GUIDELINE FOR GAS TURBINE INLET AIR FILTRATION SYSTEMS

RELEASE 1.0

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Foreword

Inlet air filtration systems are essential on any gas turbine. Filtration systems have evolved from simple coarse solid particulate removal systems to complex systems that remove both solid and liquid particles. The development of filtration systems has progressed because gas turbines have become increasingly sensitive to the particles that enter the gas turbine. This is due to increased operating temperatures and decreases in machine tolerance in modern turbines. The modern filtration system has multiple stages which are selected for the specific environment and application.

The selection of the inlet filtration system is an important part of the design of a gas turbine. Poor quality inlet air can significantly impact the operation, performance, and life of the gas turbine. Some of the consequences of poor inlet filtration are fouling, erosion, and corrosion. In order to minimize gas turbine degradation, a sufficient amount of effort should be invested to properly design and operate the inlet filtration system.

The first step in selecting an inlet filtration system is to define the expected operating environment. This includes determining what potential contaminants could be present at the installation site.. Once the expected contaminants are defined, the filters can be selected. These filters should be selected based on what they need to remove from the air and the gas turbine inlet air quality requirement. There are several different filters that can be used. The majority of modern filtration systems are multi-stage systems which allow for control of a wide variety of contaminants. After the filtration system is selected and installed, it must be properly operated and maintained in order to maintain inlet air quality.

The selection, installation, and operation of an inlet filtration system are a complex processes. This guideline summarizes the current technology and considerations for gas turbine inlet filtration systems. This document provides detailed information related to the consequences of poor inlet filtration, characteristics of air filters, types of filters which are commercially available, review of different environments where a gas turbine can be installed, how to compare filtration system options based on life cycle cost analysis, which operation and maintenance practices should be performed, and how filters are tested and classified. The guideline provides the filter engineer with much of the knowledge needed to select, operate, and maintain an inlet filtration system.

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DEFINITION OF SYMBOLS

Symbols and Units:

a	=	Availability (%)
$c_{N,d}$	=	Number concentration downstream
$c_{N,u}$	=	Number concentration upstream
cfm	=	Actual cubic feet per minute (at actual temperature and pressure)
dp	=	Pressure loss (inH2O)
e	=	Escalation or inflation rate (%)
hr	=	Time (hours)
i	=	Discount rate (%)
inH2O	=	Refers to inch of water column (pressure measurement)
n	=	Year (for LCC analysis)
p	=	Pressure (psia)
ppm	=	Parts per million
t	=	Time (years)
t_d	=	Sampling duration downstream
t_{filter}	=	Filter life (hours)
t_u	=	Sampling duration upstream
A	=	Present cost
$A_{52.2}$	=	Arrestance (%) (ASHRAE 52.2: 2007)
A_m	=	Average separation efficiency – coarse filters (G) (%) (EN 779: 2002)
ASHRAE	=	American Society of Heating, Refrigerating and Air-Conditioning Engineers
C_{kWh}	=	Cost or sale price of electricity ($/kWh)
C_{labor}	=	Cost of labor ($/hr/person)
C_{scf}	=	Cost of fuel gas ($/SCF)
CFD	=	Computational Fluid Dynamics
CNC	=	Condensation Nucleus Counter
CO2	=	Carbon Dioxide
CON	=	Condensable
E_{1822}	=	Filter efficiency (%) (EN 1822: 2009)
E_m	=	Average separation efficiency – fine filters (F) (%) (EN 779: 2002)
EPA	=	Efficient Particulate Air filter
EPA_{US}	=	United States Environmental Protection Agency
FIL	=	Filterable
FOD	=	Foreign Object Damage
FPM	=	Feet per Minute
FPSO	=	Floating Production, Storage and Offloading vessel
D	=	Degradation rate (%)
DEHS	=	Di-ethyl-hexyl-sebacate poly-dispersive aerosol
DOP	=	Di-octyl-phthalate monodispersive aerosol
GT	=	Gas Turbine
HEPA	=	High Efficiency Particulate Air filter
HR	=	Heat Rate (Btu/kWh)
HVAC	=	Heating, Ventilation, and Air Conditioning
IGV	=	Inlet Guide Vanes
LCC	=	Life Cycle Cost
LHV	=	Low Heating Value of fuel (Btu/SCF)

MERV	=	Minimum Efficiency Reporting Value (ASHRAE 52.2: 2007)
MIL	=	Military (United States)
MPPS	=	Most Penetrating Particle Size (EN 1822: 2009)
N	=	Number of personnel
N_d	=	Number of particles counted downstream
N_u	=	Number of particles counted upstream
NATO	=	National Atlantic Treaty Organization
NOAA	=	National Oceanic Atmospheric Administration
NO_x	=	Nitrous Oxides
NPV	=	Net Present Value
OPC	=	Optical Particle Counters
P	=	Power (kW)
$P_{52.2}$	=	Penetration (%) (ASHRAE 52.2: 2007)
P_{1822}	=	Penetration (%) (EN 1822: 2009)
PM10	=	Particulate matter from 2.5 to 10 microns in size
PM25	=	Particulate matter less than or equal to 2.5 microns in size
PRI	=	Primary
PSE	=	Particle Size Efficiency (%) (ASHRAE 52.2: 2007)
PVC	=	Polyvinyl Chloride
SO_x	=	Sulfur Oxides
STD	=	Standard
UK	=	United Kingdom
ULPA	=	Ultra Low Particle Air filter
US	=	United States
$\dot{V}_{s,u}$	=	Sampling volume flow rate upstream
$\dot{V}_{s,d}$	=	Sampling volume flow rate downstream
W	=	Weight (kg or lb_m)
W_d	=	Weight of test dust passing the test filter
W_u	=	Weight of dust fed
η	=	Efficiency (%)

Subscripts:

disp	=	Disposal
down	=	Downtime
ener	=	Energy
entering	=	Particles entering the filter
init	=	Initial
inst	=	Commissioning and installation costs
leaving	=	Particles leaving the filter
main	=	Maintenance
oper	=	Operation
total	=	Total
GT	=	Gas Turbine

DEFINITIONS

1. **Arrestance:** This parameter is evaluated by comparing the weight of dust penetrating the filter to the weight of the dust fed.
2. **Efficiency:** The filter efficiency is the ratio of the weight, volume, surface area, or number of particles entering the filter to the weight, volume, surface area, or number of particles captured in the filter.
3. **Depth Loading:** Depth loading refers to a type of filter which collects dust within the fibers of the filter media. Depth loading type filters must be removed and replaced at regular maintenance intervals.
4. **Dust Holding Capacity:** The dust holding capacity is the mass of dust collected in the filter when it reaches its prescribed pressure loss with standardized dust and feed rate.
5. **Efficient Particulate Air filters (EPA):** These filters are defined as having an efficiency of 85% for particles greater than or equal to 0.3 microns in size.
6. **Face Area:** The gross area of the filter exposed to airflow. This includes the surface area of the filter media. It does not include the surface area of any mounting hardware.
7. **High Efficiency Particulate Air filters (HEPA):** These filters are defined as having an efficiency of 99.95% for particles greater than or equal to 0.3 microns in size.
8. **Micron:** A unit of measurement of length commonly used in the reference to size of particles. One micron or µm is 1,000,000th of one meter.
9. **Monodisperse:** Particles of uniform size in a dispersed phase.
10. **Parts Per Million (ppm):** PPM is the mass of contaminants per million unit mass of air.
11. **Polydisperse:** Particles of various sizes in a dispersed phase.
12. **Pressure Loss:** This refers to the pressure difference across the filter. As the filter is loaded with dust, the pressure loss will increase. This value is important in the consideration of gas turbine performance. These values are reported in inches of water (inH2O) (see water column definition) throughout this document.
13. **Settling Velocity:** The settling velocity is the rate at which a particle falls out of the air.
14. **Stage:** A stage is one set of the same types of filter elements in the filtration system.
15. **Surface Loading:** Surface loading refers to collecting dust on the outside surface of the filter media. Very little dust will be captured within the filter material.
16. **Ultra Low Particulate Air filters (ULPA):** These filters are defined as having an efficiency of 99.9995% for particles greater than or equal to 0.12 microns in size.
17. **Velocity:** A filter's operating velocity is defined as the actual volumetric air flow divided by the filter face area.
18. **Water Column:** Water column refers to the water reference for a pressure measurement. For example, 1 inch of water column (or inH2O) is the same as 0.036 psia or 250 Pa.
19. **Grain:** A unit measurement of mass. One grain is equal to 0.0648 grams.
20. **Cooling Tower Drift:** Transportation of water aerosols from a cooling tower by wind or air currents. The water aerosols results from drift, blow-out, and plumes.

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Guideline for Gas Turbine Inlet Air Filtration Systems

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1. INTRODUCTION

The following guideline is intended to serve as a reference for gas turbine inlet air filtration systems (example shown in Figure 1-1). The inlet filtration system cleans the air entering the gas turbine. This guideline applies to any gas turbine inlet air filtration system in any application such as industrial power generation or offshore operation in the oil and gas industry. It is intended to provide a technically sound and practical guideline on selecting, operating, maintaining, and testing of filtration systems. This guideline discusses the purpose and advantages of inlet filtration, consequences of poor inlet filtration, selection of filtration system based on application, filters types and characteristics, filter operation and maintenance, and filter testing.

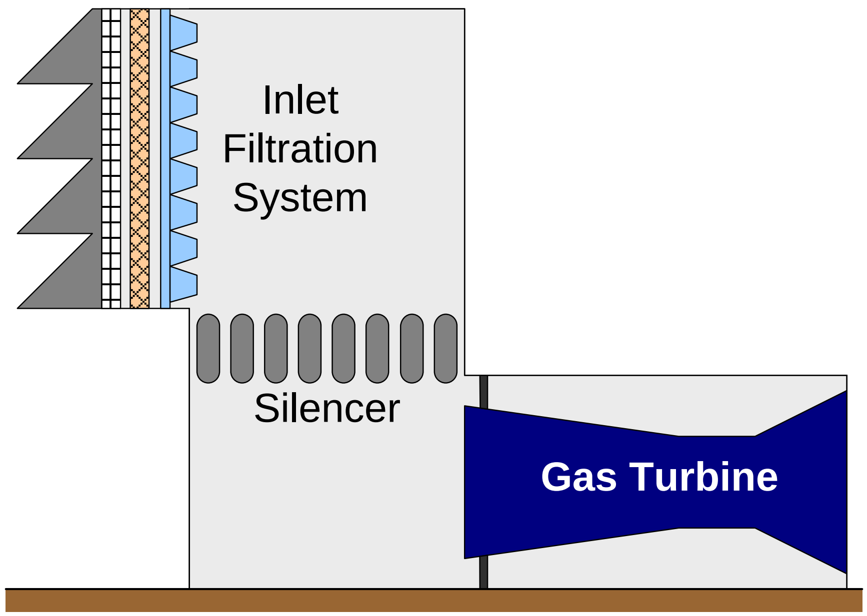


Figure 1-1. Location of Gas Turbine Inlet Air Filtration System

The development of this guideline is the result of the need for a document to summarize the specific details involved in owning and operating a gas turbine inlet air filtration system. Specifically, guidance is needed on filtration systems in coastal or marine environments. The effects of salt in dry, humid, and saturated air flows are reviewed in depth. This guideline addresses items that should be considered for all applications of filtration systems. Standards referenced in this guideline are ASHRAE 52.2: 2007, DIN EN 779: 2002, DIN EN 1822: 2009 (Part 1 through 5), and API 616 5th Edition.

2. BACKGROUND

The operation of a gas turbine, by its basic design, requires it to ingest large quantities of air. For example, a 30,000 hp Solar Turbine Titan 250 gas turbine has a reported exhaust flow of 541,590 lb/hr (at 70° F and 14.69 psia and assuming inlet mass flow is 2% less than exhaust flow the volumetric flow is 118,214 acfm). Even in relatively clean environments, a gas turbine may ingest hundreds of pounds of foreign matter each year of various sizes (Figure 2-1). For example, 1 ppm of particles in the ambient air is equivalent to 12.7 lbs of that particulate entering a gas turbine without filtration each day at a mass flow rate of 530,758 lb/hr. Also, the more advanced the turbine design, the more sensitive it is to the quality of the air ingested. Filtration is applied to the inlet air to provide protection against the effects of contaminated air. Different types of contaminants in the air from the world-wide variety of environments can cause several types of problems that negatively impact the reliability, availability, and time between overhauls of gas turbine internal components. The foremost purpose of inlet filtration is to clean the air to meet the operational goals of the machine and, secondarily, to maintain its filtration efficiency. Specific filtration designs protect against particles of various sizes and composition.

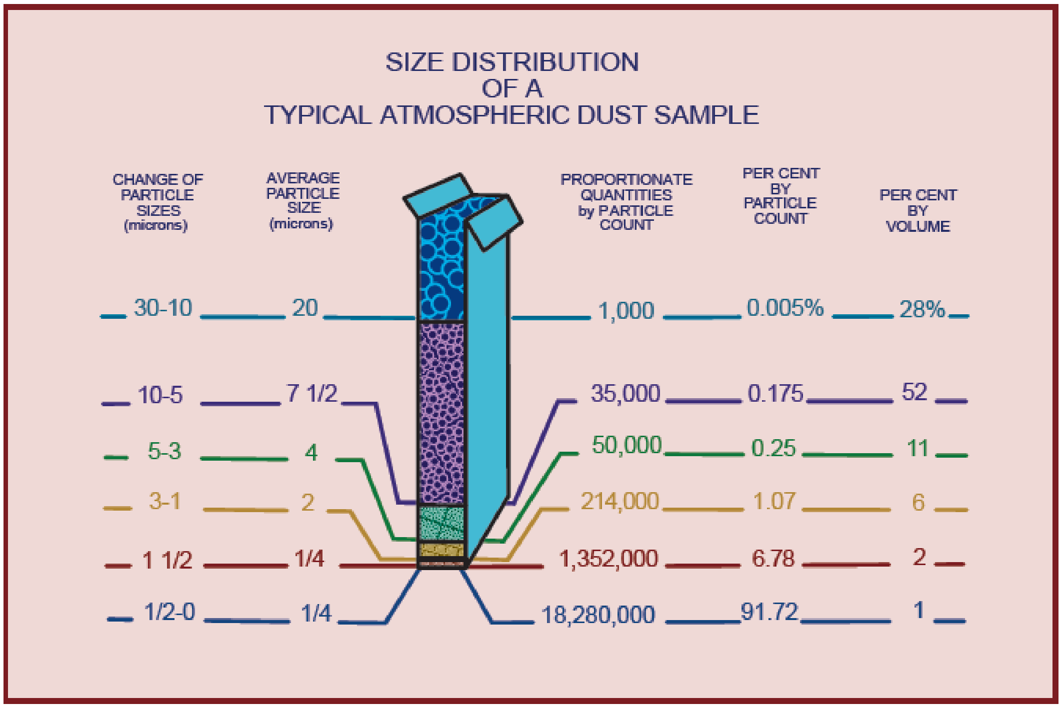


Figure 2-1. Distribution of Particles in Atmosphere
(American Air Filter, 1958)

2.1 Consequences of Poor Inlet Filtration

Proper inlet filtration is designed based on the required application in order to prevent a decrease in gas turbine performance and even destruction of the gas turbine. In order to understand the importance of inlet filtration, the effects of poor filtration on the gas turbine should be understood. The gas turbine is affected by various substances in the inlet air depending upon their composition and their particle size. Discussed below are six common consequences of poor inlet air filtration: foreign object damage, erosion, fouling, turbine blade cooling passage plugging, particle fusion, and corrosion (hot and cold).

2.1.1 Foreign Object Damage

Foreign Object Damage (FOD) can be significant in a gas turbine if there is not proper protection (see Figure 2-2). It usually occurs in the early stages of the compressor. Large objects or relatively large particles can be trapped or screened to avoid their entry into the fan or compressor section of a turbine. This accomplishment is a significant gain, because FOD has the greatest potential for secondary and extensive damage to the compressor and later parts in the air flow path. The filter system and its components are designed to prevent FOD. Poorly designed filters or systems, including filters, hardware in ducting and silencing, and other aspects lead to a risk of FOD damage and should be considered. Often

FOD screens are installed upstream of the filters for protection. Depending on the screen location and mesh size, the pressure loss across these screens can be negligible or significant.

Figure 2-2. Gas Turbine Damage from FOD

2.1.2 Erosion

Hard particles 5 to 10 microns or larger create erosion of the metal surfaces bounding the air flow path. Figure 2-3 compares the particle size range for erosion with fouling. Sand is one of the most common causes of erosion due to its prevalence at the installations of gas turbine. Impingement of small, hard particles against blade and stator aerodynamic airfoil shapes repeatedly removes tiny particles of metal, eventually re-shaping portions of the parts. In finely tuned contours of highly stressed parts, this is a double problem. Re-shaping aerodynamic surfaces changes the air flow paths, roughens the surfaces, changes clearances, and eventually reduces the cross-sectional areas that provide the strength necessary to resist the very high stresses of parts with minimal margins of safety. Also, changing the blade shape can create stress concentrations that reduce the fatigue strength, thus leading to high cycle fatigue failures. The efficiency of the gas turbine is reduced until excessive stress takes over as the main cause of problems.

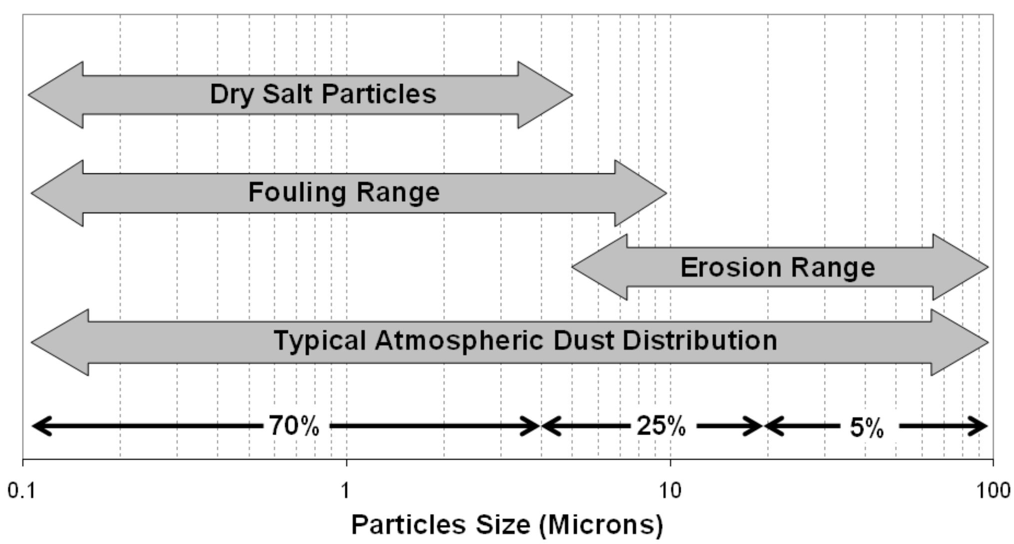


Figure 2-3. Typical Particles Size Distribution for Erosion and Fouling Range

Erosion is a non-reversible problem. The only method of bringing blades back to their original condition is with replacement. Particles of sizes greater than five microns are usually the culprit for erosion and can be easily filtered with commercially available filters. In environments with a high concentration of large dust (> 5 microns) such as deserts, self-cleaning type filters can be effective for removing these size particles. Inertial separators can also be used to remove these particles in applications with high filter velocity. An example of erosion on the leading edge of a turbine blade is shown in Figure 2-4.

