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ENVIRONMENTAL CHARACTERIZATION AND IN-SITU TESTING FOR GAS TURBINE INLET FILTER SYSTEM SELECTION

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ABSTRACT

The importance of proper inlet air filtration for the modern gas turbine is understood within the industry with respect to potential performance degradation due to compressor fouling, erosion, and corrosion. A poor performing inlet filter system can have a large negative impact on turbine performance such as increased heat rate, reduced power due compressor fouling and /or high filter pressure drop. For optimal performance, manufactures of air inlet filter systems recommended that the design of a filter system be tailored to the local environmental conditions. Typically, these conditions are generalized such as urban, rural, industrial or coastal. These generalizations are often inadequate, as are the engineering standards which rate filters. The engineering standards, ISO, ASHRAE, EN, are useful for measuring and comparing performance under controlled conditions. These standard methods test with synthetic contaminants, which replicates particle sizes seen in nature, but not always the chemical nature and particle concentrations. In addition, these rating standards do not address typical environmental conditions of high humidity, rain and snow. Coupled with the fact that many gas turbine sites have little data about their ambient aerosol contaminants supports the value of matching filter to its environment This paper discusses the various methods for identifying these conditions which affect the performance of a filter system. The discussion will include traditional methods of aerosol sampling and a novel method of in-situ testing; using a mobile air filter test laboratory. The later method allows for comparative analysis of different inlet filters while exposed to a real turbine operating environment. The on-site method has the benefit of exposing the filters to the varying conditions of the operating site but does require more time and specialized equipment. A general summary of tests conducted over the last five years and how this type testing can be beneficial to a gas turbine operator will be presented.

Introduction

The environment in which a gas turbine operates will have an impact not only the turbine's performance, but also its reliability and maintenance requirements. A key environmental factor that affects gas turbine operation is the level and type of aerosol contamination. Airborne contamination in the form of particulate can cause serious performance and maintenance issues. Specific problems that airborne particles can cause are:

- Foreign Object Damage (FOD)
  Large objects are ingested by a turbine that damages the turbine's compressor blades; often resulting in catastrophic damage.

- Erosion
  Ingestion of particles greater than 2 microns in size that over time will erode compressor blades. This erosion will result in a change of the blade's aerodynamic profile, as well as the tip clearance. These changes will decrease the performance of the compressor section and thus overall turbine performance.

- Corrosion
  Ingestion of corrosive/reactive particulate that over time will result is corrosion of turbine components such as salt particles present in coastal, marine environment. Hot end corrosion is an often-cited case, where salt present in the combustion air chemically reacts with any residual sulfur in the fuel. The result of this reaction is highly corrosive gas that will attack the blades and components of the turbine's power section.

- Plugging of cooling passages
  Ingestion of small particles that eventually plug cooling passages of the combustion blades. The result of blocking of these passages could be a thermal failure/fracture of a blade and catastrophic turbine damage.

- Fouling
  Fouling of the turbine's compressor blades is the case where small particles (< 2 micrometres) attach to surfaces the blades. Over time particles will build up on the blades ("foul them") which will alter the aerodynamic profile of the blade and increase the aerodynamic drag of the blade due to increased surface roughness. The net effect is decreased compressor efficiency, which results in reduced power output and increased heat rate of the machine.

Compressor fouling requires maintenance procedures by the operator to recover the lost power. Washing of the compressor section, both on-line and off-line (soak wash) is done to reduce the effects of fouling. Off-line washes are more effective than on-line washes but are also more expensive due to added material cost and the down time (lost production) of the turbine. Frequency of compressor washing can be reduced by appropriate inlet filtration.

There are a wide variety of inlet filtration systems to address the above risks. There are two general classifications of inlet filtration systems: static and self-cleaning. A self-cleaning system is one where the filters of the system are periodically cleaned to minimize the pressure drop cause by contaminant loading. Typically, self-cleaning of the filters is accomplished by a reverse pulse of compressed air, 7 bar for 100 ms, that dislodges the dust/ contaminant from the filters. Self-cleaning filters are usually round cartridges. Static systems are simply systems that do not self-clean and generally consistent of multiple stages. Where filtration efficiency increases with each successive stage. Static filters are commonly panel or vee bank in configuration. Within these two classes there are a wide range of filter types and filter efficiency levels.

