European Turbine Network A.I.S.B.L.

Position Paper

Gas Turbine Combustion Air Filtration “Its impact on Compressor Efficiency and Hot End Component Life”

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Technical Committee Vision

TC3: To extend the ultimate life and repair interval for key hot section components by 30%.
TC4: 25,000 hours of gas turbine operation without intervention.

Proposal to the Technical Committee

It is proposed research be undertaken to establish a framework of metrics to correlate best practice filtration in relation to compressor efficiency. The ultimate aim of the research shall be gas turbine performance enhancement and component life extension in line with the vision statements.

Executive Summary

This paper shall discuss the level of filtration required to meet existing OEM (Gas Turbine Original Equipment Manufacturer) specifications, existing filtration international test standards and the commercial and technical benefits available to operators by applying enhanced Hepa H Class filtration technology to their gas turbine fleet to significantly reduce fouling of the compressor blades and consequential power loss.

The compressor of a gas turbine consumes a substantial amount of energy during operation; consequently, the efficiency of the compressor is very important to maintain optimum performance and has a huge impact on the machine thermal efficiency, power output and its long term component health.

Engine performance and component life should be considered as a function of the total mass of contaminant ingested which is directly influenced by the type of atmospheric and industrial environment; these deposits decrease the air flow performance of the inlet compressor due to degradation in blade shape and surface finish. Ultimately the overall performance of the turbine is greatly affected.

Although the air is filtered in accordance with OEM guidelines, these guidelines are not particularly stringent and thus large quantities of dust, aerosols and water continue to pass through the filters every second and deposit on the blades of most engines in use today.

More normally associated with micro electronics production and laboratory / hospital protection, Hepa filtration provides particle removal efficiencies of up to 1000 times greater at the critical sub-micron sizes than achieved by traditional reverse pulse and static filter systems which are supplied by most gas turbine OEM's.

The primary benefits derived from enhanced filtration technology include:

- ❑ Greater machine availability (%)
- ❑ Consistent and higher power output
- ❑ Increased fuel efficiency
- ❑ Longer hot end component life
- ❑ Reduced/negate water wash process
- ❑ Improved reliability
- ❑ Lower emissions

The potential commercial upside considers:

- ❑ Increased plant revenue
- ❑ Greater production yield (i.e. Oil & Gas, Steam)
- ❑ Lower labour and fuel costs
- ❑ Lower component costs
- ❑ Greener technology use

1. Introduction

It is a fact that the performance of the air filtration system has a huge impact on the Gas Turbine thermal efficiency and component life. Frequent Water washing and good filtration will extend the life of the turbine components. Enhanced air filtration will also directly save fuel, improve machine power output and improve the reliability and availability of engines.

It must be recognized that the gas turbine provides a unique challenge to the filter designer; commercial factors such as lifetime cycle costs along with operational resistance, filter system efficiency and dust holding capacity must be considered with particular attention to the volume of contaminated air consumed in a given period.

It is well established that conventional F8 / F9 filters satisfy the GT OEM aims of acceptable hot end component life of at least 20,000 hours and also provides a power output at a predicted heat rate and efficiency for a given inlet pressure loss over the filtration system. With these parameters in mind the focus from the GT OEM is often to keep the capital cost of the filtration system to a minimum to protect sales in a competitive market.

To remain competitive GT OEM's strive to provide greater power output and improved efficiency from each new variant of gas turbine. The demand for increased performance criteria and power output has generally resulted in higher firing temperatures and the necessity for inter cooling of high pressure nozzles and other hot components. As a result, the air quality has become even more influential with respect to machine availability and life time performance.

The resistance of an air filter device or system has long been recognised to influence the gas turbine power output and heat rate but what has generally been overlooked is the impact of fouling on the compressor stages (Gas Generator).

It is generally accepted that high inlet resistance forces the gas generator to do more work as it compensates for inadequate air flow. It is also recognised but difficult to quantify, that the ingestion of sub 5 micron (µm) particulates, which impinge on the LP compressor blades, cause a 'fouling' phenomena which in turn further deteriorates the engine efficiency. To elaborate on what is not readily quantifiable; it is a direct relationship between the type of environment, levels of contamination, particle size/distribution in relation to the degree of fouling and consequential loss of efficiency in real life situations.