Figure 2-4. Erosion on the Leading Edge of a Turbine Blade

2.1.3 Fouling

As particle size and hardness reduce, the potential problems change from erosion to fouling. Fouling is the build-up of material in cavities and low flow-rate locations along the air flow path. Besides small particles as a cause for fouling, oil vapors, water, salts, and other sticky substances working individually or together create a mix of materials that find places to adhere. These particles adhere to compressor blade surfaces and turbine blade cooling passages. The effect is to change clearances, disrupt rotating balance, obstruct and plug flow paths, and reduce smoothness of rotating and stationary blade surfaces. Fouling is, however, usually recoverable since there are methods available to remove these deposits with online or offline washing or mechanical cleaning. The cost of recovery is interrupted process output and sometimes extended shutdown. If recovery by cleaning is not performed, performance suffers. It is possible to recovery the engine's performance to close to the original performance with regular cleanings. An example of change in engine performance over time is show in Figure 2-5.

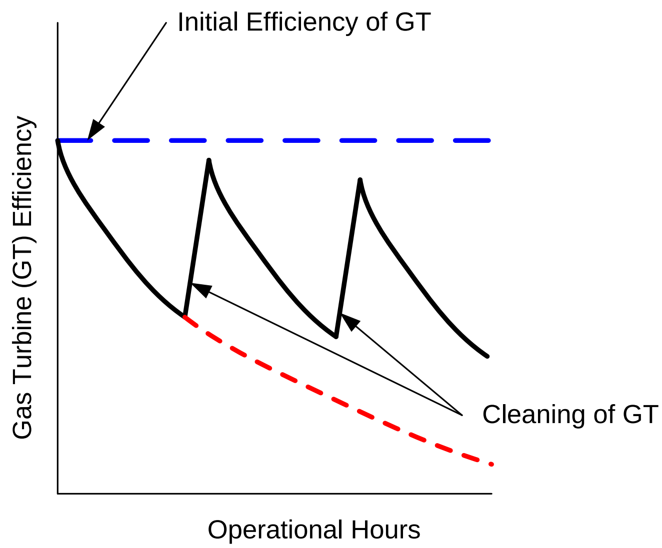


Figure 2-5. Effect of Cleaning on the Efficiency of a Gas Turbine

Hard particles in the submicron range can be easily removed with the proper filter, but other submicron components such as oil vapors and water are difficult to remove from the flow stream. Special filters are required to accomplish this. Also, the location of the inlet to the filtration system can be designed in order to avoid intake of some of these substances. For example, if it is known that an exhaust stack is located near the gas turbine inlet, the air intake system can be oriented to minimize the exhaust air ingested from this stack. Figure 2-6 shows some examples of fouling on compressor blades.

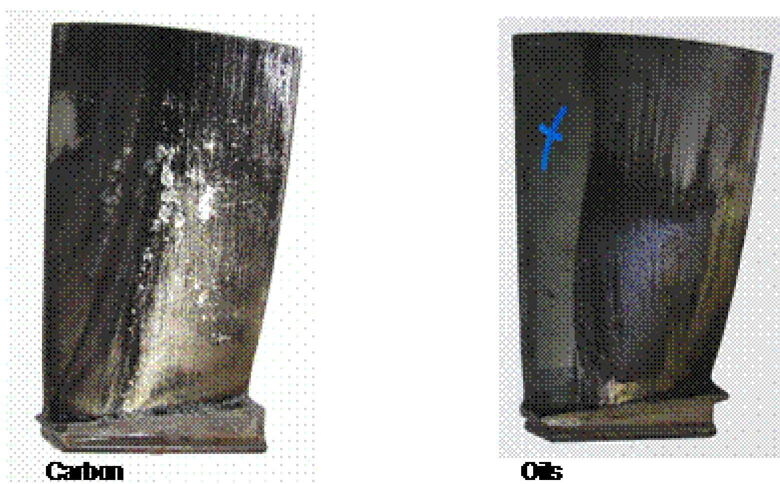


Figure 2-6. Fouling on a Compressor Blade

2.1.4 Cooling Passage Plugging

Cooling passage plugging is a specialized form of fouling. Modern high-power, high-performance gas turbines require cooling of the more critical turbine section blades and stator vanes by gas flow through internal passages. Relatively cooler air flows through these passages to carry away heat to maintain temperatures that the metals can withstand. When these flow paths become obstructed with particles that are carried in the fluids passing through them, the cooling efficiency is reduced or stopped, the part becomes over-heated, and failure can occur quickly. Coal dust, cement dust, and fly ash are the worst offenders since their small particles compress into a solid mass.

2.1.5 Particle Fusion

Small particles that migrate through the gas turbine often cause fouling, but if the melting or fusion temperature of the particles is exceeded by the combustor or turbine operating temperature, then these particles can melt and adhere to internal surfaces. These molten particles can stick to the turbine blade and change the profile or even block cooling passages leading to thermal fatigue. This phenomenon is especially true in modern engines which have higher combustor and turbine operating temperatures.

2.1.6 Corrosion

If the types of material ingested into the machine are chemically reactive, especially involving the metal in the turbine parts, the result is corrosion. There are two classifications of corrosion in gas turbines: cold corrosion and hot corrosion. Cold corrosion occurs in the compressor due to wet deposits of salts, acids, steam, aggressive gases such as chlorine, sulfides, or perhaps oxides. This can result in reducing cross-sectional properties by removal of material over an area or concentrated corrosion resulting in pitting (Figure 2-7). The results of corrosion can be very similar to erosion, except that corrosion can also intrude into cracks and metallurgical abnormalities to accelerate other damage initiation mechanisms. These corrosion effects are irreversible just like erosion. The only way to bring the blades back to the original condition is with replacement.

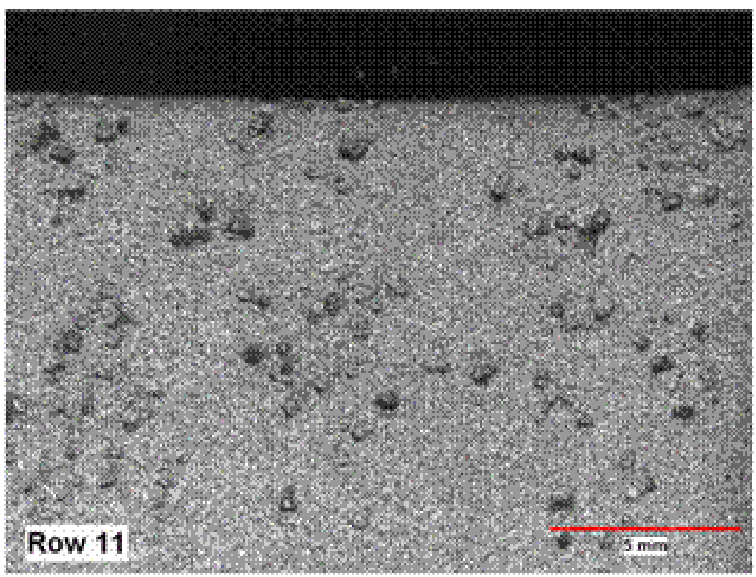
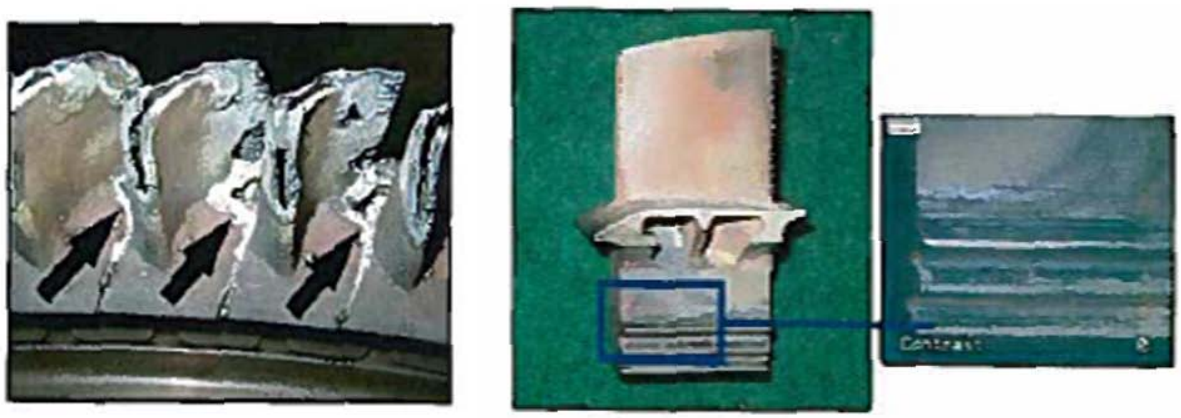


Figure 2-7. Corrosion/Pitting on a Compressor Blade

Hot corrosion occurs in the turbine area of the gas turbine. This section is exposed to materials that may intrude not just from the air, but also from the fuel or water/ steam injection which can be difficult to filter. These include metals such as sodium, potassium, vanadium, and lead that react with sulfur and/ or oxygen during combustion. After combustion, these will deposit themselves on combustor liners, nozzles, turbine blades, and transition pieces and cause the normally protective oxide film on these parts to oxidize several times faster than without it. Oxidation is a chemical reaction at high temperatures between oxygen and the components material. Hot corrosion is a form of accelerated oxidation that is produced by the chemical reaction between a component and molten salts deposited on its surface. Hot corrosion comprises a complex series of chemical reactions, making corrosion rates very difficult to predict. Degradation becomes more severe with increasing contaminant concentration levels.

The mechanism and rate of hot corrosion is highly influenced by temperature. Turbine blades are attacked by higher temperature corrosion. There is a temperature gradient across the blade. Due to this gradient, the temperature at the root is lower than the blade itself, so the root will experience a hot corrosion mechanism different than blade corrosion. The selection of appropriate alloys and coatings for the materials of the components in the hot section of the gas turbine can help to mitigate hot corrosion failures but the preferred path of preventing this type of failure is through proper filtration. If possible, the levels of sodium and potassium should be kept below 0.01 ppm with filtration to prevent hot corrosion.



Turbine Blade Failure   Root of Turbine Blade Failure

Figure 2-8. Examples of Hot Corrosion Failures
(Courtesy of Solar Turbines)

2.2 Use of Filtration

The effects of inlet air filtration are both positive and negative. The negative side of filtration is that whatever is placed in the path of air coming into the gas turbine causes a pressure loss, resulting in reduced performance or efficiency of the machine. However, inlet filtration will help sustain the gas turbine's performance above an acceptable level and minimize the occurrence of the degradation effects discussed above. Turbine inlet filtration becomes a trade-off. Cleaner air with reduced particle or moisture content controls wear and fouling at reduced efficiency. Unfiltered or less-filtered air at lower pressure loss gives better efficiency initially, but the "dirty" air can result in temporarily or permanently damaged machinery internal parts. Thus, it is clear that filtration is needed. The challenge is to keep pressure loss to a minimum while removing a satisfactory amount of particles and moisture.

Effective filtration can require several filter stages to remove different materials from the air, or to remove more particles, different phases (solid, liquid), or smaller particles. Filters to remove rain and snow, mist, smoke or dust, and finer particles all require variations in filter design. The most common approach to meet these varied needs is the use of multiple stage filtration systems, usually with two or three stages, each stage with a different purpose and design.

The selection of filtration systems is based on the expected operating environment. The changing seasons, prolonged rainy periods, snowstorms and sandstorms, changes in dust composition, insects, organic materials such as pollen, cotton residues, and leaves must all be taken into consideration. Specific local conditions influence filter design and location; wind direction, local air pollution, elevation of the inlet above ground level, and local air flows caused by buildings or terrain. There are also several other aspects of filter operation that should be considered in the design and selection process: expected operating conditions, required gas turbine availability, filter face velocity, desired pressure loss for gas turbine performance, particulate size, filter efficiency, dust holding capacity, filter loading (surface and depth), and wet operation. Various types of filters are discussed in Section 3 which are used to meet the requirements of inlet filtration. These include weather protection, trash screens, inertial separators, moisture coalescers, prefilters, high efficiency filters, and self-cleaning filters.

Filters are classified by several standard rating methods. In the United States, the methods are defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) in standard 52.2: 2007. In Europe, these classifications are set by European Standards EN 779: 2002 and EN 1822: 2009 (Parts 1 through 5). The classifications are given to the filters based on standard tests for arrestance and various efficiencies. More information about each of these standards as well as the testing and ratings will be discussed in Section 5.

3. FILTER SELECTION

Gas turbine inlet filtration is an important feature in the selection and purchase of the gas turbine. Properly selecting and maintaining the filtration system can increase the performance and life of the gas turbine and minimize the required and unexpected maintenance. This section discusses the necessary information to determine which type of filtration system is needed for different applications. It includes a review of filter characteristics related to performance, operation, life, and maintenance. Considerations for environmental factors are discussed with a focus on marine, coastal, offshore, and land based applications. Finally, a methodology for a life cycle cost analysis for filter selection is presented.

3.1 Filter Characteristics

To properly select a filtration system for gas turbine service, one must understand the contaminants that the filters need to remove. Also, it is important to understand the filtration parameters and how these are affected by the operating environment. Finally, the types of filters that are commercially available for use in gas turbine filtration systems should be known.

3.1.1 Gas Turbine Contaminants

A contaminant consists of any substance which is entrained in the air stream entering the gas turbine. These can range from solid particles, gases, and liquids such as sea salts, dust, sand, factory discharge gases, exhaust fumes containing oil and fuel vapors, particles such as chemicals, fertilizers, mineral ores, and any variety of industrial by-products. Contaminants existing in the environment where the gas turbine operates are highly dependent upon the location of the gas turbine and the surrounding local activities (other industrial sites, farming, etc.). The contaminants can vary daily or seasonally due to the fact that they are subject to climatic conditions such as wind direction, wind speed, temperature, relative humidity, and precipitation which are constantly changing. Each gas turbine site should be thoroughly evaluated for the expected contaminants. The inlet filtration system should be designed to filter contaminants expected in that environment. Table 3-1 lists some common contaminants and their typical size and the rated filters (based on applicable standards) which can remove these contaminants. Filter ratings will be discussed in detail in Section 5.

Despite the application of inlet air filtration and advancements in air filter technology, experience shows that some inlet air contaminants penetrate the filtration system and move through the engine gas path. The goal of inlet air filtration is to minimize the contaminants that enter the gas turbine to prolong the life of the turbine, prevent gas turbine degradation to maintain performance, and prevent unnecessary maintenance related to contaminant influences. Perhaps the most important consideration in selecting an air filter is the size, phase, concentration, and composition of the contaminants. The expected contaminants in various environments will be discussed in detail in Section 3.3.

Table 3-1. Common Contaminants and their Appropriate Rated Filter

Grade	ASHRAE Filter Class MERV	EN Filter Class	Particles Separated
Coarse > 10 micron	1	G1	Leaves, insects, textile fibers, sand, flying ash, mist, rain
	2	G2	
	3	G2	
	4	G2	
	5	G3	Pollen, fog, spray
	6	G3	
	7	G4	
	8	G4	
	9	G4	
Fine > 1 micron	10	F5	Spore, cement dust, dust sedimentation
	11	F6	Clouds, fog
	12	F6	
	13	F7	Accumulated carbon black
	14	F8	Metal oxide smoke, oil smoke
	15	F9	
EPA and HEPA > 0.01 micron	16	E10	Metal oxide smoke, carbon black, smog, mist, fumes
	16	E11	
	16	E12	Oil smoke in the initial stages, aerosol micro particles, radioactive aerosol
	17	H13	
	18	H13	
	19	H14	Aerosol micro particles
	20	H14	
ULPA Micro particles		U15	Aerosol micro particles
		U16	
		U17	
Note: Correlations between ASHRAE and EN standards classifications and particle size are approximate.			

3.1.2 Filter Parameters

Filters have various parameters which must be considered in the design and selection in order to obtain the filtration system most suitable for the application. Depending upon the requirements of the gas turbine, service parameters such as efficiency, pressure loss, face velocity, and filter loading must be considered. The various filter parameters are discussed below for consideration in selection of inlet filtration system.

3.1.2.1 Filtration Mechanisms

Filters are designed to use various mechanisms to remove the particles of various sizes. The mechanism employed by the filter depends on the velocity through the media, fiber size, packing density of the media, particle size, and electrostatic charge. In a single filter, the various mechanisms work together. Five basic filtration mechanisms are described below.

The first filtration mechanism is inertial impaction. This type of filtration is applicable to particles larger than 1 micron in diameter. The inertia of the large heavy particles in the flow stream causes the particles to continue on a straight path as the flow stream moves to go around a filter fiber. The particulate then impacts and is attached to the filter media and held in place as shown in the top picture of Figure 3-1. This type of filtration mechanism is effective in high velocity filtration systems.

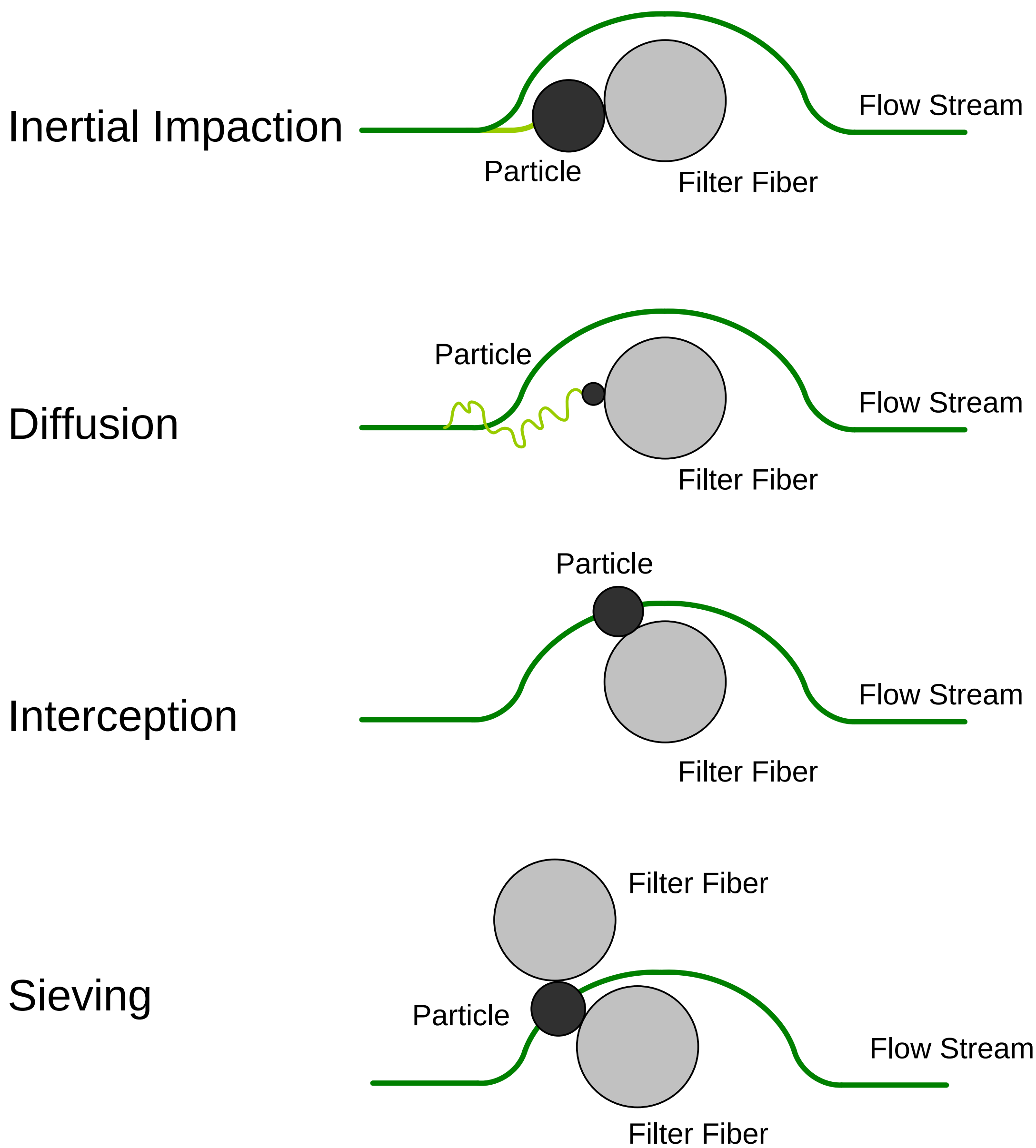


Figure 3-1. Common Filtration Mechanisms

The next filtration mechanism, diffusion, is effective for very small particles typically less than 0.5 micron in size with low flow rates. These particles are not held by the viscous forces in the fluid and will diffuse within the flow stream along a random path (second picture). The path the particle takes depends on its interaction with nearby particles and gas molecules. As these particles diffuse in the flow stream, they collide with the fiber and are captured. The smaller a particle and the lower the flow rate through the filter media, the higher probability that the particle will be captured.