Manufactures recommend that inlet systems be tailored the environment in which it will operator. Tailoring will result in optimizing performance of the gas turbine (compressor efficiency – power output, heat rate), reduced maintenance and overall life cycle cost. Examples: A self-cleaning systems is best applied in a high dust environment such as Southwest United States or the deserts of the Middle East. Self-cleaning systems are also applied in snow and ice environments, where snow may load a filter. Likewise, a static filter system with a rain vane separator and hydrophobic filter media would best applied in a coastal or marine environment. For heavy industrial environment with a high percentage of small particles, which contribute to compressor fouling, inlet systems with high efficiency filters (≥ E10 per filter test standard EN1822) would be a correct selection.

Discussion

Air filter test standards

There are several different test standards which are being used to describe performance of filters used for gas turbines. Examples included: ISO 16890, 29461, 29462 ASHRAE 52.2, EN 779, 1822. These standards measure the basic filter parameters, pressure drop, efficiency and dust holding (filter service life). Unfortunately, these tests all differ in some manner which can result in confusion for a GT operator. Currently four different rating systems are being used to define efficiency performance of GT air filters. The table below is a *simple* comparison of these standards, a full discussion is beyond the scope this paper.

Table 1: Air filter test standards

Test Standard	Efficiency Particle size µm	Electro Discharge	Rating Term	
ISO 16890	1, 2.5 , 10	yes	E_{epm}1, 2.5, 10	
EN 779	0.40	yes	G1 – F9	
ASHRAE 52.2	0.3-1.0	Optional	MERV 1-16	
EN 1822	Most Penetrating Particle Size [MPPS] Typ. 0.1 -0.2	Optional	E10 -E12	"High" eff. filters

Dust holding capacity (DHC) is often measured for GT filters and is used as a proxy or estimate for filter service life. Here too, the test standards differ, using two different test dusts to determine DHC. Table 2 below summarizes the DHC differences of each standard. The biggest difference is the type of test used. DHC results for the same filter can vary by 2 to 4 times just due to the difference in test dust. Generic description is that ISO fine test dust is SiO_3 based material that simulates desert dust and has median particle size of about 9 µm. The ASHRAE dust is a mixture of ISO fine, submicron carbon and cotton fibers, which attempts to simulate non- desert environments. It has a median size of about 3 µm and has the lower DHC values. The other notable difference is that the final dP used for test standards are lower than the levels where GT filters would be typically changed. These levels are more on the order of 750 to 1000 Pa, So, when comparing DHC test reports of different filters, it is important to verify that the same test dust and final pressure drop were used.

As dust conditions vary around the world, the standard test dusts are a poor representation of what is found at most gas turbine sites. When estimating filter life, consideration should be made of the test dust used compared to the type of contaminates at the GT site. For example, ISO fine test dust DHC is a poor proxy for a GT site located in an urban area or refinery where there is a high concentration of sub-micron particles.

Table 2: Test standard DHC comparison

Test Standard	Test dust	Final dP*
ISO16890 DHC is Optional	ISO fine	450 Pa
EN 779	ASHRAE	450 Pa
ASHRAE 52.2	ASHRAE	User defined
EN 1822	None	NA

Another shortcoming of the standard rating methods is they do not address different environmental conditions, such as high humidity rain and snow. Engineering laboratory testing can be conducted to replicate some environmental conditions, and their effect on filter performance, but these effects are not considered when filters are rated per the current standards.

Environmental Characterization

As outlined above, air filter test standards, can provide initial information when evaluating GT filter selection. But as shown, these standards can be confusing and not reflect filter performance in their operating environment. Therefore, characterizing site conditions will provide the GT operator additional information to aid their filter selection.

Figure 1 provides some general recommendation for matching various filter systems to the local environment. However, in many cases, these generalizations are inadequate and further analysis of the ambient condition is required. The analysis methods range from a simple one-time review to more complex time weighted methods, where the concentration, size distribution and chemical nature of the airborne particulates data is collected.

For new installation, data collected in this manner is very important in specifying a filter system that will provide the best life cycle cost. For existing operations, aerosol sampling and in-situ filter testing are conducted as a problem-solving tool. Problems addressed by these tests included: corrosion, short filter life, high operating pressure drop, and compressor fouling

The remainder of the paper discusses, various methods to analyse site conditions.

