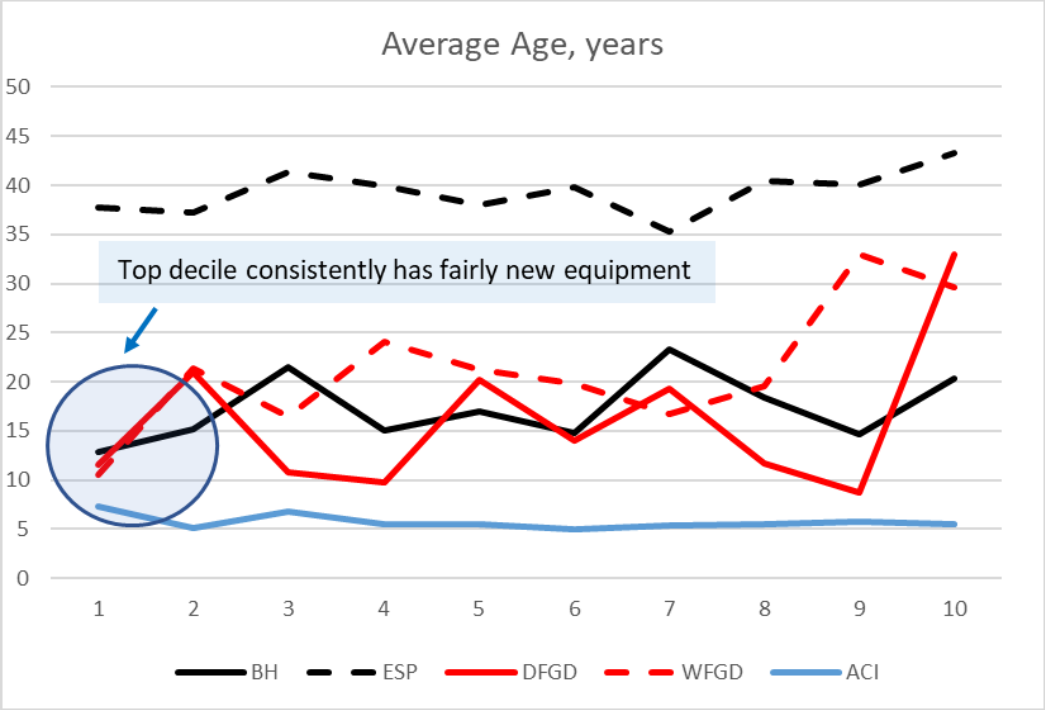
Figure 20, which shows the average age of equipment in each decile, shows another trend. It is apparent that the top decile consistently has relatively newer equipment. The trend is very apparent with the FGD systems. The bottom decile FGD systems are in the range of 25-30 years old while the top decile FGD systems are only about 10-15 years old. This is a clear indication that companies had made substantial, recent investments in the top decile units. The ESPs in most deciles were in the range of 35-45 years old. The ESP was consistently the oldest piece of air pollution control equipment on the power plant for every decile.

Figure 20. Average age of equipment in decile



F. Summary Analysis of PM data

Monthly PM data was collected and input to NRDC's database. The data published on NRDC's website, as shown in **Error! Reference source not found.**, indicates that:

- 59% of units and 61% of capacity had average annual emissions rates of 0.007 lb/MMBtu or less,
- 25% of units and 26% of capacity had average annual emissions rates of 0.003 lb/MMBtu or less,
- and 6% of units and 5% of capacity had average annual emissions rates of 0.0015 lb/MMBtu or less.

Table 5. Unit Level average, annual PM emissions rates

	Total	Unit average annual emission rate less than or equal to:		
		0.007 lb/mmBtu	0.003 lb/mmBtu	0.0015 lb/mmBtu
Number of Units	351	205	86	22
percent of total	100%	58%	25%	6%
Nameplate capacity (MW)	160,295	97,910	41,370	8,675
percent of total	100%	61%	26%	5%

As a result, reducing the PM emission limit from 0.03 to 0.007 lb/mmBtu would entail little or no additional expense for about 60% of the affected coal capacity (this does not include low-emitting EGUs that did not report quarterly emissions data in 2019). Plantwide averaging would provide additional compliance flexibility.

G. Conclusions regarding PM emissions and opportunities for reductions

The data indicates that a lower PM emission rate limit would not result in a large increase in cost for the majority of facilities. In fact, Table 6 shows that 50% of the units evaluated had emission rates at or below 0.006 lb/MMBtu, one fifth the current standard.[39] It also shows that 25% of the units had emissions levels one tenth or less of the PM standard. The top decile had a high percentage of BH, although a significant number only had ESPs. The second decile was far less likely to have a BH than the top decile, and less likely even than the bottom decile. So, while it would be expected that a BH will improve emissions, very low emissions are being achieved at units with only an ESP.

Table 6. Unit PM emissions from the population of units in the dataset [40]

Metric	Top 10%	Top 20%	Top 25%	Top 50%	All Data in Dataset
Number of units	35 (10% of 351)	70 (20% of 351)	87 (25% of 351)	175 (50% of 351)	351
Max avg, annual rate (lb/mmBtu)	0.0020	0.0026	0.0030	0.0060	0.0420
Max (lb/mmBtu) *	0.0050	0.0056	0.0090	0.0160	0.0626
Min (lb/mmBtu) *	-	-	-	-	-
Avg (lb/mmBtu)	**0.0013**	**0.0018**	**0.0020**	**0.0032**	**0.0073**
% avg is below standard	96%	94%	93%	89%	76%
* Max and Min are the maximum and minimum emissions reported for any period, not the maximum average, annual emissions for any units					

As previously noted, scrubbers (notably, dry scrubbers) were much more prevalent in the top deciles than the bottom deciles. Scrubbers alone are not the factor that determines if units are likely to have high or low PM emissions because there are a significant number of scrubbed units in the bottom deciles. And, the PM capture in a scrubber is not sufficient to explain the large differences. The higher percentage of units with BHs in the top deciles will certainly explain some of the difference. Scrubbers may also be an indicator of another important determinant of PM emissions. Scrubbers are costly investments. So, they are installed primarily on units that owners consider vital units and therefore the best maintained and equipped units. The scrubbers in the top decile were significantly lower in age than the scrubbers in the bottom decile. A more recent scrubber installation suggests that the owners recently believed the unit to be more vital and worthy of a large investment. In fact, the top decile units had consistently newer equipment, with the sole exception of ACI, which is generally newer equipment for all units.

This analysis also suggests that performance of units is driven by maintenance and operation of existing controls, regardless of configuration, as well as the equipment configuration. Units with ESPs were shown

[39] Units may comply either by maintaining a PM emission rate of 0.030 lb/MMBtu or less, or, alternatively, maintaining emissions of specific toxic metals below limits established in the MATS regulation. In this study we did not examine the metal emissions.

[40] Data from NRDC database

to be capable of low emissions, and it is expected that there are others that can further improve their emissions to a significant degree. On the other hand, factors that impact the ability of any individual ESP to achieve low emissions, most importantly treatment time and the available space to increase the size and treatment time of the ESP, might make it necessary to retrofit a baghouse on some units, while other ESPs can be upgraded to achieve very low emissions through the methods described in this report.