The next two filtration mechanisms are the most well known; interception and sieving. Interception occurs with medium sized particles that are not large enough to leave the flow path due to inertia or not small enough to diffuse. The particles will follow the flow stream where they will touch a fiber in the filter media and be trapped and held. Sieving is the situation where the space between the filter fibers is smaller than the particle itself, which causes the particle to be captured and contained.

Another type of filtration mechanism which is not shown in Figure 3-1 is viscous impingement. This type of mechanism uses the inertial impaction mechanism to capture particles. What makes this mechanism unique is that the filter is covered with a thin layer of oil which causes the captured particles to adhere to the filter surface, thus preventing them from being released downstream. The amount of particles captured is maximized by creating a torturous path for the air. This results in a filter with many changes in flow direction. This filtration mechanism is effect for medium to large size particles.

The last filtration mechanism is electrostatic charge. This type of filtration is effective for particles in the 0.01 to 10 micron size range. The filter works through the attraction of particles to a charged filter. In gas turbine applications, this charge is applied to the filter before installation during the manufacturing process. Filters always lose their electrostatic charge over time because the particles captured on their surface occupy charged sites, therefore neutralizing their electrostatic charge. As the charge is lost, the filter efficiency for small particles will decrease. However, it should be noted that as the filter is loaded, the filtration efficiency increases. This will offset some of the loss of filtration efficiency due to the lost charge. Figure 3-2 shows a comparison of a filter's total efficiency based on the various filtration mechanisms that are applied. The figure shows the difference between the filter's efficiency curve before and after the charge is lost. The performance of the filter should be based on the discharge condition.

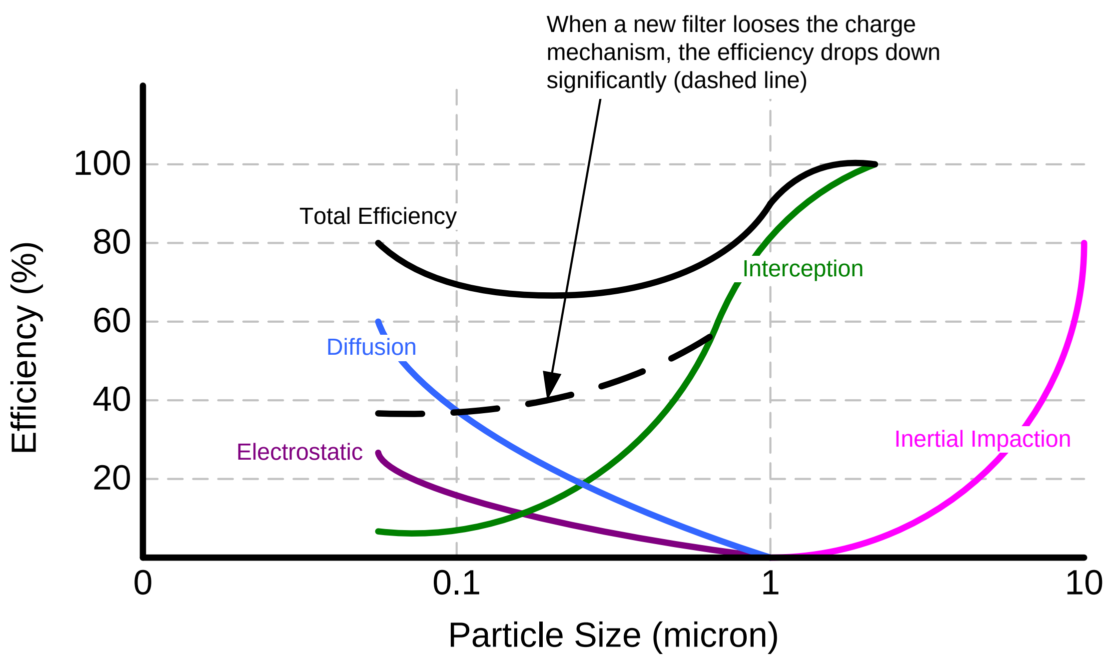


Figure 3-2. Combination of Filtration Mechanisms to Obtain Filter Efficiency at Various Particle Sizes

3.1.2.2 Filter Efficiency and Classification

Filter efficiency is a broad term. In general, the filter efficiency is the ratio of the weight, volume, area, or number of particles entering the filter to the weight, volume, area, or number of the particles captured in the filter and ratings, respectively. The weight efficiency is calculated as shown in Equation 3-1. The efficiency can be expressed in several ways: maximum, minimum, or average lifetime value. Many filters have poor performance against small particles at the beginning of their lives, but as the filter media becomes loaded with particles, it is able to catch smaller particles. In this case, the average efficiency would actually be higher than the initial efficiency. Some of the filters will never reach the quoted maximum efficiency before they are replaced.

$$\eta = \frac{W_{entering} - W_{leaving}}{W_{entering}} * 100\% \tag{3-1}$$

Filter efficiency is a trade-off against the pressure loss and dust holding capacity of the filter. Normally, the filtration system pressure loss will increase with an increase in filtration efficiency. As filters become more efficient, less dust penetrates through them. Also, the air flow path is more constricted with higher efficiency filters. This leads to higher pressure loss. Filter engineers must determine the acceptable pressure loss and efficiency for their application. Studies have shown that a higher pressure loss due to using a high efficiency filter has a lower effect on gas turbine power degradation than poor inlet air quality. Figure 3-3 shows data collected by the AAF International which shows an example of this. The gas turbine which used a F7 filter (lower filtration efficiency) had significantly more performance degradation due to fouling than the gas turbine with the F9 and H12 filters (higher filtration efficiency).

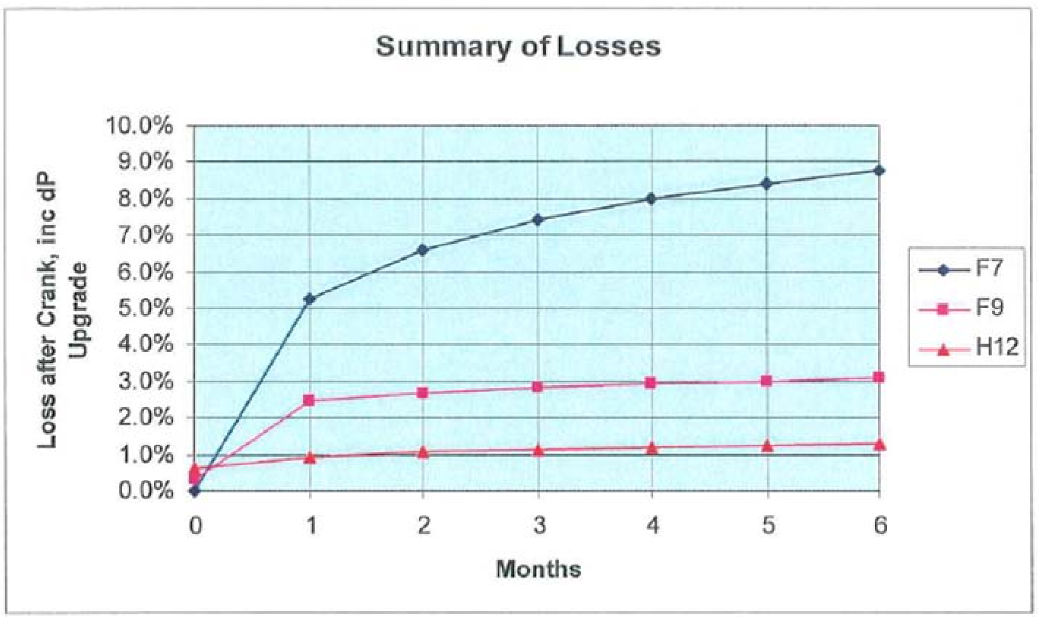


Figure 3-3. Comparison of Gas Turbine Degradation with Different Levels of Filtration
(Owens, 2009)

The efficiency of a filter cannot be stated as a general characteristic. The filter efficiencies vary with particle size, typically being lower for small particles and higher for large particles. They also vary with operational velocity. Filters designed for medium and low velocities will have a poor performance at higher velocities and vice versa. Therefore, a particle size range and flow velocity must be associated with the stated efficiency. For example, a filter may have 95% filtration efficiency for particles greater than 5 microns at a volumetric flow rate of 3000 cfm, but the efficiency could be reduced to less than 70% for particles less than 5 microns or at a volumetric flow rate of 4000 cfm.

When selecting a filter from different manufacturers based on efficiency, ensure that the comparison is for filters with consistent test standards and test conditions. Pay attention to the air velocity used for the test, particle type, environmental conditions, and particles sizes. This air velocity should be comparable to the expected operating conditions. If the actual operational velocity is significantly higher than the test velocity (ex. 50%), then it can be expected that the performance of the filter will be reduced.

When comparing filter efficiencies, it is important that the same type of efficiency is compared. An efficiency that is calculated using a mass ratio cannot be compared to an efficiency that is calculated using a volume ratio. The different types of efficiencies can have very different values. For example, consider a test air that consists of 101 spheres of the same density. There are 100 particles with a diameter of 1 micron and 1 particle with a diameter of 10 microns. Assume the filter only captures the 10 micron particle. The efficiencies based on weight (arrestance), area (dust spot efficiency), and particle count are calculated below. The efficiency values range from 0.99% to 90.91%. This example clearly shows that these different efficiencies cannot be directly compared.

- Efficiency by weight (arrestance) $$\left(\frac{1000}{1000+100}\right)*100\% = 90.91\%$$

- Efficiency by area (dust spot efficiency) $$\left(\frac{100}{100+100}\right)*100\% = 50.00\%$$

- Efficiency by particle count $$\left(\frac{1}{1+100}\right)*100\% = 0.99\%$$

Filters are rated for performance based on standards established in the United States of America and Europe. These filter ratings are based on the results of standard performance tests. In the United States, ASHRAE standard 52.2: 2007 outlines the requirements for performance tests and the methodology to calculate the efficiencies. In this standard, the efficiencies are determined for various ranges of particles sizes. The filter is given a Minimum Efficiency Reporting Value (MERV) rating based on its performance on the particle size ranges (particle count efficiency) and the weight arrestance (weight efficiency). The weight arrestance is a comparison of the weight of the dust penetrating the filter to the dust feed into the flow stream. In this standard, a filter with a MERV of 10 will have 50-65% minimum efficiency for particles 1 – 3 microns in size and greater than 85% for particles 3 – 10 microns in size.

The European standards used to determine performance are EN 779: 2002 and EN 1822:2009. EN 779: 2002 is used to rate coarse and fine efficiency filters. EN 1822:2009 presents a methodology for determining the performance of high efficiencies filters: Efficient Particulate Air filters (EPA), High Efficiency Particulate Air filter (HEPA), and Ultra Low Particle Air filter (ULPA). In EN 779: 2002, the performance is found with average separation efficiency which is an average of the removal efficiency of 0.3 micron particles at four test flow rates (particle count efficiency) for fine filters and with an average arrestance (weight efficiency) for coarse particle filters. This standards rates the filters with a letter and number designation: G1 – G4 (coarse filters) and F5 – F9 (fine filters). Filter performance is determined by the Most Penetrating Particle Size efficiency (MPPS) in EN 1822: 2009. The MPPS is defined as the particle size which has the minimum filtration efficiency or maximum penetration during the filter testing. The particle sizes tested range from 0.15 to 0.3 microns. The filter efficiency is calculated based on particle count. These filters are given a rating of E10 – E12 for EPA type filters, H13-H14 for HEPA type filters, and U15 – U17 for ULPA filters. Table 3-2 gives a general overview of the efficiencies for each filter rating and a comparison of the filter ratings between American and European standards. A detailed discussion of each of the test standards listed above is presented in Section 4.

Table 3-2. Classification of Filters Based on American and European Standards

ASHRAE Filter Class	ASHRAE 52.2: 2007			EN Filter Class	EN 779: 2002		EN 1822: 2009	
	Average Particles Size Efficiencies in X - Y micron (%)				Average Separation Efficiency (A_m)	Average Separation Efficiency (E_m)	Total Filtration Separation Efficiency (%)	Local Filtration Separation Efficiency (%)
	E_1	E_2	E_3					
MERV	0.3 - 1.0	1.0 - 3.0	3.0 - 10.0					
1			< 20	G1	50 ≤ A_m < 65			
2			< 20	G2	65 ≤ A_m < 80			
3			< 20					
4			< 20					
5			20 - 35	G3	80 ≤ A_m < 90			
6			35 - 50					
7			50 - 70	G4	90 ≤ A_m			
8			> 70					
9		< 50	> 85	F5		40 ≤ E_m < 60		
10		50 - 65	> 85					
11		65 - 80	> 85	F6		60 ≤ E_m < 80		
12		> 80	> 90					
13	< 75	> 90	> 90	F7		80 ≤ E_m < 90		
14	75 - 85	> 90	> 90	F8		90 ≤ E_m < 95		
15	85 - 95	> 90	> 90	F9		95 ≤ E_m		
16	> 95	> 95	> 95	E10			85	
				E11			95	
				E12			99.5	
				H13			99.95	99.75
				H14			99.995	99.975
				U15			99.9995	99.9975
				U16			99.99995	99.99975
				U17			99.999995	99.9999
Note: Correlations between ASHRAE and EN standard classifications are approximate.								

3.1.2.3 Filter Pressure Loss

As mentioned above, a higher pressure loss occurs with a more efficient filter due to air flow restrictions. Pressure loss has a direct impact on the gas turbine performance. This causes the inlet pressure at the compressor of the gas turbine to be lower. In order for the compressor to overcome the inlet system losses, the gas turbine must consume more fuel, and it also has a reduced power output. The relationship between the inlet filtration system and pressure loss is linear as shown in Figure 3-4. This shows that as the pressure losses increase at the inlet, the power decreases, and the HR increases linearly. A 50 Pa (0.2 inH2O) reduction of pressure loss can result in a 0.1% improvement in power output. Typical pressure losses on inlet filtration systems can range from 2 to 6 inH2O.

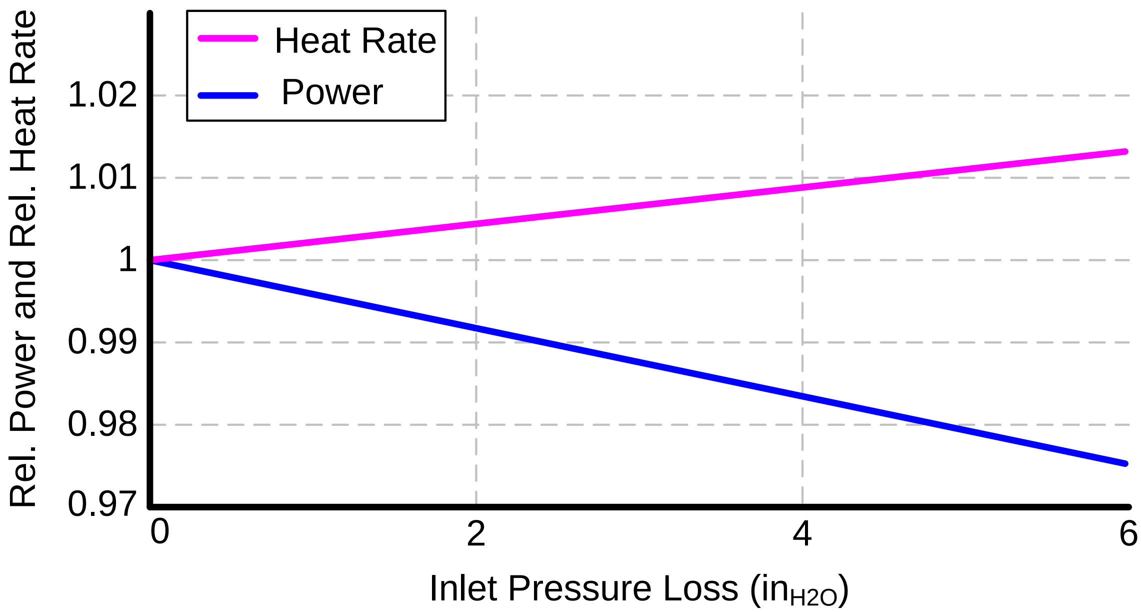


Figure 3-4. Effect of Pressure Loss at Inlet on Gas Turbine Power and HR

The filter's performance needs to be assessed for the full pressure loss range over its life, not just when it is new. The pressure loss will increase over the lifetime of the filter. If a filter is selected only based on the initial pressure loss, then the filter engineer can expect a lower gas turbine performance over the life of the filter or to be frequently changing out filters in order to maintain the lower pressure loss required for gas turbine performance. The change of pressure loss over time is highly dependent upon the filter selection and the type and amount of contaminants experienced.

One method that many filtration system manufacturers have taken to reduce the pressure loss is to decrease the filter face velocity. Decreasing the face velocity reduces the viscous and flow restriction effects which leads to lower pressure losses. Decreases in face velocity are achieved with larger filter surface area. The larger surface area also creates more fiber material for particles to be trapped in, so the filter is able to retain more dust during its life. Increased surface area seems like an ideal solution, but one must consider that more surface area means a larger filtration system. This will require more material and higher initial costs. Also, more filters will need to be replaced during maintenance intervals. Filters used in offshore or marine type applications do not have extra space for more surface area. They have volume and weight restrictions which often required the use of high velocity filters.

Reducing the pressure loss cannot only be done with increasing surface area, but also through design of the inlet system ducting. Designs that have many flow path changes and turns can cause added pressure loss or high velocities across the filters or poor aerodynamics in the ducting. Computational Fluid

Dynamics (CFD) can be very useful in designing an inlet ducting to minimize pressure loss and keep filter velocities at minimal levels. This tool allows designers to view the flow streams and estimate the pressure loss associated with the proposed design. It is easier to modify a computational model during the design stages to reduce pressure loss and minimize velocities, than a system already in operation. CFD can also be used to determine if the flow is being evenly distributed among the filter elements. Correcting this in the design phase will help to ensure that each filter element in the system is loading with dust at approximately the same rate. An example of a CFD particle flow analysis of a filtration system is shown in Figure 3-5.

