Proceedings of ASME Turbo Expo 2015: Turbine Technical Conference and Exposition
GT2015
June 15 - 19, 2015, Montreal, Canada

GT2015-43736

EVALUATION OF AIR FILTRATION OPTIONS FOR AN INDUSTRIAL GAS TURBINE

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ABSTRACT

Gas turbines ingest large quantities of air during operation. As a result, large quantities of foreign particles ranging in size from smoke (0.01 to 1.0 micron) to pollen (10 micron) enter the unit and can contribute to both fouling and erosion depending on particle size. Fouling and erosion both lead to reductions in unit output and efficiency resulting in increased operational cost. Operators have historically combatted fouling through a combination of online water washes, more effective off-line water washes, and air filtration. As is the case with almost all engineering problems, the trade-off between the cost and effectiveness of these methods must be evaluated. Online washing is somewhat effective but has led to first stage blade erosion and unit trips in some cases. Off-line washing is more effective at cleaning the unit, but requires the unit to be shut down for extended periods of time. Air filtration can help prevent foreign particles from entering the unit, but higher efficiency filters are generally associated with a larger inlet pressure drop, leading to decreased unit output; this is balanced against reduced fouling rates. These tradeoffs between the costs associated with higher efficiency filters and the frequency of compressor washing need to be evaluated on a plant-by-plant basis to determine the best combination of air filtration and compressor washing programs. This paper presents a field study carried out to determine the effectiveness of high efficiency filters in preventing compressor fouling. Fourteen units at four sites were monitored over a 9 month to 3 year time period to determine the changes in unit performance and the impact of water washes on unit performance for both pre and final filters of lower and higher efficiency ratings. Results to date indicate that higher efficiency filters are effective at reducing the need for off-line water washes and potentially reduce life-cycle cost. Reduced output from the higher pressure drop, high efficiency filters is offset by the better performance retention offered from reduced fouling rates.

INTRODUCTION

There is long-term interest in evaluating the life-cycle cost of various gas turbine air filters. Life-cycle cost includes initial filter cost, replacement and maintenance costs, effects on plant heat rate (influenced by inlet pressure drops resulting from the filter), and rates of degradation [1]. Furthermore, the operational environment and unit loading profiles also play an important role in selecting the best filter. The work described in this paper is designed to help form the basis for a life-cycle cost evaluation.

OVERVIEW OF CONTAMINANTS

Depending upon particle size, there are three main degradation mechanisms to consider. First, erosion is caused by larger particles (>5 microns), such as sand, impinging upon the compressor rotor blades and stator vanes. Each impact removes a small amount of metal, eventually leading to reshaping of the aerodynamic surface. The rate of erosion is affected by the particle density and hardness in addition to its speed and angle of impact. This can cause stress concentrations, changes in clearances, and reductions in airflow and efficiency. In addition to power output reductions, changes in shape can reduce component strength and accelerate failure. Erosion is a form of non-recoverable degradation since the parts are irreversibly damaged. Only component replacement or off-line refurbishment can recover unit performance. For this reason it is essential that erosion be prevented. Fortunately, the larger particles that drive erosion can be easily filtered out. Erosion can also be caused by contaminated chillers, foggers, and online washes [2,3].

Smaller-sized particles (0.1 to 10 microns) generally do not have sufficient mass to erode the airfoils. Instead, they result in a buildup of materials in cavities and low flow-rate locations [1]. Particles less than 1.0 micron are typically less than 3% by weight of all dust particulate but make up more than 98% of the number of overall particles. In addition to small airborne particles, oil vapors, carbon smoke, hydrocarbons, water, salts, and other sticky substances increase the tendency for particles to adhere to surfaces. Fouling is generally recoverable degradation since water washing can remove many of these particles. Small particles such as metal oxide smoke, carbon black, smog, and fumes may be less than one micron in size and may pass through high efficiency filters.

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The final common degradation method is corrosion. There are two forms of corrosion, hot and cold. Cold corrosion affects the compressor and is caused by wet deposits of salt particles, acids, steam, and certain gases. The result is removal of material over an area or pitting. The end result is similar to erosion; a loss in performance and increased chance of failure due to stress concentrations and changes in the aerodynamic surface. Hot corrosion occurs in the turbine and is not only driven from external air contaminants, but also from impurities in the fuel. The effects of hot corrosion may be more serious with advanced gas turbines firing at higher temperatures. Depending on operational environment the contaminant sizes and types will vary. As a result there are many different filter types to allow the user to customize to a site's specific needs.