Environment	Contaminant	Filtration
Coastal	Salt	Pre-filter and/or high efficiency filter
	Cooling tower aerosols	Coalescer
	Land based contaminants	Pre-filter and/or high efficiency filter
	Water (rain, sea mist)	Vane separators, coalescers, weather hood
	Sand	Pre-filter and/or high efficiency filter
Marine	Salt (wet)	Vane separators, coalescers
	Salt (dry)	Pre-filter and/or high efficiency filter
	Sand	Pre-filter and/or high efficiency filter
	Ice	Anti-icing: compressor bleed
	Water (rain, sea mist, waves, wakes)	Vane separators, coalescers, weather louvers
Offshore	Salt	Pre-filter and/or high efficiency filter
	Cooling tower aerosols	Coalescer
	Land based contaminants	Pre-filter and/or high efficiency filter
	Water (rain, sea mist)	Vane separators, coalescers, weather hood
	Sand	Pre-filter and/or high efficiency filter
	Hydrocarbons, soot, exhaust	High efficiency filter
	Sand blasting	Pre-filter
Desert	Sand	Self-cleaning filters, inertial separators
	Pollen, sticky substances	Pre-filters
	Fog or high humidity	Coalescer and vane axial separator

Figure 1: Environment/filtration recommendations;
from GMRC guideline for gas turbine inlet filtration systems [1]

Observation/Available data

Simple common-sense observation is the first step in reviewing a gas turbine site. Items to note in the initial observation include: topography, prevailing wind direction and typical speed, near-by contaminant generators such as cooling towers, refineries, industrial plants and freeways. This first order review is helpful in comparing the findings to the general recommendations of figure 1.

Often a search of available information will provide greater detail for the site conditions. Examples include: pre-construction aerosol sampling, and aerosol monitoring stations where 2.5 and 10 µm size particle concentrations (PM 2.5, PM10) data is recorded. An example of such data is given in figure 2.

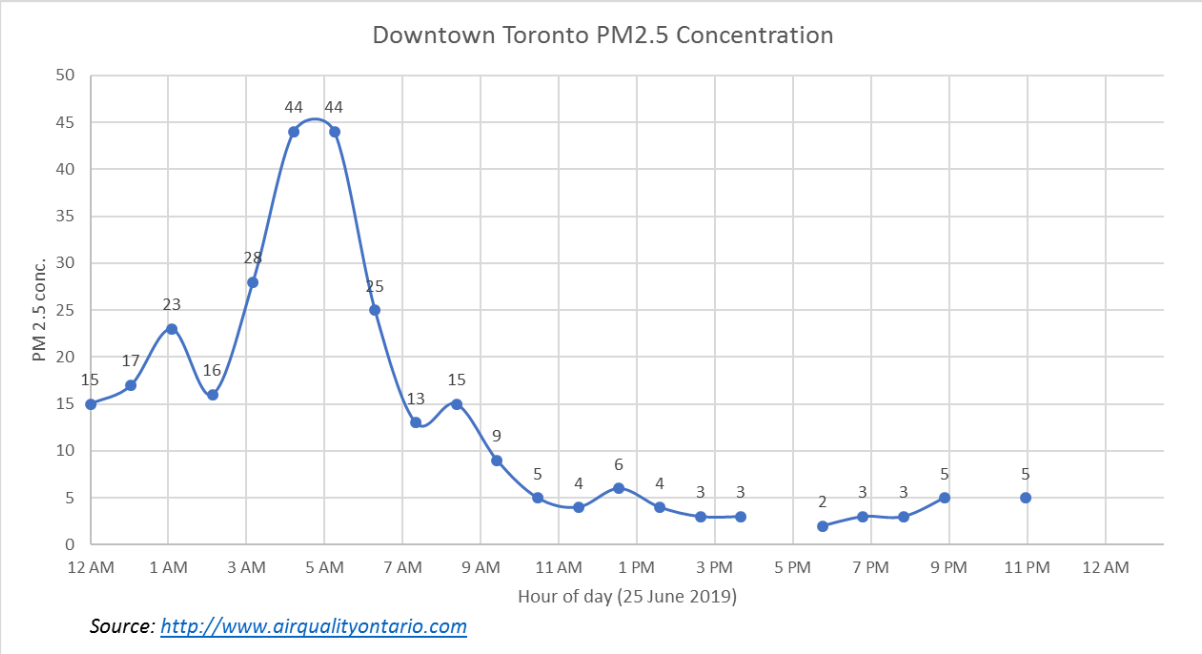

Figure 2: Typical PM2.5 Data

Existing operations

For existing operations, the next step of a site review is to analyse the historical turbine and filter systems data. In addition, it is beneficial to conduct an analysis on a filter element from the site.

The historical analysis includes reviewing the data trends of: filter pressure drop, compressor degradation, and heat rate. Also, the frequencies of compressor washes, and the amount of degradation recovery are good indicators of fouling severity and the associated particulate environment.