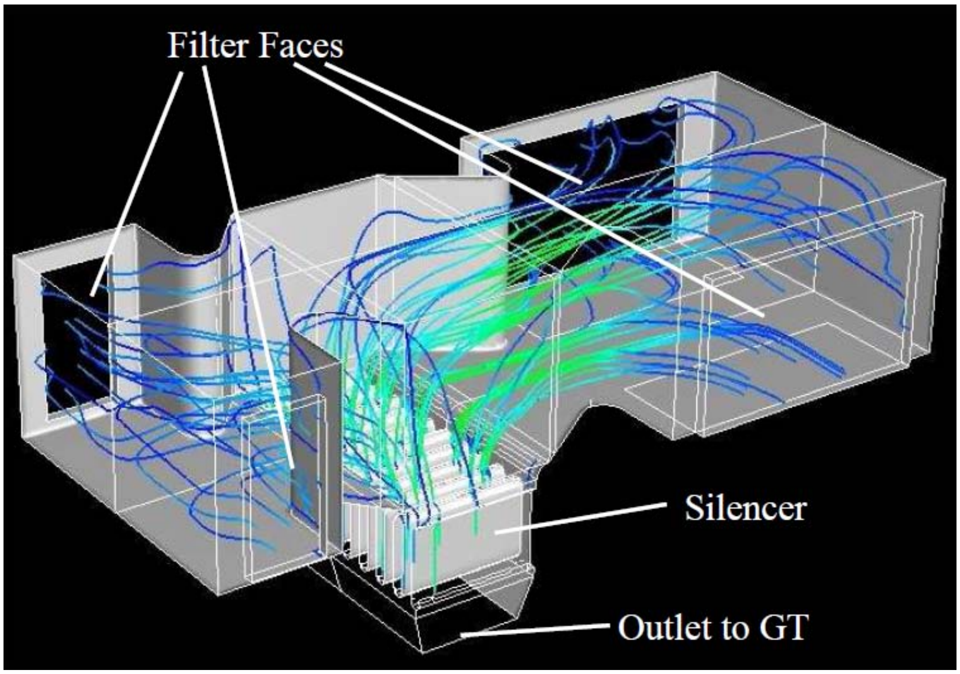


Figure 3-5. Example of CFD Analysis in Inlet Filtration System
(Hiner, 2005)

3.1.2.4 Filter Loading

During operation as the filter collects particles, it is slowly loaded until it reaches a "full" state. This state is usually defined as when the filter reaches a specified pressure loss, or when the maintenance interval has been met. Filters are loaded in two different ways: surface and depth loading. Depth loading is the type of filtration where the particles are captured inside of the filter material. To regain the original pressure loss or condition, the filter must be replaced. The life of these types of filter is often monitored based on pressure loss.

When using depth loaded filters, it is important to understand what dust holding capacity the filter has. A high specific dust holding capacity indicates that the filter can collect more dust, while the pressure loss increases at a slower rate. Figure 3-6 shows a graphical differentiation between a low and high specific dust holding capacity filters. The low capacity filter will have a higher pressure loss with the same amount of dust collected as the high capacity filter. The dust holding capacity is not only dependent upon the filter construction but also the particle size distribution. A filter will load up more quickly with fine dust than with large dust. For a given pressure loss, a filter can hold a greater mass of large particles than of small particles.

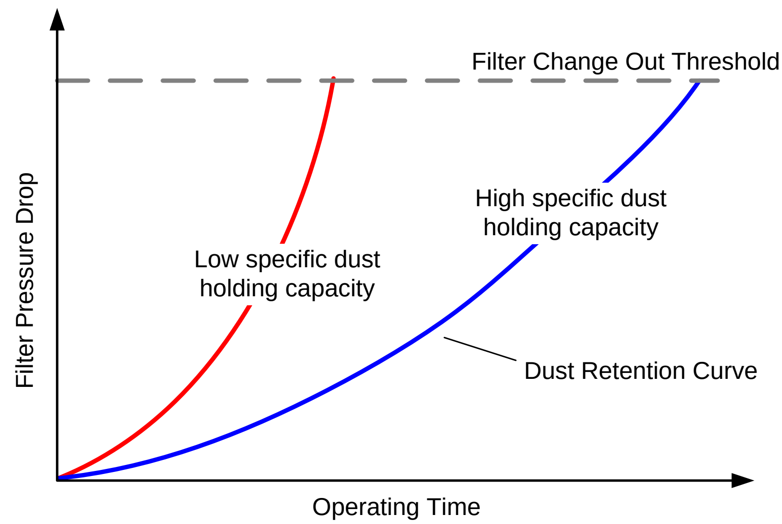


Figure 3-6. Comparison of High and Low Specific Dust Holding Capacity Filters

The low capacity filter may be used in an environment with a low amount of dust in the air where minimal filtration is required. In areas with medium to high dust concentrations or with fine dust particles, a high capacity filter is used to maximize the time between filter replacements and reduce maintenance and replacement costs. Also, if the filters are changed based on a fixed maintenance interval due to plant shutdowns, the lower average pressure loss over time will allow better overall gas turbine performance.

The other type of filter is a surface loaded filter. With this type of loading, the particles collect on the outside surface of the filter. Some of the particles may infiltrate the fiber material, but not enough to call for replacement of the filter. Surface loaded filters are most commonly used in, but not restricted to, self-cleaning systems. This is due to the fact that the dust can easily be removed with pulses of air once the filter differential pressure reaches a certain level. Once the filter is cleaned, the pressure loss across the filter will be close to its original condition. The surface loaded filter's efficiency actually increases as the surface is loaded with dust. This is due to the fact that a dust cake develops on the surface of the media creating an additional filtration layer and also decreases the amount of available flow are in the filter media.

3.1.2.5 Face Velocity

Filtration systems are distinctively classified as high, medium, or low velocity systems. The velocity of the filtration system is defined as the actual volumetric air flow divided by the total filter face area. Low velocity systems have air flow at less than 500 fpm (feet per minute) (2.54 m/s) at the filter face. Medium velocities are in the range of 610 to 680 fpm (3.1 to 3.45 m/s). High velocity systems have air flows at the filter face in excess of 780 fpm (4 m/s).

High Velocity Systems

Historically, high velocity systems are used on marine vessels and offshore platforms where space and weight are premiums. However, today, low, medium, and high velocity systems are found on marine and offshore applications. High velocity systems have the advantages of reduced size (cross sectional area), weight, and initial cost. From a lifecycle cost perspective, the reduced size also results in fewer filter elements to replace. A disadvantage is that there are more performance losses due to higher pressure loss through the inlet system. Also, filter efficiencies for small particles are significantly lower than those of lower velocity systems, and dust holding capacities are lower. Ultimately, this type of system requires more filter replacements when compared to the lower velocity system. The size and weight of the filtration system is usually only important if one of these is a criterion. Filter housing design should be based on the environment it is operating in rather than size, weight, or cost.

Low Velocity Systems

Low velocity systems are the standard on land based applications; however, high velocity systems are also used in some coastal applications. The low velocity systems are characterized by large inlet surface areas, large filter housings, and usually multiple stages of filters. The two or three stage filters provide an advantage over high velocity systems, because they have a high efficiency filter stage as the final stage to remove many small particles (especially salt) below 1 micron and to keep water from entering the gas turbine. The lower velocity also provides a lower pressure loss and higher filtration efficiency. This increase in efficiency provides more time between compressor washings and filter replacements leading to a lower lifecycle cost. Overall, low velocity systems can be more effective at reducing the mass of contaminants which enter a system. See Figure 3-7 for a size comparison of high and low velocity systems.

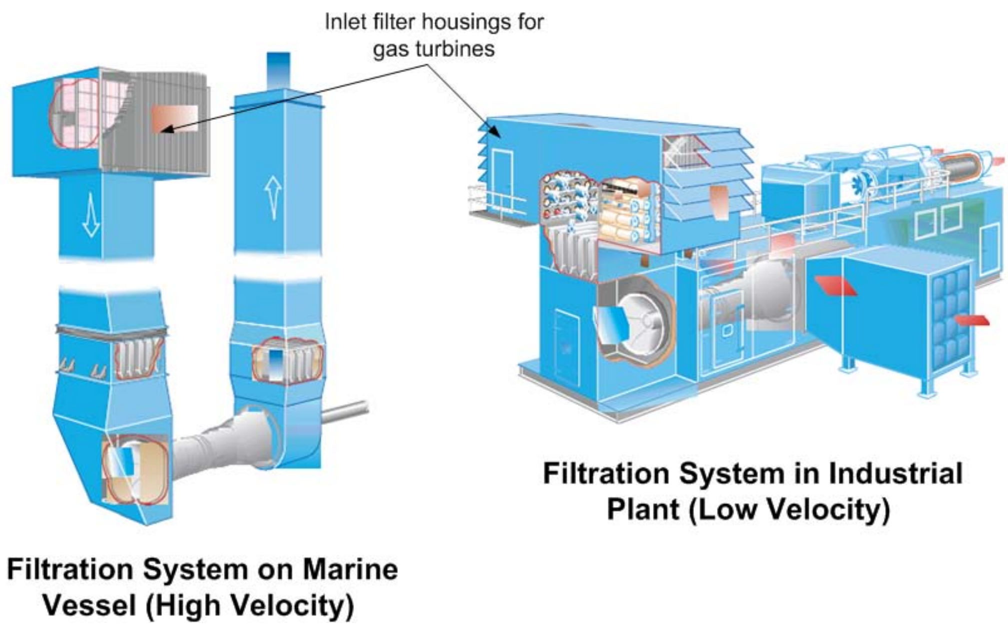


Figure 3-7. Comparison of Size Difference Between High and Low Velocity Systems
(Courtesy of Camfil Farr)

Velocity Importance in Filter Performance

A filter's performance is given at a nominal velocity which is chosen by the entity requesting the performance test. Gas turbine filter manufacturers test their filters at flow velocities representative of a typical in-service velocity. The testing of the filter is conducted at this nominal velocity, and the values reported in the manufacturer literature will be at this velocity. If the operational velocity of the application is close to or the same as the nominal velocity, then the filter may perform as expected. If the operational velocity of the application is higher than this velocity, then the filter will have a higher pressure loss, deviation from reported efficiency, and reduced dust holding capacity.

3.1.2.6 Operation in Wet Environment

Many environments where gas turbines operate will have wet ambient conditions. This could be in a jungle or at a coast where it rains a significant amount of time or a location with ocean/ lake mist. Table 3-3 is a list of the different types of moisture that can be experienced with their particle size. Most filters are not designed to operate in a wet condition, but some filters are required to do this due to their ambient conditions. The difference between filter operation in wet and dry conditions can be significant. In some cases, the pressure loss across a filter can increase significantly even with a little moisture. This is true for cellulose fiber filters which swell when they are wet. These filters will also retain the moisture which can lead to long periods of time when the pressure loss across the filter is elevated.

Table 3-3. Different Types of Moisture Experience in Inlet Filtration Systems

Description	Liquid Size (microns)
Humidity	vapor form
Smog (more smoke than humidity)	0.01 to 2
Cooling Tower Aerosols	1 to 50
Water mist	1 to 50
Clouds and fog	2 to 150
Water Spray (ship wake, ocean spray)	10 to 500
Drizzle	50 to 400
Rain	400 to 1000

Early morning fog can also add moisture to filters. Operational experience has shown that the pressure loss across certain filtration systems increases during the occurrence of fog and for many hours after the fog has cleared. If the environment where the gas turbine is operating has high frequency of moisture entrainment in the filtration system, then this should be accommodated for. Coalescers can be used to remove the droplets of moisture. Filter fiber materials can be selected for wet operation. Also, the operator should expect to have a reduced filter and gas turbine performance during periods of wet operation.

3.1.2.7 Salt Effects

Salt can have a direct effect on the life of a gas turbine if not removed properly. As discussed in Section 2.1.6, salt in the gas turbine can have serious consequences. Salt can also deposit on the compressor blades which leads to fouling and reduced aerodynamic performance. The salt on compressor blades must be removed through water washing methods or direct scrubbing of the blades. Gas turbine manufacturers usually recommend stringent criteria on the amount of salt which can be allowed to enter the gas turbine (less than 0.01 ppm). In coastal environments, the air borne salt can easily range from 0.05 to 0.5 ppm on a typical day. If the filtration system is not equipped to handle the salt, then it can pass directly through to the compressor and to the hot section of the gas turbine. Salt is present in the air due to two main sources: seawater (sodium chloride, magnesium chloride, and calcium sulfate) and exhaust gases (SOx and NOx). Salt may also come from localized sources such as a dry salt bed.

In land based filtration systems, dry salt particles can be removed with common filtration practices (for example, use of high efficiency fiber filters). However, removing salt that has dissolved into the moisture in the air is more complicated. The moisture in the air is present in two forms: as liquid water droplets and as water vapor (humidity). The majority of the liquid droplets can be removed with a coalescer or vane separator. These devices are effective for particles larger than 5 microns in size. The water droplet removal efficiency depends on the air velocity through the device. The remaining liquid droplets may make it to the high efficiency filters. There are many high efficiency filters which prevent water from penetrating the filter, but not all filters have this capability. If liquid droplets are allowed to penetrate the filter, then they can carry any absorbed salt downstream into the gas turbine. Gas turbines in high moisture and salty environments should have filters which minimize or eliminate liquid penetration. Water vapor cannot be removed by mechanical filtration. Any moisture in a vapor (or gas) form will travel through the filtration system into the gas turbine. Any salt that is absorbed by this moisture as it condenses will also travel into the gas turbine. However, a vapor at ambient conditions will most likely remain in the gas phase as it travels through the gas turbine. More discussion on the filtration of salt is presented in Section 3.3.

3.2 Types of Filters

In order to meet the requirements of the various filter parameter and different operating environments, many different types of filters have been developed. These range from high efficiency self-cleaning filters to filters that remove liquid droplets from the flow stream. The various filters will be discussed in detail in order for the filter engineer to gain a better understanding of the premise behind their use and operation.

3.2.1 Weather Protection and Trash Screens

Weather louvers or hoods and trash screens are the most simplistic of the filtration mechanisms but they are important in order to reduce the amount of moisture and particles which enter the main filtration system. These are not classified as filters, but they provide assistance in removal of large objects or particles carried in the flow stream.

Weather hoods are sheet metal coverings on the entrance of the filtration system (see Figure 3-8). The opening of the hood is pointed downward so the ambient air must turn upwards to flow into the inlet filtration system. The turning of the air is effective at minimizing rain and snow penetration. Weather hoods and louvers are used on the majority of inlet filtration systems, and they are essential for systems in areas with large amounts of rainfall or snow. In tropical climates, weather hoods deflect a large amount of rain, so the inertial separators (see Section 3.2.2,) are not overloaded and the amount of water traveling to downstream high efficiency filters is minimized. Medium size hoods can be used to deflect rain. The maximum recommended inlet velocity for a weather hood minimizing rain in the flow stream is 650 ft/min. In arctic environments, snow penetration is minimized with weather hoods. Since snow falls at a slower rate than rain, the weather hood must be larger. This larger hood increases the air entrance surface area which decreases the upward flow velocity. The maximum recommended face velocity for a weather hood with snow is 250 ft/min. Weather hoods or another comparable weather protection system are strongly recommended for all systems with high efficiency filter.

Figure 3-8. Weather Hood on Inlet Filtration System
(Courtesy of Camfil Farr)

After the weather hood is a series of turning vanes called weather louvers which redirect the air so that it must turn. The weather louvers are also effective at minimizing water and snow penetration. After the weather hood or louver is a trash or insect screen. Trash screens capture large pieces of paper, cardboard, bags, and other objects. If these pieces are allowed to enter the gas turbine, they can obstruct the air flow through the filters. The screens also deflect birds, leaves, and insects. Screens that are installed specifically for preventing insects entering the filtration system are referred to as insect screens. These screens will have a finer grid than trash screens. Weather hoods, louvers, trash screens, and insect screens are used on the majority of filtration systems due to their inexpensive cost and construction, and negligible pressure loss.

Anti-icing protection is used in climates with freezing weather. Freezing climates with rain or snow can cause icing of inlet components which can result in physical damage to inlet ducts or to the gas turbine compressor. This ice can also affect the performance of the gas turbine. If ice forms on filter elements, then ice on those filters will be blocking the flow path which will cause the velocity at the other filters to increase. This causes a decrease in filtration efficiency. Also, the filter elements with ice can be damaged. Figure 3-9 shows an example of ice formation on filters due to cooling tower drift (see Section 3.3.2.2 for definition of cooling tower drift).

Figure 3-9. Cartridge Filters with Frost Build-Up Due to Cooling Tower Drift
(Courtesy of Camfil Farr)

At the inlet bell mouth to the compressor, the air pressure decrease slightly due to the increase in velocity from the converging cross section of the mouth. This decrease in pressure causes a decrease in temperature which can lead to the water vapor in the air condensing and freezing on the bell mouth, inlet guide vanes, and initial compressor stage blades. Build up of this ice will cause a decrease in the performance of the gas turbine or worse. If the ice breaks off the components and enters the compressor, it can cause FOD. Heaters or compressor bleed air are often used in the inlet system in frigid environments to prevent the moisture in the air from freezing on the inlet bell mouth or filter elements.

3.2.2 Inertial Separators

Inertial separation takes advantage of the physical principles of momentum, gravity, centrifugal forces, and impingement, and the physical difference between phases to cause particles to be moved out of the gas stream in such a way that they can be carried off or drained. The higher momentum of the dust or water particles contained in the air stream causes them to travel forward, while the air can be diverted to side ports and exit by a different path than the dust. There are many types of inertial separators, but the ones commonly used with gas turbine inlet filtration are vane and cyclone separators.

Vane axial type separators are an axial flow device with hooks or pockets on the side-walls which capture water droplets. There are two primary types: single pocket vane (or hook), and double pocket vane (Figure 3-10). As the gas turns along the vane, the water droplets impinge on the metal surface, are pushed to the pocket by the forces of the gas flow, and are then captured in the pockets. The closed pockets have a space for the liquid droplets to collect and drain out which reduces the potential for re-entrainment.

The vane type separators are effective for water particles greater than 10 microns. The double type pocket separators are also effective for capturing particles in the range of 5 to 10 microns. The efficiency of the separators is based upon the design air velocity. The separator will have the highest filtration efficiency at its design velocity. Vane separators have a relatively low pressure loss (0.1 to 0.5 inH2O). They are effectively used for removal of water in high velocity filtration systems which are used in marine and offshore applications. Aluminum, stainless steel, or PVC are used as the material of construction, due to their corrosion resistance properties.

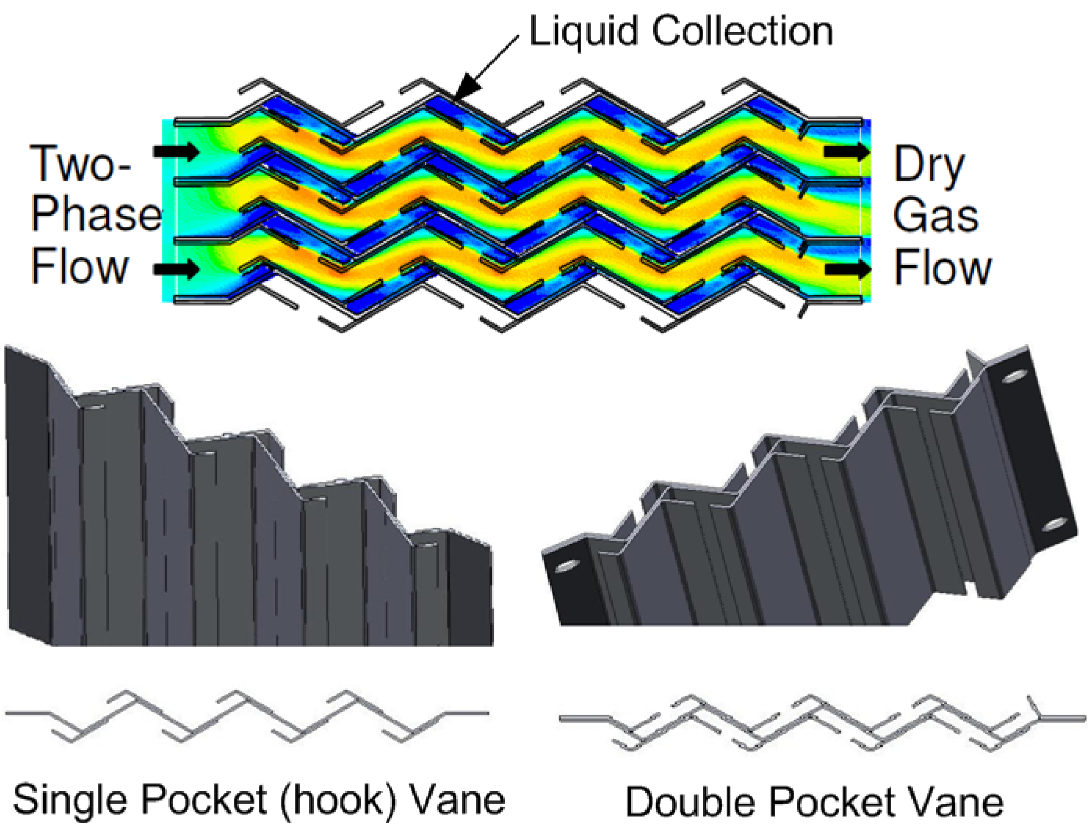


Figure 3-10. Vane Axial Separators
(Courtesy of Burgess-Manning, Inc.)