The emissions data summarized above raises the question: "How have so many facilities reported emission rates much further below the standard of 0.030 lb/MMBtu?" The answer is not that companies engaged in major retrofits. Relatively few BHs were installed in response to MATS. Few units with ESPs engaged in more expensive ESP upgrades, such as "gut and stuff", and fewer (if any) enlarged the ESP or added fields in response to MATS. Instead, what happened was that companies:

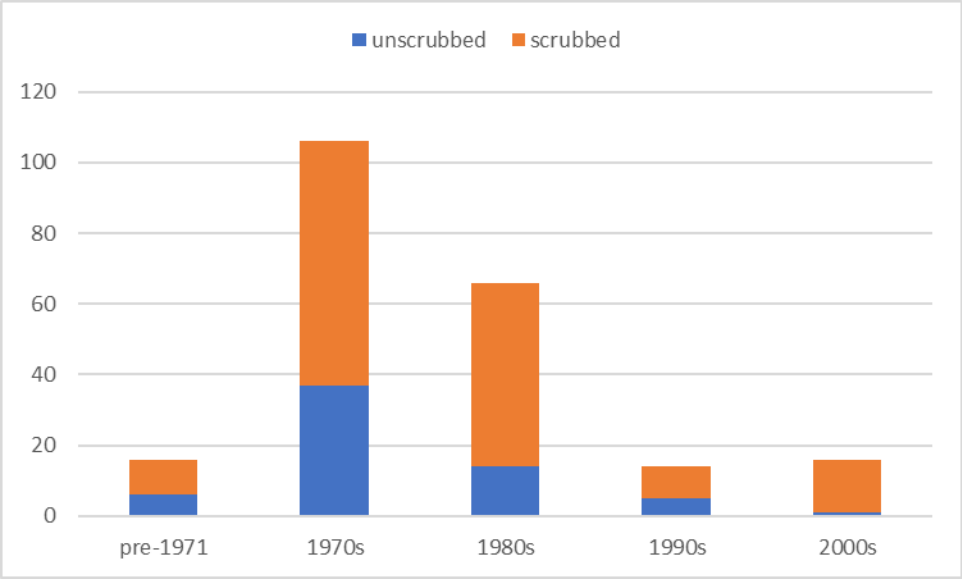
- Paid greater attention to their PM emissions because of the monitoring and reporting requirements of the MATS rule.
- Made efforts to restore their ESPs and other equipment to the performance level that they were designed for by correcting deficiencies (upstream leakage, failed electrodes and insulators, etc.). In some cases, old, corroded plates and electrodes were replaced. Most of the ESPs were originally installed 35 or more years ago and may have never undergone a complete rebuild. As a result, there was a great deal of improvement possible with the ESPs simply by correcting some of the deterioration that had occurred over the ESP lifetime.
- Made modest improvements to the ESPs when needed, such as addition of high frequency TR sets.
- Companies with BHs replaced and/or upgraded filter media as needed, made efforts to minimize wear and tear on filter bags, and paid more attention to BH operation.

In effect, most of the improvements to comply with the MATS PM standard were achieved at relatively little expense – far less than anticipated by US EPA. As noted by Staudt in 2015, EPA anticipated that MATS would motivate many more baghouse installations than actually occurred.[41] There were a small number of ESP retrofits, such as the Marion unit 4 that restored original or somewhat better than original performance.[42] Major retrofit efforts that amounted to large improvements in ESP treatment time through casing enlargement, or addition of fields, or addition of a BH to comply with the MATS rule were rare. A relatively small number of BH installations occurred, but many of them were also associated with addition of dry FGD in response to the Regional Haze Rule. In effect, the industry, faced with a requirement to control PM emissions, found low-cost ways to achieve lower PM emissions that were not anticipated in 2011. It is reasonable to conclude that more operators could similarly deploy these lower cost improvements to reduce PM emissions if the PM standard were tightened. Or, operators that utilized lower cost improvements to comply with MATS could explore some moderate cost methods to further improve performance of their ESP.

[41] Declaration of James E Staudt to United States Court of Appeals for the District of Columbia Circuit, Case No. 12-1100, September 24, 2015. Many of these forecasted installations that did not occur may have been assumed by EPA to be necessary to provide adequate Hg or acid gas capture while remaining below the PM emissions limit.
[42] As noted earlier, the new plates were optimized to increase treatment time within the existing ESP casing.

Recalling Figure 3, older ESPs were designed for lower treatment times and therefore were not as large as more recently constructed ESPs. The population of ESPs that are not on units that also have a fabric filter was examined, and the results are in Figure 21. It showed that the largest number of ESPs were built in the 1970s (106 in total). Of them, 69 were on scrubbed units. Unscrubbed units are likely to be more challenged – in part because they do not benefit from the additional removal by the scrubber, but also because unscrubbed units are likely to have reduced the sulfur level of the coal as a means of reducing SO_2 emissions, which will increase fly ash resistivity. Nevertheless, in the top decile there are three units that only have ESPs and are unscrubbed. These are 38, 35 and 36 years old, built in the 1980s. In the second decile there were four units that had ESPs only and no scrubber with ages that ranged from a low of 21 years to a high of 41 years. Therefore, it is clear that some of the older ESPs can achieve low PM emission rates.

Figure 21. Units equipped with ESPs and no fabric filter/baghouse, by year of ESP construction.



An Upper Prediction Limit (UPL)[43] was calculated by EPA in 2011 to determine the PM emissions level in the MATS rule that could be used for the non-Hg metals limitation. An updated UPL was calculated using the 2019 data assembled by NRDC and this was compared to the UPL calculation by EPA in 2011. The result is shown in Figure 22. As shown, the UPL in 2011 resulted in a value of 0.028 lb/MMBtu, or 0.030 when rounded up. The calculation with the 2019 data resulted in a UPL of 0.005 lb/MMBtu, or about one sixth the previous estimate. This is due to two things:

1) generally lower average emission rates, especially for the 65 higher emitting units, and

[43] The UPL takes into account the average of the best units plus an allowance for variation that is determined by a confidence level that the UPL will not be exceeded. The allowance for variation is determined by the number of standard deviations from the mean for the confidence level and the standard deviation. A higher standard deviation and higher confidence level that the UPL will not be exceeded will result in a higher calculated UPL result, and lower standard deviation will result in a lower UPL for any given confidence level.

2) much less variability in emissions for each individual unit.

This is attributable to the aforementioned reasons for the improved emission rates, particularly the greater attention to PM emissions as a result of increased monitoring and reporting requirements.

Figure 22. Comparison of 2011 MACT floor UPL calculation to UPL calculation using 2019 data

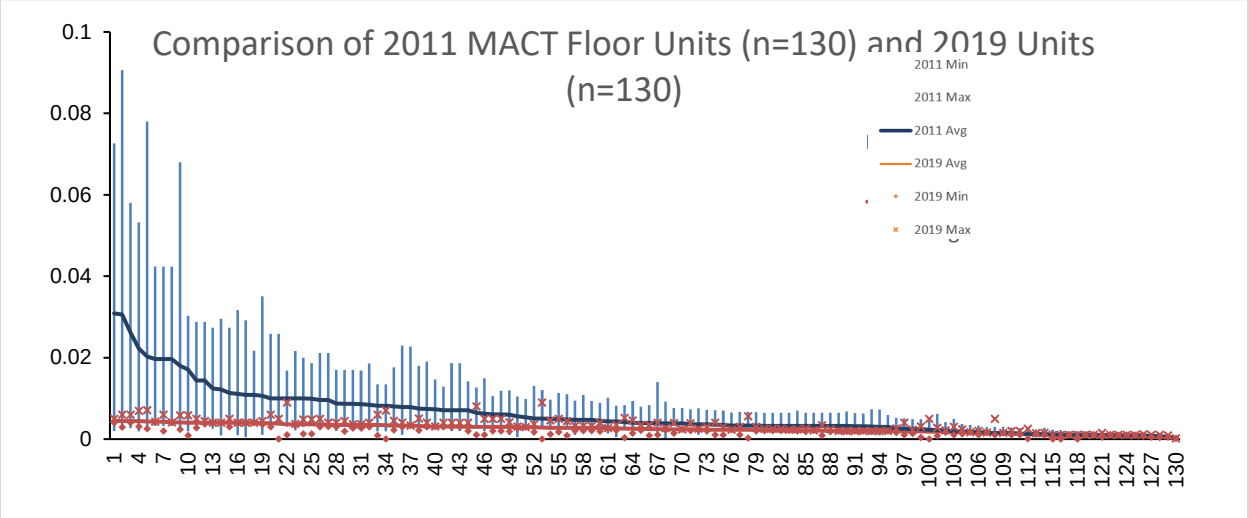


Table 7 shows the estimated impact of reductions in the PM emission standard. The current standard is 0.030 lb/MMBtu. As previously noted, half of the evaluated units had emissions at or below 0.0060 lb/MMBtu. This means that roughly half of the units can comply with an emission limit of 0.0070 lb/MMBtu with little or no modifications.[44] Units with ESPs might have to make some modifications to comply, some more involved than others, depending upon the age and current circumstances of the ESP. Units with baghouses could comply with little or no effort, perhaps upgrading filter bag material or improving operating practices to minimize bag failure rate. At 0.003 lbs/MMBtu, some units with ESPs would need to install baghouses but roughly half of units with ESPs are expected to be able to meet this standard with modest upgrades or no additional costs.