Submitting a used filter to a filtration laboratory provides information as to the performance of the system in local environment. Also, the contaminant collected by the filter is characterized. Typical tests conducted on a returned gas turbine filter are:

- Airflow pressure drop – confirms field data
- Filtration efficiency – identifies current performance
- Filter media sectioned
    - Strength of filter media
    - Contaminant analyzed via SEM

One method to analyze the collected contaminant is to examine a section of dirty filter media with a scanning electron microscope (SEM). Where the size and shape of individual particles can be determined, figure 3. Also, some SEM's have the capability to determine the elemental nature of the particles by using energy dispersive X-ray spectroscopy (EDX). EDX is an optional instrument that works in conjunction with the SEM. The EDX will identify what chemical elements are present in the sample of filter media, figure 4. For example, if salt were present in a sample the EDX would identify the Na and Cl; from this data the inference would be made the NaCl was the particulate.

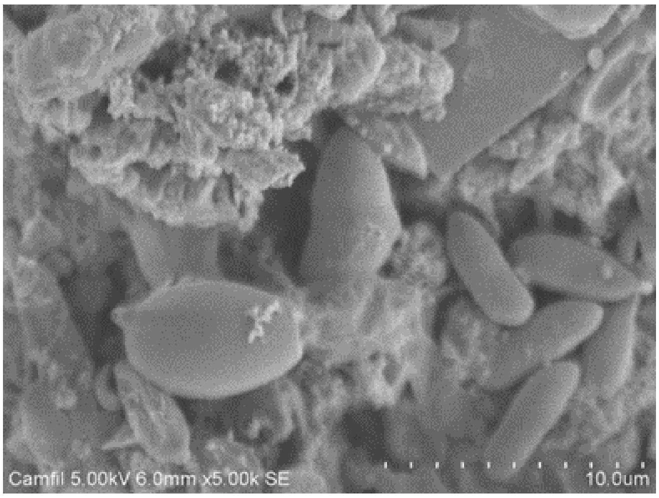

Figure 3: SEM Image of used filter media

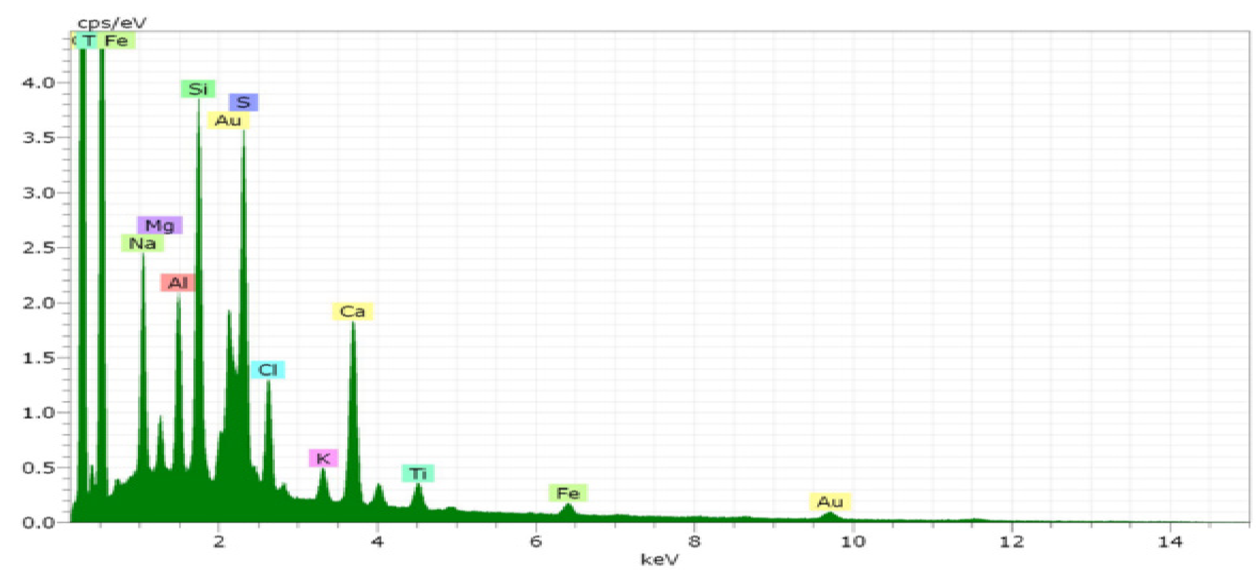

Figure 4: EDX elemental chemistry of used filter media

On site particle sampling

On-site particle sampling provides a snap shot of the air quality present at the site. This analysis is typically conducted over a 24-hour period, and includes particle size distribution, contaminant concentrations and chemical analysis.