Another type of inertial separator uses stationary blades to put the flow into centrifugal motion. This spinning action causes the solid and liquid particles to move to the outside of a created vortex or cyclone flow due to centrifugal forces (Figure 3-11). The heavier particles on the outside are then scavenged by a bleed fan system, while the cleaner air is drawn through a center tube to the gas turbine. These devices have a higher pressure loss than vane separators. They are effective for the removal of liquid and solid particles. As the flow velocity increases, the pressure loss across the cyclone separator increases, and the filtration efficiency also increases. Acceptable pressure loss levels in these systems range from 1 to 1.5 inH2O. These devices require significant frontal area for their inlets.

A cyclone separator can be cast or fabricated. They are modular in nature. A well designed inertial separator can remove about 99% of particles larger than 10 microns. These devices are effective at preventing erosion and corrosion caused by particles greater than 10 microns in size. They are used as a primary form of filtration followed by some type of high efficiency filter.

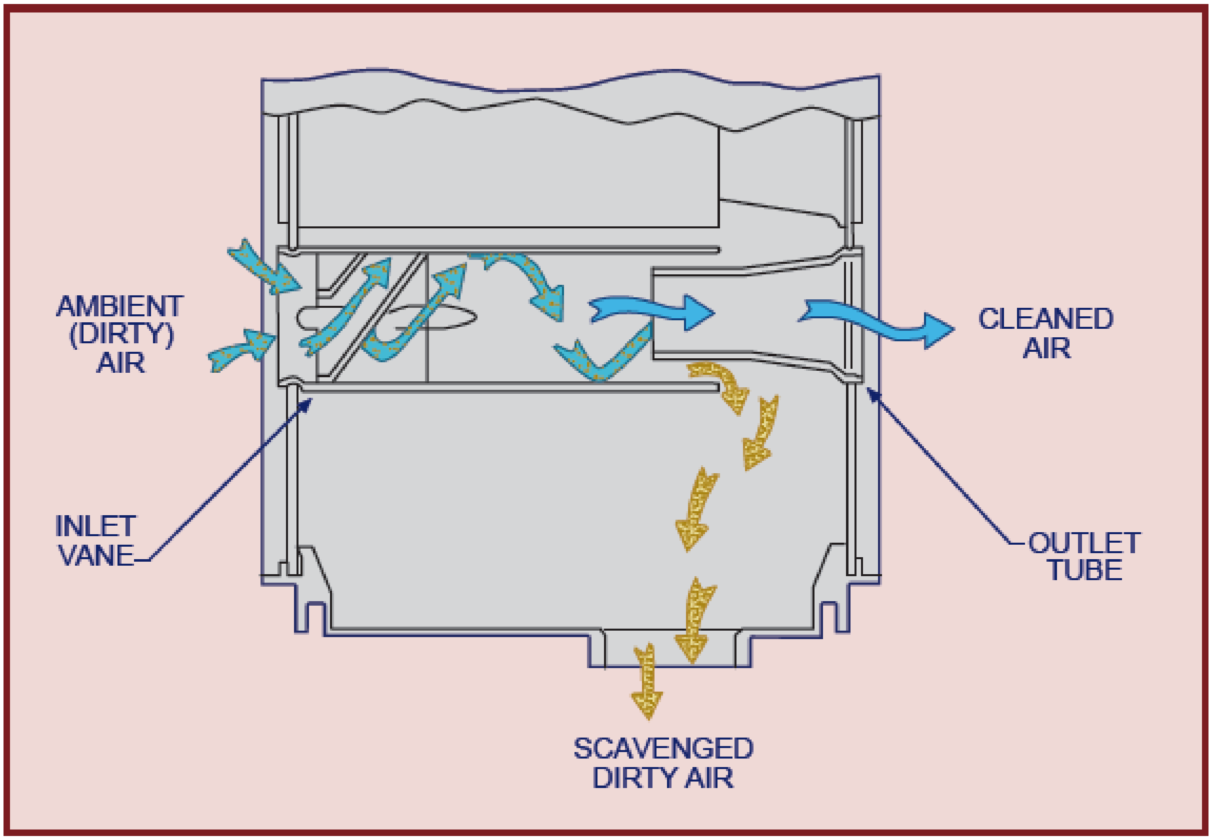


Figure 3-11. Operation of an Inertial Separator
(Courtesy of Mueller Environmental Design, Inc.)

3.2.3 Moisture Coalescers

In environments with high concentration of liquid moisture in the air, coalescers are required in order to remove the liquid moisture. The coalescer works by catching the small water droplets in its fibers. As the particles are captured, they combine with other particles to make larger water droplets. Coalescers are designed to allow the droplets to either drain down the filter or be released back into the flow stream. If the larger drops are released, then they are captured downstream by a separator. Figure 3-12 shows an example of how the droplet size distribution changes across the coalescer which releases the droplets.

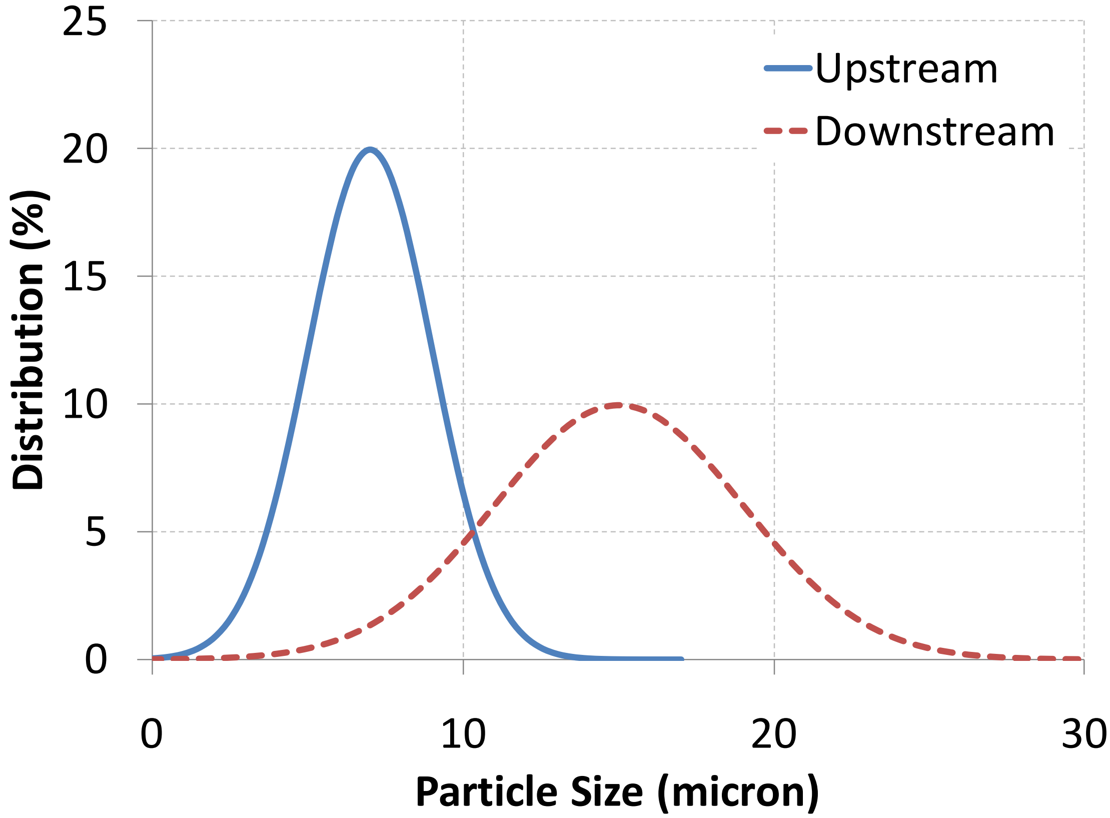


Figure 3-12. Coalescer Droplet Formation Distribution

Many other types of filters are designed for solid particulate removal and not liquid droplet removal. The efficiency of the other filters can be significantly reduced if the filter becomes wet. The placement of coalescers is important. If the coalescer is placed too far upstream, the particles the coalescer collects lead to a decrease in coalescer efficiency. However, placing the coalescer downstream of filters allows liquid droplets in the solid particle filters which will affect their performance. The solid particle filters must stay dry to maintain their solid particulate removal efficiency. Therefore, coalescers must be placed upstream of prefilters and high efficiency filters.

3.2.4 Prefilters

The air has a mixture of large and small particles. If a one-stage high efficiency filter is used, the build-up of large and small solid particles can quickly lead to increased pressure loss and filter loading. Prefilters are used to increase the life of the high efficiency filter by capturing the larger solid particles. This allows the high efficiency filter to only remove the smaller particles from the air stream which increases the filter life. Prefilters normally capture solid particles greater than 10 microns. Some prefilters will also capture the solid particles in the 2 – 5 micron size range. These filters usually consist of large diameter synthetic fiber in a disposable frame structure. Bag filters are also commonly used for prefilters (example shown in Figure 3-13). These offer higher surface area which reduces the pressure loss across the filter. Sometimes a charge will be applied to the filter in order to increase the initial efficiency of the filter. This charge will be lost as the filter neutralizes and the filtration efficiency for smaller particles will decrease.

Figure 3-13. Prefilter/ Coalescer
(Courtesy of Camfil Farr)

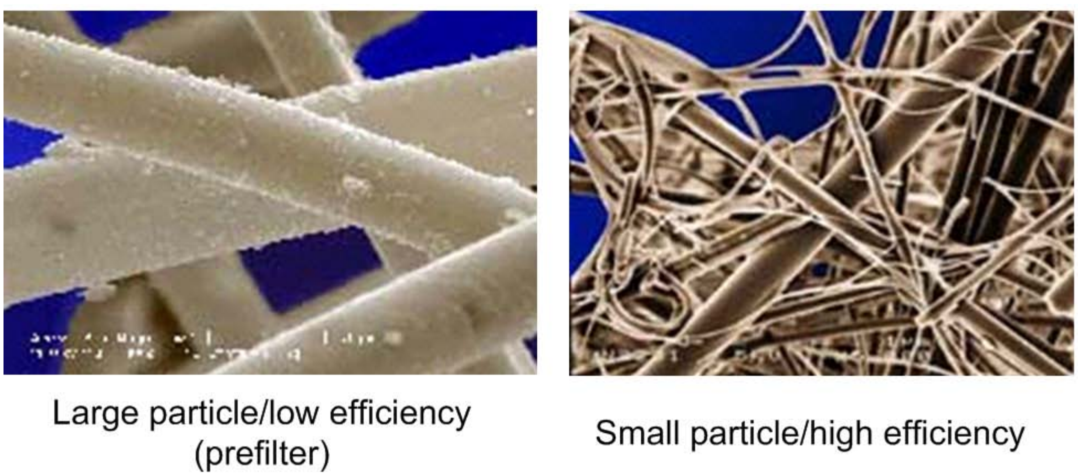


Figure 3-14. Comparison of Fiber Structure for Low and High Efficiency Filters
(Courtesy of Camfil Farr)

3.2.5 High Efficiency Filters

As discussed above, there are filters for removing larger solid particles which prevent erosion and FOD. Smaller particles which lead to corrosion, fouling, and cooling passage plugging are removed with high efficiency filters. These types of filters have average separations greater than 80%. Three common types of high efficiency filters are EPA, HEPA and ULPA. EPA and HEPA filters are defined as having a minimum efficiency of 85% and 99.95%, respectively, for all particles greater than or equal to 0.3 microns. ULPA filters have a minimum efficiency of 99.9995% for particles the same size or larger than 0.12 microns. Often, these names are used loosely with discussion of high efficiency filtration. However, the majority of the high efficiency filters used in gas turbine inlet filtration do not meet these requirements.

The high efficiency filters used with gas turbines have pleated media which increases the surface area. In order to achieve the high filtration efficiency, the flow through the filter fiber is highly restricted which creates a high pressure loss. The pleats help reduce this pressure loss. Initial pressure loss on high efficiency filters can be up to 1 inH2O with a final pressure loss in the range of 2.5 inH2O for rectangular filters and 4 inH2O for cartridge filters. The life of the filters is highly influenced by other forms of filtration upstream. If there are stages of filtration to remove larger solid articles and liquid moisture, then these filters will have a longer life. Minimal filtration before high efficiency filters will lead to more frequent replacement or cleaning. High efficiency filters are rated under various standards. The majority of filters used in gas turbines are not classified as EPA, HEPA, or ULPA. The filters used in gas turbines are rated with ASHRAE 52.2: 2007 and EN 779: 2002.

High efficiency filter media is fiberglass, treated paper, or synthetic fibers which is comprised of extremely large number of randomly oriented micro-fibers (as shown in the right image in Figure 3-14) which utilizes the majority of the filtration mechanisms to achieve its effectiveness on sub-micron particles. There are many different constructions of high efficiency type filters: rectangular, cylindrical/ cartridge, and bag filters. The rectangular high efficiency filters are constructed by folding a continuous sheet of media into closely spaced pleats in a rectangular rigid frame (Figure 3-15). Rectangular filters are depth loaded; therefore, once they reach the maximum allowable pressure loss, they should be replaced.

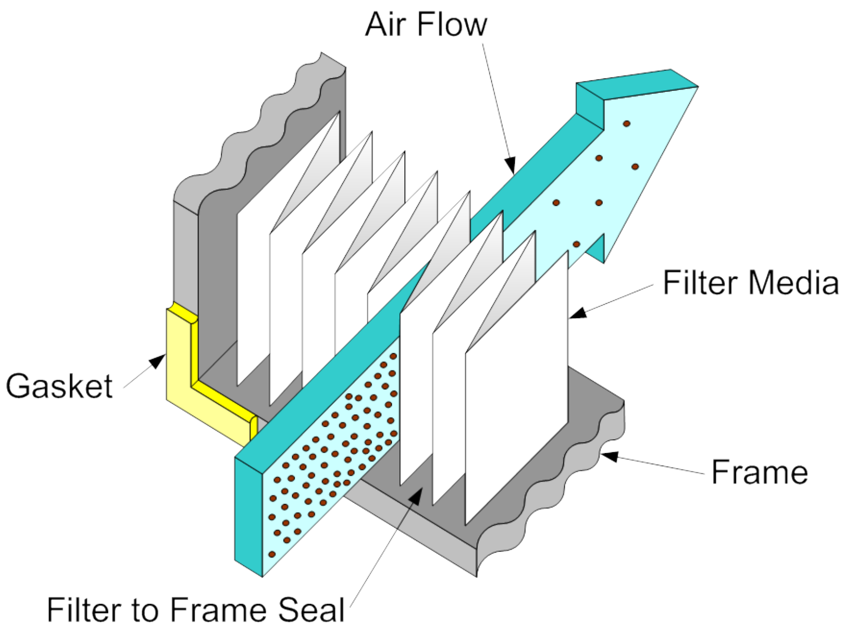


Figure 3-15. Construction of Rectangular Pleated High Efficiency Filter

There are two critical sealing points in rectangular filters. The first is the filter to frame seal. This is where the filter media connects to the filter frame. Polyurethane is commonly used for this seal. In addition, a seal is required on the outside frame of the filter when it is installed to prevent air from passing around the filter elements. These sealing requirements are true for all types (low and high efficiency) of rectangular filters. They are more critical to high efficiency filters due to the small sized particles being removed from the air stream. Two examples of rectangular high efficiency filters are shown in

Figure 3-16. Bag filters also are installed in rectangular frames. The surface area of bag filters depends on the length of the bag.

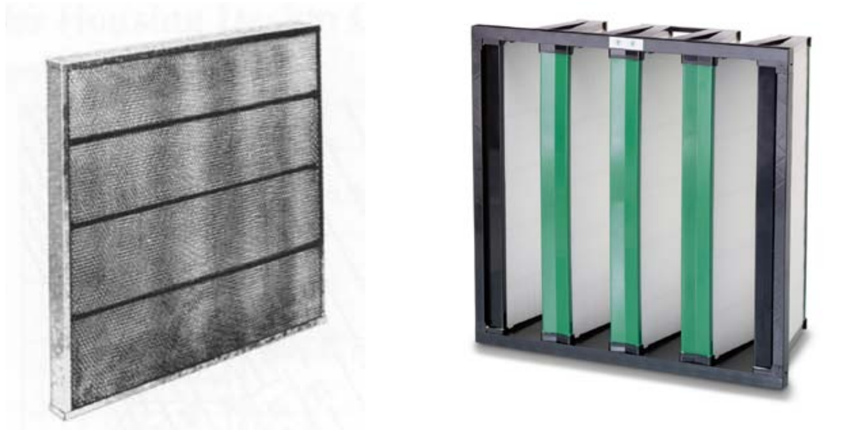
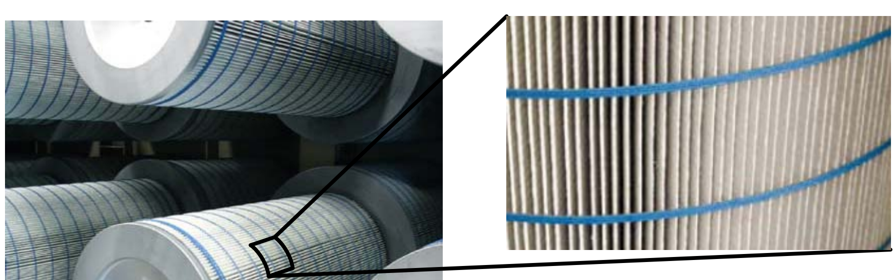


Figure 3-16. Rectangular High Efficiency Filters
(Courtesy of Burgess Manning and Camfil Farr)

Cartridge filters typically have a higher dust holding capacity than rectangular filters. For example, a cartridge filter will retain 2500 grams of Arizona fine dust, where a comparable rectangular filter will hold only 400 to 700 grams. Another advantage of cartridge filters to rectangular filters is that the sealing mechanism on the cartridge filter is made up of a single sealing element. For rectangular filters, multiple sealing elements or a single sealing element with a complex geometry is required. This makes the construction of the cartridge filter's sealing gasket easier, and there is less potential for a poor seal between the fiber media and filter frame.

Cartridge filters are also made up of closely spaced pleats, but they are in a circular fashion (Figure 3-17). Air flows radially into the cartridge. They are installed in a horizontal or vertical fashion (hanging downward). These types of filters can be depth or surface loaded. The surface loaded filters are commonly used with a self-cleaning system, but not all of them are designed for self-cleaning. Cartridge filters used in self-cleaning systems require a more robust structural design in order to protect the filter fiber media during the reverse air pulses. The more common structural support is a wire cage around the pleated media on the inside and outside of the filter. The filters shown in Figure 3-17 are not designed for a self-cleaning system since there are no structural supports on the outside of the filter. Self-cleaning filtration systems are discussed in the next section.



View of Pleats in Cartridge Filter

High Efficiency Cartridge Filters

Figure 3-17. High Efficiency Cartridge Filters
(Courtesy of Camfil Farr)

3.2.6 Self-Cleaning Filters

All of the filters with fiber type media previously discussed are required to be replaced once they reach the end of their usable life. In some environments, the amount of particles can be excessive to the point where the filters previously discussed would have to be replaced frequently to meet the filtration demand. A prime example of one of these environments is a desert with sand storms. In the 1970s, the self-cleaning filtration system was developed for the Middle East where gas turbines are subject to frequent stand storms. Since then, this system has been continually developed and utilized for gas turbine inlet air filtration.

