Multi-Pollutant Control Using Membrane –Based Up-flow Wet Electrostatic Precipitation

FINAL REPORT

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ABSTRACT

This is the Final Report of the "Multi-Pollutant Control Using Membrane –Based Up-flow Wet Electrostatic Precipitation" project funded by the US Department of Energy's National Energy Technology Laboratory under DOE Award No. DE-FC26-02NT41592 to Croll-Reynolds Clean Air Technologies (CRCAT). In this 18 month project, CRCAT and its team members conducted detailed emission tests of metallic and new membrane collection material within a wet electrostatic precipitator (WESP) at First Energy's Penn Power's Bruce Mansfield (BMP) plant in Shippingport, Pa. The Membrane WESP was designed to be as similar as the metallic WESP in terms of collection area, air-flow, and electrical characteristics. Both units are two-field units. The membrane unit was installed during the 2nd and 3rd quarters of 2003.

Testing of the metallic unit was performed to create a baseline since the Mansfield plant had installed selective catalytic reduction equipment for NOx control and a sodium bisulfate injection system for SO3 control during the spring of 2003. Tests results on the metallic WESP were consistent with previous testing for PM2.5, SO3 mist and mercury. Testing on the membrane WESP demonstrated no adverse impact and equivalent removal efficiencies as that of the metallic WESP. Testing on both units was performed at 8,000 acfm and 15,000 acfm. Summary results are shown below.

Summary of Wet ESP Removal Efficiency Comparison

Collection Material	H2SO4	PM2.5	Elemental Hg	Oxidized Hg	Particulate Hg
Metallic WESP	88%	93%	36%	76%	67%
Membrane WESP	93%	96%	33%	82%	100%

Testing of the membrane material for strength, wetting capability and visual inspection showed the polypropylene material had no deterioration in strength, improved wetting capability and visually looked satisfactory after 6 months of service. Long-term testing- i.e. five years is recommended to determine the membrane material's ability to withstand long-term exposure to flue gas and sparking. The acceptance of membrane material as a collection medium within a Wet ESP will be greatly determined by its ability to resist stretching, plugging and fire over a number of years. Metallic materials have a life of 10-20 years. Any cost savings from using membrane material, estimated at between 5%-15% of a project's value, would be negated if the membrane material had to be replaced every few years due to stretching, plugging or burning of the membrane material from sparking were experienced.

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5. Introduction

This is the Final Report of the "Multi-Pollutant Control Using Membrane –Based Up-flow Wet Electrostatic Precipitation" project funded by the US Department of Energy's National Energy Technology Laboratory under DOE Award No. DE-FC26-02NT41592. Croll-Reynolds Clean Air Technologies (CRCAT) was the project leader and First Energy's Penn Power's Bruce Mansfield Plant (BMP) located in Shippingport, Pa. was the host site. Ohio University and Southern Environmental were participating team members. In this 18 month project, CRCAT and its team members conducted detailed tests of metallic and new membrane collection material within a wet electrostatic precipitator (WESP). The project's overall objectives were:

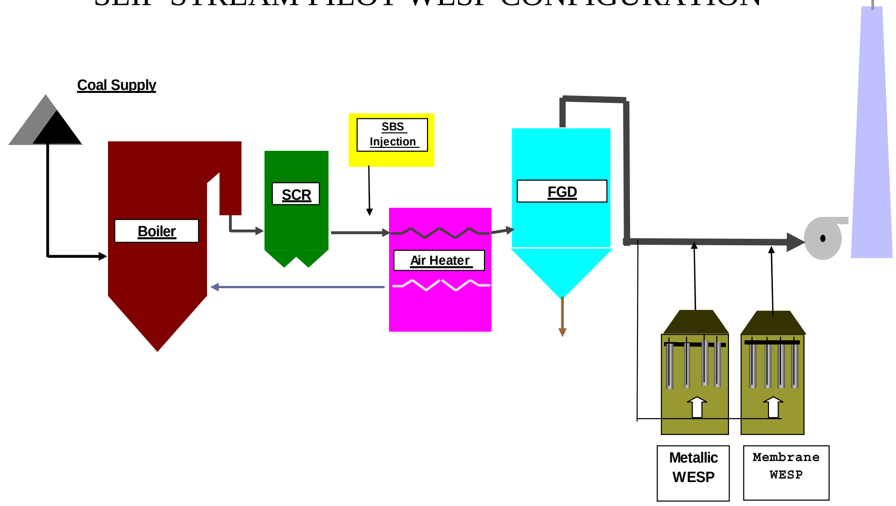
- To compare the performance of metallic collecting surfaces to the performance of membrane (fabric) collecting surfaces in a wet electrostatic precipitator (ESP), in terms of their efficiency in removing fine particles, acid aerosols, and mercury from an actual power plant flue gas stream.

- To determine the relative durability and overall cost-effectiveness of the membrane collectors versus metallic collectors.

Croll-Reynolds installed at BMP in 2001 a 316L stainless steel metallic pilot WESP, which uses a slipstream of flue gas from the exhaust of the venturi scrubbing system on BMP Unit No. 2. BMP installed the WESP to test for PM2.5 and SO_3 mist removal as a potential control technology to reduce visible emissions. This project utilized the existing 2-field WESP infrastructure installed at BMP as a baseline to compare the membrane technology. A new 2-field membrane WESP similar in design to the metallic WESP was installed alongside the existing metallic WESP during July of 2003.

BMP started up new Selective Catalytic Reduction (SCR) with ammonia injection equipment in May. Additionally, the plant installed a sodium-bisulfate SO_3 mitigation injection technology. Because it is expected that these new control systems will significantly change the composition of the flue gas, testing of the metallic WESP was repeated during the summer of 2003 to gain a new baseline against which to compare the membrane WESP. Testing of the membrane WESP was also conducted during August, September, and October of 2003.