FOULING MITIGATION TECHNIQUES

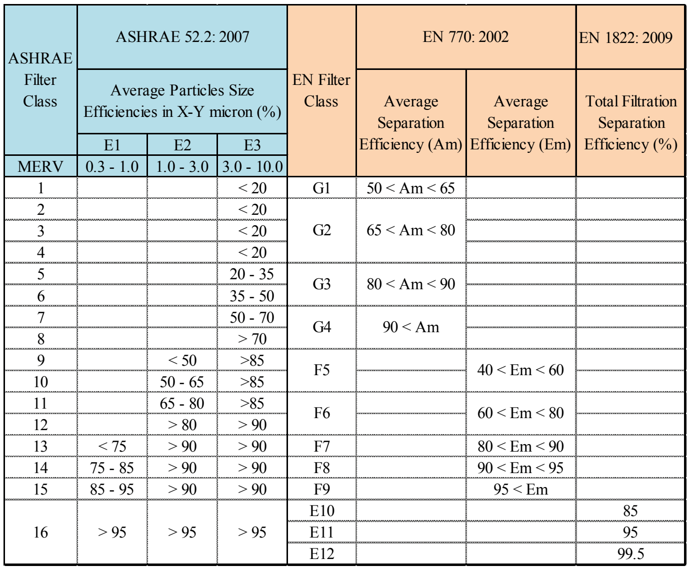
Gas turbines ingest large quantities of air during operation. For example, a GE 7FA gas turbine ingests on the order of 3,500,000 lbm of air per hour [7]. If the ingested air has a relatively low amount of contaminants (i.e. 1 ppm), this results in approximately 80 lbm of contaminants ingested into a large 7FA unit each day. Without filtration, contaminants can foul and erode the compressor, leading to reduced power output and efficiency; blocked cooling holes can lead to reduced turbine parts life; corrosion can also occur depending on the contaminant. While methods such as offline and online water washing exist to remove contaminants after they have entered the unit, they are not 100% effective at preventing fouling and unit degradation. Of the two washing techniques, off-line washing is more effective; however, it requires a unit to be shutdown which can be costly [4]. Online washing allows the unit to remain running; however, it is not as effective at removing contaminants and has a tendency to only remove contaminants from the front stages of the compressor while leaving the aft stages fouled [5]. Recently there has been increased interest in using very high efficiency filtration as a means to prevent fouling [6]. While more efficient filtration can help prevent contaminants from ever entering the unit, it also comes with the cost of increased inlet air pressure drop. This can have a significant impact on power output and heat rate. Conventional rules-of-thumb equate a 4 inches H2O inlet pressure drop to a 1.4% decrease in power output and 0.45% increase in heat rate [7]. A summary of fouling prevention and mitigation techniques is shown in Table 1. No method is without tradeoffs; ideally a cost-benefit analysis should be performed to identify the optimal combination of techniques for a particular site.

Table 1: Summary of Contaminant Mitigation Techniques

	Prevention of Fouling	Cleaning Effectivness	Effect on Power Ouput	Effect on Unit Downtime
Online Washing	⇩	⇗	⇗	⇨
Offline Washing	⇩	⇧	⇧	⇘
Air Filtration	⇧	⇨	⇘	⇨

FILTER RATING AND SELECTION

Filters are rated by their ability to capture contaminants in specific size ranges. Efficiency is often measured by weight (percentage of contaminants captured), dust spot efficiency, and particle count (% of particles captured). When comparing filters for efficiency one must ensure they are comparing the same measurement of efficiency. Two standards are used to rank relative filter performance. In the U.S. ASHRAE standard 52.2: 2007 provides a Minimum Efficiency Reporting Value (MERV). In Europe, EN 779:2002 and EN 1822:2009 provide standards for low and high efficiency filters respectively. Figure 1 provides a general comparison of U.S. and European filter standards.



ASHRAE Filter Class	ASHRAE 52.2: 2007			EN Filter Class	EN 770: 2002		EN 1822: 2009
	Average Particles Size Efficiencies in X-Y micron (%)				Average Separation Efficiency (Am)	Average Separation Efficiency (Em)	Total Filtration Separation Efficiency (%)
	E1	E2	E3				
MERV	0.3 - 1.0	1.0 - 3.0	3.0 - 10.0				
1			< 20	G1	50 < Am < 65		
2			< 20	G2	65 < Am < 80		
3			< 20				
4			< 20				
5			20 - 35	G3	80 < Am < 90		
6			35 - 50				
7			50 - 70	G4	90 < Am		
8			> 70				
9		< 50	>85	F5		40 < Em < 60	
10		50 - 65	>85				
11		65 - 80	>85	F6		60 < Em < 80	
12		> 80	> 90				
13	< 75	> 90	> 90	F7		80 < Em < 90	
14	75 - 85	> 90	> 90	F8		90 < Em < 95	
15	85 - 95	> 90	> 90	F9		95 < Em	
16	> 95	> 95	> 95	E10			85
				E11			95
				E12			99.5

Figure 1: Filter Classification (ASHRAE and EN) [1]

STUDY OVERVIEW

To characterize the performance levels of different filters, EPRI is engaging in a project with its members to test different filter types from several manufacturers to isolate effects of filter performance in gas turbine performance and degradation. Since the best air filter selection for a particular site is also dependent on the operational environment and unit operational profile, several different filter types from different OEMs are being tested on units in rural, coastal, and urban areas. A summary of the units being tested is shown in Table 2. All units are GE 7FAs.

The baseline filters for all units are 'lower' efficiency F8 final filters. As part of this ongoing test, the baseline filters were replaced with higher efficiency final filtration filters, as listed in Table 2. In some cases the F8 filter rating was maintained, but a different OEM was tested. This paper will not attempt to distinguish differences in filter performance between OEMs, but will show general performance gains that can be attributed to varying levels of filtration. The end goal is to isolate changes in long term performance for each unit that result from the changes in filter type. More specifically, effectiveness of each filter at preventing compressor fouling is of interest. Ongoing monitoring is being performed on sister units in an attempt to continue to isolate and remove unit-to-unit variation in filter performance. More experience will be needed to isolate the impact of E12 final filtration.

