As appeared in February 2012 APC Copyright CSC Publishing www.APCmag.net

Particulate matter control for coal-fired generating units: Separating perception from fact

Gary Grieco Consulting Engineer, Air Consulting Associates, LLC

A decision frequently made at U.S. coal-fired plants is whether to upgrade an existing electrostatic precipitator (ESP) or replace it with a fabric filter collector (FFC). In the recent past, this decision was based on technical/economic feasibility studies and was conducted with minimal fanfare. Today, however, this tradeoff has become more difficult to evaluate due to a politically charged atmosphere, uncertainty over evolving stack emissions regulations, and emerging state-of-art emissions control technologies.

This article attempts to go beyond traditional evaluation parameters such as economics and environmental impact to explore intangibles such as industry and public perception.

In all cases we compare state-of-art ESPs with state-of-art FFCs, as supplemented by state-of-art mercury control technologies, and this comparison is made in light of today's stringent regulatory environment.

Background

On December 16, 2011, EPA Administrator Lisa P. Jackson signed a final ruling that redefined allowable emissions from existing coal-fired power plants. By so doing, she altered the ground rules for the electrostatic precipitator versus fabric filter collector comparison. The particulate matter emissions standard was set at 3.0E-2 lb / mmBtu (3.0E-1 lb / MWh) of filterable particulate matter for all existing coal-fired generating units. At this PM emissions rate, a state-of-art ESP will nearly always be the more economical choice when compared to a fabric filter collector. But this December, 2011 ruling also set new mercury and hydrogen chloride emissions standards, as well as a lengthy list of non-PM emissions standards. It is when addressing these new mercury, hydrogen chloride, and non-PM standards that a fabric filter collector may prove to be the better technical or economical selection when compared to an electrostatic precipitator.

To fully understand our current situation, we should first look back on the history of particulate matter (PM) control in the U.S. electric utility industry. To simplify the matter, we can consider three phases of PM regulatory control, each phase having an impact on the type and cost of a coal-fired utility boiler's PM control equipment:

- The 1970s, when PM emissions were regulated to 0.10 lb / mmBtu or higher.
- The late 1970s to 1990s, when PM emissions were regulated down to 0.03 lb / mmBtu
- Our present situation; typically PM emissions are regulated to 0.015 lb / mmBtu or lower, and control of mercury (Hg) emissions as well as several other previously unregulated pollutants are now required.

Until the late 1970s, ESPs had dominated the marketplace. FFCs were too costly, took up too much site space, and their inherently higher PM collection efficiencies could not be justified when seeking PM emissions levels of 0.10 lb / mmBtu or higher.

Around 1978, the mix of PM control solutions started to include a greater number of FFCs. While ESPs were still the dominant player, there were coals in the United States that were more difficult to handle in an ESP, such as the low-sulfur, low-sodium Western sub-bituminous and low-sulfur Eastern bituminous coals. At the time, these difficult coals required very large ESPs to meet tighter PM emissions regulations;

hence FFCs became the economical choice. There was a rule of thumb back then: if a weighted-wire design ESP required a specific collecting area (SCA) of 600 sq ft/kacfm or greater to meet 0.030 lb/mmBtu PM emissions, as sometimes was the case when firing a difficult coal, then installing an FFC was the more economical selection.

Our present regulatory environment is radically different from that of the recent past. In some instances interveners have lobbied for tighter emissions limits at mature coal-fired generating stations which subsequently resulted in plant shutdowns. It is in this new arena that the U.S. utility industry strives to deliver low-cost, reliable electric power that is in compliance with all applicable environmental regulations.

Table 1

ESP fundamentals

Precipitation step	PM size range effected (in microns)
1. Establish a corona (corona onset)	All
2. Charge particles in gas stream	
•Field charging	Above 0.5
•Diffusion charging	Below 0.2
3. Particle migration toward grounded plate	All
4. Particle collection onto grounded plate	All
5. Rap particles off plate and into hopper	All

State-of-art ESP

An ESP is a device that electrostatically separates particles from a flue gas stream while imposing minimal pressure loss on the stream. Unlike with PM removal devices such as cyclonic collectors, venturi scrubbers and FFCs, high gas stream pressure loss, and associated high draft fan energy consumption is avoided when using an ESP.

As shown in Table 1, electrostatic precipitation is a multistep process that has an Achilles' heel in its particle-charging step: fine particles in the 0.2–0.5 micron range tend to resist accepting an electric charge, and by lacking a saturation charge they typically do not behave as well as they should during the next two steps.