As emission standards tighten, the impact to the coal fleet will be increased. At a sufficiently low standard (0.0015-0.0020 lb/MMBtu or less), most units with ESPs would likely seriously consider installation of a fabric filter or another substantial upgrade. All units with fabric filters should be able to achieve such a standard, providing that they take measures to avoid significant leakage from filter bags or bypassing of filters, such as improved operating practices or installation of improved fabrics.

[44] The difference between annual averages and 30-day averages is acknowledged, as well as the need to maintain a degree of "compliance margin", controlling to a level below the standard to avoid exceeding the standard.

Table 7. Estimated impact of reduction in PM emission rate standard[45]

PM Limit (lbs/MMBTU) *(Current standard is 0.03 lbs/MMBTU)*	**Implications for facilities with ESPs**	**Implications for facilities with baghouses**	**Implications for fleet as a whole** *(Preliminary estimates)*
0.007	• Most units can meet with modest improvements • Units with ESP built in last 20 years should be able to achieve with modest maintenance costs (~$20/kW or less) • A few units with significantly older ESPs may need to undergo ESP upgrades/rebuilds (~$50/kW)	• Virtually all units can easily meet this limit with no additional costs • A few units may require some maintenance or bag replacement ($2-5/kW)	• More than half of all units can achieve with little to no additional costs, 42% of fleet is above 0.007 lb/MMBtu • $268M annualized cost with >7,200 tons PM reduction (preliminary estimate)
0.003	• Many units may need to make upgrades but should be technically feasible for all units • Roughly half of units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW • Units with ESPs and wet scrubbers may not be able to fit baghouse before scrubber, but could install wet ESP after scrubber ($100-150/kW)	• Many units can still meet this with little to no costs • Some units may need modest upgrades. For instance, units may need to replace bag ($2-5/kW) and replace every 3 years rather than 5 years.	• About 25% of fleet can achieve with little to no additional costs • $1.29B annualized cost with >16,800 tons PM reduction (preliminary estimate)
0.0015-0.002	• Most units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW) • Some ESPs would still not require additional investments	• Many units can still meet this with little to no costs • Some units would need modest upgrades ($5/kW)	• 12-20% of the fleet can achieve with little to no additional costs • $2.4B annualized cost with >22,900 tons PM reduction (preliminary estimate)
Less than 0.0015	• Nearly all units with ESPs would need to make substantial upgrades, including installing baghouses	• Most units would need to make modest upgrades	• Most units would require modest to substantial improvements • $2.5B+ annualized cost (preliminary estimate)

[45] Estimated costs and PM reductions are approximate, and based upon an assumed BH upgrade cost of $5/kW for upgraded bags, $20/kW for a minor ESP upgrade, $50/kW for major upgrade, and $150/kW for installation of BH.

III. Methods of mercury (Hg) control

Setting aside the vacated Clean Air Mercury Rule (CAMR), MATS was the first nationwide Hg emission standard requirement for coal-fired power plants. Prior to MATS, Hg emissions were only controlled and reported in those states that had Hg control and reporting standards. Moreover, the requirements varied from state to state. As a result of the changing regulatory requirements and the relative novelty of Hg regulation, technology has evolved rather quickly for control and monitoring of Hg. In the following section the methods of controlling Hg will be discussed.

A. Control from PM and SO_2 control devices

How they work

PM and some SO_2 control devices will capture Hg. Some NOx control devices will also enhance Hg capture in the PM or SO_2 control device. The Clean Air Mercury Rule (CAMR) was intended to primarily take advantage of increased Hg capture from the addition of new SO_2, PM and NOx control devices associated with other rules. For example, a PM collection device will capture that Hg that is contained in the filterable PM. Scrubbers will capture Hg as well. Wet FGD systems will capture that Hg that is in a water-soluble form. Dry scrubbers capture Hg in a baghouse. SCR NOx control systems enhance Hg capture by converting more Hg to the oxidized form, which is easier to capture in downstream PM or SO_2 control systems.

Hg may be in one of three forms:

1) Elemental Hg – this is in a gaseous form and tends to be difficult to capture unless it is first converted to one of the other forms of Hg.
2) Oxidized Hg – this is water soluble and is also readily attracted to PM surfaces. As a result, it is captured in wet scrubbers and, to some degree, in PM control devices.
3) Particulate Hg – this is effectively captured in PM control devices.

Therefore, one of the ways to optimize inherent capture of a PM or SO_2 control device is to convert elemental Hg to one of the other forms that is easier to capture and also to prevent Hg that is in the oxidized form or particulate form from transforming to the elemental form. Once Hg is in the particulate form, it is generally quite stable and will not convert back to the elemental form.

For PM control systems, Hg that is contained on the PM is captured in the ESP or BH and removed from the exhaust gas. Hg is more effectively captured in a BH because the intimate contact between the PM and the exhaust gas as the gas passes through the filter enhances oxidation of elemental Hg to oxidized mercury and enhances conversion of Hg to the particulate form. Halogens are necessary for mercury to be in the oxidized form. One way to enhance Hg oxidation is to add halogens, especially bromine, to the gas through the coal or other means.

ACI is a means for enhancing Hg capture in the PM control device, but it will be discussed separately.

Developments in enhancing the inherent Hg capture of PM and SO_2 control devices

The MATS rule created motivation for industry to optimize the inherent Hg capture of their FGD and PM control systems. Pre-2011 there were limited "best practices" because Hg controls had only been only deployed in a few states. In the case of mercury regulation, necessity has been the mother of invention; with a widespread requirement to control Hg emissions, power plant owners and technology providers became creative in finding better ways to reduce Hg emissions.

Developments for wet FGD

Prior to MATS, wet FGD systems were considered highly effective at capturing oxidized mercury in most situations. Therefore, efforts were made to fully understand mechanisms for oxidizing elemental mercury prior to the scrubber so that it could be captured. In 2011, chemicals for oxidizing mercury prior to a scrubber were under development but not yet deployed widely. And, the interrelationships between SCR catalyst activity, ammonia injection and mercury oxidation across the SCR catalyst were not well understood.

In the time since MATS implementation, chemicals for oxidizing Hg have been developed and deployed. Also, the interrelationships between mercury oxidation across the SCR catalyst and SCR system operation and catalyst design and activity are better understood. Catalyst suppliers now supply catalyst that is optimized both for NOx reduction and mercury oxidation.[46] These innovations were not available prior to MATS implementation.

However, the improved understanding of mercury oxidation was not enough. Pre-MATS a phenomenon called "re-emission" made mercury capture in wet scrubbers lower in some cases, with higher elemental mercury measured at the outlet than at the inlet of the scrubber. This phenomenon was later determined to be a result of unstable scrubber chemistry that, under some conditions, caused Hg captured in the scrubber liquor to reduce to elemental Hg and be "re-emitted." In the period since 2011, chemicals and operating practices have been developed to prevent captured mercury from reducing back to elemental mercury and rather be retained in the scrubber solids. By 2014, Nalco-Mobotec had introduced the MerControl family of chemicals that included chemicals for mercury speciation and chemicals for wet and dry scrubbers.[47] Operating practices included measuring the redox potential of the scrubber liquor to prevent reducing reactions and manage the redox potential through the sparging of the liquor. In addition, activated carbons and other chemicals were developed to keep the captured Hg in the scrubber solids, where it would later be removed. Many of these methods are described in a 2014 ICAC document.[48]

Other technologies that were under development, but not available in 2011, included absorber systems that could be installed in the mist eliminator section of the wet scrubber. One version of this technology made by W.L. Gore Mercury Control System is a fixed bed absorber that captures both Hg and SO_2. This

[46] https://cormetech.co/advancedscrcatalysts/; https://www.jmsec.com/air-pollutants/mercury-hg/?L=0

[47] Meier, J., "Alternatives to Activated Carbon Injection", 2014 APC Round Table and Expo Presentation, July 14-15, 2014, Louisville, KY

[48] Institute of Clean Air Companies, "Improving Capture of Mercury Efficiency of WFDGs by Reducing Mercury Emissions", June 2014

technology can also be installed downstream of a PM control system, but the most widely used application has been in combination with a wet FGD system. These systems have been found to be effective means of Hg capture for scrubbers that have the space available for the fixed bed absorber in what normally would be the mist eliminator of the scrubber.[49]

Activated carbon is also an option for increasing the Hg capture through injection upstream of the ESP or BH. However, carbons available in 2011 were not effective in environments typical of that location due to high SO_3 concentrations that interfered with Hg capture. Activated carbon has also been used in situations where it is injected upstream of a wet scrubber so that the captured mercury remains with the scrubber solids. Advances in activated carbon are discussed further in a later section.