Table 2: Filter Test Matrix

Unit #	Filter Rating	Time Since Filter Install	Location
1	E10	~ 2 years	Rural
2	E10	~ 2 years	Rural
3	F8	~ 2 years	Rural
4	F8	~ 2 years	Rural
5	E10	~ 1 year	Rural / Coal plant
6	E12	~ 1 year	Rural / Coal plant
7	E10	~1 year	Rural / Coal plant
8	F9	~ 9 months	Rural / Coal plant
9	F8	~ 9 months	Rural / Coal plant
10	E10	~ 9 months	Rural / Coal plant
11	E10	~ 9 months	Rural / Coal plant
12	E10	~ 9 months	Rural / Coal plant
13	E11	~ 9 months	Urban
14	E12	~ 9 months	Urban

ANALYSIS METHOD

In order to isolate long term trends of using high efficiency air filtration, a method was needed to normalize operational data across seasonal and daily variations. Overall, factors influencing gas turbine performance include air temperature, ambient pressure, humidity, inlet and exhaust losses, fuel temperature, compressor bleed air, steam injection, inlet cooling, and load (firing temperature) [7]. Each factor is summarized in the subsequent subsections followed by a description of how a correction factor was applied to the data.

Ambient Temperature

As the ambient temperature increases, the air density decreases, resulting in a lower mass flow through the unit. This results in lower power output. In addition, it also increases heat rate. Evaporative coolers and inlet chillers, discussed later, are used to keep compressor inlet temperatures low. Figure 2 shows a generic correction curve that allows for comparison of gas turbine (GT) output and heat rate across a range of ambient temperatures. This type of a curve is commonly referred to as a correction curve and isolates the effect of a single parameter, temperature in this case, on the GT performance. Correction curves are generated for new-and-clean units by the OEM for base load conditions. Multiple correction curves can be linearly added to each other to estimate the impact of changes in multiple external factors. The plant performance at a given point can then be compared to the expected performance from the correction curves to give a sense of how much the unit has degraded. Correction curves can also be generated for part-load conditions; however, only base load was considered for this study.

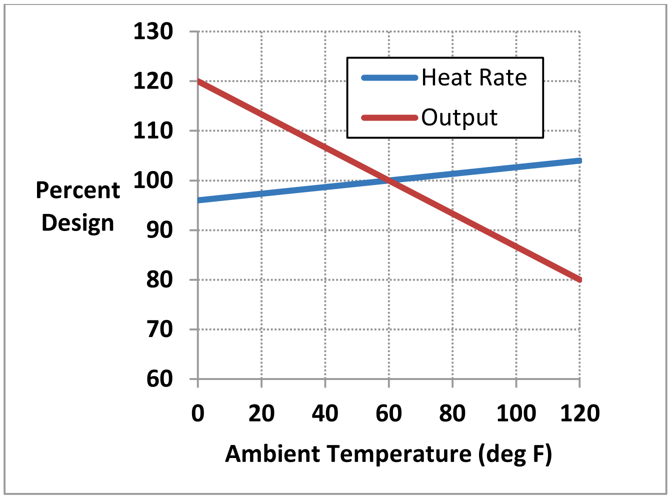


Figure 2: Effect of Ambient Temperature on GT Base Load [7]

Inlet and Exhaust Losses

Reductions in inlet pressure from air filtration, inlet blockage, or poor design will lead to reductions in performance. As the pressure decreases, air density decreases resulting in reduced power output. Furthermore, exhaust pressure drop, which is caused by pressure drops throughout the HRSG and exhaust stack creates a backpressure that reduces power output. As is the case with air temperature and humidity, pressure losses are considered to be a linear effect and common corrections, shown in Table 3, were used to correct for effects of inlet pressure and exhaust pressure drop [7].

Table 3: Inlet and Exhaust Loss Corrections [7]

	Power Output Loss	Heat Rate Increase	Exhaust Temperature Increase
Inlet Drop (4 inches H2O)	1.42%	0.45%	1.9 F
Exhaust Drop (4 inches H2O)	0.42%	0.42%	1.9 F

Fuel Effects

Differing fuel types can have a dramatic effect on GT performance due to different fuel calorific content; however, the plants were operated on natural gas throughout the monitoring window of this analysis, so fuel type correction was not a needed. In addition to fuel type and composition, fuel temperature also has an effect on output. At base load, a gas turbine is often controlled to a fixed firing temperature, so increases in fuel temperature result in lower fuel consumption. Higher fuel temperatures mean less heat from the combustion process is needed to bring the fuel-air mixture to firing temperature. As a result, fuel consumption is reduced. There is a small secondary effect in that power output is slightly reduced from the small reduction in mass-flow through the turbine; however, the overall effect of higher fuel temperature is beneficial from a heat rate perspective. For this reason, fuel gas heating is often used at combined cycle power plants. Hot water from the intermediate pressure (IP) steam system is often used to pre-heat the fuel gas before combustion.

The performance data indicated that a large majority of base-load operation occurred at constant fuel temperature, therefore corrections to performance based on fuel temperature were not necessary in this analysis.

Compressor Bleed Heat

Air is extracted from the aft stages of the compressor to heat compressor inlet air during some modes of operation. In cold temperatures inlet heating may be used to prevent icing. In cold weather the exhaust gas temperature can drop due to reductions in ambient temperature. As a result the temperature entering the HRSG will be reduced leading to reduced power output from the steam turbine. Depending on the combustion system, inlet heating may also be used for emissions control. Finally, during startup and low load operation bleeding air from the compressor alleviates backpressure that can lead to stall and surge.