ESPs have been the utility industry's workhorse since the early 1920s. ESP design, however, has recently undergone a facelift. Developments such as customized rigid discharge electrodes, high-frequency power supplies, and micromanaged ESP gas velocity distribution have advanced the technology to a point where the old rule of thumb, breakeven point, a 600 sq ft/kacfm weight-wire type ESP with 9-inch collecting plate spacing, has been decreased to an SCA of 250 sq ft/kacfm with 16-inch collecting plate spacing. In other words, similar PM emissions performance can be achieved with a modern ESP that is approximately 25 percent smaller than an outdated

Table 2

State-of-art ESPs vs conventional ESPs in the open literature

Generating unit	Tested SCA (sq/kacfm)	Collecting plate spacing (in)	Tested SCA corrected to 12-inch spacing (sq ft/kacfm)	Tested PM emissions (lb/mmBtu)	Coal-fired	Comments
State-of-art:						
Unit A	225	16	299	0.0048	Powder River Basin Coal	25 kHz Sets, RDE electrodes
Unit B	266	16	355	0.0047	70% PRB/30% E.Bit.	25 kHz Sets, RDE electrodes
Unit C	326	16	432	0.0038	Powder River Basin Coal	25 kHz Sets, RDEs, upstream multiclone
Average:			**363**	**0.0044**		
Conventional						
Pleasant Prairie 1	440	9	330	0.0018	Western Sub-bituminous	Weighted-wire ESP, SO_3 conditioning
Naughton 1	576	12	576	0.0015	Western Sub-bituminous	Rigid mast electrodes
Johnsonville 4	256	10	213	0.0097	Eastern Bituminous	RDE electrodes
Dave Johnson 1	661	12	661	0.0035	Powder River Basic Coal	Rigid mast electrodes
Boardman 1	697	12	697	0.0053	Powder River Basin Coal	Rigid mast electrodes
Average:			**495**	**0.0044**		

Note: Information in this table was compiled from the following references: 3, 9, 10, 11, and 12.

weighted-wire design ESP (see Table 2). This is a development that should not go unnoticed.

Up until the late 1970s, the industry used weighted-wire type discharge electrodes, typically 0.109-inch in diameter, that were prone to premature failure due to corrosion, electrical erosion, and mechanical wear. When a thin wire electrode fails, it can wave around in the gas stream until it shorts out its electrical bus section, hence artificially reducing the size and effectiveness of the ESP.

European-style ESPs, introduced into the U.S. utility market in the early 1970s, feature rigid-frame or rigid-mast type electrodes that can be considered more reliable. Most designs are comprised of sturdy masts or bed frames into which are suspended smaller diameter electrode elements; however, most of these electrode element designs are also prone to premature failure.

Toward the end of the 1970s, U.S. manufacturers began to develop and field test what is now known in the industry as rigid discharge electrodes, or simply RDEs. With tube diameters ranging from 3/4-inch up to 2 1/2-inches these discharge electrodes are virtually unbreakable. Furthermore, the configuration of the RDE—tube's diameter and the concentration of its sharp-pointed corona emitters—strongly influences the quality of corona voltage and corona current flow. This development made it possible for manufacturers to mix and match several different discharge electrode configurations within the same ESP to optimize corona power input and to improve an ESP's performance.

The advent of the high-frequency power supply in 1998 further enhanced ESP performance. It's a simple concept: when higher corona power levels are delivered to the dirty gas stream, the result is higher PM collection efficiencies. A high-frequency power supply's AC input voltage is rectified, filtered, and then switched at high frequency on the order of 25 kHz or higher. Most importantly, its corona voltage waveform's "ripple effect" is only 3 to 5 percent of DC voltage as compared to 35 to 45 percent for a traditional 60 Hz transformer-rectifier set. This is important because electrical disturbances such as sparking and arc-over occur at peak corona voltage, not average corona voltage, and these electrical disturbances limit an ESP's operating corona power level. Reducing the corona voltage waveform's ripple effect narrows the gap between peak and average corona voltage and allows the ESP to develop 10 to 20 percent higher average corona voltage levels at the same peak corona voltage level. This advancement has proved to be a significant contributor to optimized ESP performance (2).