SLIP-STREAM PILOT WESP CONFIGURATION



6. Executive Summary

During the third and fourth quarter of 2003, testing on SO3, PM2.5 and mercury was performed on both the metallic WESP and the membrane WESP at 8,000 acfm and 15,000 acfm air flows. In addition, mercury inlet loading across the FGD scrubber was taken to measure incremental mercury removal efficiency across both the FGD and WESP.

Test results demonstrated the membrane material had no adverse impact and achieved similar removal levels as that for the metallic unit. Differences between removal efficiencies is attributable to either averaging differences due to the limited number of test runs and/or improved collection properties of the membrane collection material. The results are summarized below.

Table 1

Summary- 316L SS Metallic WESP Removal Efficiencies

(Percent Removal)					
ACFM	H_2SO_4	PM2.5	Elemental Hg	Oxidized Hg	Particulate Hg
8000	88%	93%	36%	76%	67%
15000	65%	70%	26%	50%	67%

Summary- Membrane WESP Removal Efficiencies

(Percent Removal)

ACFM	H_2SO_4	PM2.5	Elemental Hg	Oxidized Hg	Particulate Hg
8000	93%	96%	33%	82%	100%
15000	71%	81%	23%	61%	100%

Results show that WESP devices, when properly designed and built, can achieve multi-pollutant control with very high PM2.5, SO3 and mercury removal efficiencies. Removal efficiencies are significantly impacted by velocity through the device. While the WESP unit originally provided to First Energy was designed for 90% removal efficiency on PM2.5 at 5,000 acfm, the units were capable of achieving in excess of 90% at 8,000 acfm, once modified to a Croll-Reynolds patented two-field design.

PM2.5 and SO3 mist are removed at the same relative rates, since both are primarily fine particles. However, due to particle size distribution, with the average SO3 mist particle size being 0.3 microns and PM2.5 being 1 micron, PM2.5 is easier to collect due to its larger average size.

As a final polishing device in an integrated air pollution control system after a FGD system, a WESP can achieve additional mercury removal capability on all mercury species. 95% removal of particulate and oxidized mercury was achieved across the FGD and WESP systems. The FGD system achieved 69% removal of oxidized mercury with the WESP achieving an additional 86% removal.

For elemental mercury, the FGD system actually degassed some of the collected oxidized mercury in the scrubber liquid back into elemental mercury, creating an additional 14% of elemental mercury. Conversely, the WESP was able to oxidize 18% of the inlet elemental mercury and capture it as oxidized mercury. It is believed that the WESP's ability to generate ozone from corona discharge was responsible for the oxidation of elemental mercury.

In January 2004, a section of the membrane WESP material was removed from the membrane WESP pilot to measure how well the membrane material withstood six months of use in a coal flue gas environment. Mullen burst strength testing on the polypropylene material reported no deterioration in material strength. Wetting properties shows improved wetting capability and the material visually appeared to be in satisfactory condition. There was no evidence of excessive wear or holes from sparking/arcing within the WESP.

In summary, WESP technology was demonstrated to be an effective PM2.5, SO3 mist and mercury removal device on coal flue gas. Membrane and metallic collection materials in WESP devices can achieve similar collection efficiencies for these pollutants. The membrane material appears not to have deteriorated over six months of service. It is a less expensive material than stainless steel and other expensive corrosion resistant alloys with the inherent advantage of being lighter weight. The primary risks to using membrane material appear to be long-term deterioration of the material after several years of service, potential plugging of the membrane material from salt build-up, the potential to blow holes in the membrane material from arcing if not saturated and the fire hazard potential if there is loss of water within the WESP. Longer term testing of the membrane material is recommended to determine the membrane material's ability to resist stretching, plugging of pores from salts and resistance to fire from sparking/arcing within the WESP. Any cost-saving from use of the membrane material would be offset if replacement of membrane material were required every few years.

7. Experimental

Design Parameters

The original Wet ESP installed by Croll-Reynolds during 2001 was designed for an industrial customer for 90% removal of PM2.5 at 5,000 acfm. It was a single field wet ESP incorporating 28- 10' long vertical 10" diameter tubes. After testing in September of 2001, it was felt collection efficiency could be improved by modifying the Wet ESP into 2 fields per a Croll-Reynolds Clean Air Technologies patent. For this membrane pilot project, the object was to compare membrane collection material vs. the 316L SS material incorporated in the existing wet ESP installed at BMP. Due to mechanical limitations dictated by the membrane collection material, square tubes were utilized rather than round tubes. Design parameters were kept as similar as possible so direct comparison between a conventional metallic wet ESP and the membrane material could analyzed. The table below shows how the two units compare.

Table 2 Wet ESP Design Parameters

Parameter	Metal Wet ESP	Membrane Wet ESP
Configuration	Round	Square
# of tubes	28	16
Tube diameter	10" dia.	11 ½" sq.
Tube Length	10' long	10' long
Collection area	724 sq. ft.	613 sq. ft.
Designed air-flow	5000 acfm	5000 acfm
Designed velocity	6 ft./sec.	6 ft./sec.
# of electrical fields	2	2
Residence Time	2 seconds	2 seconds
Specific Collection Area	145 $ft.^2$/1000 acfm	123 $ft.^2$/1000 acfm
Specific Power	2000 watts/1000 acfm	2000 watts/1000 acfm

Air-Flow

The metallic pilot wet ESP was originally designed for an industrial customer for 90% removal of PM2.5 at an air flow of 5,000 acfm within a single field wet ESP. However, all testing has been performed at 8,000 acfm, 60% beyond the design airflow. Because a wet ESP is a volumetric device, it is very sensitive to air flow and velocity. Any increase in velocity decreases performance due to less time to collect particles. Conversely, reducing air flow increases performance. One of the purposes of this project was to observe removal performance at velocities close to 15ft./second. This would allow for a smaller less costly wet ESP to be designed that matched the diameter of most FGD scrubber vessels. Therefore, testing at 15,000 acfm was also performed to compare to the 8,000 acfm air flow.

Electrical

Voltage and current levels were maintained at consistent levels between the membrane and metal plate units. To eliminate any differences in performance due to electrical supply, both pilot

WESP's were powered by the same single-phase conventional high voltage transformer rectifier (TR) sets.