What has become apparent to some machine users who have increased the efficiency of their air filter systems is that a higher system resistance has had little negative impact. More importantly the consistent cleanliness of the compressor has reflected in a significant improvement in all round performance of the gas turbine. In other words, compressor fouling appears to be more influential in the health, life and economics of the engine than inlet resistance.

Enhanced Hepa filtration undoubtedly reduces fouling and helps maintain compressor efficiency but this does need to be balanced with the additional system pressure loss, environmental conditions and the type of machine operation.
An introduction to the effects of poor air quality on a gas turbine is described overleaf.

2. Air Quality

Modern gas turbine rotating parts are complex in design and structure and have a critical profile for maximum working efficiency. The high pressure blades/nozzles sometimes have small air holes to deliver cooling air as the working temperatures are close to the limit of the material. Compressor blades are made of a very sophisticated alloy of metals to provide strength and durability and these are coated with a protective layer for durability. This makes effective filtration a major factor to the long term life of the gas turbine.

Particles, which have sufficient mass to irreversibly wear the internal rotating components, are typically identified as being greater than 10 µm in diameter. Their hardness velocity and concentration in the air stream can cause **Erosion** in a time-related manner. Such particles can be removed by inertial filters or pre-filters with consummate ease.

Those pollutants which are less than 5 µm diameter do not have sufficient mass to cause wear, but they can impinge onto the surface of the rotating and static components and in a short time period change the blade profile away from its ideal shape. This is commonly referred to as **Fouling** of the Gas Turbine. These small particles can also plug the cooling air holes located in the blades which will increase the operational temperature of components. This phenomenon of fouling is reversible and is addressed by water-washing using detergents and copious quantities of fresh water.

On some gas turbine applications, it can be normal operational practice to compensate for a short term loss of compressor efficiency by employing higher firing temperatures or increased compressor speed. However this is not always possible and is dependent upon the application and the gas turbine e.g. single shaft synchronous machines.

Figure 1: The black deposits on the compressor blades is fouling caused by hydrocarbon contaminants in the atmosphere

Corrosion of the LP and HP parts of the Gas Turbine is a risk if airborne salts pass through the filter system. It is a chemical process which is not dependent on the particulate size but on the presence of moisture and an electrolytic reaction between salts and metals of different types. Airborne salt and water ingestion causes low temperature corrosion whilst the combination of NaCl with air/fuel borne sulphur results in high temperature sulphidation/oxidation or 'hot gas' corrosion.

Hot Gas Corrosion is of particular concern especially in coastal and offshore locations where NaCl is prevalent both as a dry particle and in solution in water. When mixed with sour (sulphurous) fuel it will cause accelerated degradation of key hot section components.

A **combination of Erosion and Low Temperature Corrosion** can lead to blade failure. Poor filtration erosion can result in removal of the blade protective coating, which will leave the blade susceptible to low temperature corrosion from a combination of salt and water. Should pitting corrosion develop near the root of the blade it could eventually result in catastrophic failure through detachment of the blade due to the excessive loads at the weakened blade root.

To protect the rotating machinery from the impact of fouling, erosion or corrosion, gas turbine manufacturers (OEM's) issue mandatory air quality requirements to filtration suppliers. The level of these requirements is not particularly stringent but also takes into consideration that regular water wash and maintenance of the gas turbine will also be required. For original equipment supply this enables the OEM to remain commercially viable in a competitive market whilst balancing the performance, health and life of the turbo-machinery.

3. Filtration Standards

In order to achieve combustion air cleanliness as specified by the machine Original Equipment Manufacturer (OEM), gas turbines have traditionally employed barrier filters which provide an efficiency level of F8 / F9 to European test standard EN 779:2002 (or MERV15 / 16 to the American ASHRAE 52.2 test standard).

European filter classifications are covered by two standards EN779:2002 and EN1822:2009 the classifications of which are summarised in table 1.

EN779 air filter test standard challenges the fine dust filter with a DEHS oil droplet aerosol after multiple ASHRAE dust loading steps up to a given pressure drop while coarse dust filters are tested with dry dust. In 2002, the standard introduced a discharged efficiency to ensure a clearer filter performance was published, rather than an efficiency which was still influenced by the electrostatic charge from a newly manufactured synthetic filter.