Table 3

Fraction PM efficiencies for state-of-art ESP vs conventional ESP vs FFC

Less than PM diameter (in microns)	State-of-art ESP (% efficiency)	Conventional ESP (% efficiency)	Pulse-jet FFC (% efficiency)
Total PM	99.91	99.89	99.94
PM 10	99.73	99.62	99.76
PM 5	99.63	99.16	99.72
PM 2.5	99.37	98.59	99.54

Note: Information in this table was compiled from references 3 and 13.

As shown in Table 3, manufacturers can now provide an ESP that is not only economically sized but also capable of overcoming its Achilles' heel by nearly reproducing the PM2.5 collection efficiency of an FFC.

State-of-art FFC

FFCs are devices that remove PM from a flue gas stream by cloth filtration. Dirty flue gas passes directly through fabric filter bags, which then separate the PM from the flue gas stream. While this may seem like a simple solids screening process, there are actually multiple particle collection mechanisms at play depending upon the diameter of the particle to be collected, as listed in Table 4.

Filter bags are periodically cleaned of their collected PM by various means, such as shaking, clean gas backwash, and high-pressure pulsing. In a pulse-jet FFC, the filter bags are cleaned by a momentary, high pressure back-pulse of compressed air into the bag as delivered from the clean side of the bag.

One would expect a properly designed FFC, in the absence of failed filter bags, to achieve close to 100

Table 4

Fabric filter fundamentals

Steady-style collection mechanisms	PM size range effected (in microns)
Impaction	Greater than 1
Diffusion	0.01 to 0.5
Electrostatic	0.01 to 5
Gravity	Greater than 1

Note: Information in this table was compiled from reference 14.

percent PM collection efficiency regardless of the particle's diameter. However, this is not the case, as shown in the field test data presented in Table 3. Similar to an ESP, a drop-off in PM collection efficiency occurs as finer and finer particles are filtered, although the drop-off is not as steep as with a conventional ESP. This fine particle efficiency drop-off can be abated with use of advanced filtration media such as membrane filter bags, but at the penalty of significantly higher cost.

A distinct advantage FFCs have over ESPs is their independence from the effects of PM electrical resistivity. The PM's electrical resistivity is a key indicator of how much corona power can be developed in an ESP during steady-state operation. Less corona power (such as when lower watts per square foot of collecting plate area is delivered into the gas stream) requires that the ESP be sized larger to achieve a specified PM collection efficiency. FFCs operate independently of PM electrical resistivity, and as we have already seen, they are somewhat less sensitive to the PM's particle size distribution than with an ESP. However ESPs have an advantage over FFCs when it is necessary to operate at or near the gas stream's acid dewpoint and also when collecting very abrasive PM; both scenarios substantially reduce a filter bag's usable life.

A significant FFC advantage is that whenever a secondary reaction requires contact between an injected reagent and flue gas, such as with dry sorbent SO_2, SO_3, HCl, and mercury removal, the FFC provides a longer gas-reagent residence time and more intimate gas-reagent contact than is afforded by an ESP. Hence, reagent usage rates are nearly always less with FFCs when compared to ESPs, and FFCs have the potential for higher removal efficiencies for these pollutants.

FFC design has come a long way since the technology's introduction into the utility industry in the 1970s. Reverse-air FFCs, large devices that require plant personnel to conduct routine maintenance in a confined and dirty environment, have fallen by the wayside as pulse-jet FFCs have taken their place. And pulse-jet FFC design has come a long way since its invention in 1956 by Thomas Reinauer of Mikro-Pul Corporation. Modern pulse-jet FFCs have a lower installed cost and a more compact footprint due to the advent of tall (10 m, 32.8 ft) filter bags. Today's state-of-art pulse-jet FFCs also have improved reliability and operability due to superior filter bag materials, improvements in gas flow distribution, more reliable pulse valves, and advanced I&C concepts that enhance both operability and problem troubleshooting.

State-of-art mercury control

In 1894, the *Times of London* estimated that by 1950, every street in the city would be buried 9 feet deep in horse manure. One New York prognosticator in the 1890s concluded that by 1930, horse droppings would rise to Manhattan's third-story windows (5). What is the moral of this story? Clearly, we must stay abreast of new and developing technological advances; we must look forward and not in the rear-view mirror when planning our future.