PRIMARY POWER:	57 KVA
PRIMARY VOLTAGE:	480 VAC
PRIMARY CURRENT:	150 AAC
SECONDARY VOLTAGE:	110 KVDC peak, 60 KVDC avg.
SECONDARY CURRENT:	400 mADCavg

Because the mechanical limitations of using the membrane required a square configuration, versus the round diameter of the metallic WESP, and we wanted to make the metal and membrane units match as close as possible in terms of cross-sectional area, fewer tubes and therefore electrodes were installed in the membrane pilot. To maintain the same relative power input with fewer discharge electrodes, the discharge electrode design was made more aggressive with more points, allowing both units to impose 2000 watts/1,000acfm of specific power.

Water Flow

The membrane material was wetted using recycle water from a sump at the bottom of the WESP housing. A recycle pump and a bypass line were used to mix caustic with the sump water to balance the pH. A continuous slipstream from the recycle bypass line of 9 gpm was used to wet the membranes. The membrane water passed through a strainer and flow meter then to the membrane distribution heads. The recycle water flowed through and on the surface of the membranes to a trough system at the bottom of each membrane sheet which fed to a common drainpipe into the sump.

The interaction of the saturated process gas and the wetted surfaces of the membrane and metallic collectors created an excess amount of water which had to be constantly bled from the system during operation, so no makeup water was needed for either WESP unit. The sump was periodically blown down to reduce any solids buildup in the bottom of the sump by simultaneously opening the drain valve and supplying fresh water.

Test Method

Three specific pollutants were sampled and analyzed to determine their concentration before and after the precipitators – mercury (oxidized, particulate-bound, and elemental), sulfuric acid aerosols, and particulate matter. Mercury concentration in the form of oxidized, elemental and particulate bound mercury measured before and after the precipitator using the Ontario Hydro Method. Cold Vapor Atomic Absorption Spectroscopy was done using a Leeman Hydra AA unit. Acid aerosol concentration was measured using a modified version of EPA Method 17 and Consol's Controlled Condensation Technique. For the modified Method 17 tests, the filter was kept at 200-210°F to keep the acid in the liquid phase, but minimize water condensation on the filter. Particulate was measured using EPA Method 5.

Problems Encountered

The fan installed on the pilot WESP to draw flue gas encountered repeated problems with vibration during start-up and operation and had to be replaced. The 19’ long observation tube used to visually inspect removal performance had to be replaced due to the fan vibration, which cracked the weld seams. Installation of the membrane WESP took longer than expected, mostly due to alignment of ductwork. No significant problems were encountered in design, installation or operation of the membrane WESP.

8. Results and Discussion

A. Impact of SCR, ammonia injection and SBS injection

The impact of adding SCR equipment, ammonia injection and sodium bi-sulfate injection is reflected in lower levels of SO3 mist being reported at the Wet ESP inlet. Inlet concentrations of SO_3 during 2001 and 2002 ranged from 8.5 ppm to 11.5 ppm. Testing during 2003 showed SO_3 levels had dropped to the 2-6 ppm level.

B. The 316L SS Metallic Wet ESP

PM2.5 & SO3 Results

Appendix B shows the test results of the metal wet ESP from September, 2001, November 2001 November 2002 and July 2003. URS performed all testing during 2001 while Ohio University performed those during 2002 and 2003. Only SO3 testing was performed during 2002 due to limited funding. The September 2001 results were with the wet ESP configured as a single field, while all subsequent tests reflect modification to a two-field wet ESP.

The September 2001 results show 79% removal efficiency for PM2.5 and 76% for SO3. After modification to a two-field configuration, efficiencies increased to 96% for PM2.5 and 92% for SO3. Testing by Ohio University showed consistent results with 89% removal for SO3 in November of 2002 and 88% in July of 2003. PM2.5 testing in July 2003 reported 93%. Differences can be attributable to test method inaccuracies, test experience and instrument calibration.

The important points are
- Adding a second field to the existing WESP improved removal efficiency dramatically
- The WESP achieved relative high removal efficiency(>90%) at 60% beyond design
- The results by two different testing parties were consistent with one another
- Results from three different time periods were consistent
- Removal efficiency for PM2.5 was always slightly higher than for SO3 mist, likely due to particle size distribution.

Mercury Removal in the Metallic Wet ESP

Appendix C reports the inlet and outlet concentrations for the three species of mercury present in flue gas taken during the July 2003 test run. The majority of mercury at the inlet to the wet ESP was in the elemental form, approximately 79%, (average elemental mercury inlet of 6.2µg/m^3 vs. total mercury inlet of 7.88µg/m^3). This was expected since the FGD scrubber installed at BMP would remove most of the oxidized and particulate fraction prior to the wet ESP inlet.

Elemental mercury collection averaged 36%, with inlet concentrations averaging 6.2 µg/m^3 and outlet concentrations at 4.03µg/m^3.

Oxidized mercury collection averaged 76%, with inlet concentrations averaging 1.63 µg/m^3 and outlet concentrations averaging 0.4µg/m^3.

Particulate mercury collection averaged 67%. However, inlet levels were so low (0.023 μg/m^3) that removal efficiency cannot accurately be determined. Outlet concentrations averaged 0.01 μg/m^3.

The table below summarizes the mercury tests performed by URS during 2001 and those performed by Ohio U during July 2003. Inlet concentrations and removal efficiencies are similar, providing confidence in the performance of the wet ESP and testing methodology.