The compressor bleed flow percentage was not available from the plant performance data for this study. Fortunately, the performance data by the end-user had corrections to heat rate and power output embedded as a function of inlet bleed heat delta temperature, which was available. These linear corrections, shown in Figure 3 and Figure 4 were extracted and used to correct out the effects of bleed heat on performance.

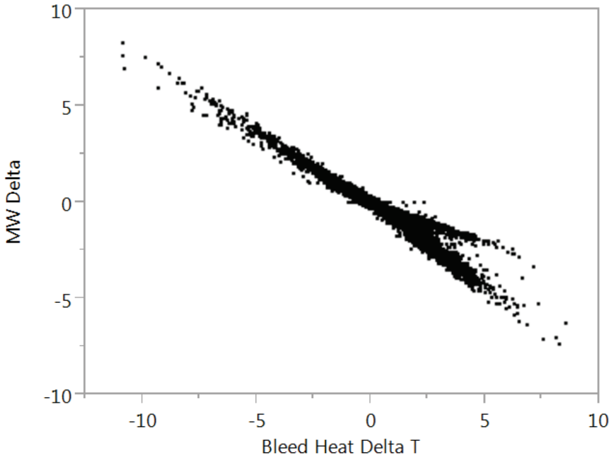


Figure 3: MW Bleed Heat Correction

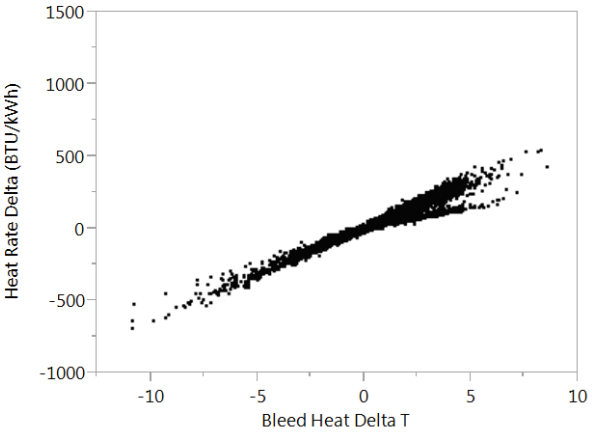


Figure 4: Heat Rate Bleed Heat Correction

Evaporative Cooling

As shown in the ambient temperature correction curve, Figure 2, reducing compressor inlet temperature increases power output significantly and contributes to a minor improvement in heat rate.

There are several options available to reduce compressor inlet temperature including foggers, chilled water, and evaporative cooling. The units in this study use evaporative cooling, the effects of which are described in Reference 7. While evaporative cooling is most effective in hot, dry climates, there is a significant effect even in more humid conditions.

COMBINED CORRECTION METHOD

To normalize GT performance across the monitoring window the following correction equations were applied to the units after filtering to base load operation. The general goal of the correction process is to isolate the effect of external conditions on gas turbine operation. By 'correcting out' external influences on performance including inlet and exhaust pressure drop, compressor bleed heat, and temperature, the efficiency and power output of the unit can be compared to the 'new-and-clean' rated performance. This ratio between expected performance and rated new-and-clean provides information on how the unit has degraded. By examining data before and after water washing, compressor performance trends can be isolated. The correction equation for power output is shown in Equation (1) and the correction for heat rate is shown in Equation (2). The MWrated and HRrated are the ISO rated output of 171.7 MW and 9360 Btu/kWhr respectively. Pressure drops are measured in inches of water. The delta bleed heat corrections are derived from Figure 3 and Figure 4, discussed previously. These normalized values can be trended over time to track GT degradation.

$$MW_{norm} = \frac{MW_{65F}}{MW_{rated}\left[1-0.0142*\left(\frac{Filterdp}{4}\right)-0.0042*\left(\frac{Exhaustdp}{4}\right)\right]+MW_{delta,Bleed}} \quad (1)$$

$$\boldsymbol{HR_{norm}} = \frac{\boldsymbol{HR_{65F}}}{\boldsymbol{HR_{rated}\left[1-0.0052*\left(\frac{Filterdp}{4}\right)-0.0047*\left(\frac{Exhaustdp}{4}\right)\right]+HR_{delta,Bleed}}} \quad (2)$$

OFF-LINE FILTER TESTING

As part of this study, both new and used filters are being tested in a lab environment. These tests are used to validate vendor claims, compare products from different vendors, monitor pressure drop and efficiency trends over time, and examine the mechanical integrity of the filters. Used filters, of various efficiency ratings and from multiple sites, were removed at regular intervals and tested using ASHRAE 52.2 and/or EN 1822 protocols. Results from these tests for the high efficiency filters in this study are shown below. F7 and E10 correspond to the EN ratings of the pre and final filter stages.