There was a time in our industry, not too long ago, when we all thought coal-fired power stations would be buried beneath mountains of activated carbon, as this was the only known sure-fire technology for removing mercury from a flue gas stream. However, we now understand, somewhat better, anyway, that mercury removal is dependent on many factors including the speciation of mercury, fly ash chemistry, fly ash unburned carbon (UBC) content, and the flue gas temperature at the collection platform. Mercury speciation is a key parameter and it ranges from the "uncontrollable" elemental mercury (Hg°); to a gaseous oxidized form of mercury (Hg^{2+}), which is water soluble and readily collected in a wet FGD system or wet ESP; to particulate-bound mercury (Hg^p) which is readily collected in ESPs and FFCs.

Also, the fireside or in-duct addition of a small quantity of calcium bromide ($CaBr_2$) is now proven to be a viable and economic means of promoting the oxidation of elemental mercury, which greatly enhances its downstream removal efficiency in a wet FGD system (6).

Mercury control strategies have proven to be extremely site-specific and quite varied in their range of complexity. At some rare sites, fly ash chemistry and mercury speciation is so favorable that 90 percent or higher removal efficiency can be achieved in an FFC without the need for any additives at all. In other instances 90 percent or higher removal efficiency can be achieved by adding aqueous calcium bromide solution onto the coal feeder belt and collecting particulate-bound mercury at the ESP platform and gaseous oxidized mercury at the wet FGD platform. Sites that do not have wet FGD systems have experienced success with the injection of chemically treated activated carbon products upstream of both FFCs and ESPs (7). And there are sites without wet FGD systems where plant engineers are not at all pleased with the economics of mercury capture when injecting activated carbon upstream of an existing ESP.

There are still questions to be answered and issues to be resolved, but mercury control strategies have finally moved beyond the "Is it feasible?" stage to the "What will it cost?" stage. Once a site-specific investigation has been completed, mercury control becomes just another cost, expressed either in dollars per pound of Hg removed, or as a cost of energy increase in mills/kW-hr, to be considered along with other emissions control device decisions. And the cost of mercury control today is 25 to 75 percent less than 1999 estimates of $60,000/lb Hg removed (6).

Fact vs perception

In light of what was just discussed, we can explore some common misunderstandings when comparing a state-of-art ESP to a state-of-art pulse jet FFC. We will start with some of the broad-based issues and work our way toward more detailed ones.

FFCs are an absolute filter—nothing can possibly get through them.

As shown in Table 3, the PM collection efficiencies of ESPs and FFCs are both less than 100 percent. And when comparing state-of-art technologies, PM collection efficiencies are approximately equivalent across the board for all PM size ranges.

ESPs can be detuned at night to pollute, whereas FFCs cannot.

Yes, utilities could do this if nobody was looking. But opacity monitors do not turn a blind eye on a nasty stack plume, regardless of the time of day.

An ESP fails to provide a particulate "barrier"—when it's offline, you can stand at the outlet end of an ESP and see clear through to its inlet.

Yes, this issue has been raised, and I'm almost at a loss for words here. Perhaps we should rename ESPs "electrostatic barriers."

ESPs cannot collect carbon particles.

Yes, an undersized ESP with poor energization and perhaps also poor gas flow distribution will not be very good at capturing fine carbon particles. But a state-of-art ESP will have no trouble collecting both UBC and injected activated carbon particles at high removal-efficiency rates.

FFCs provide fuel flexibility, whereas ESPs do not.

This statement is true only when comparing an FFC to an undersized ESP. An ESP can be sized and designed to accommodate a very wide range of coals and process conditions. But if the ESP's size becomes exceedingly large, the ESP option can become too expensive when compared to an FFC; in this situation—all other issues aside—the proper choice would be to install an FFC.

There are certain fuels and operating conditions where ESPs perform better than FFCs, such as when it is necessary to operate at or near the gas stream's acid dewpoint when firing high-sulfur-content coals or when collecting abrasive PM such as can be produced when firing Texas lignite.

An ESP cannot achieve high PM collection efficiencies when its aspect ratio (i.e., the length of its treatment zone divided by its height) is less than 1.

Aspect ratio is only one of several ESP design parameters, which include SCA, gas treatment time, treatment zone gas velocity, electrical sectionalization, and electrode rapping sectionalization. It is illogical to single out one particular parameter, assign it an arbitrary number, and make critical decisions based on whether or not that parameter is above or below the arbitrary number. All ESP design parameters must be evaluated in concert; that is why applications engineers are required to use sophisticated ESP performance computer models. And yes, state-of-art ESPs with aspect ratios less than 1 achieve high collection efficiencies and low PM emissions.

An FFC is "greener" than an ESP.