Table 3- Mercury Test Comparison-metallic unit

	Particulate	Oxidized	Elemental		Particulate	Oxidized	Elemental
Date of Test	Sept –01	Sept -01	Sept –01		July -03	July-03	July-03
Air-Flow	8000	8000	8000		8000	8000	8000
Tested By	URS	URS	URS		Ohio U	Ohio U	Ohio U.
Units	ug/dscm	ug/dscm	ug/dscm		ug/dscm	ug/dscm	ug/dscm
Inlet	0.011	0.689	6.245		0.03	1.4	6.2
Outlet	0.004	0.158	3.474		0.01	0.3	4.0
Removal %	**64%**	**77%**	**44%**		**67%**	**79%**	**36%**

Elemental mercury should not be readily captured in a precipitator, unless in aerosol form. It is theorized that some mercury condenses near the water on the collecting electrode surface, but calculations indicate this should not account for the 40%+ capture seen in some experiments. One possibility is that some oxidation of mercury occurred due to ozone generated by the corona discharge of the charging electrodes. The oxidized mercury then formed an aerosol which was captured in the precipitator.

<u>Effect of Higher Velocity through Metallic Wet ESP</u>

Testing was performed on both the metal and membrane pilot wet ESPs at both 8,000 acfm and 15,000 acfm to demonstrate the effect of increasing velocity through a wet ESP. At 8,000 acfm, velocity was 10ft./second and at 15,000 acfm velocity through the wet ESP was 15ft./second. The significance of being able to increase air flow & velocity is that most modern FGD scrubbers operate at 12-14 ft./second. Demonstrating Wet ESP performance at these higher velocities allows the Wet ESP to be mounted on top of the FGD vessel and the diameter to match that of the FGD vessel, simplifying design, reducing size and cost. While removal efficiency decreased, the wet ESP still achieved respectable levels of collection for PM2.5 (70%), SO3 (65%), and mercury.

Table 4-Velocity impact on Removal Performance in Metallic WESP

Approx.		Percent	Removal		
SCFM	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
8000	88%	93%	36%	76%	67%
15000	65%	70%	26%	50%	67%

C. The Membrane Wet ESP Results

PM2.5 & SO3

Appendix D reports test results for all pollutants within the membrane wet ESP pilot unit at both 8,000 acfm and 15,000 acfm. The membrane unit removed 96% of PM2.5 and 93% of SO3 mist compared to 93% and 88% with the metallic unit. Particulate inlet concentrations were similar, 106 for the membrane test and 125 mg/m^3 for the metallic unit. Sulfuric acid concentrations were similar though higher in the membrane test, 4.11 ppm vs. 2.57-3.11 ppm for the metallic test. The test results indicate that the membrane collection material offers potential to remove fine particulate and acid mists at similar, if not slightly higher levels than conventional alloy wet ESP collectors.

Mercury Removal

Appendix D also reports the inlet and outlet concentrations for the three species of mercury present in flue gas taken during the September 2003 test run on the membrane wet ESP. The majority of mercury at the inlet to the wet ESP was in the elemental form, approximately 80%, (elemental mercury inlet of 8.9µg/m^3 vs. total mercury inlet of 11.12µg/m^3).

Elemental mercury collection was slightly lower than the metallic pilot unit at 33%, with inlet concentration of 8.9µg/m^3 and an outlet concentration of 6.0µg/m^3. There appears to be no advantage to the membrane precipitator for collection of elemental mercury. And while some effect of flow rate is noticed in the results of the metal-plate unit, it is not a significant effect, indicating that perhaps the capture of elemental mercury is due to localized condensing at the water-gas interface.

Oxidized mercury collection was slightly higher than the metallic pilot at 76%, with inlet concentration of 2.2.µg/m^3 and an outlet concentration 0.4µg/m^3. Oxidized mercury results exhibit trends very similar to those found in the particulate and acid aerosol results. This indicates the oxidized mercury was in a form that readily formed aerosols for collection in an ESP.

Particulate mercury collection reported 100% collection. However, inlet concentration was only 0.01µg/m^3 with no outlet detection possible.

Effect of Higher Velocity through Membrane Wet ESP

Similar to the metallic pilot, the membrane pilot was tested at higher air flows to see the impact of running at 15ft./second velocity. The table below shows the impact. While removal efficiency decreased, the membrane wet ESP still achieved respectable removal efficiencies for all pollutants.

Table 5- Velocity Impact on Membrane WESP

Approx.	Percent Removal				
ACFM	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
8000	93%	96%	33%	82%	100%
15000	71%	81%	23%	61%	100%

D. Incremental Mercury Removal Across FGD scrubber and Wet ESP pilot

One of the objectives of this pilot WESP project was to measure the incremental mercury removal efficiency through the existing FGD scrubber and pilot Wet ESP pilots. The table below shows the respective removal efficiencies of the FGD and WET ESP for mercury species.

Particulate mercury- The FGD scrubber on boiler # 2 at Plant Mansfield is also used as their primary particulate collection device in addition to control of SO2. There is no fabric filter or dry ESP. The scrubber removes 80% of particulate form of mercury with the wet ESP achieving an additional 76% removal. Total particulate mercury removal across the two devices is greater than 95%.

Oxidized mercury- The scrubber achieves 69% removal of oxidized mercury and the wet ESP an additional 86% removal. Total oxidized mercury removal is greater than 95%.

Elemental mercury- The negative values shown reflect the de-gassing of oxidized mercury in the FGD scrubber. It is hypothesized that the degassing is due to water chemistry. The membrane wet ESP achieved 18% removal of elemental mercury, a lower efficiency than the 36%-44% achieved in previous tests. Total elemental mercury removal across the FGD and WESP was only 6%.

Total Mercury Removal- Total inlet mercury concentration measured at the inlet to the FGD scrubber was 12.94µg/m^3. Total mercury concentration at the outlet of the Wet ESP was 2.85µg/m^3. Total mercury removal achieved was 78%.

