kiln Pilot Unit after 5,000 hours operation.

Appendix A: Membrane Chemical Resistance

In order to test how various membrane materials behave in highly corrosive environments at elevated temperatures, a closed loop testing system was constructed as schematically shown in Figure A1. The system is designed for long-term, continuous operation without interruption. The system produces hot water at 80°C (175^0 F) elevated temperature testing of nine separate chemical solutions-fabric combinations.

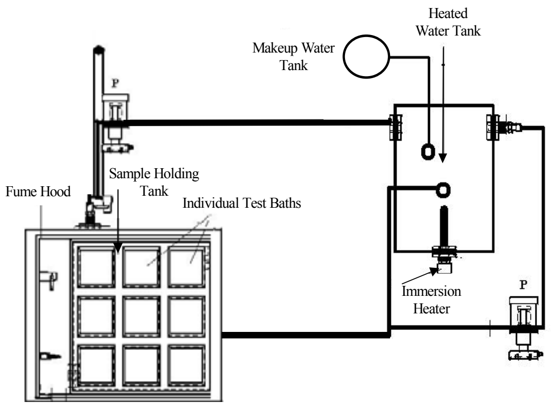

Figure A1: Accelerated Chemical Corrosion Testing Apparatus

The nine tanks contain combinations of the materials Ryton, Polypropylene and Teflon in solutions of acids and bases. Specifically, the solutions are:

- “Sulfuric Acid” – H_2SO_4 and H_2O to pH of 1.5;
- “Ammonia” – 1500 ppm NH_4Cl, 1% $(NH_4)_2SO_4$ in distilled water;
- “Reactive” – 800 ppm HF, 30000 ppm HNO_3, 60000 ppm H_2SO_4, 8000 ppm HCl in distilled water.

The materials were sampled and tested for Mullen Burst Strength over time. These results are shown in the following figure.

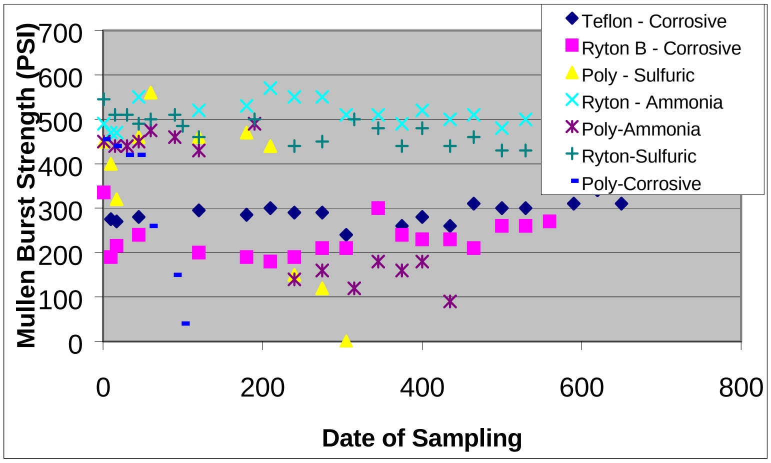

Figure A2. Accelerated chemical corrosion strength testing results