The self-cleaning system operates primarily with surface loaded high efficiency cartridge filters. The surface loading allows for easy removal of the dust which has accumulated with reverse pulses of air (Figure 3-18). The pressure loss across each filter is continuously monitored. Once the pressure loss reaches a certain level, the filter is cleaned with air pulses. The pressure of the air pulses ranges from 80 to 100 psig. The reverse jet of compressed air (or pulse) occurs for a length of time between 100 and 200 ms. To avoid disturbing the flow and to limit the need for compressed air, the system typically only pulses 10% of the elements at a given time. With this type of cleaning, the filter can be brought back to near the original condition.

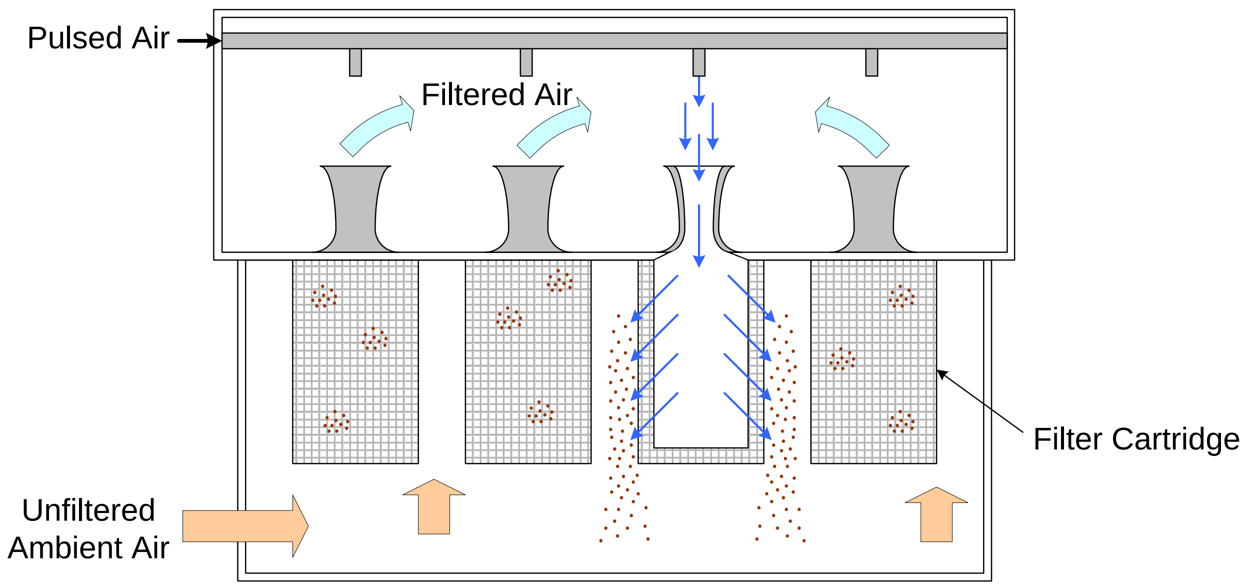


Figure 3-18. Example of Operation of an Updraft Self-Cleaning Filters

It should be noted that the filter elements in a pulse cleaning system will degrade overtime. This is due to the effects of some types of particulates captured by the filter, UV rays, heat, and the life of the filter media. Because of these effects, after a pulse cleaning the filter can return to near the original condition. Figure 3-19 shows an example of how the performance of the filter degrades overtime. In this example the pulse cleaning slowly becomes less effective at reducing the pressure drop of the filter. Once the pulse cleaning of a filter is no longer effective, it should be replaced. The filter should also be replaced once it reaches the materials maximum recommended life. Cartridge filters in a self-cleaning system have a life in the range of 1 to 2 years.

These filters are constructed of specially treated cellulose, synthetic fibers, or a combination of both types of fiber. A metal cage around the outside of the filters helps them retain their shape during pulse cleaning. There is also a metal cage on the inside of the filters to retain the filter shape during normal operation. The filters are used in low approach velocity systems. The low air velocity assists in preventing dust that is being removed from a filter with air pulsing from being re-entrained in the airflow stream, when normal flow is re-established. The efficiency of the filters actually increases over time. As the surface of the filter is loaded with particles, it decreases the available flow area through the filter which increases their efficiency. The pressure loss for cleaning is set based on the filtration system design and the design performance effects on the gas turbine.

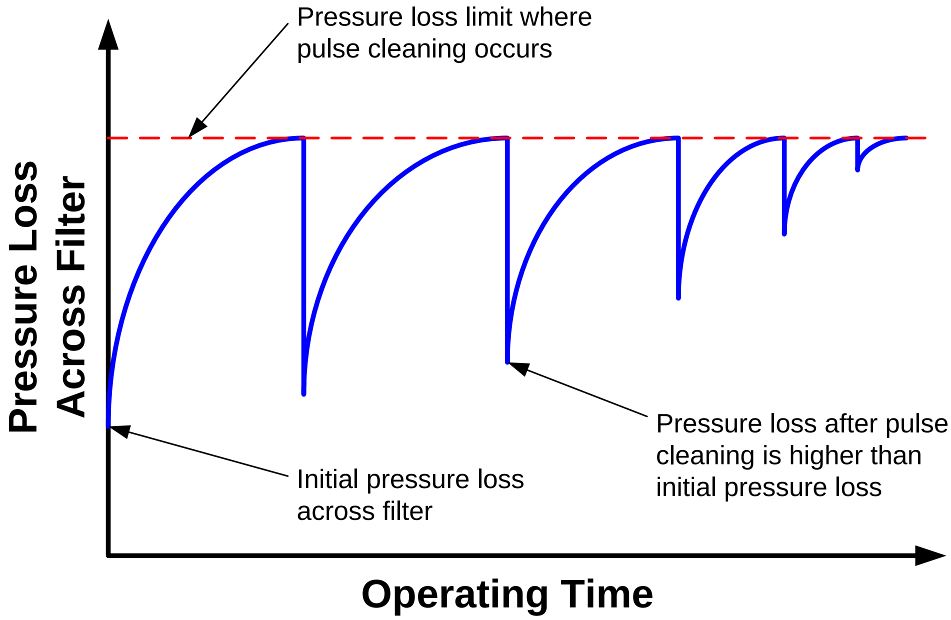


Figure 3-19. Example of Pressure Loss Curve over Time on a Self-Cleaning Filter

Self-cleaning filters provide an attractive system for maintaining filter performance while controlling filter pressure loss, but they also have their disadvantages. This type of filtration system is very useful in dry environments with high levels of dust. However, pulse clean filter systems are not necessary with medium or low levels of airborne particles due to the fact that they operate on the basis of surface loading. The filter becomes more efficient as particles collect on the outside of the filter. In areas with low dust levels or small particles, the dust may actually be captured in the fibers of the filter. It is extremely difficult to remove particles that have penetrated the filters. These filters are not designed to operate as depth loaded devices. Also, these filters work poorly in environments with sticky contaminants such as pollen. Once the sticky substances have been captured by the filter, they cannot be removed with air pulses. In order to mitigate some of the contaminants that reduce the effectiveness of the self-cleaning filter, pre-filter socks are wrapped around the cartridge filters. These socks are inexpensive and can be replaced on a more frequent basis than the cartridges. They protect the cartridges from the contaminants which would reduce the performance of the self-cleaning mechanism.

The self-cleaning filter is prone to high pressure losses and other problems in high moisture environments. Some of the filter cartridges are made of cellulose fibers which swell when wet and retain moisture. If particles that are captured on the filter media swell with moisture, then they will become very difficult to remove. Lastly, these types of systems have higher purchase and installation cost than the conventional system. However, this cost can be justified if they are used in an environment which would require frequent filter maintenance and replacement. Of course, these systems are not maintenance free. Self-cleaning devices may require less filter maintenance, but the equipment on the system needs to be maintained itself. This equipment includes the solenoids, valves, and compressors that are needed to generate the air pulses.

3.2.7 Oil Bath Filters

There are other filters that are of older design and are effective for removing certain contaminants. One type will be briefly mentioned here since it is not normally included in new, modern air filtration systems. Rotating oil-bath filters use oil to capture dust, creating a sludge that needs to be cleaned by settling tanks or centrifugal motion. The type of oil needs to be matched to the type of dust. Oil carry-over can be a problem to the gas turbine. Oil-coated roll type filters consist of a moving mat that is wetted by an oil bath and then scrolled in front of the turbine inlet. Dust adheres to the oil wetted mat. Problems with this filter design occur when the oil is allowed to dry due to periods of shutdown or excessive heat. Many times, leakage occurs around the edges of the mat. These filters can also retain water and freeze. Their efficiency decreases when any of these problems occurs.

3.2.8 Staged Filtration

Any gas turbine application typically needs more than one type of filter, and there are no "universal filters" that will serve all needs. Therefore, two-stage or three–stage filtration systems are used. In these designs, a prefilter or weather louver can be used first to remove erosive particles, rain, and snow. The second may be a low to medium-performance filter selected for the type of finer-sized particles present or a coalescer to remove liquids. The third filter is usually a high-performance filter to remove smaller particles less than 2 microns in size from the air. Figure 3-20 shows a generalized view of a filtration arrangement. This arrangement is not correct for all cases due to the fact that the filter stages are highly influenced by the environment they are operating in. More examples of multi-stage filtration systems for different environments are summarized in Section 3.3.5.2.

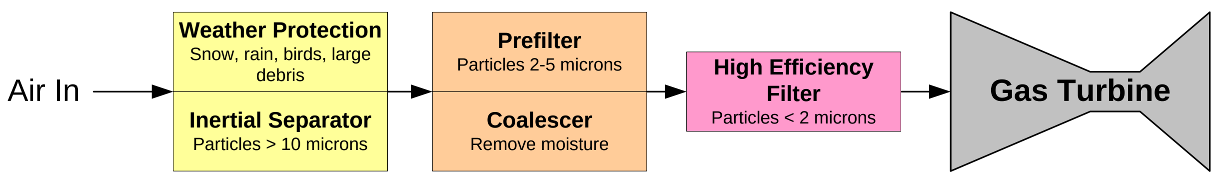


Figure 3-20. Multi-Stage Filtration System

Some of the things to consider when designing and selecting an inlet filtration system are:

- Which types of particles need to be removed and at what efficiency,
- Which loading characteristics are needed for the filtration system, will high amounts of water droplets be present, will water be allowed through the filtration system,
- The expected face velocity, and
- What type of weather protection is needed for the system.

Once this information is known, the number and type of filtration stages can be determined.

Figure 3-21 is an example of an inlet filtration system for a land based gas turbine. It can be seen on the left hand side picture that the filtration system has weather hoods. After the weather protection, a vane axial separator (1) is installed which removes liquids. The second stage (2) is a pre-filter which removes particles larger than 2 microns. The last stage (3) is a high efficiency filter to remove particles smaller than 2 micron in size. The system shown would be useful for a wet environment with a low to medium quantity of various particles sizes such as a coastal site.

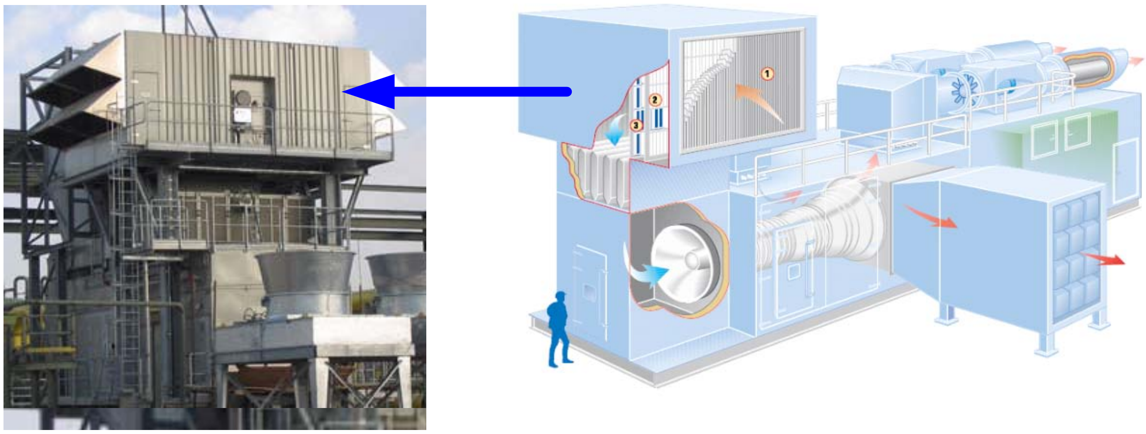


Figure 3-21. Example of Inlet Filtration System for Land Based Gas Turbine
(Courtesy of Camfil Farr)

3.2.9 Structural and Ducting Design

Once the number and type of filtration stages has been selected, there are many other design features and considerations that must be evaluated. Proper design of the filtration system structure and inlet ducting is as important as the selection of the filters themselves. Poor structural and ducting design can lead to leaks in system allowing unfiltered air to enter the gas turbine, material failures due to corrosion and wear, difficulty in conducting maintenance on filtration system, or poor performance of the gas turbine due to excessive pressure loss from poor inlet ducting aerodynamics.

As discussed before, CFD is an effective tool in inlet ducting system design. A CFD analysis can be used during the design phase of the filter intake system in order to ensure that proper aerodynamics are applied to the design. Improper design can lead to higher velocities at the filters which will decrease performance and increase pressure loss. The velocity profile should be evenly distributed across the filter bank. Also, the air velocity at the filter should be consistent with the nominal velocity stated for the filters from the manufacturer. Using CFD can help to avoid regions of high recirculation or turbulence near the inlet of the gas turbine. A lower pressure loss can be achieved if each of these effects is minimized in the inlet housing design. Filtration system manufacturers should have completed this type of analysis on their system designs.

The design of the inlet ducting and structure should consider the maintenance that will be necessary for the filtration system. This includes design of walkways, handrails, platforms, ladders, and inspection ports. Maintenance personnel should be able to easily access the filter elements for repair or replacement. The set-up should also consider access to filter elements for inspection during operation. If possible, inspection ports should be located to minimize the amount of unfiltered air which will enter the gas turbine during inspection procedures. Inspection ports should not be opened during gas turbine operation. If inspection ports are in a location that allows unfiltered air to enter the gas turbine, then they should be set to alarm when they are open. This will prevent them from being left in the open position after the inspection is complete.

Often, pressure relief protection is installed on the filtration system in case excessive pressure loss or explosions from the gas turbine occur. These include negative and positive pressure releases. The negative pressure releases are usually implosion doors. These doors will open inward when the pressure loss across the filters reaches the maximum allowable difference (for example 8 inH2O). The doors are designed to automatically release when a specified suction pressure is applied to them. Of course, when implosion doors open, unfiltered air will enter the gas turbine, but this will prevent damage to the filter housing structure due to high forces from increase pressure loss across the filter. These doors should also be set to alarm if they are opened. This will alert the operator that the pressure loss is high or that the doors have malfunctioned.

Positive pressure doors (burst panels) or bladders (rubber or plastic transition pieces) are used to prevent structural failures of the filter housing or damage to the filter if the gas turbine backfires. The pressure relief devices will open or break outward during a backfire event to prevent high pressure spikes in the filtration system. These devices should have a relatively large area to adequately protect the filters. Negative pressure relief devices are usually installed, but positive pressure relief devices are not used as often.

The placement of the filter housing can have as large of an effect on the performance of the gas turbine as the environment it is operating in. Housings should be placed at least 20 feet off the ground. This height has been shown to prevent half of the ground dust from being ingested by the gas turbine. Placement of inlets to filtration systems in marine or offshore applications should consider the expected wave heights and where the water and waves break on the ship. Figure 3-22 shows a poor placement of an inlet to the filtration system on a FPSO. In addition to any water spray from the ship wake and ocean, the filtration system is subjected to water spray from the flare. The inlet to the filter housing should be placed upwind. This will assist in avoiding many of the particles carried through the air by the wind. Lastly, the inlet housing should not be placed in a location near the exhaust of another process. Exhaust particles are typically very small and difficult to filter. If the inlet system must be placed near an exhaust stream, then this should be considered in the selection of types of filters.

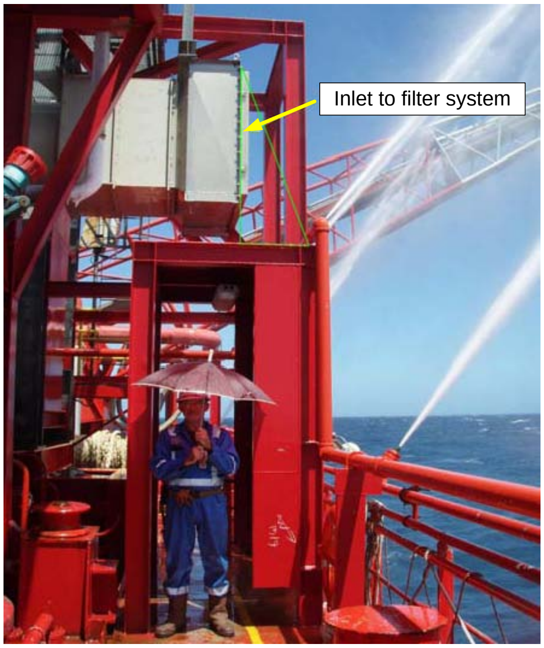


Figure 3-22. Example of Poor Placement of Inlet to Filtration System
(Courtesy of Solar Turbines)

In corrosive environments inlet structural components should be fabricated with stainless steel. In non-corrosive environments the housing may be made of other grades of steel; however, the housing should be treated for rust and corrosion resistance on the inside and outside. The housing should be designed to withstand the severe environmental loading expected in that region such as snow and ice buildup, high winds, and seismic activity. The constructions of the housing should follow the local building codes and applicable industry standards (ex. ANSI A58.1).

Because of the large sizes of inlet housings (especially in land based applications), inlet compartments are usually shipped in several sub-assemblies. These are often seal welded in the field for final assembly. All seal welds should be checked for air leakage. Housing components that are clamped and sealed with gaskets and bolts should be aligned properly and checked for leaks. These include framing gaskets and filters to frame gaskets. If any leaks are present in the inlet housing system, then this defeats the purpose of having the filtration system. Also, all bolted connections should be painted after they are fully installed. This will protect the nuts, bolts, and surrounding metal area from oxidation (rusting).

3.3 Application

Before a filtration system is designed and selected, criteria for the system must be established. These criteria should be based on the inlet air quality criteria established by the gas turbine manufacturer. The design should also consider the system maintenance strategies including filter replacements, offline or online washing, time between overhauls, and desired uninterrupted operation hours. The most important consideration of filter selection is the local environment. The particles present in the local environment are what the gas turbine will be ingesting which can lead to degradation. The ratio of the contaminants existing in the local environment to manufacturer's required inlet air quality will define the filter efficiency required.

One common misconception is that the environment where the gas turbine will be operating is easy to evaluate. The environmental conditions are constantly changing with the seasonal variations of local weather patterns or changes in the local area such as new construction or agricultural cycles. Even changes in the operational philosophy of the gas turbine itself can affect the inlet filtration. Selecting the wrong system for the environment can mean more frequent filter changes, high inlet pressure loss, unscheduled shutdowns or turbine failures, and associated cost or loss of profitability. Figure 3-23 shows the differences in pressure loss for many different filters in different environments. It can be seen that the use of different or incorrect filters can affect the system significantly in terms of pressure losses.