Table 6- Incremental Mercury Removal Efficiency

	FGD Inlet		FGD outlet		Wet ESP outlet		Total
	µg/m^3	Removal %	µg/m^3	FGD Removal %	µg/m^3	WESP Removal %	Total Removal %
Ash Hg	4.37	0%	0.85	80%	0.20	76%	95%
Hg^{2+}	6.02	0%	1.88	69%	0.26	86%	96%
Hg^{0}	2.55	0%	2.92	-15%	2.39	18%	6%
Total Hg	12.94	0%	4.88	62%	2.85	41%	78%

E. Visual Observations of WESP Performance

An observation tube 19' long was installed after the wet ESP to replicate the diameter of the top of the Plant flue gas stack for quick visual observation of the wet ESP performance by viewing into a clear port with a light source at the opposite end. (See pictures –page 21)

The observation tube indicated close to "zero" opacity when full electrical power was utilized. As power was reduced, visibility through the unit was correspondingly reduced until the tube was completely dark at zero power input. During the first series of tests when only a single electrical field was installed in the wet ESP, an orange haze appeared when velocity through the unit was increased to over 10,000 acfm. After modification of the ionizing section into two fields according to a Croll-Reynolds patent and installation of a larger fan to increase velocity, the observation tube remained clear at air flow levels in excess of 15,000 acfm or face velocity within the wet ESP tubes in excess of 16 ft /second.

CRCAT estimates that First Energy's 50% opacity levels as measured from the exit of the stack were reduced to less than 10% based upon outlet loadings for PM2.5 and SO3 mist.

F. Life Cycle testing of the Membrane Material

Strength Testing

Several linear feet of polypropylene membrane were removed from the pilot unit attached to Bruce Mansfield Unit 2. The membrane, shown in Figure 6, was tested for both wetting properties and for burst strength using a Mullen Burst tester.

The results of the burst strength test are shown in Table 7. The average burst strength was 515 psi with a standard deviation is 72 psi. This compares very well with "virgin" polypropylene felt with an average burst strength of 480 psi and standard deviation of 85 psi. While the average is slightly higher for the Mansfield membrane, the results are more properly interpreted as no loss of strength, rather than any gain in strength.

Table 7- Mansfield Membrane Burst Strength Data

Burst Strength (psi)
570
400
540
560
570
450

Wetting Properties

The material wetting properties were examined through qualitative and quantative analysis using our standard membrane water-delivery headers. It is very significant to note that the membranes actually improved in their water distribution characteristics as they became "dirty." That is, as particles that were not washed by the sheeting action of the water over the membranes found their way into the membrane fibers, the water transport within the membrane via capillary action improved. Also, the sheeting flow of water, which occurs when the gaps between the fibers are saturated with water, became more uniform.

To quantify the wetting characteristics, virgin polypropylene was wetted and dried, as were samples of a used piece of membrane from another membrane pilot. Water was then applied to the upper strip of a membrane, vertically suspended from a small water header, at a rate of 1 gallon per minute. The results were striking. For the previously-wetted virgin material, approximately 40% of the material was saturated in 2 minutes (enough time to reach a steadyflow condition) and external flow could hardly be described as sheeting, with nearly 50% of the external surface uncovered. However, the “dirty” membranes wetted completely via capillary action within 20 seconds, and nearly 100% of all the surfaces were covered in sheeting flow of water within 30 seconds (0.5 minutes).

G. <u>Cost Comparison</u>

One of the benefits of membrane material as a collection material is its lower cost versus that of stainless steel and other alloys. However, all associated components that support the membrane collection plate must be of metallic material, including tensioning bar, top support piping, internal baffling, bottom support piping, water distribution and collection system and ground wire.

For a 30’ high x 6’ long collection surface, with 360 sq. ft of collection area (30’x 6’x 2 sides) the membrane collection plate and its associated components would have an estimated cost of approximately $3.00/sq.ft while a 316L SS collection plate and its associated support components would cost approximately $20.00/sq. ft. The cost savings increase as more exotic alloys are required for corrosion resistance.

As a percentage of total value of a full scale wet ESP system, the collecting electrode cost represents only approximately 10%. Therefore, if membrane collecting material replaced 316L SS tubes, a potential savings of 8% could be achieved. This could potentially increase to 15% if nickel-based alloys were required.

There are additional structural steel and erection cost savings that accrue because of the membrane’s lighter weight. These cost savings must be balanced against the risk of having to replace the membrane every few years due to stretching, plugging, and/or burning due to sparking and the associated costs of replacement material, labor and most importantly outage time and loss of revenue.

9. Conclusion

Results on testing a metallic WESP and a Membrane WESP confirm a Wet ESP's capability to achieve high removal efficiency on a multitude of pollutants- PM2.5, SO3 mists and mercury as a final polishing device after a FGD scrubber system.

The results of testing with membrane collecting surfaces in wet electrostatic precipitators indicate that inexpensive materials can be used for highly effective collection if properly designed. Membranes offer the potential for cost savings for retrofit and new installation of polishing units for control of fine particulate, acid aerosol and mercury, especially when compared to nickel-based alloys for use in corrosive environments.

Visual observation and testing results showed that the fibrous membranes uniformly distributed water throughout the membrane by gravity-assisted capillary action, creating a complete-coverage sheeting flow when saturated. Further, the membrane material was able to withstand the harsh environments in terms of acid resistance and abrasion, with no loss of material burst strength after 5000 hours of operation. In fact, the capillary action of the membrane was shown to actually improve as particulate filled fiber gaps.

The reduced flow rate needed for uniform water sheeting in the membrane unit offers particular advantages for future applications. By requiring significantly less water for more uniform coverage, the problems of wet-dry interfacing and mist-related field disruptions are reduced, leading to longer operating time between outages and improved collection.

Combining improved collection efficiency with corrosion resistance and decreased cost, wet membrane electrostatic precipitators offer an attractive option for plants seeking to control fine particulate, acid aerosol and oxidized mercury emissions. These advantages must be weighed against the lack of operating time and data to support long-term (20 years) operation and the risk of stretching, plugging, and/or fire that would require an outage to replace the damaged membranes, compared to a conventional metallic Wet ESP.