Particle size distribution

This analysis is conducted with a portable particle counter. A particle counter is an instrument that uses light or laser diffraction to determine the size of a particle in the air. Once the size of a particle is determined, the instrument counts number of particle in each size range or bin. A typical counter will have 6 -8 size bins. The instrument provides the number of particles counted in each size bin. From this information, the counter will calculate a contaminant concentrations and particle size distribution. To insure representative data is collected, it is recommended that several samples be taken at different times of the day. Also, because the primary area of interest is that of compressor fouling, the measurement range of the counter should be on the order of 0.3 to 3 μm. Figures 5 and 6 give examples of a remote particle counter and the type of data collected.

Figure 5: Portable particle counter

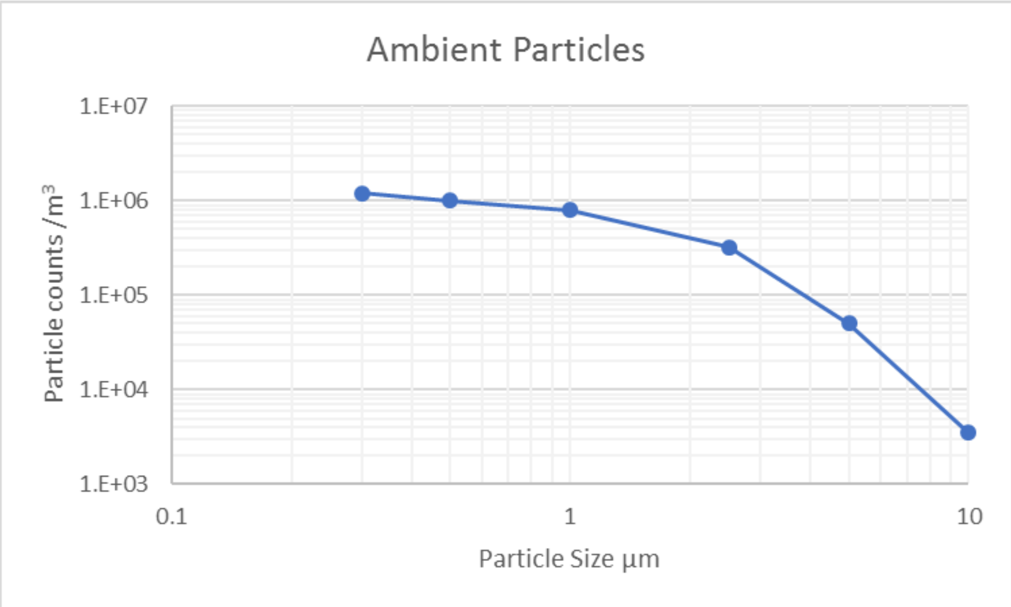

Figure 6: Particle counter data

Contaminant Concentrations

An alternative to a particle counter is to measure the aerosol concentration. There are several commercial instruments available for this measurement. This data provides macro level information, similar information to that provided by PM2.5 and PM10 monitors. These instruments report the mass concentration of particles in a size range such as 0.3 to 2.5 µm. A negative aspect of these instruments is that particle size distribution is not reported.

Chemical analysis of particle

It is often useful to know the chemical make-up of the particles challenging the turbine, especially when corrosion is a concern. If a used filter is unavailable to collect contaminant for analysis, then on-site sampling is conducted. A very macro level analysis is to conduct a soil sample. This sampling will provide some insight, but it may not be representative of particles that become airborne.

More useful information is provided when aerosols can be separated by size and then conduct chemical analysis on those particles. One method to conduct this test is with a Cascade Impactor. A cascade impactor is an aerosol sampling instrument that collects particles by size. The instrument works on the principle of inertial separation of the particles.

Typically, particles are divided into six to eight different size ranges. For each size range, particles are collected on a small membrane filter. Analytical chemistry techniques, such as ICP-OES (inductively coupled plasma optical emission spectroscopy), are then used to determine chemical identity of the particle. Figures 7and 8 illustrate a cascade impactor at test site and typical data. The data given in figure 8 shows relatively high concentrations of both Cl and Na indicating salts in the environment.