Table 1: The European filter classifications EN779:2002 and EN1822:2009

Standard	Contaminant Type	Class	Arrestance (A) Efficiency (E) (%)
EN-779	Coarse Dust Filter	G1	<65 (A)
		G2	65-80 (A)
		G3	80-90 (A)
		G4	>90 (A)
	Fine Dust Filter	F5	40-60 (E)
		F6	60-80 (E)
		F7	80-90 (E)
		F8	90-95 (E)
		F9	>95 (E)
EN-1822:2009	High Efficiency Particulate Air Filter (HEPA)	E10	85
		E11	95
		E12	99.5
		H13	99.95
		H14	99.995
	Ultra Low Penetration Air Filter (ULPA)	U15	99.9995
		U16	99.99995
		U17	99.999995

Note: The revised EN1822:2009 nomenclature has changed within the former H-class.
The classification is now EPA E10, E11 E12 rather than HEPA H10, H11, H12. Efficiencies are identical, but the E-class has no obligation to individual test each filter prior to delivery.

For the High efficiency Particulate air filter EN1822 does not challenge any operational life since there is no measurement on the dust loading capacity. EN1822 determines the most penetrating particle size (MPPS), in clean condition only, and this is used as the basis to determine filter classification E10 to U17.

It should be noted that in both cases, ASHRAE and EN Standards, the filter elements are individually tested in a dry duct environment and real life operation and performance will differ from laboratory results.

There is currently no recognised international standard for testing filters in wet conditions to quantify the filters resistance to water in a dynamic situation. This is a particularly important factor and should not be underestimated for filters applied on gas turbine intakes. A filter could have a good efficiency classification but if it was not impervious to water, salt (in solution) could migrate through the filter. Over time, with changing environmental conditions the water would evaporate resulting in salt crystalline growth downstream of the filters and ingestion by the gas turbine. In time this would lead to compressor fouling, low temperature corrosion in the compressor section and if the air or fuel also has a high sulphur content, hot gas corrosion with a consequential reduction in hot end component life.

Note: EN 779:2002 and EN1822:2009 standards relate to air filters in an air conditioning plant. There is currently no existing recognised filtration ISO, CEN or ASHRAE standard relative to turbo machinery.
However ISO currently has a working group developing a new standard as part of the technical committee ISO TC142/SC-WG09. The aim of this group is to introduce a new air filter test standard specifically for rotating machinery and as such it will replace those standards currently adopted by the industry. i.e., ASHRAE 52.1, 52.2, EN779 & EN1822.

This new standard 'Air intake filter systems for rotating machinery – Test Methods' will be issued in 5 parts:
Part 1 Static Filter elements
Part 2 Reverse Pulse Filter systems
Part 3 Integrity testing (environmental conditions, mechanical strength)
Part 4 In-Situ testing – real operating performance
Part 5 Test method and classification of Offshore & Marine filters

AAF, Camfil and Donaldson and some other filter companies are represented on the committee. The first part of the standard is scheduled to be released in 2011

4. Filtration Selection

Hepa class filters remove sub-micron sized particles and droplets using proven techniques of particle attraction and diffusion. A major component of this technique is the air speed past the fibres and the diameter of those fibres. This means that a lower air-stream velocity will result in improved particle removal efficiency. Optimum filter media areas are determined by test and it is recognised that pleat shape and size contribute greatly to the overall performance of the filter.

Fundamental to filter selection is the recognition that all filter stages upstream of the final filter are employed as pre-filters to maximize the final 'fine' filter life and suitable weather protection is provided to limit the ingestion of rain, fog, ice and snow.

For static, non pulse, filter systems the Hepa class filter stage is most of the time an additional 3rd stage. The Hepa stage (typically E10-H13) shall be protected with "normal" up-stream stages typically 1st stage pre-filter type G3-F6 and 2nd stage F8-F9. Commercial and practical restrictions occasionally force alternatives to this and in some instances, only one pre-filter stage can be selected.

Single stage reverse jet pulse filters are best suited to high dust laden environments, such as deserts, but currently no such long term proven product exists which will give a true Hepa efficiency on a single stage self-cleaning, so they are to be considered as pre-filters to protect a final stage of Hepa class filters.

That said, there are new emerging products on the market with membrane type Hepa technology and these have been employed in both static and single stage pulse applications in low dust load applications. However, the long term performance, reliability, scale-ability of the technology is still to be determined.