10. List of Acronyms and Abbreviations

BMP- Bruce Mansfield Plant
CEMS – Continuous Emissions Monitors
CRCAT- Croll-Reynolds Clean Air Technologies
FE- First Energy
OU- Ohio University
PPM- parts per million
SEI- Southern Environmental, Inc.
WESP- wet electrostatic precipitator

11. GRAPHICAL MATERIAL

FIGURE 2
GENERAL ARRANGEMENT DRAWING

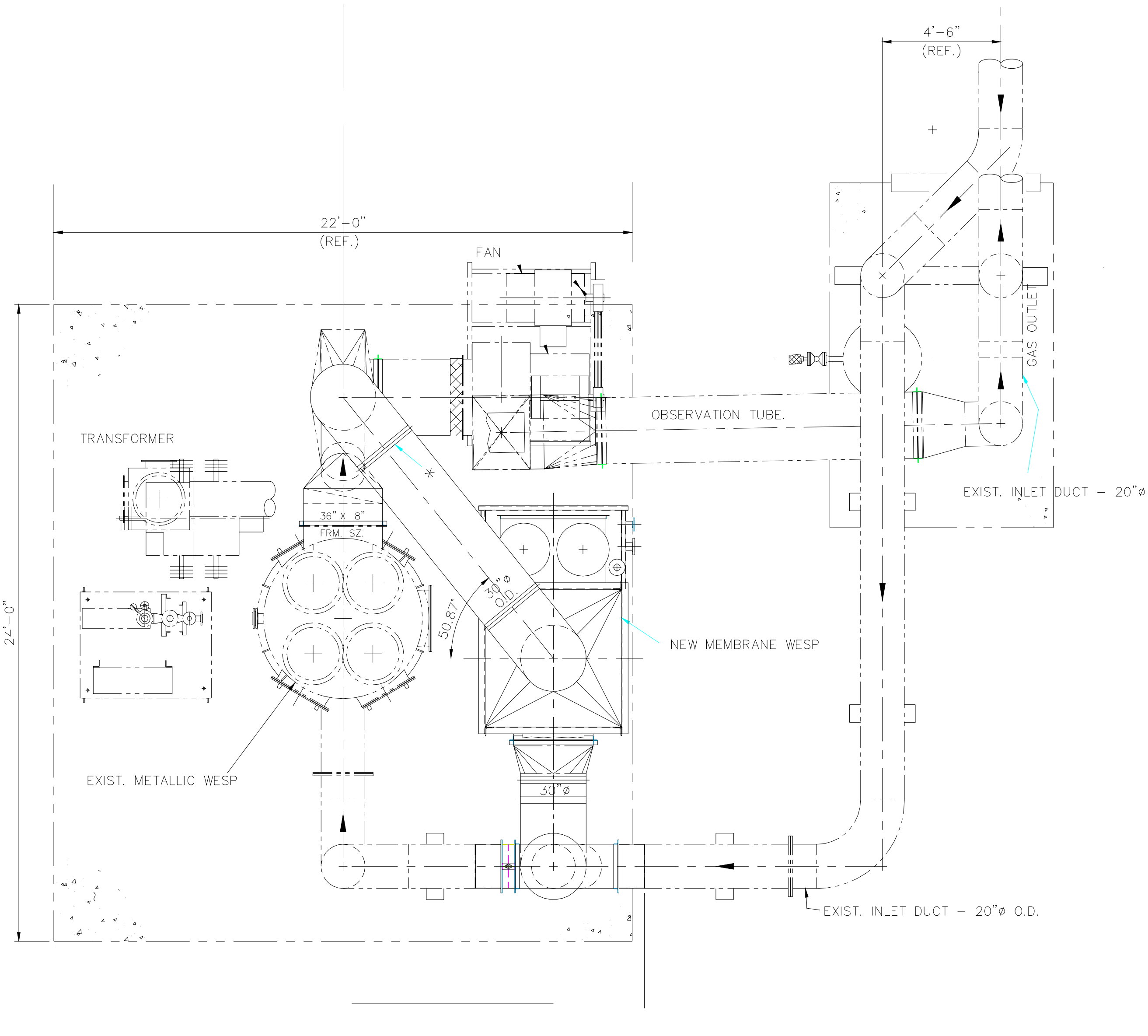
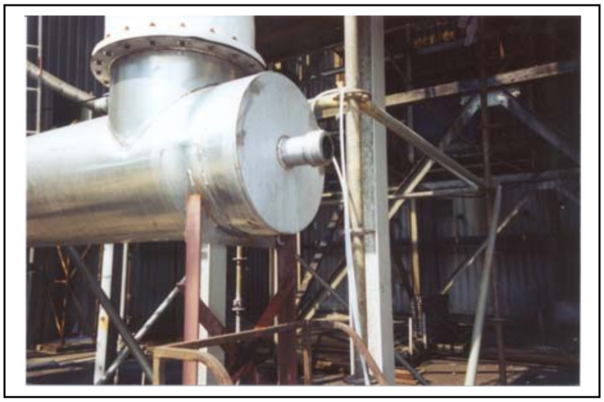


FIGURE 3
INLETS TO METALLIC (left) and MEMBRANE (right) PILOT WESPS

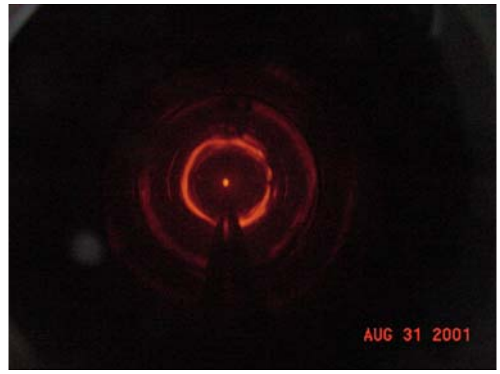
FIGURE 4

PERSPECTIVE OF MEMBRANE & METALLIC WESP AT BRUCE MANSFIELD PLANT

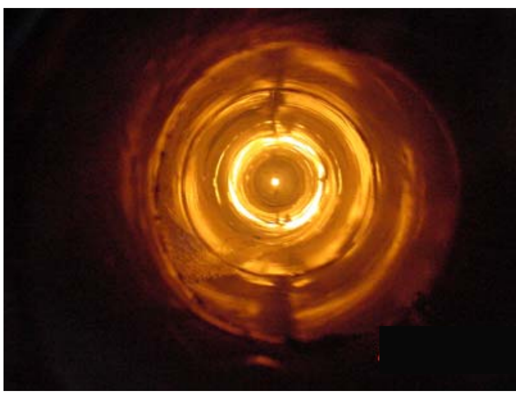
FIGURE 5
PICTURES LOOKING INTO OBSERVATION TUBE



Observation port on one end of the 19' long, 20" diameter observation tube.