Figure 7: Cascade impactor

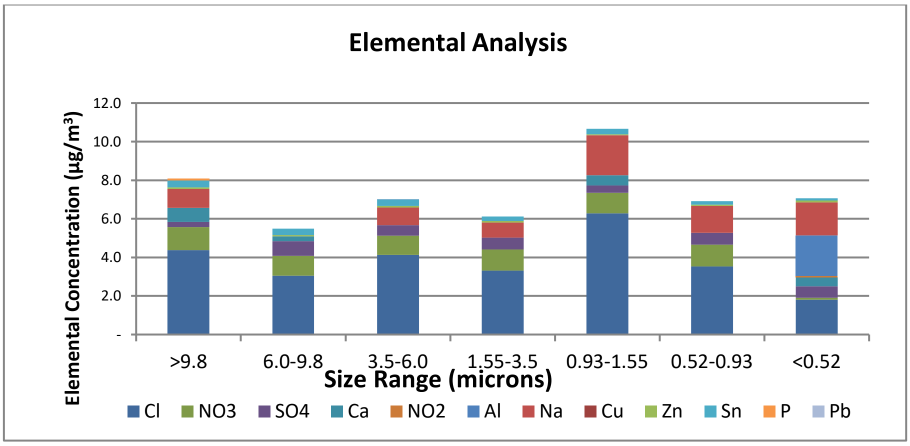

Figure 8: Cascade impactor data

In-situ filter testing

In most cases, the above data gathering methods combined with knowledge of filter performance will provide enough information to specify what type of air inlet system/filters should be used for a given gas turbine site. However, for some very high value sites or sites with unique environments, testing of filter elements can be conduct on site. The advantage of in-situ testing is that filters are exposed to the real contaminant and not a standard synthetic contaminant of the engineering test lab. Filters may react differently to the actual contaminant vs. the laboratory standards; especially with respect to pressure drop due caused by contaminant loading.

There are two primary approaches to conduct on site filter testing. The first approach can be done for existing operations. In this case, the filter elements under consideration would be installed in the current filter house and the results, (pressure drop, compressor degradation) are benchmarked against the original filter elements. This approach has several negative aspects that render it impractical. Issues include the cost of prematurely replacing filters, time required to obtain meaningful data, the variability in operations against the benchmark period. If a developmental filter is being evaluated, there are potential operation risks such as high pressure drop or excessive compressor fouling. If the site operates more than one gas turbine, a better option is side by side testing. In this case, one could conduct a comparison of filter A against filter B when installed on adjacent systems. While this approach reduces some of the operational variables, it still has the time, cost and risk issues.

An alternate approach is a mobile air filter test laboratory. This is a hybrid approach – the blend of engineer lab, aerosol sampling and full-scale system testing. An on-site test laboratory has several advantages; the biggest being testing can be conducted at new or proposed sites. This approach allows comparison of different types of filter elements in real operating environments.

One type of mobile test laboratory is shown in figures 9,10 and 11. This trailer laboratory has four independent test ducts, allowing to test four different types of filters Both cartridge pulse and static style filters can be tested. For static filters, up to 3 stages of filtration can be installed. Each duct has its own variable speed fan with an airflow range of 500 to 4500 cubic feet per minute. The primary functions of the unit are measuring filter efficiency - as a function of particle size, and filter pressure drop over time. The efficiency measurement is conducted by an on-board particle counter. This instrument records the ambient particle counts (upstream counts) and then records the particle counts downstream of the filter and thus filter efficiency is calculated. Particle counts are based on a sampling technique which averages six data points; this technique reduced variability and enhances the quality of the data. Environmental conditions of temperature, humidity, and aerosol mass concentration are also measured. All measured data is recorded by an on-board data logger. The laboratory is designed to be operated un-staffed, and is monitored, and controlled remotely via a cellular phone – internet connection. The control system also includes the ability to send an email alert if there is problem, such as a power failure.

Figure 9: Mobile air filter test laboratory

Figure 10: Mobile air filter test laboratory

Typically, the mobile air filter laboratory would be on site for three to six-months. This is usually enough time to develop trends in filter pressure drop and filtration efficiency. Direct comparison can be made between potential filter options. Pressure drop, and environmental data is recorded every twenty minutes, filter efficiencies are recorded every seven hours. The odd hour for efficiency sampling provides a more random sampling basis; thus, over the test period efficiencies will be measured "around the clock". In addition to real time monitoring, the data is downloaded for trend analysis in spreadsheet form.

Examples of the data collected by mobile laboratories are given in figures11- 14.

Figure11 is a screen shot of lab's data logger showing ambient dust concentration for a five-day time.