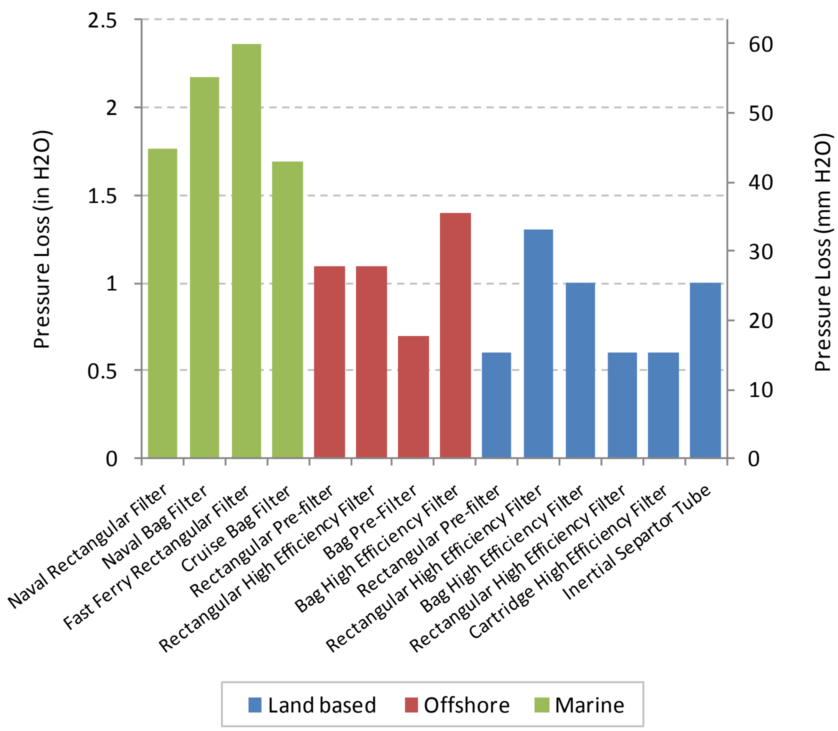


Figure 3-23. Pressure Loss of Different Filters in Various Environments
(Adapted from Oswald, 2006)

In order to provide the filter engineer with a better understanding of the considerations for selecting filters, several different environments are reviewed below including coastal, marine, offshore, deserts, arctic, tropical, rural, large cities, industrial areas, and other environmental effects. An example of criteria for gas turbine inlet air quality is reviewed. Common contaminants and how they are generated is discussed. The effects of site layout for the gas turbine installation are reviewed, and a site evaluation questionnaire is provided to assist the filter engineer in defining their environmental conditions.

3.3.1 Gas Turbine Inlet Specifications

When a gas turbine is purchased, the manufacturer is going to provide the purchaser with recommended set of criteria for the air that is ingested by the gas turbine. The filter engineer should, at a minimum, follow the manufacturer recommendations. However, they may choose to implement a more robust filtration system based on their expected operating conditions, the desired length of life for the turbine, the desired efficiency and degradation of the gas turbine overtime, what the operator is willing to invest towards the initial cost for a filtration system, and the maintenance strategy of the operator. The initial selection of the filtration system is a balance between the cost of the system, the filtration efficiency (or what rate of degradation is acceptable for the gas turbine), and pressure loss across the filter (or how it will affect the gas turbine efficiency). The operator (with a solid knowledge of filtration technologies) should work with the gas turbine and a filter manufacturer to determine the best filtration strategy for the gas turbine.

Below is an example of a criteria for a General Electric LM2500 that was installed on a US Navy vessel (GE Marine Engine, Installation Design Manual, MID-IDM-2500-18).

- Particulate
    - 95% of the time, solid particles must not exceed 0.004 grains/1000 ft^3 (0.0076 ppm)
    - 5% of the time, solid particles must not exceed 0.04 grains/1000 ft^3 (0.076 ppm)
    - For limited exposure, up to 48 hours per year, it is acceptable to operate with solid particle ingestion up to 0.1 grains/ft^3 (190 ppm).
    - No more than 5% of the solid particles should exceed 10 micrometers
- Water
    - The amount of water entering the gas turbine should not exceed 0.5% of the inlet air flow
- Salt
    - Salt Aerosol Efficiency: sea salt entering the gas turbine should not exceed 0.0015 ppm average, or 0.01 ppm maximum

The values listed above for the LM2500 alone cannot be used to determine the filter efficiency. They do not specify the conditions upstream of the filtration system. By establishing what types of contaminants and how many are present in the environment the gas turbine will operate in, the filter efficiency needed can be found.

3.3.2 Common Contaminants

Contaminants come from three main sources: water (fresh or ocean), ground dust or vegetation, and emissions. Once these contaminants are released into the air, these particles are carried by wind currents from their source. Air turbulence patterns keep the contaminants aloft for a certain amount of time depending upon their settling velocity of the contaminant and wind speed. Due to weather and seasonal variations, the contaminants present are constantly changing. Some contaminants are present in environments on a long term basis, such as ground dust. However, some contaminants will only be present during parts of the year (short term). For example, during the agricultural growing season, fertilizer particles may need to be removed from the air. Contaminants can be in the gas, liquid, or solid phase.

3.3.2.1 Gas Contaminants

Gas contaminants are only of a concern if they are released relatively near the gas turbine. This category excludes contaminants that condense shortly after they are released forming aerosol droplets. Some examples of gas contaminants are ammonia, chlorine, hydrocarbon gases, sulfur in the form of H_2S or SO_2, and discharge from oil cooler vents or local exhaust stacks. Gas phase contaminants cannot be removed by mechanical filtration. As long as gas contaminants remain in the gas phase, they will not impact the gas turbine. However, if they interact with liquid, they will be partially absorbed and can lead to degradation. There are special filters that can remove gas contaminants, but they have several characteristics that make the use of them with gas turbine prohibitive. First, these types of filters require a very low air flow (lower than conventional low velocity systems that are in use). Due to this, the filtration system would require a much larger surface area than that used in conventional systems. Also, the process used to remove the contaminants is typically some type of absorption with a membrane. This can require special chemicals or additional equipment for the filtration system. This type of filtration is not used with gas turbines. A better option is to have adequate site planning during the design phase, so the placement of the gas turbine inlet minimizes the ingestion of gas contaminants.

3.3.2.2 Liquid Contaminants

Liquid contaminants are present as aerosols. Aerosols may be generated by condensation of vapor phase mixtures as mentioned above or by liquid agitation. Some common sources of aerosols are cooling tower drift, wave action at coastal sites, condensation of moist exhaust plumes in cold weather, petrochemical discharges, rain, fog, and chiller condensates. The components contained in these contaminants that are detrimental to the gas turbine are chloride salts in water, nitrates, sulfates, and hydrocarbons. The first three mentioned are corrosive agents that can cause permanent damage to the gas turbine. Hydrocarbons can also contain corrosive agents, but may also lead to fouling of compressor blades. The hydrocarbon particles that make it through the filters and adhere to the compressor blades and surfaces must be removed through water washing strategies. Liquid contaminants are typically removed with a coalescer or moisture separator. The coalescer collects the smaller aerosol droplets and coalesces them into large droplets which can be easily removed. Moisture separators or inertial separators remove liquid particles with the help of the inertia of the larger droplets. In a dusty climate, an inexpensive pre-filter is often used before the coalescer to reduce the rate that the coalescer is loaded with solid particles.

One of the most important contaminants ingested by the gas turbine, typically in aerosol form, is salt. Salt can be ingested as dry particles, but in this case, the fiber filters can adequately remove it from the air stream. Salt absorbed by liquid aerosols, mainly water, is another issue. Salt from seawater can become airborne in significant quantities due to wind and wave action. Seawater is composed of approximately 3.5% salt. The salt contains 55% chloride, 30.6% sodium, 7.7% sulfate, 3.7% magnesium, 1.2% calcium, 1.1% potassium, and 0.7% of minor constituents. When the wind has low to intermediate speeds at the water surface (in excess of approximately 4 m/s), air is entrained by the waves which then plunge or spill back into the ocean. During this process, bubbles are produced which rise to the ocean surface and burst. The bubble bursts create small droplets of seawater which are evaporated into the air. When wind speeds are higher (in excess of 10 m/s), whitecaps are generated which also release bubbles (formed beneath the breaking wave). A secondary effect of high winds is that seawater droplets can literally be torn from the wave crests into the air. In any of the processes described above, water droplets can be created which are from submicron to several hundred microns in size. The aerosols generated at sea will be suspended in the air depending on their size, local wind effects, and the humidity. The wind can carry the salty air to locations far away from the aerosol source. The sea-salt concentration in the air and aerosol size distribution varies significantly from location to location and is a seasonally dependent quantity.

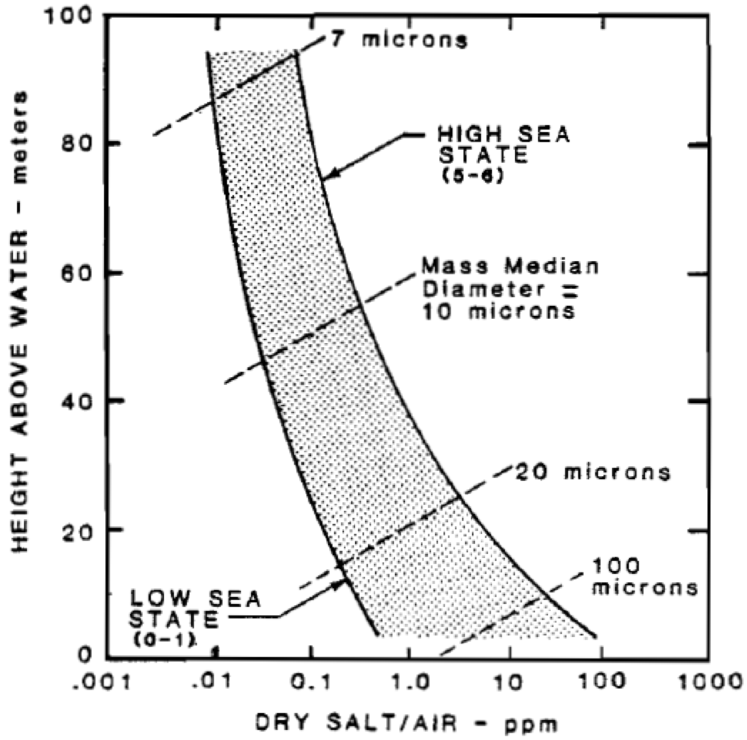


Figure 3-24. Generalized Characteristics of Salt Aerosol Boundary Layer above Water/ Air Interface
(Shelton, 1984)

In addition to the natural generation of sea aerosols, the motion of any ship through the ocean water will generate a wake and bow wave. Bubbles form in the wake and bow wave of the ship due to liquid agitation and burst forming liquid droplets or aerosols. The ship has a boundary layer where the salt aerosols will be present which is dependent upon the wind state, ship speed, heading, and hull form. The density and height of the aerosol boundary layer profile is a function of the ambient conditions. Figure 3-24 shows a generalized range of boundary layer height/ density relationship based on at-sea survey data collected during the Gas Turbine Inlet Development Program executed by the US Navy in 1975. The average "wet" particle mass median diameter is also shown in the figure. This figure includes the effects of natural and ship generated aerosols. Ship generated or non-natural aerosols tend to be heavier and wetter than the naturally generated aerosols. Due to this, they will drop out or remain at the lower levels of the aerosol boundary layer.

The humidity plays a large role in the phase of the sea salt and the size of the aerosol particles. It is commonly accepted that salt will exist in the dry state at a relative humidity below 40% and in the wet state above 70%. Anywhere between these two levels, the salt will be in a transitional state. As the relative humidity decreases below 70%, the salt aerosols become tacky or sticky in nature until they reach 40%, where they become dry salt particles. However, as the humidity increases to above 40%, the salt particles will stay in the dry particle state until they reach a relative humidity of 70%, where they are rapidly absorbed by the moisture present. Figure 3-25 graphically represents how the aerosol particles change with changes in the relative humidity. As the relative humidity changes, the concentration of salt in the air does not change, only the amount of moisture that is present. As the humidity drops, the size of aerosols will typically shrink until at the approximately the 40% relative humidity range, where the dry salt particles exist.

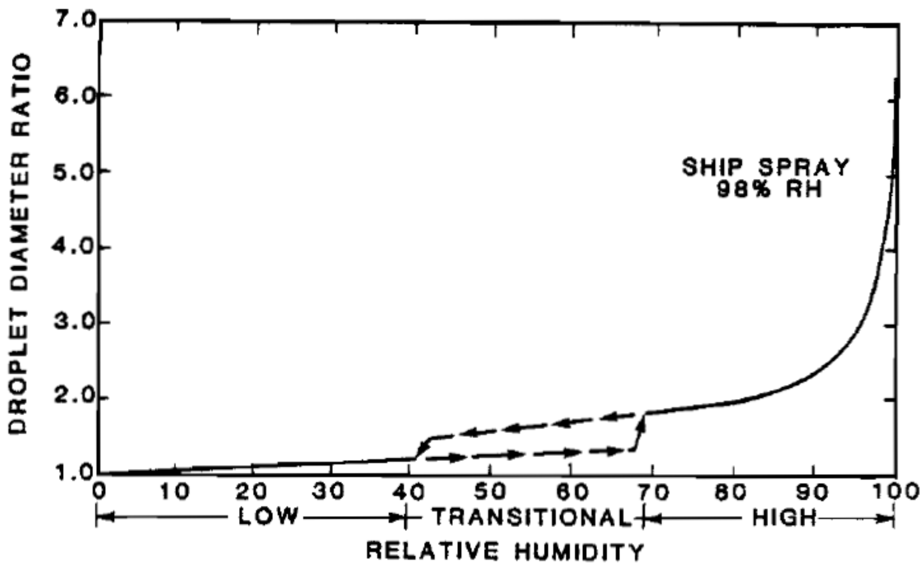


Figure 3-25. How Sea Salt Particle Size Varies with Relative Humidity
(Gas Turbine Design Handbook, 1983)

Cooling tower drift is water droplets that are generated at cooling towers that can be transported to a nearby area. The droplets can form from three different events: drift, blow-out, and plume. Drift is when water droplets are carried out of the tower with the exhaust air of the fan. These droplets can be minimized with eliminators which are baffle-like devices. Blow-out is when water droplets are generated and transported by the wind. These are minimized by windscreens, louvers, splash deflectors, and water directors. The last drift mechanism is a plume. Plume is created by water vapor from the cooling tower which condenses when it comes in contact with cooler ambient air. A plume can be the most detrimental to inlet filtration systems since it has the same characteristics of fog: a large amount of small water droplets which are difficult to completely remove with a filtration system. Also, the plume can lead to icing hazards in a freezing environment.

3.3.2.3 Solid Contaminants

Solid contaminants are spread from their source carried by the wind. Heavier and larger particles drop out of the air stream quickly, within a few hundred feet or less form the source. Smaller particles in the range of 30 to 50 microns will remain airborne until they fall out due to air turbulence dropping off or the particles settling out of the air. Particles less than 10 microns will stay airborne the longest. Some common examples of solid particles are sand, silica, road dust, dust from fertilizer and animal feed, airborne seeds, alumina, rust, calcium sulfate, and vegetation. Solid contaminants are easily removed with static or self-cleaning filters. The filters used to remove solid particles will not necessarily remove liquids or aerosols.

There are three physical processes by which solid contaminants move from their source: creep, saltation, and suspension. These phenomena are shown in Figure 3-26. The process of choice depends on the size of the particles and wind strength. Suspension describes the process where particles are carried by the wind and air currents. This process is favorable for smaller particles and strong winds. Large particles, as mentioned above, will fall quickly to the earth, but smaller particles can be carried for thousands of miles and reach heights of thousands of feet. The suspension of particles is also strongly dependent on the settling rate of the particles. The settling rate is the rate at which the particle falls to the earth. Larger and heavier particles will have a faster settling rate, where smaller particles will have a lower settling rate and can remain suspended in the air for days at a time. Figure 3-27 shows the relationship of the settling velocity with different particles sizes. Suspension is a main contributor to the creation of dust storms.

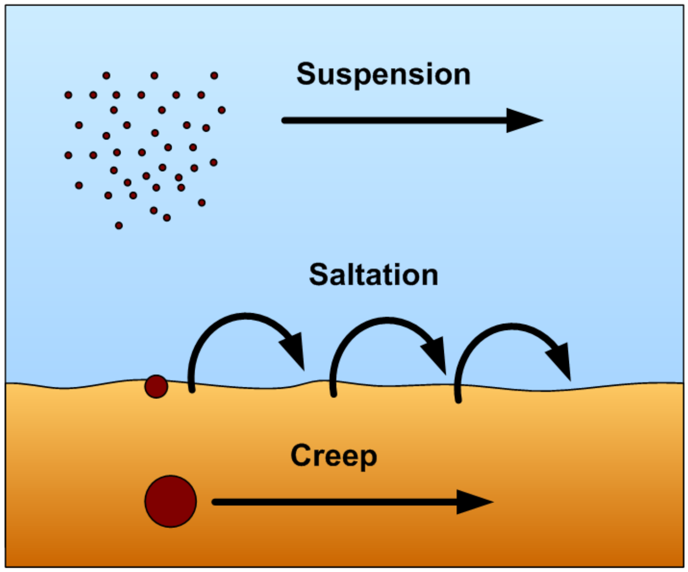


Figure 3-26. Solid Contaminant Transportation Processes

Saltation is when the particles move forward on the ground through a series of leaps and jumps. Particles commonly move up to four times farther along the ground than in height. When a particle returns to the ground, it will either collide with another particle and transfer some of its energy, or it will bounce and leap back into the air. Depending on the size of the particles, it will continue to move forward through one of the three processes. Creep is when the particle will travel across the ground during heavy winds. These contaminants are not lifted into the air but move through rolling or sliding action. This process can, over time, move contaminants great distances and accounts for approximately 25% of grain movement in the desert. Smaller particles that are already moving with wind by saltation collide with large particles and cause them to creep along the terrain.

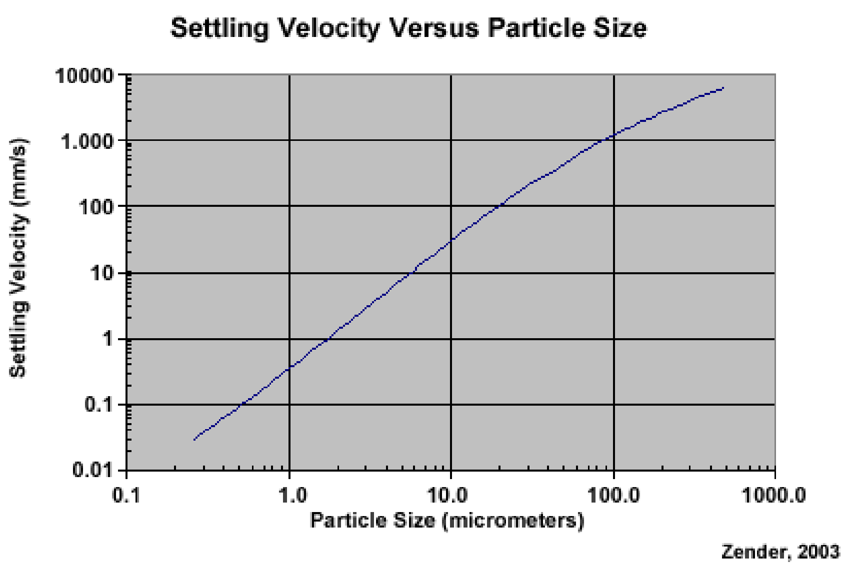


Figure 3-27. Settling Velocity of Different Sized Particles
(COMET Program)

Areas with very fine solids and sand are more likely to be potential source regions for dust storms or high dust concentration in the air. These areas commonly have poor vegetation such as dry lakebeds, deserts, and loess (areas of fine-grained soil made from particles of silt and clay deposited by the wind). Levels of precipitation and vegetation also have strong effects on the levels of solid contaminants. Precipitation will bind the particles together therefore reducing the ability of the wind to lift the larger particles off the ground. Vegetation will bind the particles together and cover and protect them from the wind. Deforestation and over-grazing will significantly increase the potential for solid particles to be released into the air. Studies have shown that the majority of solid contaminants reside near the ground. Elevating the filter compartment at least 20 feet in the air approximately halves the amount of dust that will be ingested.