Looking through observation port with low power input into the WESP pilot- almost completely black.



Looking through observation port with moderate power input- some orange plume visible

Looking through observation port with maximum power on – no visible plume visible.

FIGURE 6
LOOKING DOWN ONE MEMBRANE TUBE

FIGURE 7
MEMBRANE MATERIAL AFTER 6 MONTHS OF SERVICE

Picture of membrane taken from the Mansfield Pilot ESP. Note that the color of the membrane is consistent with the “sooty” color of the recycled water.

APPENDIX A

TEST PLAN DOCUMENT

From the testing done in November 2002, we learned the limits of precipitator performance. As a result, we recommend changing the test plan from what was proposed to three cases – testing at “maximum” flow rate and full power, at “standard” flow rate and full power.

The key measurements that must be taken regard the ability of the precipitators to

1. Withstand corrosion and material degradation
2. Remove acid aerosols
3. Remove condensable hydrocarbons (soot) and other fine PM
4. Remove oxidized and elemental Hg.

The key parameters of operation will be

1. Volumetric flow rate through the precipitator
2. Collecting electrode substrate material
3. Field strength/power of the precipitator

Because the flue gas composition may have changed due to the installation of SCR for NOx reduction, the initial testing will repeat many of the tests performed in November on the metal membranes. Then, there will be downtime for testing while the membranes are installed.

Below is a proposed timeline, assuming the plant is brought back on-line in mid-May and a shakedown period for the new SCR installation.

July 21– Sampling at scrubber inlet for Hg concentrations (to get baseline, which is expected to shift due to SCR installation). We will start with two Ontario Hydro sampling events. They will be sent for analysis and if the results deviate by more than 10%, further testing to quantify Hg levels and speciation will be done later in the summer

July 28-August 8 – Testing with metal plates (all testing at both inlet and outlet of precipitator)

- 8000 acfm and full power
    - (4) runs for Ontario Hydro (Hg^0 and Hg^{2+})
    - (2) runs for modified Method 17 (SO_3)
    - (2) runs for Method 5 (particulate and soot)
- 15000 acfm and full power
    - (3-4) runs for Ontario Hydro (Hg^0 and Hg^{2+})
    - (2) runs for modified Method 17 (SO_3)
    - (2) runs for Method 5 (particulate and soot)

August 11-15- complete any tests that need to be re-run and switch over to the membrane unit.

August 18-29- Testing with membranes

- 8000 acfm and full power
    - (4) runs for Ontario Hydro (Hg^0 and Hg^{2+})
    - (2) runs for modified Method 17 (SO_3)
    - (2) runs for Method 5 (particulate and soot)
- 15000 acfm and full power
    - (3-4) runs for Ontario Hydro (Hg^0 and Hg^{2+})
    - (2) runs for modified Method 17 (SO_3)
    - (2) runs for Method 5 (particulate and soot)

Testing Methodology

- Measure Hg (elemental and oxidized) using Ontario Hydro (sample for three hours)
- Measure SO_3 using modified Method 17
- Measure soot using Method 5 and a differential mass technique. (Specifically, use Method 5 to collect fines. Before drying the filter, use water to get sulfur, and heat it to point to drive off collected sulfur. Heat again (to higher temp) to oxidized carbon. Measure differential mass after sulfur volatilization and carbon volatilization to get soot mass concentration.

APPENDIX B

COMPARATIVE TEST RESULTS -METALLIC WET ESP
PM2.5 & SO_3 MIST

	PM2.5				SO_3 Mist				
	URS Testing	URS	Ohio U.		URS Testing		Ohio U.		
Test Series	Sep-01	Nov-01	July-03		Sep-01	Nov-01	Nov-02	Nov-02	July -03
Airflow-acfm	8394	8235	8000		8394	8235	8000	15000	8000
Velocity – ft./sec.	10	10	10		10	10	10	>15	10
# of fields	1	2	2		1	2	2	2	2
Power Levels	100%	100%	100%		100%	100%	100%	100%	100%
units	gr/dscf	gr/dscf	Mg/m3		ppm	ppm	ppm	ppm	Ppm
Inlet	0.0292	0.0506	125		11.5	10.01	8.9	8.5	3.1
Outlet	0.0063	0.002	9		2.7	0.85	1.0	3.2	0.4
Removal %	**79%**	**96%**	**93%**		**76 %**	**92%**	**89%**	**62%**	**88%**

APPENDIX C

Metal Tube Wet ESP Results (June-July 2003)

8000 scfm	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
	(ppm)	(mg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)
Inlet	2.57	113	5.7	1.4	0.03
Outlet	0.33	11	3.4	0.3	0.01
% removal	***87%***	***90%***	***40%***	***79%***	***67%***
Inlet	3.14	137	6.8	1.7	0.01
Outlet	0.36	7	4.6	0.4	0
% removal	***89%***	***95%***	***32%***	***76%***	***100%***
Inlet			6.2	1.8	0.03
Outlet			4.1	0.5	0.02
% removal			***34%***	***72%***	***33%***
Average %	**88%**	**93%**	**36%**	**76%**	**67%**
15000 scfm	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
	(ppm)	(mg/m^3)	(µg/m^3)	(µg/m^3)	(µg/m^3)
Inlet	6.22	103	7.2	2.0	0.03
Outlet	1.98	30	5.8	0.9	0.02
% removal	***68%***	***71%***	***19%***	***55%***	***33%***
Inlet	4.51	128	5.3	1.5	0.03
Outlet	1.7	39	3.6	0.8	0.01
% removal	***62%***	***70%***	***32%***	***47%***	***67%***
Inlet			5.6	1.7	0.02
Outlet			4.1	0.9	0
% removal			***27%***	***47%***	***100%***
Average %	**65%**	**70%**	**26%**	**50%**	**67%**