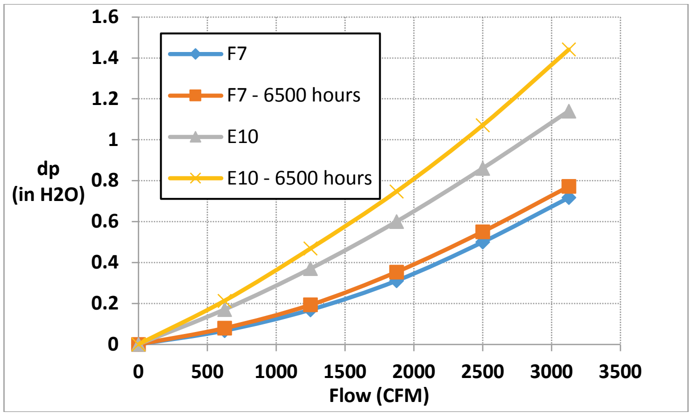


Figure 5: ASHRAE 52.2 Test Results : dP

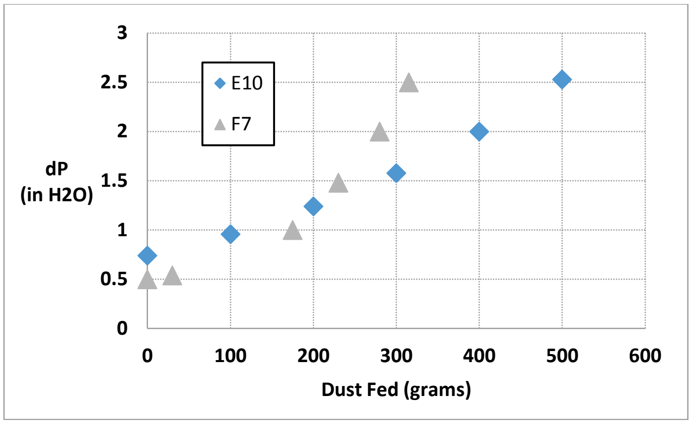


Figure 6: ASHRAE 52.2 Test Results: Dust Holding Capacity

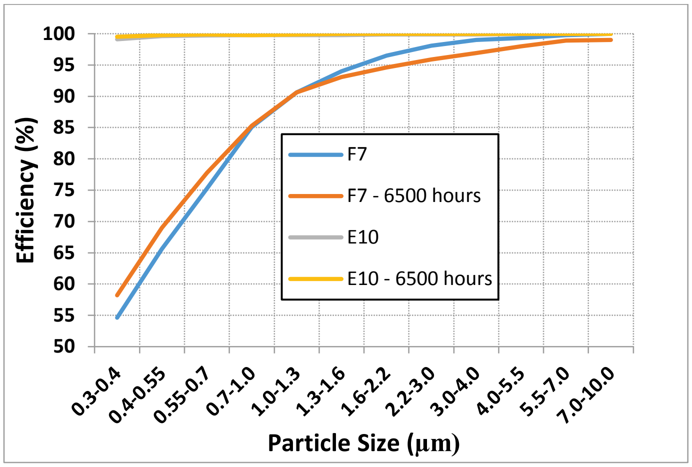


Figure 7: ASHRAE 52.2 Test Results: Efficiency

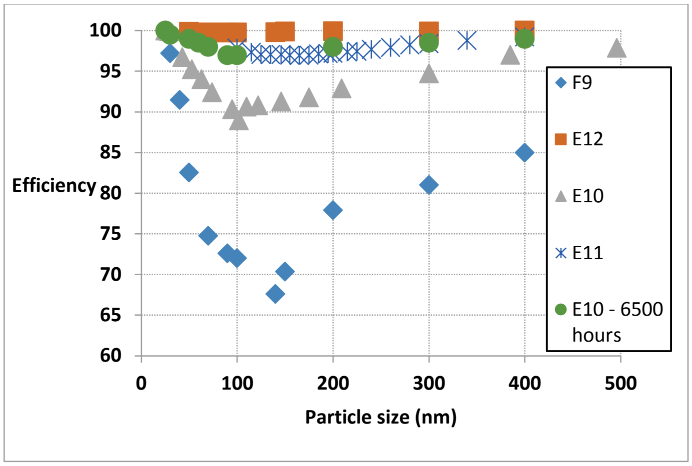


Figure 8: EN 1822 Test Results

Figure 5 shows the results of the ASHRAE 52.2 dP vs. flow test results where dP is shown on the y-axis in inches of H2O and flow is shown on the x-axis in cfm. The higher efficiency E10 filter has a higher initial pressure drop than the F7 filter by about 0.3" at 2500 cfm. The higher efficiency filter also increased in dP more over the same period of time. This indicates that the higher efficiency filter is removing a larger number of particles from the air and that there is a significant amount of fine particles at this site. The rise in dP can be used to estimate filter life using the dP vs. dust collected curve (Figure 6) as filter change out is typically recommended at 2.5 inches H2O for final filters. Note that the E10 filter in this case is of an extended length design which provides a higher dust holding capacity and lower initial pressure drop relative to normal length designs.

In Figure 7 the results of the efficiency portion of the ASHRAE 52.2 test are presented. Clearly, the E10 filter is much more efficient, especially with respect to the finer particles. As expected, filter efficiency did not change much over time. In theory, as the filter is loaded the efficiency should actually increase slightly. The efficiency testing is primarily to confirm that the mechanical integrity of the filter is being maintained. Throughout the many tests that have been performed as part of this project most filters have exhibited this behavior. However, certain electrostatically charged synthetic medias have shown a significant drop in efficiency after being subjected to run time in a power plant environment. The results were inconsistent with the Appendix J test which was performed on a new version of the same product. This suggests that the Appendix J protocol is not reflective of filter performance in harsh environments and caution should be taken before selecting an electrostatically charged synthetic media as a final protective stage.

Figure 8 shows the results of several EN 1822 tests and compares the efficiencies of F9-E12 filters. This chart shows how the primary difference between HEPA filters and lower efficiency filters lies within their ability to filter out fine particles (0.05-0.5 microns). Note that the E10 filter that was re-tested after 6500 hours of service had increased in efficiency to the point where it had achieved an E11 rating.