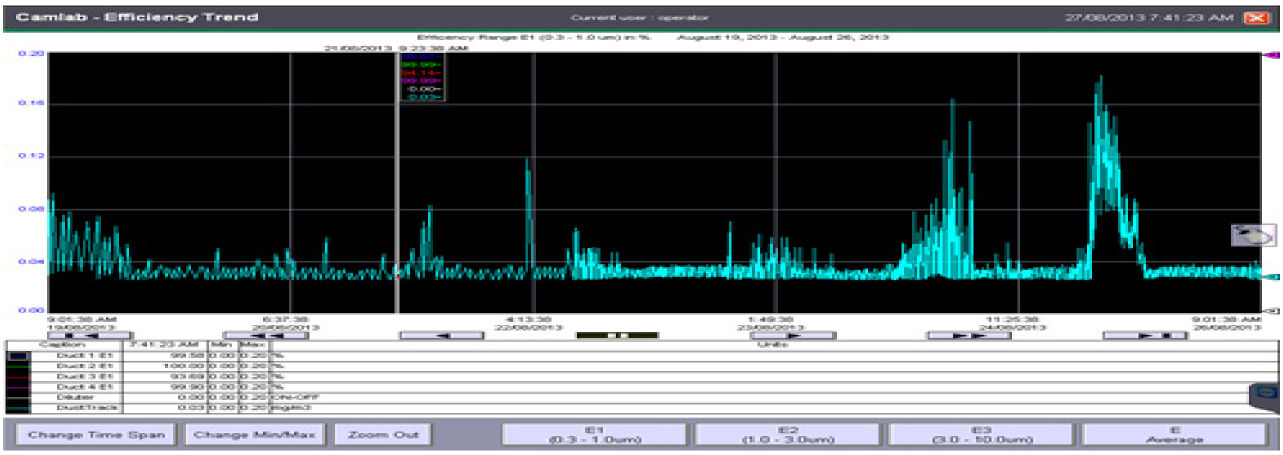

Figure 11: Mobile test laboratory aerosol concentration

Figure 12 shows the filter pressure drop(dP) trend of a test; noting one filter has a greater dP increase than the other.

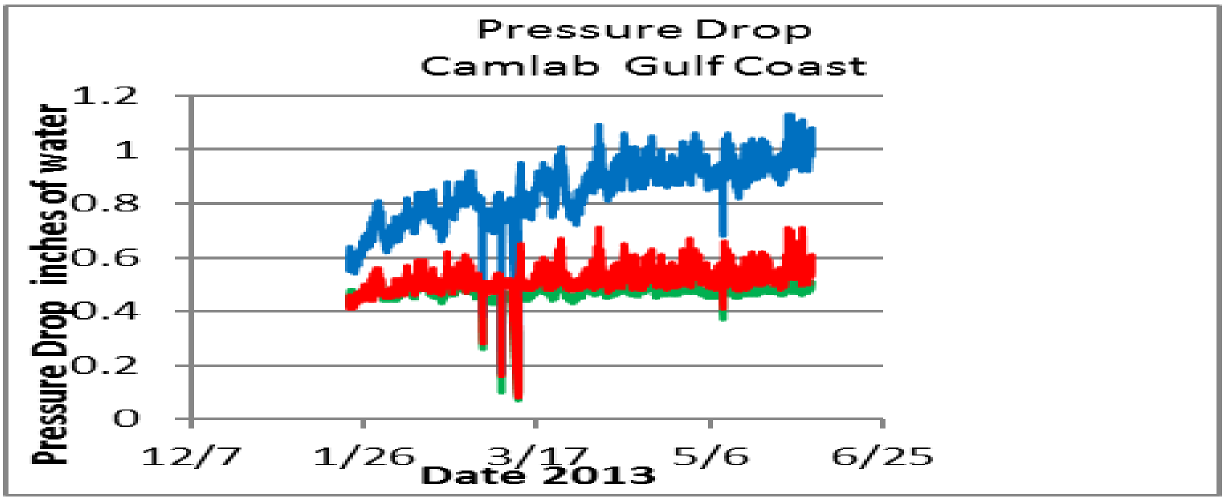

Figure 12: dP Trend data from mobile test laboratory

Figure 13 gives the efficiency trend of 0.4µm particles from another test. The key result of this test was the large reduction in filtration efficiency from about 90% to about 20% on one of the filters. This filter has a media that relies on electrostatic properties. In this environment, the media discharged – lost is electrostatic property over a 2-month time drastically reducing its efficiency performance. Such performance in application would greatly increase compressor fouling. After 2 months efficiency began to slowly increase due to a mechanism known as “dust cake” filtration. Dust cake filtration is a condition where as the media collects more particles, those particles act as a filter themselves, thus increasing efficiency. Note that the other two filters in this test maintained high efficiency levels.