APPENDIX D

Membrane Material Wet ESP Test Results (Sept 2003)

8000 scfm	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
	(ppm)	(mg/m^3)	($\mu g/m^3$)	($\mu g/m^3$)	($\mu g/m^3$)
Inlet	4.11	106	8.9	2.2	0.02
Outlet	0.3	4	6.0	0.4	0
% removal	**93%**	**96%**	**33%**	**82%**	**100%**
15000 scfm	H_2SO_4	Particulate	Elemental Hg	Oxidized Hg	Particulate Hg
	(ppm)	(mg/m^3)	($\mu g/m^3$)	($\mu g/m^3$)	($\mu g/m^3$)
Inlet	3.18	115	6.6	1.5	0.01
Outlet	0.91	22	5.1	0.59	0
% removal	**71%**	**81%**	**23%**	**61%**	**100%**

APPENDIX E

Total Mercury Removal Efficiency Across FGD & Membrane WESP

		Scrubber inlet	ESP Inlet	ESP Outlet	Scrubber Removal	WESP Removal	Total Mercury Removal
SCFM	**Hg(ash)**	µg/m³	µg/m³	µg/m³	%	%	%
8000	**Run 1**	4.37	0.85	0.202	81%	76%	95%
15000	**Run 2**	4.64	0.69	0.230	85%	67%	95%
	Hg(oxidized)						
8000	**Run 1**	6.02	1.88	0.261	69%	86%	96%
15000	**Run 2**	5.59	1.80	0.550	68%	69%	90%
	Hg(elemental)						
8000	**Run 1**	2.55	2.92	2.395	-15%	18%	6%
15000	**Run 2**	3.63	3.66	3.030	-1%	17%	17%
8000	**Total Hg**	12.94	5.65	2.86	56%	49%	78%
15000	**Total Hg**	13.86	6.15	3.81	56%	38%	73%

APPENDIX F
Test Results for Particulate Collection –Both Units

Precipitator	Air Flow	Power	Fields	Inlet loading	Outlet Loading	Removal
Metal/Membrane	*acfm*			*(mg/dscm)*	*(mg/dscm)*	
Metal	8394	100%	1	67	14	79%
Metal	8235	100%	2	116	5	96%
Metal	8410	100%	2	113	11	90%
Metal	8220	100%	2	137	7	95%
Metal	15850	100%	2	103	30	71%
Metal	15880	100%	2	128	39	70%
Membrane	8140	100%	2	106	4	96%
Membrane	15330	100%	2	115	22	81%

APPENDIX G
Test Results on Acid Aerosol – Both Units

Precipitator	Air Flow	Power Level	Inlet loading	Outlet Loading	Removal
Metal/Membrane	*Acfm*		*(ppm)*	*(ppm)*	
Metal	8235	100%	10	0.9	91%
Metal	8430	100%	8.9	1.0	89%
Metal	8270	60%	11.1	4.3	61%
Metal	15310	100%	8.5	3.2	62%
Metal	15150	60%	9.8	4.4	55%
Metal	7880	100%	2.6	0.3	88%
Metal	7920	100%	3.1	0.4	87%
Metal	14570	100%	6.2	2.0	68%
Metal	14940	100%	4.5	1.7	62%
Membrane	8430	100%	4.1	0.3	93%
Membrane	15190	100%	3.2	0.9	72%

APPENDIX H

Test Results on Particulate-bound mercury collection – Both Units

Precipitator	Air Flow	Power Level	Inlet loading	Outlet Loading	Removal
Metal/Membrane	*acfm*		*(μg/dscm)*	*(μg/dscm)*	
Metal	8000	100%	0.011	0.004	64%
Metal	7880	100%	0.03	0.01	67%
Metal	8050	100%	0.01	0.00	100%
Metal	8120	100%	0.03	0.02	33%
Metal	14430	100%	0.03	0.02	33%
Metal	15110	100%	0.03	0.01	67%
Metal	14780	100%	0.02	0.00	100%
Membrane	8100	100%	0.02	0.00	100%
Membrane	8210	100%	0.85	0.20	76%
Membrane	15060	100%	0.01	0.00	100%
Membrane	14910	100%	0.69	0.23	67%

Test Results on Elemental Mercury –Both Units

Precipitator	Air Flow	Power Level	Inlet loading	Outlet Loading	Removal
Metal/Membrane	*acfm*		*(μg/dscm)*	*(μg/dscm)*	
Metal	8000	100%	6.2	3.5	44%
Metal	7880	100%	5.7	3.4	40%
Metal	8050	100%	6.8	4.6	32%
Metal	8120	100%	6.2	4.1	34%
Metal	14430	100%	7.2	5.8	19%
Metal	15110	100%	5.3	3.6	32%
Metal	14780	100%	5.6	4.1	27%
Membrane	8100	100%	8.9	6.0	33%
Membrane	8210	100%	2.9	2.4	17%
Membrane	15060	100%	6.6	5.1	23%
Membrane	14910	100%	3.7	3.0	19%

Test Results on Oxidized mercury – Both Units

Precipitator	Air Flow	Power Level	Inlet loading	Outlet Loading	Removal
Metal/Membrane	*acfm*		*(μg/dscm)*	*(μg/dscm)*	
Metal	8000	100%	0.7	0.2	71%
Metal	7880	100%	1.4	0.3	79%
Metal	8050	100%	1.7	0.4	76%
Metal	8120	100%	1.8	0.5	72%
Metal	14430	100%	2.0	0.9	55%
Metal	15110	100%	1.5	0.8	47%
Metal	14780	100%	1.7	0.9	47%
Membrane	8100	100%	2.2	0.4	82%
Membrane	8210	100%	1.9	0.3	84%
Membrane	15060	100%	1.5	0.6	60%
Membrane	14910	100%	1.8	0.6	67%