LONG TERM FILTER PERFORMANCE

The goal of this analysis is to use the data processing methods, described above, to assess the impact of upgrading to higher efficiency filtration. Since the intent of this analysis is to isolate the effect of changing to high efficiency filters, the average GT performance for all units for the week prior to and after each off-line water wash was compared. In addition to the normalization process described previously, this will further isolate changes in performance to compressor degradation. Since off-line washes are conducted during outages there may be other maintenance activities which will affect heat rate and power output; therefore, compressor efficiency will also be compared before and after each wash to correlate changes in compressor efficiency to changes in power output and heat rate. Large recoveries in GT performance after each off-line wash indicate the filtration system is not doing a good job at preventing compressor fouling. Small or minimal changes in performance after each wash indicates the filters are performing well at preventing compressor fouling.

To establish an operational baseline, the units were examined over two years prior to installing the new, high performance filters. To provide a common basis for comparison, operating data was filtered to examine only operational points at baseload. The following conditions were used to identify base-loaded operating points:

- Inlet Guide Vanes (IGV) full open
- RPM within +/-5 of 3,600 rpm (full speed)
- Unit operating on baseline control curve

While the first two checks for base load operation are straightforward the third item merits some explanation. GE single-shaft units are operated on a control curve which is a linear function of exhaust gas temperature vs. compressor discharge temperature. Therefore, any operating points that do not lie on this line can be removed from the analysis.

Figure 9 shows long term trends of power output and heat rate corrected to a standard day for one of the units. Data points are plotted for every 30 minutes of operation. Note the corrections to remove the effects of bleed heat and inlet and exhaust pressure drop have not yet been applied. The data has been color coded to show when the filters were upgraded and when the pre and final filters were changed out. Blue indicates the original filter set. In summer of 2012, both the pre and final filters of the original low efficiency filters were changed. Then the low efficiency pre filter was changed in late 2012. Finally, the new high efficiency filters were installed in March of 2013. Since filter change intervals were not regular or evenly spaced, degradation in heat rate and power output has been calculated in terms of change in MW or percent heat rate per million megawatt hours (MMWHr). This allows for comparison between operational periods. The purpose of this plot is to show that even with good quality data there is significant scatter, even in the days immediately preceding and following each offline wash; therefore, it makes sense to examine recovery across each water wash as test points that are part of a random distribution.