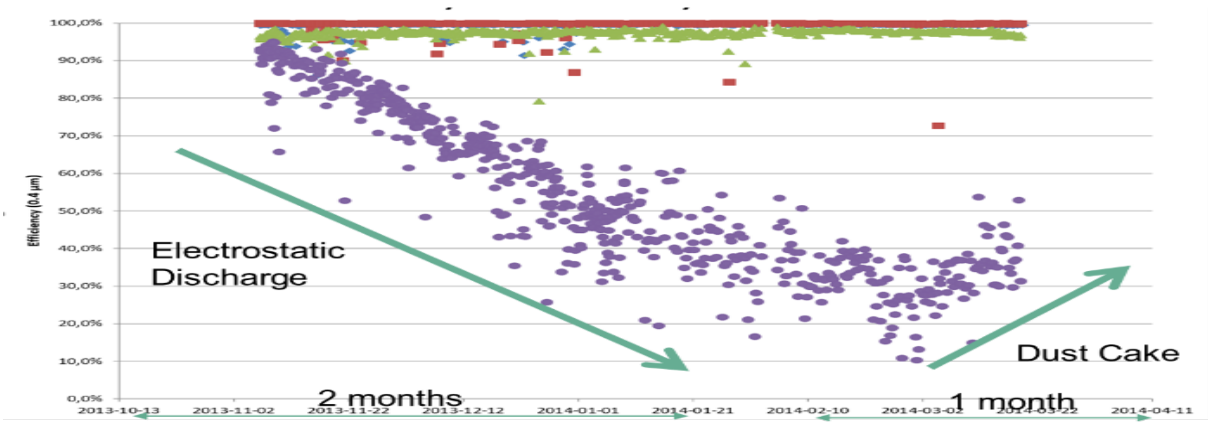

Figure 13: Efficiency trend data from mobile test laboratory

The findings of the test given in figure 14 shows how a filter performed in high relative humidity (RH) conditions. The filter's dP reaction as the RH increased was apparent from the start of test. Because of the test, that filter was not recommended for that installation.

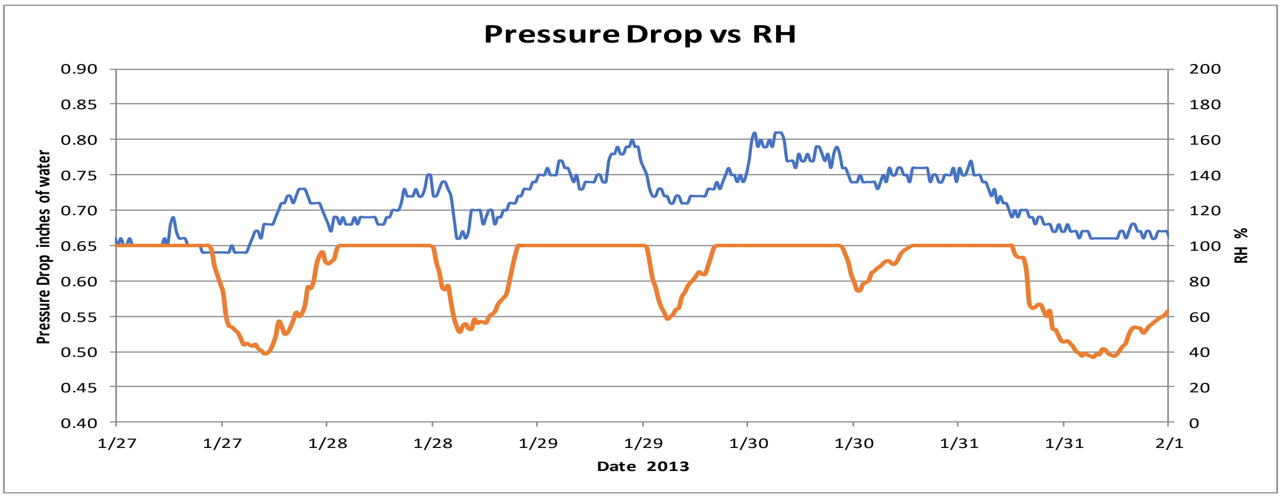

Figure 14: Humidity influence on dP

Using two mobile laboratories, more than 14 tests have been conducted over the last 5 years, yielding data useful for application recommendations. The mobile air filter laboratory has proven to be an effective bridge between the engineering laboratory and full-scale testing when evaluating gas turbine air filter performance.

Summary

Performance of stationary gas turbine engines can be optimized by the correct selection of the air inlet filtration system; specifically, the performance losses due filter pressure drop and compressor fouling. An important factor in the selection of the air filter system is understanding the local environment in which the system will be operating. Several different methods were presented to evaluate the site's particulate environment, including the use of a mobile air filer laboratory which has demonstrated to be an effective tool.

References

[1] Wilcox M, Baldwin R, Garcia-Hernandez A, Burn K. *Guideline for Gas Turbine Inlet Air Filtration System*. Gas Machinery Research Council, Southwest Research Institute. 2010.