Developments for dry FGD systems

For bituminous coal units equipped with dry FGD systems, Hg capture was generally found to be very effective – frequently achieving well over 90% Hg capture without addition of ACI. However, for coals that are low in halogen content, such as western coals, Hg capture was determined to be poor in many cases.

Although the solution of introducing halogens was generally known in 2011, it was not being deployed widely. In the time since MATS, it has not only been deployed on systems with dry FGD systems that have insufficient inherent halogen content, but suppliers have also refined chemicals and methods for delivery, to include introduction in the fuel, introduction on activated carbon, and other means. These efforts have improved performance and reduced cost.

Developments for unscrubbed units only equipped with PM control devices

The capture in PM control devices can be enhanced by converting more of the gaseous mercury to particulate mercury. One way is with the use of ACI. ACI will be discussed separately.

Another way is to add halogens to the flue gas – either by addition to the coal or injection into the flue gas. This will increase oxidation of elemental mercury to oxidized mercury, which more readily attaches itself to fly ash that is captured in the downstream PM control device. Depending upon the circumstances, this may be sufficiently effective in reducing Hg emissions that the emissions limit may be achieved without ACI. At the very least, it will enhance ACI effectiveness. This is an approach where experience was limited prior to 2011, but experience expanded rapidly once MATS was implemented. In fact, as late as 2013, activated carbon was considered the principal method of controlling mercury for unscrubbed units, but by 2015 bromine injection started to be recognized as another very viable approach to be used alone or in combination with ACI. [50]

B. Activated Carbon Injection (ACI)

Most unscrubbed units will rely largely on ACI for Hg capture. In some cases units with a BH will have sufficient inherent Hg capture without addition of ACI. ACI is discussed further in the following section.

[49] https://www.gore.com/products/gore-mercury-control-systems
[50] https://cen.acs.org/articles/93/i11/Bromine-Comes-Rescue-Mercury-Power.html

Developments in ACI

Units that were unable to achieve Hg capture in the scrubber needed to capture Hg in the PM control device. To do that, the gas-phase Hg had to first be converted to particulate Hg. ACI was found to be the most effective means of doing that. ACI essentially is a "dial up" technology that increases the mercury capture beyond that provided purely by the inherent Hg capture in the PM control device or scrubber. Hg capture could be increased through increased carbon injection. How responsive mercury capture is to carbon injection was found to be related to many factors, including:

- How effectively the carbon was introduced into the flue gas
- The type of PM control device installed, with BH being much more effective than an ESP
- The presence of SO_3 in the exhaust gas – SO_3 interferes with Hg capture
- The presence of NO_2 in the exhaust gas, which is often increased when sodium-based DSI is in use, with NO_2 interfering with Hg capture
- The presence of ammonia in the exhaust gas, which could also interfere with Hg capture

In addition to these considerations, the impact of carbon on the marketability of fly ash was a concern. The best market for fly ash is as a Portland cement substitute; however, the presence of activated carbon can adversely impact that use. Activated carbon suppliers were challenged to develop carbons that have less adverse impact.

In 2011, ACI was generally viewed as ineffective in situations where PM control was with an ESP and SO_3 was present in significant levels, especially where units were burning high sulfur coals or where SO_3 was injected for flue gas conditioning. Similar issues were being found in applications where trona or sodium bicarbonate were being used for SO_2 or HCl capture – a particular problem for units when considering the importance of controlling HCl for MATS compliance. And, although "concrete friendly" activated carbon formulations did exist, they were often not as effective in capturing mercury – increasing injection levels and cost of control.

In the time since 2011, activated carbon suppliers have made great advances in activated carbon technology for Hg capture. In fact, in 2011 it was anticipated that a BH was necessary for high Hg capture in many situations. Circumstances where DSI was in use or SO_3 was elevated were among those situations. Along with other factors, this contributed to a large overestimation by EPA of the number of BHs by 100 GW and dry FGD by 18 GW to be installed in response to MATS as described in a declaration to the DC Circuit.[51] However, in practice, during and since MATS implementation, technology suppliers responded with far more effective carbons and other technology choices.

Pre-MATS activated carbons that were available were mostly first- or second-generation carbons. First-generation carbons were carbons originally used for other purposes, but then repurposed for Hg capture. Second-generation carbons had some degree of modification, such as addition of halogens or treatment to reduce concrete impact.

[51] Declaration of James E Staudt to United States Court of Appeals for the District of Columbia Circuit, Case No. 12-1100, September 24, 2015

The third-generation carbons were developed in the years since MATS implementation. The third-generation carbons were specifically engineered for Hg capture in flue gas. The porosity and the surface chemistry of these products were specifically designed to address the more difficult situations such as high SO_3, NO_2, etc. They were also designed for much lower treatment rates and lower impact on the fly ash marketability. Because the market for activated carbon used for Hg control is highly competitive, activated carbon research and development continues at the major carbon suppliers, and this activity is focused on continuing to improve treatment rates and Hg capture on the various flue gas conditions that exist.

Fessenden[52] contrasted the performance of 1st and 2nd generation carbons with 3rd generation carbons available in 2017. As shown in Table 8, the costs of control for several applications using early-generation carbons, particularly for ESP applications, are all at or over about 1 mill/kWh and are as high as 3 mills/kWh for a moderate sulfur bituminous coal controlled to 90% Hg capture. It also illustrates some of the more challenging applications. For example, sites C and E are both low sulfur subbituminous units with ESPs. However, site C is capable of 90% removal at a cost of 0.92 mill/kWh with a halogenated carbon (designated as LH), while site E was capable of only 67% capture at a cost of 1.49 mill/kWh using unhalogenated carbon. It also shows the challenges with SO_3 are present in sites F and G.

Table 8. Estimated cost of Hg control for first and second generation carbons.[53]

Coal-Fired Site	Product	AQCS	Fuel	FGC	% Removal Hg	mill/KWh
A	DARCO® Hg	ESP/FF (TOXECON)	Low Sulfur Bit.	None	90	0.53
B	DARCO® Hg-LH	SDA/FF	Low Chlorine Subbit.	None	90	0.55
C	DARCO® Hg-LH	ESP	Low Chlorine Subbit.	None	90	0.92
D	DARCO® Hg	ESP	Blended Subbit./Bit	None	80	1.06
E	DARCO® Hg	ESP	Low Chlorine Subbit.	None	67	1.49
F	DARCO® Hg-LH	ESP	Low Chlorine Subbit.	SO3 (5.2 ppm)	75	1.50
G	DARCO® Hg	ESP	Moderate Sulfur Bit.	None	90	2.98

Table 9 shows the results for third generation carbons. Some applications with ESPs are only about 0.25 mill/kWh and the most difficult application shown, a high sulfur bituminous coal, is just under 1 mill/kWh at 96% Hg removal. These demonstrate that applications that were regarded as very difficult can now be addressed more easily. Also, sites 2, 3, and 4 are very similar sites, using the same activated carbon. Sites 2 and 3 have the same Hg removal, and have very similar costs of 0.222-0.244 mill/kWh. On the other hand, site 4 has a higher Hg capture rate of 87%, but this also shows a higher cost of 0.328 mill/kWh. This illustrates that increased Hg capture is possible at a higher cost, and demonstrates that ACI will be injected up to the point where the necessary Hg capture is achieved. Because there is no advantage to controlling beyond a target emission control level and there is an increased cost, ACI is generally only operated up to the level that is necessary to meet the Hg limit with some margin (perhaps 20% or so). This "dial up" aspect of ACI is discussed later.