"Green" is in the eye of the beholder, a moving target at best. But because this statement has been made in the past, it needs to be addressed. In 2010 there were approximately 400 coal-fired utility units with emissions control systems consisting of an ESP followed by a wet FGD system. If each ESP were to be replaced by an FFC, the auxiliary power for each generating unit would increase by approximately 1 MW due to an increase in draft system loss that must be overcome by an upgraded or new draft fan. This 1 MW difference is a net gain measured after the old ESP, with its transformer-rectifier sets, rappers, and other components, has been completely removed and a new FFC brought online. And the auxiliary power is generated solely by the host unit, which of course is coal-fired. Thus, if all 400 ESPs were to be converted to FFCs, one would create a phantom 400-MW generating unit that generated no electric power but would produce all of the pollution, greenhouse gas emissions, and waste products of a 400-MW coal-fired unit.

We should also not lose sight of the fact that FFCs require filter bag change-outs every 3 to 6 years, whereas ESPs do not. The manufacture of new filter bags, the transportation of new filter bags to the site, the fugitive dust emissions associated with dirty filter bag change-outs, and the disposal of dirty filter bags are all negative impacts on the environment that are avoided with ESPs.

Of course, there certain green advantages associated with FFCs. When the particulate control device is the only platform for mercury and/or acid gases removal, an FFC will reduce reagent consumption rate when compared to an ESP. And as the field data listed in Table 3 clearly demonstrates, an FFC will collect more PM fines than an ESP.

ESPs cannot collect mercury.

Both FFCs and ESPs collect mercury; however FFCs are more efficient mercury collectors due to longer and more intimate gas-reagent contact during the process of dirty gas filtering. For example, if an ESP were the only platform available for mercury removal, activated carbon consumption would be reduced and operating cost significantly lowered if this ESP were to be replaced by an FFC. In some instances, depending on site specifics, it may prove to be too difficult to reliably maintain a 90 percent or higher mercury removal rate without switching from an ESP to an FFC. In this latter scenario, the trade-off between an ESP and an FFC ceases to become one of economics, as the only technically viable solution would be an FFC.

Table 5

ESP rebuild vs FFC conversion for a 600-MW coal-fired generating unit (year 2011 USD)

Item	State-of-art ESP rebuild	ESP to pulse-jet FFC conversion
Installed cost:		
Collector	$28.5M	$32.0M
ID fan replacement	0	$4.5M
Boiler stiffening	0	$7.0M
Total	**$28.5M**	**$43.5M**

If specifying an FFC for 0.015 lb/mmBtu PM emissions, an equivalent ESP would have to be specified for 0.012 lb/mmBtu PM emissions. This is required because an ESP's failed electrical field cannot be repaired online, whereas with an FFC, you can isolate a compartment and replace a failed filter bag while remaining online.

This concept draws its roots from earlier days when conventional ESPs were sized too small and their thin weighted-wire electrodes frequently failed. State-of-art ESPs have virtually unbreakable RDE-type electrodes, and all of their high-voltage equipment and moving parts, such as collecting plate and discharge electrode rappers, are located and easily accessed on the ESP's roof. If the specifying engineer is uncomfortable with the fact that the treatment zone of an ESP cannot be maintained while the ESP is online, then redundancy should be built into the ESP's emissions performance guarantee. For example, the specifying engineer can reasonably request that "the ESP shall emit 0.015 lb/mmBtu with 10 percent of its high-voltage power supplies out of service."

An ESP-to-FFC conversion will fit into a congested site better than a straight ESP rebuild.

When considering an FFC conversion or an ESP rebuild, each having the same emissions performance requirements, in nearly all situations, these two technologies can share the same-sized existing ESP casing. The approximate trigger point for a retrofit as opposed to an upgrade/conversion is an existing weighted-wire type ESP with an SCA of 350 sq ft/kacfm. There are of course extenuating circumstances such as an existing upstream precollector that could significantly reduce this SCA trigger point.

The efficient use of space is made possible by use of the FFC's tall filter bag technology and the ESP's tall collecting plate technology. In many instances, the rebuilt ESP's aspect ratio will fall slightly below unity, but as previously discussed, this is an imaginary barrier that cannot be used as the sole indicator of an ESP's worthiness.

ESPs do not have the flexibility to satisfy future, more stringent emissions regulations.

ESPs can be and have been designed for anticipated future conditions. In some cases this is accomplished by providing extra fields of treatment zone, while in other cases it is accomplished by providing "empty fields" which can be back-fitted with ESP internals when required at a future date.