Consequently, provision of Hepa filtration protection to the engine normally requires an additional stage of filtration over and above that employed to meet the GT OEM mandatory requirements. This increases the inlet system resistance over the filtration system however this can be alleviated by increasing the filter surface and may result in a larger filter package. The total filter system capital investment will be higher than a system without a Hepa stage, but can be compensated with a good pay-back of the investment.

5. Proven Benefit of Improved Filtration

Experience already exists on land-based and offshore installations with Hepa grade filters referenced as E10-H13 efficiency. These installations are much more efficient at sub-micron particulate removal than the traditional F8 & F9 filtration systems. Of course special treatments to prevent hydrocarbons interacting negatively with the filter and techniques for rapid water removal from the inlet together with elimination of water penetration through the fine filter is also essential. To help appreciate the step change that Hepa filtration can offer, please refer to the attached comparison in Appendix A which demonstrates how E12 vs F8 Filtration will result in the quality of the combustion air ingested by the gas turbine being 1000 times (sub micron) cleaner.

To highlight the benefit of Hepa filtration, two examples of improved systems are detailed below: 25MW turbine with E12 filtration and a 45MW turbine with E10 filtration.

Example A: 25 MW

Due to an improved level of filtration this example highlights the operational commercial benefit of increased revenue through reduced downtime for offline water washing. The analysis does not take into account the additional cost benefit associated with the life extension of hot end components and the consequential reduction in engine removal, upgrade and off line refurbishment activities.

Table 2: Gas Turbine Operational Cost Analysis – 25 MW Machine

Filtration Efficiency	**F7/F8**		**F9**		**E12**
Engine wash frequency – Hours	750		2000		8000
Expected filter life – months	24		24		12
Filter costing (Filters+Labour) / year	**$10,000**		**$15,000**		**$40,000**
Annual Washing Cost (12 hrs off-line/event)	**$29,167**		**$10,938**		**$2,497**
Annual Production loss (20,000 barrels oe/d @ $75 / barrel)	**$8,823,072**		**$3,308,652**		**$755,400**
Total Annual Cost Impact	**$8,862,239**		**$3,334,590**		**$797,897**
Net Annual Cost benefit with F9 Filtration – per machine			**$5,527,649**		
Net Annual Cost benefit with H12 Filtration– per machine					**$8,064,342**

Note 1 – The costs for washing and production are from a recognized North Sea Operator

Note 2 The example is to show the potential benefit to the operator of applying H12 filtration and relates to a specific type of installation where the production is constant.

<u>**Example B: 45 MW turbine.**</u>

Original 2-stage filter system - F6 & F9

The 45 MW turbine was originally provided with a F6 pre-filter stage and a F9 final stage.
Target production for this application is 45MW. During 22 weeks of operation the turbine was frequently on-lined washed >30 times with no improvement of performance and two off-line wash @ 4 hours with only minor improvement of performance. The total loss of power during 22 weeks operation is 2300 MW.
Due to performance loss the economical impact was an income reduction of Euro 172,000.

Improved filter system - F7 & E10

The 45 MW turbine was provided with a F7 pre-filter stage and a H10 final stage. 22 weeks of operation with no off-line and no on-line washing. Negligible power loss measured and target production of 45MW reached during the 22 weeks of operation.
Investment of improved filter efficiency is less than 10% of Euro 172,000.

This example shows the need to analyse local conditions to best optimise the filter system and that the filter system arrangement needs the possibility to be easily modified after installation on site. This example also shows the need to balance pressure drop and efficiency. For this site the higher final stage efficiency only decreased the power output due to pressure drop, in addition with a slightly higher filter price.

6. Conclusion and Observations

Feedback from some operators that have added Hepa filtration, indicate that the increase in filter resistance has not been problematic and the impact on engine heat rate and power output has been minimal. The cleaner combustion air has prevented deterioration in performance by avoiding compressor fouling and so the engine thermal efficiency has remained stable. However, depending upon the application other users are focused to minimise the impact of pressure drop associated with an additional filter stage.

Experience has proven that whilst Hepa filters will have a higher capital investment cost and the inlet system has to be designed to achieve the best solution, the benefits are huge in comparison. Extended hot end component life, improved availability and increased revenues can potentially reduce filter pay-back in a matter of days.