[52] Fessenden, J., Satterfield, J. "Cost Effective Reduction of Mercury Using Powder Activated Carbon Injection", March 2, 2017

[53] Ibid., % removal is removal attributed to the activated carbon

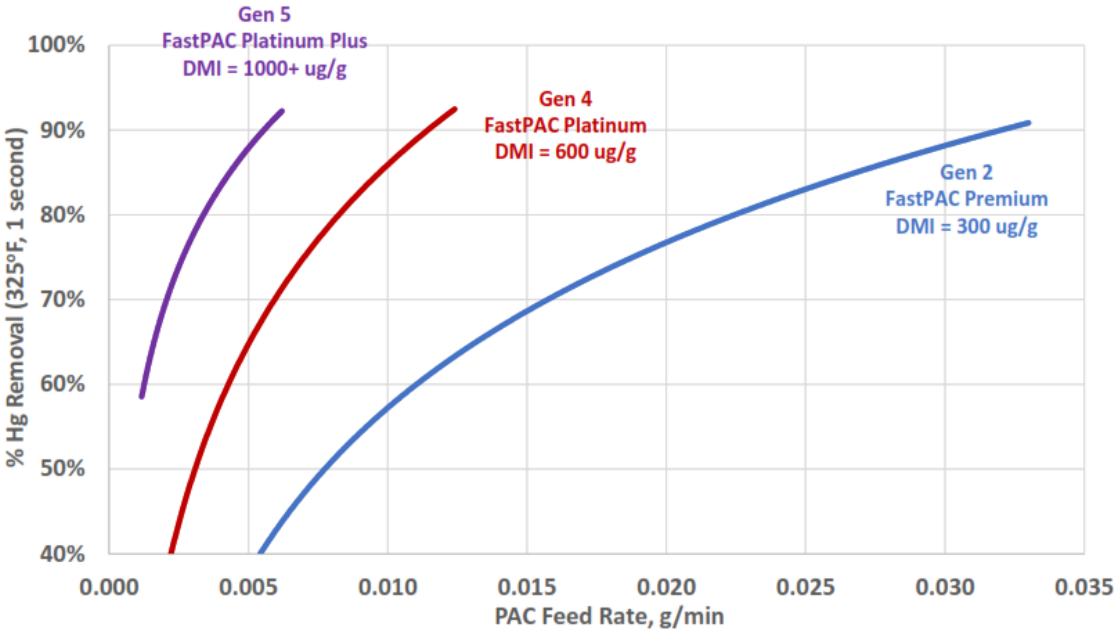
Table 9. Estimated cost of Hg control for third generation carbons[54]

Coal-Fired Site	Product	AQCS	Fuel	DSI	FGC	% Removal Hg	mill/Kwh
1	DARCO® Hg-LH EXTRA SP	SCR/FF	Low Chlorine Subbit.	None	None	94	0.086
2	DARCO® Hg-LH EXTRA SP	CS-ESP	Local W.Subbit	None	None	80	0.222
3	DARCO® Hg-LH EXTRA SP	CS-ESP	Local W.Subbit	None	None	80	0.244
4	DARCO® Hg-LH EXTRA SP	CS-ESP	Low Chlorine Subbit.	None	None	87	0.328
5	DARCO® Hg-LH EXTRA TR	CS-ESP/wFGD	High Sulfur Bit.	Calcium-based	None	82	0.375
6	DARCO® Hg-LH EXTRA TR	CS-ESP	PRB/Bit. Blend	Sodium-based	None	88	0.663
7	DARCO® Hg EXTRA	CS-ESP	Low Chlorine Subbit.	None	SO_3 (6ppm)	90	0.789
8	DARCO® Hg-LH EXTRA SR	CS-ESP	PRB	None	SO_3 (7ppm)	90	0.872
9	DARCO® Hg EXTRA SR	SNCR/ESP/wFGD	High Sulfur Bit.	None	None	96	0.980

Pre-MATS, 90% mercury capture was viewed by many as the practical upper limit of Hg control in nearly any circumstance. Some situations were recognized as being easier than others (for example, situations with bituminous coals and dry FGD). Some were much more difficult and it was believed that a BH retrofit would be necessary (situations with bituminous coals and an ESP, for example). However, technology developments proved otherwise.

The impact of carbon advancement is also illustrated by laboratory data for different generations of carbon developed by ADA Carbon Solutions.[55] As shown, in Figure 23, treatment rates to achieve 90% removal were reduced by roughly a factor of 6 from the Gen 2 to the Gen 5 FastPAC products.

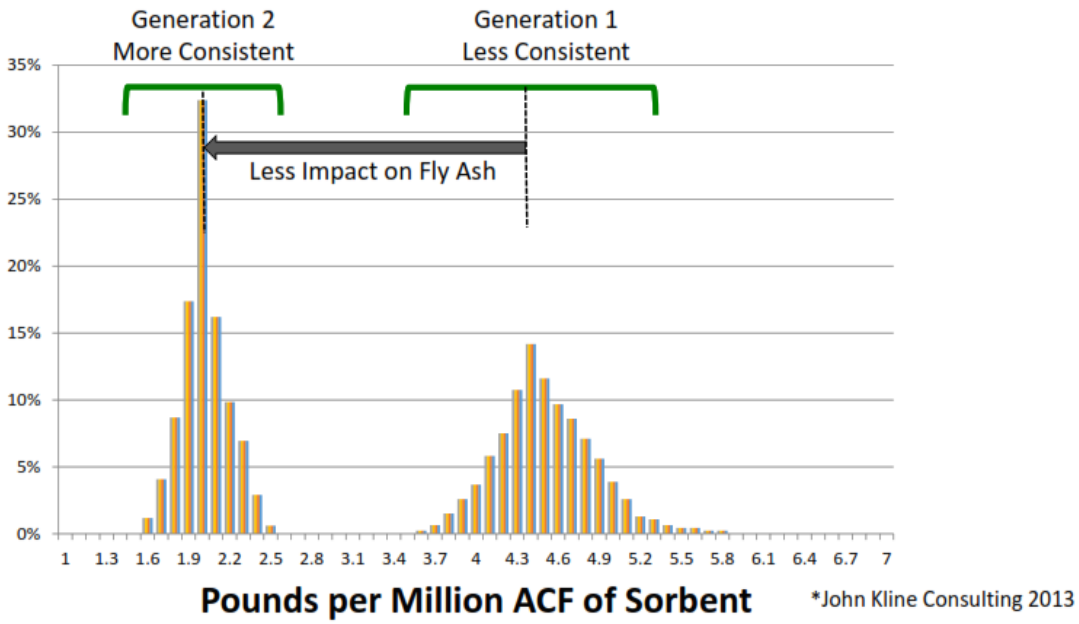
Figure 23. Comparison of laboratory data for different carbons[56]



[54] Ibid., % removal is removal attributed to activated carbon
[55] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018
[56] Ibid., DMI stands for Dynamic Mercury Index, and is a measure of the sorbent's ability to capture mercury

Improvements leading to lower treatment rates also led to less adverse impact on fly ash marketability. This is illustrated in Figure 24, which shows lower treatment rates for actual ACI projects in terms of pounds of sorbent per million actual cubic feet (lb/million ACF)[57] of exhaust gas.

Figure 24. Impact of advanced PACs on fly ash – Generation 1 versus Generation 2 PACs[58]



C. ACI, a "dial up" technology

PM and SO_2 controls provide varying degrees of Hg control. Greater capture of Hg beyond that possible from the inherent capture of the PM or SO_2 control device may be desirable. This is especially the case for units that are only equipped with ESPs for pollution control. The units with only ESPs tend to have lower inherent Hg capture than units with scrubbers or fabric filters and are therefore more likely to require additional Hg capture. ACI was originally developed to increase Hg capture beyond the inherent capture of the other devices. By adding ACI it is possible to increase Hg capture, and the capture will increase with treatment rate. But, is there a practical limit to the removal rates of activated carbon? This will be examined with unit data later in this document and will be examined here from a more theoretical perspective.