ESPs and FFCs have just about the same installation cost.

The flange-to-flange installed cost of state-of-art ESPs and state-of-art FFCs is approximately on equal footing, although occasionally the size and cost of the ESP is prohibitive due to site specifics such as poor coal chemistry or an unusually low PM emissions requirement. However, when retrofitting an FFC at a site at which there is an existing ESP, it is almost always necessary to upgrade or replace the ID fan, stiffen ESP ductwork, and perhaps even stiffen boiler buckstays for higher negative pressure operation. These balance-of-plant modifications tip the scale strongly in favor of the ESP, as shown in Table 5.

All things considered, ESPs are more expensive to install and operate than FFCs.

ESPs almost always have a lower operating and maintenance cost when compared to FFCs due to the previously mentioned incremental ID fan power cost and also due to required periodic filter bag change-outs.

Conclusions

Traditional U.S. utility technical/economic feasibility studies start with the question, "Will it work?" If the answer is yes, then the next question asked is, "How much will it cost?"

If our goal is to deliver low-cost, reliable electric power that is in compliance with all applicable environmental regulations, it is in everyone's best interest to put aside the rhetoric, examine all available technologies as they apply to the application at hand, then confidently select the lowest cost solution that is technically qualified to do the job.

If we adhere to these time-honored tenets, then FFCs and ESPs will each have their unique roles to play in coal-fired generating stations' emissions control systems.

References

1. Electrostatic Precipitator Discharge Electrode Geometry and Collecting Plate Spacing—Selection Considerations, Gary J. Grieco, Power Gen '95, Orlando, Florida, December 7-9, 1994.
2. SMPS: Present Application & Future Investigation, Gary J. Grieco, NWL Transformers White Paper, NWL.com, 2009.
3. Effect of Modern ESP Design Produces Particulate Emissions Comparable to Fabric Filters, Mick Chambers, Gary J. Grieco, Air & Waste Management Association 103rd Annual Conference & Exhibition, Calgary, Alberta, Canada, June 22-25, 2010.
4. Mikro-Pulsaire® Dust Collectors, MikroPul Sales Brochure, March, 2001.
5. Superfreakonomics, Steven D. Levitt, Stephon J. Dubner, Harper-Perennial, 2009.
6. DOE/NETL's Mercury Control Technology Field Testing Program, Preliminary Analysis of Wet FGD Co-Benefit Enhancement Technologies, U.S. Department of Energy's Office of Fossil Energy, National Energy Technology Laboratory's Innovations for Existing Plants Program, May, 2008.
7. An Update on DOE/NETL's Mercury Control Technology Field Testing Program, U.S. Department of Energy, National Energy Technology Laboratory, Science Applications International Corporation, July, 2008.
8. Comparison of Baghouse and Electrostatic Precipitator Fine Particulate, Trace Element and Total Emissions, William R. Lane, Anup Khosla, ASME-IEEE Joint Power Generation Conference, Indianapolis, Indiana, September 27, 1983.
9. Cold-side Precipitators Performing Well on Western Coal Power Plants, Robert W. Smock, Electric Light & Power, pp. 21-22, May, 1981.
10. Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies, John P. Gooch, Guillaume H. Marchant, Jr., Electric Power Research Institute, FP-792, Volume 3, Research Project 413-1, Tasks 1.1 and 1.3, Final Report dated August, 1978.
11. One Year's Operating Experience with SO_3 Conditioning on a Large Coal-Fired Unit's Electrostatic Precipitator, Bryan J. Eskra, Bill G. McKinney, 75th Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana, June 20-25, 1982.
12. Characteristics of Inhalable Particulate Matter Concentration and Size Distribution from Power Plants in China, Yi, Hao, Duan, Li, Guo, Journal of the Air & Waste Management Association, 56:1243-1251, September, 2006.
13. Fundamentals of Fabric Collectors and Glossary of Terms, ICAC Publication No. F-2.

APC

__Gary Grieco's__ expertise includes wet and dry ESPs, flue gas conditioning systems, multipollutant control systems, pulse-jet baghouses, wet scrubbers, semi-dry scrubbers, VOC control systems, NO_x control systems, air toxics emissions, and novel concepts for pollutant removal. Gary has 38 years of experience practiced in the utility, IPP, pulp and paper, petrochemical, steel, nonferrous metals, textile, cement, fiberglass, waste-to-energy, biomass, and fiberboard industries. Gary can be reached at 973-829-0011.