It is proven therefore that air quality can be provided which is in excess of traditional levels used on rotating machinery with huge financial and technical benefits to the user. These greatly exceed the additional capital cost and cost of the consumable filters.

In summary, clean air can advantageously change the economics of Turbo-machinery operation:

- *Better machine availability*
- *Lower operating costs*
- *Potential longer hot-end component life*
- *More predictable performance*
- *Improved preventative maintenance*
- *Less green house impact*

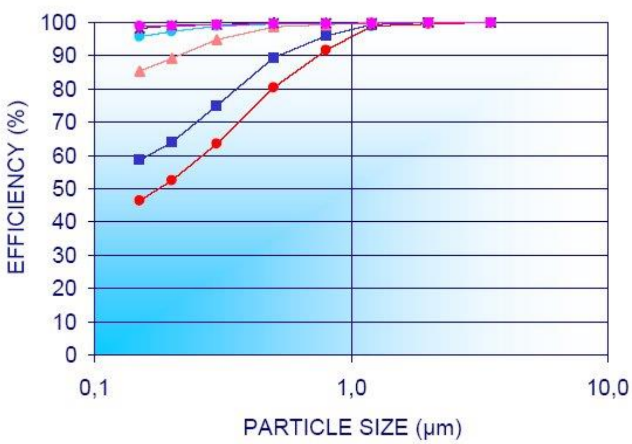
However, it must be considered that long ‘hot end’ component life has not necessarily been in the interest of all parties in the supply chain of capital equipment and not all sectors of the industry have recognised the benefits of high quality air filtration.
Technical solutions for high performing filter system has been available for decades, it’s more a matter of willingness to invest from OEM’s and user’s side.

It is also important to note that even higher air quality than E10-H13, which are the most used Hepa alternatives, can be provided which is way in excess of anything required by rotating machinery. European test standards, EN779:2002 & EN1822:2009 together list 17 grades of filter efficiency from G1 through to U17. Many levels of even higher efficiency filters can also be provided. The gas turbine industry is not stretching the capabilities in air filtration technology but it can benefit by it without risk.

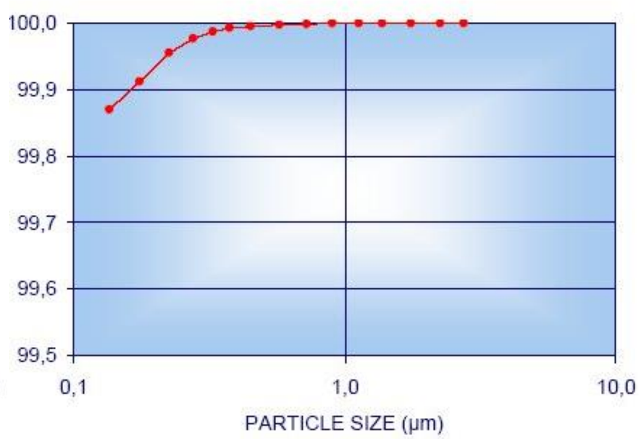
Hepa filtration will make a significant step towards achieving the ETN TC3 and TC4 vision statements:
TC3: To extend the ultimate life and repair interval for key hot section components by 30%.
TC4: 25,000 hours of gas turbine operation without intervention.

Appendix A

F8 Filter



E12 Filter



Note - The above curves are typical only and are provided to help give an appreciation of the step change in efficiency moving from F8 to E12 classification.

Sub Micron Filtration Comparison

Example A
Consider 1,000,000 particles size 0.5µm diameter upstream of the filter F8 Initial efficiency at 0.5µm ~ 60%, therefore penetration = 400,000 particles E12 Initial Efficiency at 0.5µm ~ 99.98%, therefore penetration = 200 particles
Comparison E12 vs F8; 400,000/200 = 2000 more efficient at 0.5µm
Therefore E12 is x2000 more efficient than F8 at 0.5µm

Example B
Consider 1,000,000 particles size 0.3µm diameter upstream of the filter F8 Initial efficiency at 0.3µm ~ 50%, therefore penetration = 500,000 particles E12 Initial Efficiency at 0.3µm ~ 99.95%, therefore penetration = 500 particles
Comparison E12 vs F8; 500,000/500 = 1000 more efficient at 0.3µm
Therefore E12 is x1000 more efficient than F8 at 0.3µm