Hg capture with ACI relies upon three critical mechanisms, as described by Huston[59]:

- *Contact* – getting the carbon in contact with the mercury.
- *Conversion* – converting elemental mercury to oxidized form.
- *Capture* – capturing and retaining the mercury in the carbon.

[57] This relates to the amount of carbon injected per actual volume of flue gas being treated, and relates to the concentration of activated carbon in the exhaust gas.
[58] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018
[59] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018

Contact is achieved with injection systems designed to get the carbon distributed so that the entire gas field is treated. In some cases, mixing devices have been installed. Recognizing this limitation on performance, the technology associated with carbon injection technology has advanced rapidly. It has become standard practice to model injection systems on the computer to optimize the design. In some cases, physical models are also performed. This enables the designer to develop a highly effective injection system. So, while this may have been a very limiting issue in the early days of activated carbon systems,[60] it is not such a large limitation now.

Conversion is generally effective when sufficient halogen is present either in the exhaust gas or on the surface of the carbon. Halogen addition to the coal, to the exhaust gas, or to the carbon is a common approach to this challenge.

Capture: Once the mercury is captured, it is usually well retained by the carbon. However, some situations are more challenging for capture because SO_3, NO_2 or other species that may be present in exhaust gases can compete with mercury for capture and reduce the capture efficiency of the activated carbon. This has been a major focus for carbon developers – to optimize the surface chemistry and physical characteristics of the carbon to capture Hg when these other species are present.

Furthermore, at the time MATS was being developed, there were numerous misunderstandings about ACI technology. Staudt addressed some of these in 2008,[61] but most of these misunderstandings persisted for several more years. Today, these misunderstandings about the technology are largely cleared up. So, in combination with improved understanding of the capabilities of activated carbon and the very substantial improvements in ACI technology, ACI today is capable of much more than it was in 2011.

In the face of the dramatic improvements, it is reasonable to ask whether there is a limit to Hg capture from ACI. The answer is:

- Theoretically, perhaps, but experience shows that we are not close to having reached any such limit
- Practically, however, there is a level of diminishing returns.

As will be shown later in this report, Hg emissions from coal power plants have been controlled to levels about 0.060 lb/TBtu – one twentieth of the MATS limit. This demonstrates that if there is a theoretical limitation to the ability to reduce Hg, such as a thermodynamic equilibrium limitation, the level must be below that concentration.

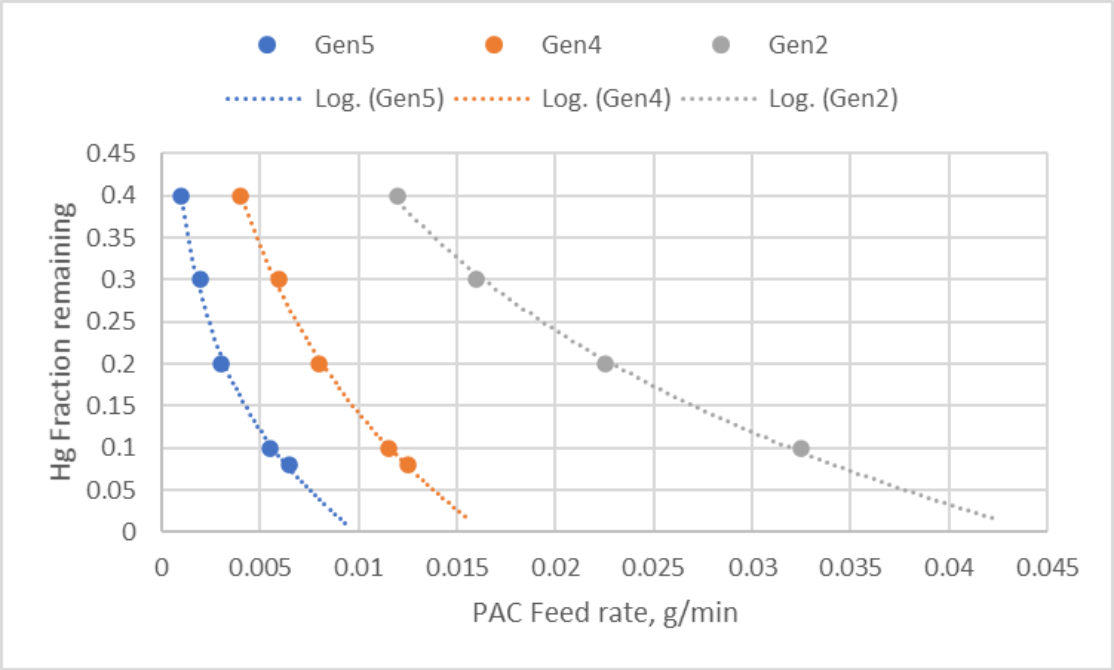
Reducing Hg with activated carbon further on any given unit to lower levels than currently achieved will require additional carbon injection, or some other means of incremental control. Figure 25 shows the data of

[60] Staudt, J., "Does ESP Size Really Matter", at https://www.andovertechnology.com/wp-content/uploads/2021/06/Does-ESP-size-really-matter.pdf; See discussion on Yates unit 1

[61] Ibid., this paper was intended to address numerous misunderstandings regarding ACI technology that, unfortunately, persisted for several years.

Figure 23, but plotted differently. The data, plotted as Hg fraction remaining versus feed rate, plots exactly as a log function, consistent with a single-step reaction mechanism. This doesn't mean that it is truly single step, but that one step is the most important one because it is the most limiting. That is consistent with most real reaction mechanisms. It is reasonable to assume that this trend could be extended beyond the data, and this forecast is shown. But, does the trend in Figure 25 match the data? Recalling Table 9, coal power plant sites 1 and 9 show Hg capture rates well above 90%. Site one is a fabric filter application, but site 9 is an ESP application. Clearly, Hg capture with ACI and an ESP can go beyond 90%. However, there is more data to examine as will be addressed in the following discussion.

Figure 25. Data of Figure 23, plotted as Hg fraction versus feed rate



ACI is not the only means to achieve additional Hg capture. For scrubbed units it can be done with scrubber chemicals. Some of these chemicals are halogens to promote oxidation. Other chemicals are used to promote precipitation of mercury into scrubber solids. Some of these are flocculants. These tend to be widely used in wet scrubber applications, sometimes in combination with ACI. But, although other means to enhance mercury capture exist for both PM and SO_2 control equipment, ACI provides a means for estimating the additional cost of mercury capture while recognizing that less expansive approaches may be available in some cases, and this will be examined further.

D. Evaluation of Hg data

Except for a small number of low mass emitters, coal power plants must monitor Hg emissions continuously. The NRDC's database shows reported monthly Hg capture from for 2020 for both not low-rank coals and low-rank coals. Of these 416 units where data were collected and emissions information was available on a unit basis, 393 were not low-rank coal and 23 were low-rank coal.

Not low-rank coals

Table 10 compares the Hg emission rates of the top 10% of reported not low-rank coal units to those of the bottom 10% of reporting not low-rank coal units. "Min" and "Max" are the minimum or maximum for any given period. As shown, there is close to a fifteen-fold difference in the average emissions level between the top and bottom performing units. However, among the top and bottom units are significant numbers of each listed coal type (bituminous, subbituminous, and refined coal).

Table 10 Emission rates of top and bottom 10% not low-rank coal units

	No. of Units	Emission Rates (lb/TBtu)		
		Min	Max	Avg
Top 10%	39	-	0.1660	0.0905
Bottom 10%	39	0.8386	1.3861	0.9427

ATP further examined the NRDC database and broke the data into deciles by mercury emissions rate. The lowest emitting units were in decile 1 and the highest emitting units were in decile 10. ATP also took the step of estimating the Hg capture rate – comparing the outlet emissions rate to the Hg content of the coal. Coal Hg content was estimated from IPM documentation. IPM documentation chapter 9 has representative coal mercury content for coals from different regions.[62] Subbituminous coals were assumed to be Wyoming PRB. Bituminous coals were assumed to be IL basin, PA, central Appalachian or western bituminous coals, depending upon location. Lignite coals were assumed to be local lignite. This provides an approximate estimate of percent mercury capture since actual coal mercury content data wasn't available, but rather, an estimate from IPM documentation.