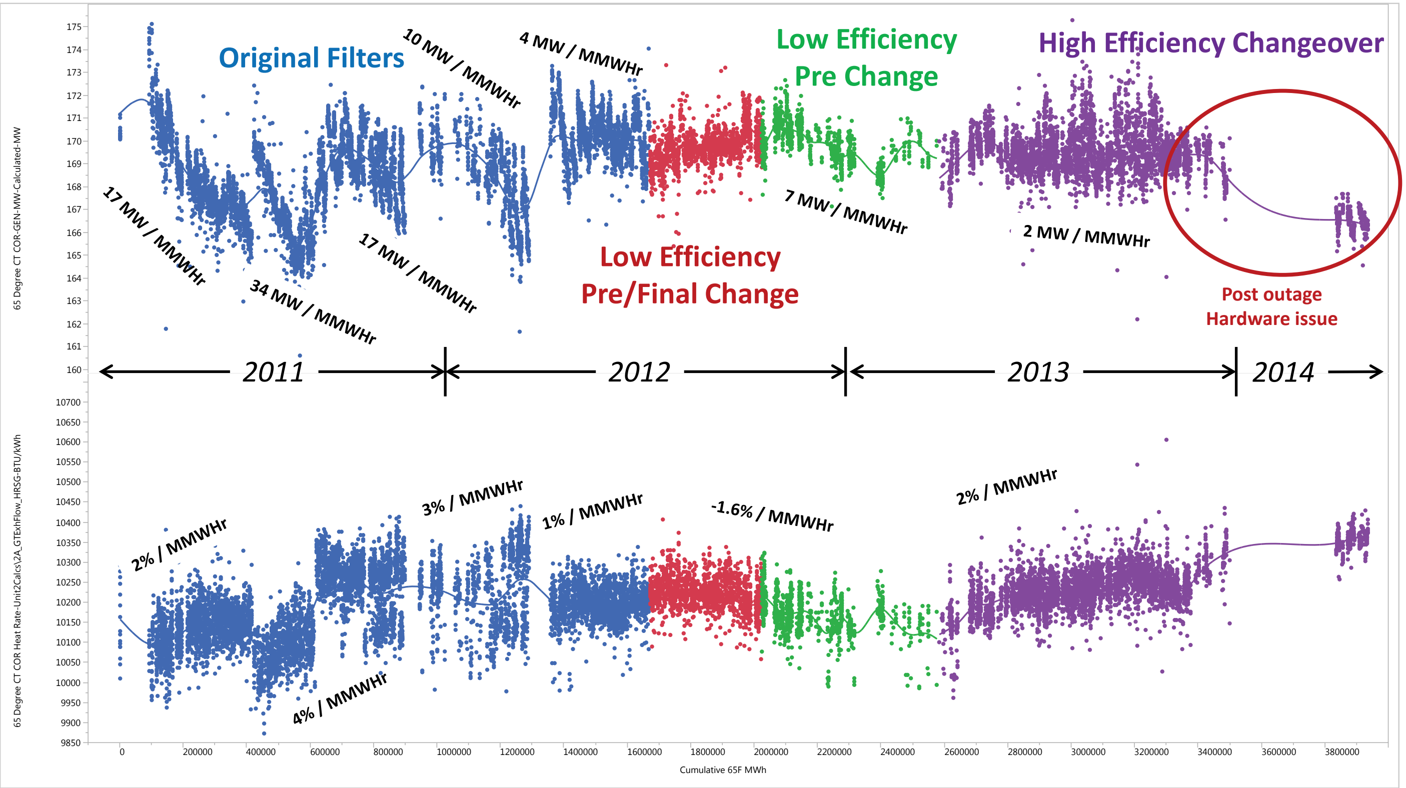


Figure 9: Example Unit Base Load Long Term Trends

In order to better quantify the long term effects of the new filters across all units from Table 2, the cumulative MWh (corrected to 65F) between each off-line wash was used to calculate the MW recovered during each wash per million of MWh run time. By normalizing power recovered during each wash per MW hour, differences in time and usage between washes can be accounted for. Using MWh is essentially a surrogate for total amount of mass that has entered the unit; using only running time does not account for changes in load over time. This also enables comparison between units with different wash schedules and capacity factors. Compressor efficiency, also corrected to a 65F day, was also normalized by cumulative MWh between washes. More than 100 data points (i.e., pre/post offline wash analysis) were collected across the 14 units over the three year monitoring period for F8 final filter ratings, 20 data points were collected for E10 filtration, and one and two data points were collected for F9 and E12 filters respectively. Extreme outliers and obviously bad data points were removed from the analysis.

Figure 12 is a histogram showing the compressor efficiency recovered by offline washing for the F8 and E10 filter ratings. The histogram shows the number of data points recorded for each range of compressor efficiency recovery per MMWh. Only single data points are available for F9, E11, and E12, and are shown in Table 4. There are some points that show negative recovery, which may be the result of inaccuracies in measurement, data collection and recording, the data correction process, or other events that may have occurred during the offline wash. A high value of recovery is indicative of more fouling on the compressor and therefore less effective filtration than a low value.

On average an increase in compressor efficiency of 2% per MMWh was recovered for the F8 filters; however, the spread in the data is quite wide. Recovery up to 11% per MMwh was recorded in some instances. There were also some instances of a reduction in compressor efficiency after an offline wash which explains the recovery for F8 including some negative values; however, these instances were relatively infrequent. Furthermore, more than 80% of the E10 data points showed between 0-1% compressor efficiency recovered per MMWh. When compared to the E10 data there are two noticeable and important observations. First, an average of one-third percent efficiency was recovered from offline washing when E10 filtration was installed. This means that E10 filters were effective at retaining an additional 1.5% compressor efficiency over F8 filters after one million MWh (or approximately 6,000 firing hours at baseload). The F9 filter performance only has a single data point to date, and while it lies nicely between the F8 and E10 averages, more data is needed to show the F9 filter's relative performance. The E12 data point appears to lie close to the E10 average; however, there is often significant variation from measurement, wash effectiveness, and operating conditions and more data is needed to analyze this trend. The second important observation that can be gleaned from Figure 12 is that E10 filtration has a smaller distribution on compressor performance recovery and therefore less variation in the performance when using E10 filtration.

Figure 13 and Table 4 show the results of the same analysis for power output. The overall conclusions are similar to those from analyzing compressor efficiency recovery. E10 filtration provides both a better, and more consistent power output by almost four percent rated output. Here again the F9 lies between the F8 and E10 averages, and the E12 data points lie to the left of the E10 average recovery Again, less performance recovery after an offline wash means that the filtration is more effective. The F8 average recovery lies close to 5% output per MMWh whereas the E10 curve averages 1.5% output per MMWh recovery resulting from each offline wash. This represents significantly less performance degradation over time. Figure 13 contains a handful of data points that show a reduction in power output, this may be due to other maintenance activities that occur during the outage. This is why it is also important to examine both compressor efficiency and power output when attempting to make conclusions on the effect of filtration.

Some of the E10 filters were left in place for almost a year before offline washing, further verifying their long term benefit. In addition to analytical and performance based metrics, a visual inspection of IGVs and 1st stage compressor blades when using the F8 and E10 filters are shown in Figure 10 and Figure 11 respectively. These two units are located at the same site, with similar operating profiles, which reduces the possibility of operating environments leading to any observed differences. The F8 filter, which had two offline washes during 5,000 hours of operation showed significant fouling on the IGVs and 1st stage blades. The E10 filters, after 6,500 hours show little evidence of fouling compared to the F8 filter. This is especially noticeable when examining the leading edge of the 1st stage blades.

Figure 10: F8 Filtration after 5,000 Hours (Two Offline Washes)

Figure 11: E12 Filtration after 6,500 Hours (No Washes)