Figure 26 shows the Hg concentration and estimated capture efficiency. For decile 1, the average emissions rate is 0.0905 lb/TBtu with an average estimated capture efficiency of 98.7%. This decile includes units with only ESPs and ACI, demonstrating that high levels of Hg capture are possible using this control configuration. The bottom decile has an average emission rate of 0.9427 lb/TBtu and an average estimated capture rate of 85.4%.

Figure 27 shows the trends in coal type. The top decile is majority bituminous coal. In this analysis, refined coal was examined to determine the type of origin coal and categorized by the origin coal type. The bottom deciles are majority subbituminous.

[62] See Figure 9-1 and Table 9-5 in the Integrated Planning Model documentation, Chapter 9.

Figure 26. Average Hg concentration and estimated percent capture by decile for not low-rank virgin coal

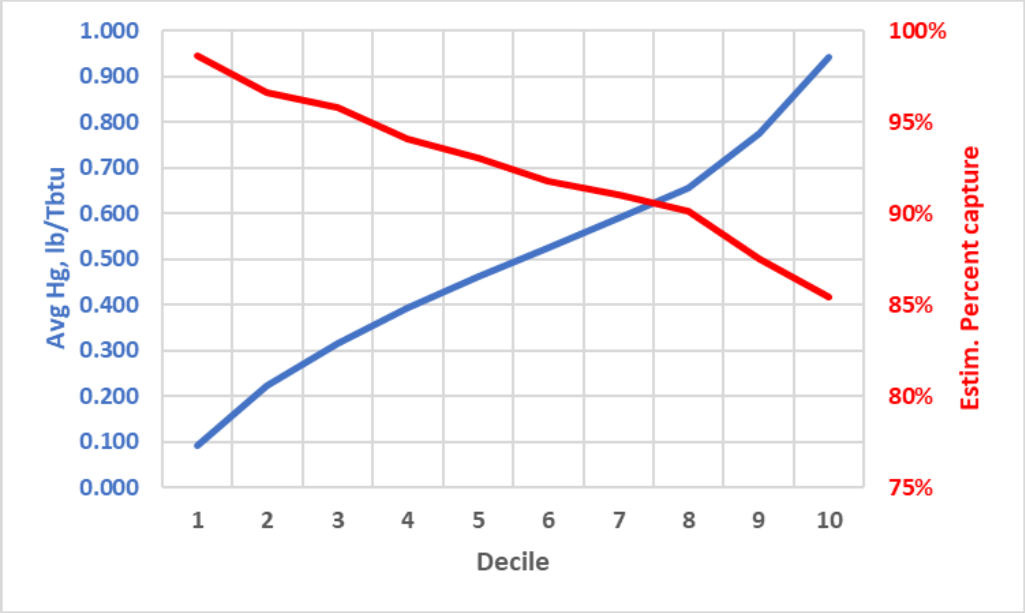
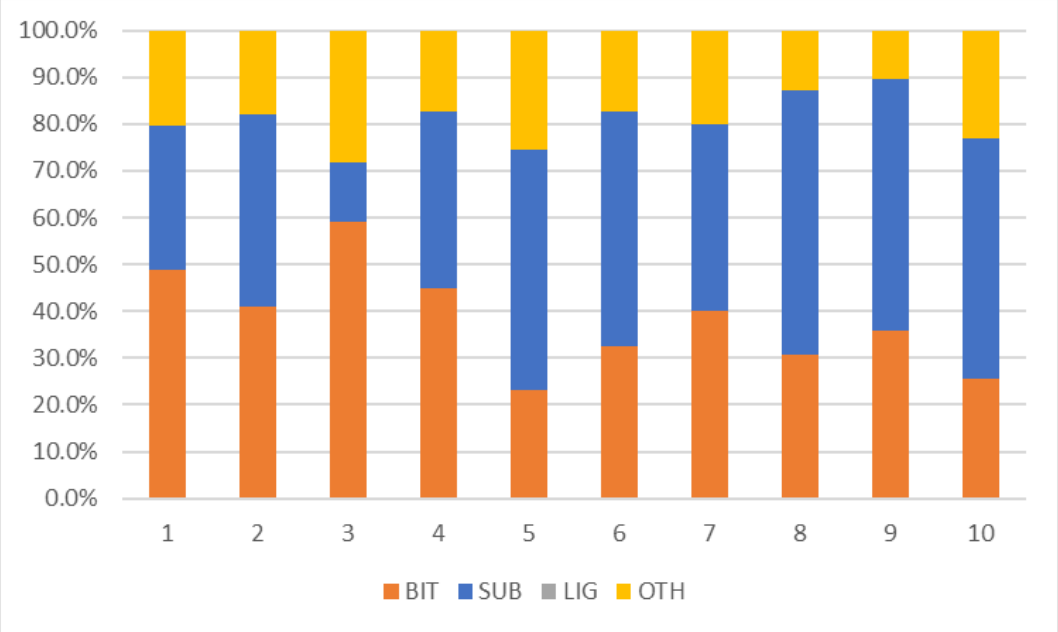
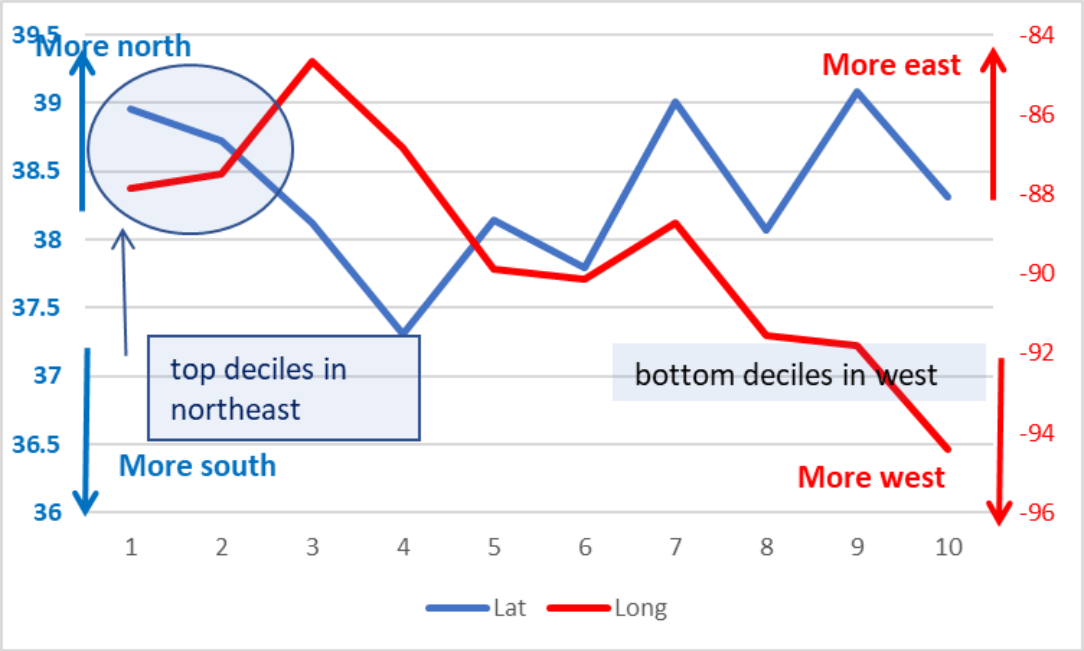


Figure 27. Coal type by decile, not low-rank virgin coal



Top deciles of not low-rank coal are more likely to be northeast (consistent with higher likelihood of bituminous coal). Figure 28 shows the average latitude and longitude by decile. Consistent with the finding that the top deciles were likely to be bituminous coal units and the bottom deciles were more likely to be subbituminous coal units, the top deciles are located in the east and the bottom deciles in the west. The top two deciles are solidly in the Northeast US.