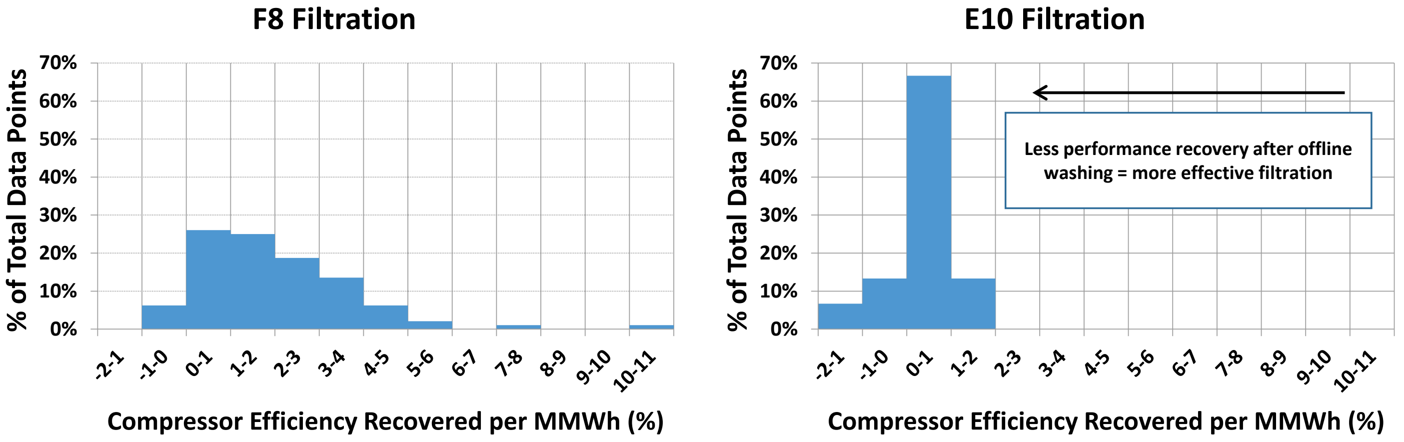


Figure 12: Histogram of Compressor Performance Recovery per MMWh Resulting From Each Offline Wash

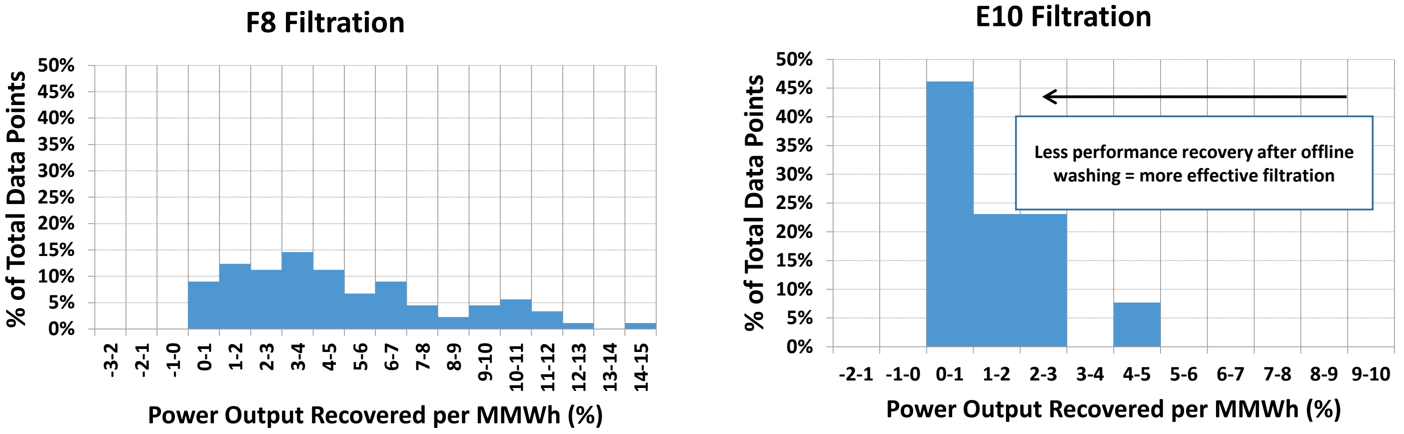


Figure 13: Histogram of Power Output Recovery per MMWh Resulting From Each Offline Wash

Table 4: Isolated Data Points for F9, E11, and E12 Filters

Filter Rating	Compressor Efficiency Recovery per MMWh (%)	Power Output Recovery per MMWh (%)
F8	2.0 *(Average Across All Sites)*	5.0 *(Average Across All Sites)*
F9	1.5 *(Single Data Point)*	2.2 *(Single Data Point)*
E10	0.33 *(Average Across All Sites)*	1.5 *(Average Across All Sites)*
E11	Not Available	0.9 *(Single Data Point)*
E12	0.4 *(Single Data Point)*	0.25 *(Two Data Points)*

CONCLUSIONS

A method has been applied to assess the effectiveness of various air filters at preventing compressor fouling and analyze data to account for various operating conditions at base load. Analysis on fourteen units at have shown that E10 filtration helps retain 1.5% compressor efficiency and 4% rated power output over approximately 6,000 firing hours relative to F8 filtration. While the higher efficiency filtration does carry a higher pressure drop, testing indicates this would only reduce output by 0.25 to 0.5 percent rated power. This still results in a long term gain of more than 3% rated power output on average. In addition to significant gains in performance retention, several of the E10 filters were run for an entire year without offline washing, further underlining their much improved performance over the F8 filters. More analysis is needed to understand the cost-benefit of E12 filters relative to E10; however, the very preliminary results shown here look promising on a performance basis. These benefits will manifest themselves not only through increased revenue from retained power output, but could allow for a reduction in the number of offline washes, should the cost-benefit merit this for a specific site. In addition to the monetary benefits that result from improved performance, other benefits of improved filtration include reduced risk of component failure from erosion and corrosion issues.

Although the study used filters manufactured by different filter manufacturers, each manufacturer produces a multitude of products at different performance levels and the intent was not a comparison between manufacturers. Higher efficiency filter arrangements have shown consistently better gas turbine performance over time and have demonstrated the ability to minimize compressor fouling as indicated by performance retention over time.

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