Figure 28. Average latitude and longitude by decile

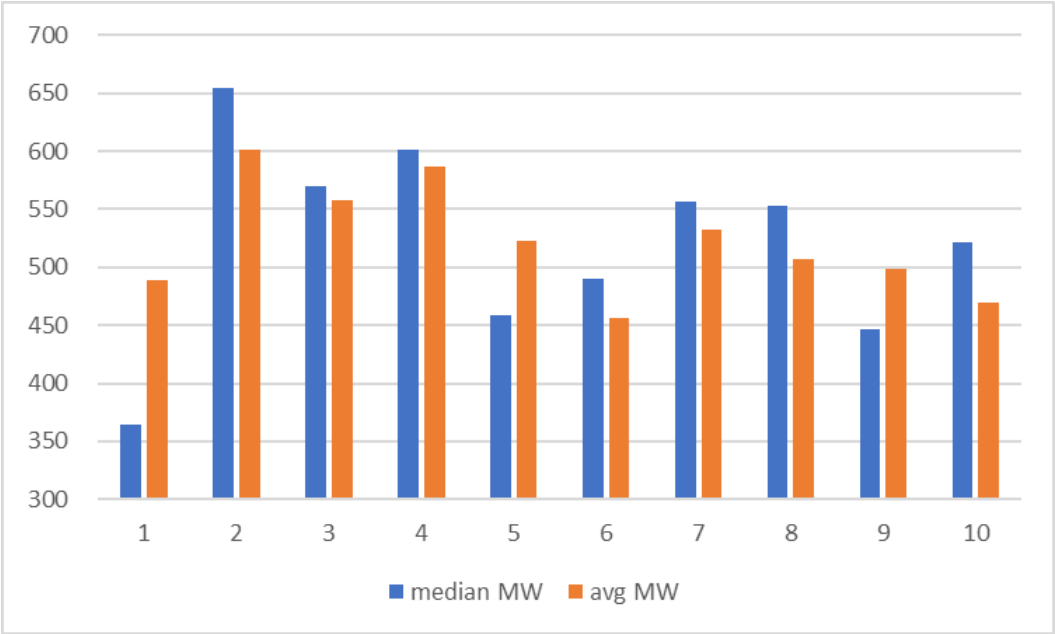


Bituminous coal has higher sulfur, which usually has a negative impact on Hg capture. Therefore, it is surprising to see a higher capture rate, and lower emissions from bituminous units. Subbituminous has lower halogens, but this is easily addressed.

There is no reason to believe that subbituminous coal is more difficult to capture mercury from than bituminous. Lower sulfur is a good impact while shortage of halogens is easily addressed. It is likely that this is more of an impact of equipment. Therefore, equipment configurations were examined.

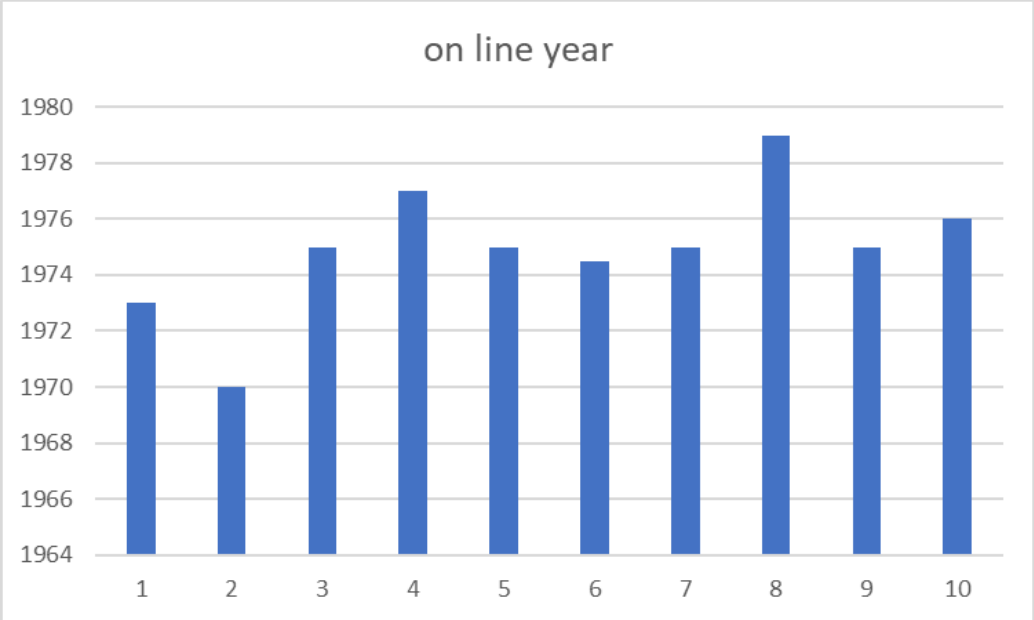
Figure 29 shows the median capacity of each decile. Decile 1 has the smallest units and decile 2 the largest, and there is no real pattern to the rest. Decile 2 has significantly larger units than any other decile. The size of the units can be significant in that it can be an indication of the importance of the unit in the utility fleet.

Figure 29. Median MW capacity by decile



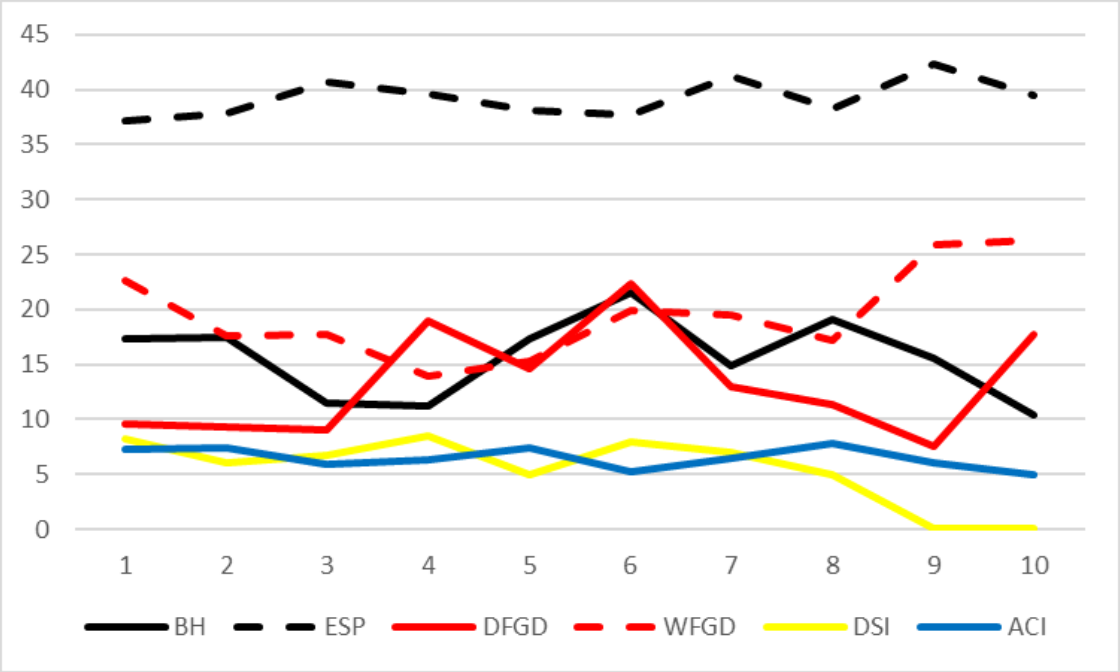
As Figure 30 indicates, the lower deciles may have a slightly more recent on-line year than the top deciles. However, it is not a large difference.

Figure 30. Median on-line year of each decile



The average age of equipment is shown in Figure 31. There are no apparent trends in air pollution equipment age, except that ESPs in top deciles are slightly newer than those in bottom deciles.

Figure 31. Average age of equipment (years) by decile



Baghouses are more likely in the top decile, as shown in Figure 32. ACI is more likely in the lower deciles, wet FGD is most common in mid-deciles. DSI is more common in top deciles. Because BHs are highly effective for mercury control, it is not surprising to see them in the top decile. The significance of ACI in the bottom deciles is consistent with ACI being one of the few technologies that owners and operators can "dial up" to get the level of capture needed because those units are only barely complying with the standard. For these ACI-equipped units that can effectively adjust their treatment rate to achieve just below the standard, there is little incentive for achieving a Hg emissions rate well below the limit because it would require additional cost associated with activated carbon.

As shown in Figure 33, baghouses in combination with ESPs are more frequent in the top decile – 30% of the top decile. ACI is most common in lower deciles. Scrubbers are most common in mid deciles.