3.3.3 Coastal, Marine, or Offshore Applications

The locations where a gas turbine is installed are classified into two main areas: coastal/ marine/ offshore and land based applications. The main difference between these areas is the concentration of salt in the atmosphere which is highly present in coastal/ marine/ offshore applications. However, this does not mean that salt cannot be present in land based applications, too. As discussed above, salt is a main contributor to corrosion in both hot and cold parts in the gas turbine. The high concentration of salt in the atmosphere can also lead to fouling of the compressor blades.

The area where sea salt is a significant contaminant can be classified into the three locations: coastal, marine, and offshore. Coastal areas refer to gas turbines which are installed on land but within 10 miles of the shoreline. In a marine environment, the gas turbines are installed on vessels. The inlet to the turbines is typically within 100 feet from the ocean surface. Offshore applications have the gas turbine inlets above 100 feet from the ocean surface and are commonly installed on oil production platforms. Each of these environments is discussed in greater detail below.

3.3.3.1 Coastal Application

Operation of gas turbines at or near the coast presents many of the challenges that exist with salt filtration and land based applications. There is much higher dust concentration than marine or offshore applications and higher salt concentrations than typical land based applications. During design and selection of the inlet filtration system, consideration must be given to expected salt concentration and phase and the contaminants from the land based environment where the gas turbine is located. In order to remove all contaminants, a multi-stage inlet filtration system is used.

Contaminants

The salt present in the ambient air is derived from seawater aerosols carried by the wind. Cooling towers can also contribute to the salt concentration. Some of the coastal sites use seawater for cooling water. The aerosols and mist from these towers will contain salt. Depending on the relative humidity, the salt particles may be present in aerosols, in the sticky state, or as dry particles. The humidity will also have an effect on the size of the salt particles or aerosols. Relative humidity lower than 50% (seen frequently in the Middle East) can cause salt particles to reduce in size below 1 micron. The salt concentration present in the air from the seawater is the highest at the shore and falls rapidly until approximately 10 miles off the shoreline, where it reaches an equilibrium value of 0.002 to 0.003 ppm by weight. However, the concentration can vary significantly depending on the wind speed, direction, elevation, and topography. In some locations, higher salt concentrations have been seen farther inland than along the shoreline due to high winds carrying the salt aerosols.

Filtration System

These systems are multi-stage systems with arrangements similar to the offshore filtration systems. They will begin with some type of weather protection (typically a weather hood) to minimize the amount of water that enters the inlet. At sites with high precipitation, the filtration system may have vane separators as the first stage to remove the water that penetrates past the weather hood. The coastal environment is unique compared to the offshore or marine environment. As mentioned above, the filtration system must be designed to handle the moisture and salt that is experienced near the ocean, but it also will have filters selected for the land based contaminants that are present. After the weather protection or vane separators, the filtration system may have some type of pre-filter and high efficiency filter arrangement. These components will remove the particles from the air which could lead to erosion or fouling.

Even though salt is a primary concern in corrosion of the gas turbine, other contaminants present in coastal environments can also lead to gas turbine degradation. Weather conditions can run from dry and sunny to rain, snow, and freezing fog. Blowing sand, industrial dust, and unburned hydrocarbons are present in many coastal environments. Also tropical condition such as heavy rains, high humidity, and large quantities of insects can occur. Several land based applications are discussed in more detail in Section 3.3.4 which can provide guidance on selection of filters for these different environments.

3.3.3.2 Marine Application

In the marine environment, there are many gas turbines in use. Some are used for vessels propulsion, others provide torque to generate power, and gas turbines are also used for driving compressors. The inlet filtrations system in this environment is primarily concerned with removal of salt and seawater. This is the most abundant contaminant and the most damaging element present in the marine environment. However, some gas turbines on marine vessels travel closer to shorelines for extended periods of time or may be docked at a port. Therefore, dust can be an important contaminant. Also, the port environment provides dirty inlet air. Marine inlet filtration systems are unique in their limitations of size and weight. Vessels have tight space restrictions which in many instances will impose undesirable design constraints leading to compromised engine performance. In the long term, these compromises will result in decreased engine performance and increased engine operating and overhaul costs. Tradeoffs are made between the inlet filtration system performance and the engine life and performance.

Contaminants

The primary contaminants, as mentioned above, are salt and seawater. Salt is almost always present in the wet form due to the closeness of the gas turbine inlet to the ocean surface. The salt is generated naturally and mechanically from ship wake and bow wave. Three design variables help to dictate what size and how much salt aerosol is present at the inlet: height, orientation, and location.

The distance the inlet of the gas turbine is from the ocean surface significantly affects the amount of seawater and salt aerosols which must be removed from the air. As the height above the ocean surface increases, there is a lower concentration of water and salt. Also, the particle size decreases. However, the height a gas turbine inlet is from the ocean surface is not necessarily constant. The height of the waves will affect this distance. In stormy conditions, the inlet of the gas turbine could be very close to the ocean surface. If high wave height variability is expected, then vane axial separators should be used. In all instances, the inlet to the gas turbine should be placed as high as possible. The height of the inlet should also consider the vessels design features such as space limitations, vessel structure, and installation requirements for other critical systems.

The orientation of the inlet can affect the loading of the filtration system. Studies conducted on several ships found that if the gas turbine inlet is placed at least 50 ft (15 m) above the ocean surface, the orientation of the inlet will not have significant effects on the salt and water loading of the inlet (Shelton 1984). However, below 50 ft (15 m) placing the inlet of the gas turbine in different orientations can reduce the amount of water and salt which will be ingested. Forward facing inlets will experience higher loading mainly due to ship generated spray.

Lastly, the location can affect the loading of the inlet. During many studies, loading of the inlet was studied for the effect of the prevailing wind direction and location of the gas turbine inlet. It was found that the lee side of the ship experienced as much as two-and-a-half times higher inlet loading than the windward side due to the lee vortex (Figure 3-28). To minimize this vortex effect, the inlet was inset into the side of the ship or a non-perforated platform was installed outward of the inlet. The survey data also showed that insetting the inlet a distance of at least twice the inlet height sufficiently removed the effect of the lee vortex. In order to minimize the loading on the gas turbine inlet the inlet face should be placed at the highest possible location above the ocean surface, the inlet face should be sheltered to reduce effects of wind conditions, and the inlet face should be placed as far away from the deck edge (Phillipi 1976).

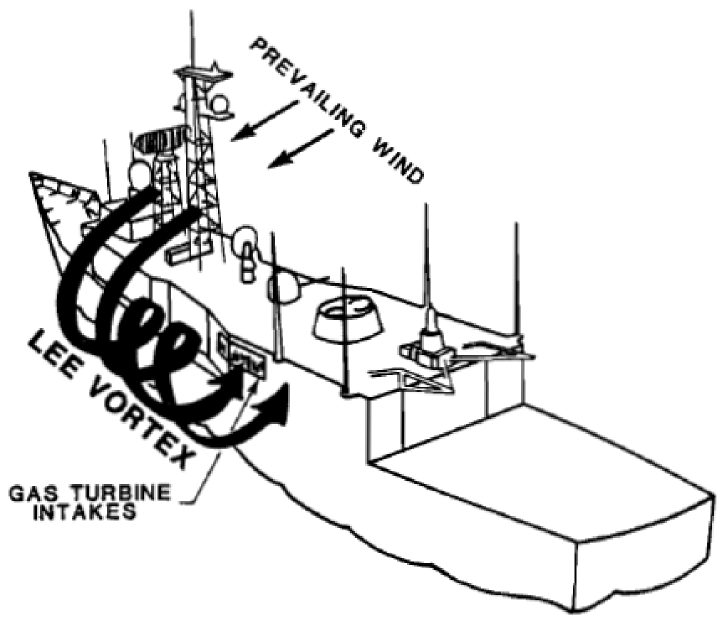


Figure 3-28. Lee Vortex Effect
(Shelton, 1984)

As mentioned before, salt removal has been given priority to dust filtration. Dust filtration is needed for gas turbines operating for an extended period of time near the coast or near regions with high dust concentrations. This dust could be present from sand storms or contamination from burning oil installations, both of which have proven to be issues for gas turbine operation. Also, many ships have been subjected to the airborne sand and dust from local coastlines. This typically occurs near coastal deserts or arid regions such as the Persian Gulf area. In these cases, wind blowing off the land carries the fine sand and dust particles out to sea for distances up to 200 miles (300 km). Figure 3-29 shows dust being carried off the coast of Africa from the Sahara Desert. Some of the solutions to the dust loading are to use a pre-filter in the filtration system. These, however, only remove large particles and still allow the fine particles to proceed through to the gas turbine.

Marine vessels are mobile and travel to many different locations including arctic environments. The danger of inlet icing is taken very seriously, and many vessel inlet systems have some type of anti-icing installed upstream of the filtration system. Ice can form anywhere in the inlet system from the filters, inlet ducting, to inlet guide vanes. Anti-icing systems are usually comprised of compressor bleed air which is re-injected into the inlet of the filtration system.

The marine environment sees two types of icing: glaze and rime ice. The main sources that contribute to ice formation on vessels are precipitation, freezing spray, condensation, and fog. Spray or precipitation lead to glaze ice which is formed when large quantities of water freeze over an extended period of time. This type of ice is smooth, has high adhesive strength, and is transparent. It threatens the inlet system by blocking inlet screens, filter elements, and louvers. Rime ice is opaque in appearance, has low adhesive strength and is rough. The low adhesive strength is due to the process of rime ice formation. This type of ice develops when super cooled seawater aerosols and droplets impact filtration system components. Rime ice is a threat to the inlet filtration system because large chunks can break loose and will potentially impact filter elements or be ingested by the engine and damage initial compressor stage components.

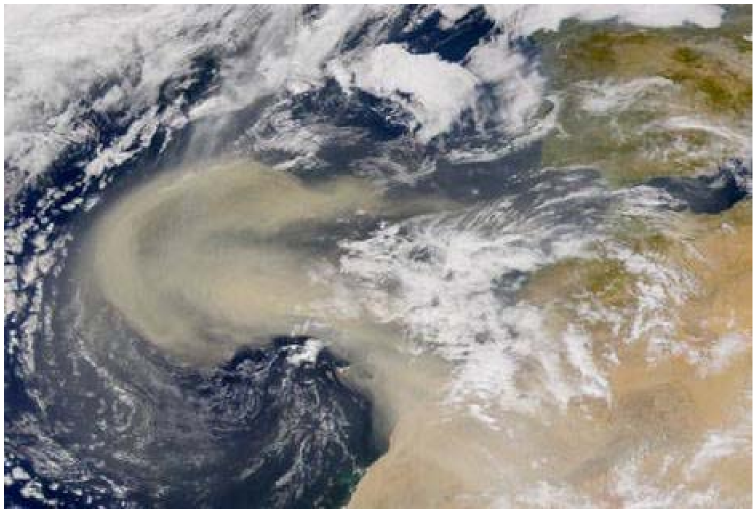


Figure 3-29. Large Dust Storm Moving from the Coast of Africa
(SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE)

Icing on inlet filtration components without protection can form in any or all of the conditions listed below occur simultaneously during gas turbine operation on a marine vessel.

- Air temperature equal to or less than 0 deg C (32° F)
- Sea temperature equal to or less than 5 deg C (41° F)
- Wind speed equal to or greater than 9 m/s (17 knots)
- Wave height equal to or greater than 3 m (10 ft)

Many ships will travel to various locations during their operating life and have the possibility of encountering icing conditions. Proper icing protection can prevent damage to the inlet system or gas turbine.

Filtration System

The most common filtration system used on marine vessels is currently the vane separator/ coalescer/ vane separator three stage system. These are high velocity systems which have high efficiencies in capturing water particles and salt dissolved in water particles (salt aerosols). The first separator serves to remove the large quantities of water either from mist from ship wake or waves, rain, or wet snow. This separator prevents the coalescer from being overloaded. The coalescer collects the smaller water droplets which the first vane separator did not capture and coalesces them into large droplets that either drain off or are re-entrained into the air stream. The coalescer also sometimes acts as a particulate filter which is able to catch larger dust particles. This filter is typically made of a non-woven polyester or a similar material. This is also useful for operation of gas turbines near coastlines. Any large droplets re-entrained in the air stream are captured by the second vane separators. The filtration system is fitted with a drainage and water/ salt removal system so the moisture and salt can be properly directed away from the gas turbine.

Marine vessels are independent water vehicles that continually operate even in adverse conditions. The continuous operation is often more important than the health of the engine. Multiple gas turbines are used on the ships, so there is a spare if one needs to be shut down for maintenance. However, if a filter is clogged, damaged, or blocked and causing excessive pressure loss, the engine will not necessarily be shut down. Implosion doors are installed on the inlet filtration system in order to ensure that operation is not interrupted if required at the time. These doors are a bypass to the filtration system and if used, unfiltered air will be ingested into the turbine.

Inlet filter housings on marine vessels must be corrosion resistant due to the significant presence of salt. The metal components of the system will be constructed out of a stainless steel or aluminum with adequate corrosion resistant properties or carbon steel with a corrosion protective coating. These housings, depending where the gas turbine is located, can have many turns and bends which can add aerodynamic pressure losses to the system. It is best to minimize the length of the inlet ducting to the turbine and the number of turns and bends. With the decrease in the space allocated to gas turbine inlet ducting, this has become increasingly difficult and can often restrict the pressure loss across the inlet system. The inlet face of the filtration system should also be designed to have a uniform inlet velocity. If this is not done, then parts of the vane separator can be overloaded and not be able to remove all the water droplets necessary. Also, poor velocity distribution will contribute to an increase in the pressure loss.

Filtration systems on marine vessels are primarily designed for salt filtration but considerations should also be given for the dust loading and icing protection. In summary, when selecting a filtration system for a gas turbine on a marine vessel, the following items should be reviewed and considered for the optimization of the design.

- Design the system to operate in the expected environments considering the salt, water, and dust removal.
- Include a bypass system to maintain constant operation and icing protection, if the vessel will be used in cold climates.
- Intakes (if possible) should face aft or inboard or should be inset or have protective covering. This will make a significant contribution in minimizing the salt and water content of the ingested air.
- Ensure that no re-ingestion can take place between the exhaust from any machinery and the intake system.
- Maintain a uniform velocity distribution across the intake opening.
- The equipment should be designed to have the same life as the vessel upon which it is installed.
- The weight of any component is to be kept to a minimum with the appropriate materials for the operating conditions and requirements of the design and life of the equipment.
- Maintenance at sea is to be kept to a minimum and restricted to replacement/ cleaning of second stage coalescers.
- Use of high velocity systems takes up less space than conventional filtration systems. The large filtration systems take up more space and must be considered in the structural design of the vessel.

3.3.3.3 Offshore Application

The offshore environment, just as coastal and marine applications, is subject to wet and dry salt particles. However, in addition to salt, this environment has other contaminants that exist with the operation of the offshore platform. Just as in marine vessels, the offshore platform depends on the gas turbine for its operability. Any downtime associated with the gas turbine affects the entire production of the platform. Corrosion is a common concern with the presences of salt, but the gas turbine also experiences significant fouling issues. Compressor fouling has been reported to be the reason for 70 to 80% of the performance degradation on offshore gas turbines.

In the offshore environment, the gas turbine can limit the maximum production capacity of the platform. As the gas turbine's performance degrades and the pressure decreases over the life of the oil and gas reservoir, the production may be limited. More power is required of the gas turbine since the compressor must be used to generate more head. However, overhauls will renew the gas turbines performance and minimize reduction of available power.

Contaminants

Offshore gas turbine inlet filtration systems have a diverse range of contaminants that must be removed. The most prevalent contaminant is salt. Salt aerosols are naturally present from the agitation of the seawater and waves breaking against the platform. However, the concentration of salt is not as severe as on a marine vessel since the gas turbines are often elevated above 100 ft from the ocean surface. The amount, type, and size of the salt aerosols or dry particles changes with the wind direction, humidity, and weather. In some offshore platforms, significant gas turbine performance degradation has been reported after foggy weather. Fog aerosols are often too small for water separators to collect. The coalescer may capture some, but often these aerosols will gather on the pre-filter or high efficiency filters.

If the high efficiency filters are not designed to prevent water penetration, then the water can travel through the fiber filters to the inlet of the gas turbine. This water can absorb the dry salt particles or other captured soluble contaminants and transfers them from one side of the filter to the other, releasing them into the gas turbine. This event is mainly true for high velocity systems, where the air flow is strong enough to push the water through the filter. Also, the moisture can load the filters causing a higher pressure loss. This loss can be recovered after the fog lifts and the filters dry out, but the gas turbine must be cleaned to remove the salt and other contaminants that unloaded from the filter during the fogging event.

The offshore platform is a very condensed industrial plant. This environment comes with all the expected plant type emissions. This includes hydrocarbons, soot from exhaust and flares, vapor from oil tanks, drilling dust, paint fumes, and particles from maintenance activities such as grit blasting. Depending on where the platform is located, the inlet filtration system may also need to operate in rain or dry conditions, dust storms or haze from local coastal regions, and freezing conditions. In most offshore locations, the dust concentrations will be in the range of 0.01 to 0.1 ppm of dry, non-erosive particles from 0.01 to 5 microns in size.

Erosive conditions are usually only a concern if the area is near a desert or dust laden coast where the platform will be subject to dust storms or dust haze. Some short term events such as grit blasting near the gas turbine inlet can provide erosive particles. Hydrocarbons from oil tanks or the exhaust from combustion engine exhaust from ships loading oil can be harmful for the gas turbine and filtration system. The hydrocarbons will reduce the electrostatic charge on filters reducing their filtration efficiency, especially for smaller particles. Also, some of the submicron hydrocarbon aerosols will not be captured by the filters which can lead to fouling of the compressor blades. The exhaust can also contain sulfur which contributes to corrosion in the gas turbine. The offshore environment has some typical long term conditions such as the presence of salt, but consideration should be given to potential short term conditions too.

Filtration System

In these systems, there is not much concern for erosive particles, but the filtration system must remove the smaller particles to prevent fouling and remove moisture and salt to avoid corrosion. These systems will typically have a combination of a water removal (vane separator and coalescer) system and high efficiency filtration system. The high efficiency filter causes the majority of the pressure loss in the filtration system. For some systems, it is the last filter before the air enters the gas turbine. In other designs, it also has a coalescing function. In the last design, a vane separator would be installed after the filter to capture the larger droplets that are re-entrained into the air stream. If the environment has a high dust concentration (local dust storms or dust haze), then a pre-filter may be used to remove the larger particles and extend the life of the high efficiency filter. Filter housings are typically made of corrosion resistant stainless steel or aluminum. Sometimes, carbon steel with a corrosion resistant coating will be used. Due to the large amount of salt and moisture present in this environment, corrosion protection is highly important on the metal components of the filtration systems.

3.3.4 Land Based Applications

Land based gas turbines are subjected to many different environments. These range from cold arctic environments where removal of snow and ice are a main concern, to tropical environments where large amounts of rain and insects must be filtered. Each of these environments has unique contaminants and seasonal variations. These environments can be characterized by their typical weather patterns and air quality, but short term or seasonal variations must also be considered. Several land based environments that gas turbines can operate in are discussed below including deserts, arctic locations, tropical sites, rural countryside, large cities, industrial areas, and other applications and considerations. The various contaminants experienced in these environments are discussed along with typical inlet filtration systems.

3.3.4.1 Desert Application

The desert is a unique environment that is characterized by dry climate with long sunny periods, high winds, sand and dust storms, and occasional heavy rains. The main regions of the world which can be characterized by desert like environments are across the Sahara desert in Africa, the Middle East, and parts of Asia. However, small localized areas with high dust concentrations do exist. These can include gas turbines installed near quarries, dried lakebeds, loess, industrial areas, dirt tracks, dry agricultural land, and construction sites. Figure 3-30 shows the dust concentration across the world highlighting the major dust areas.

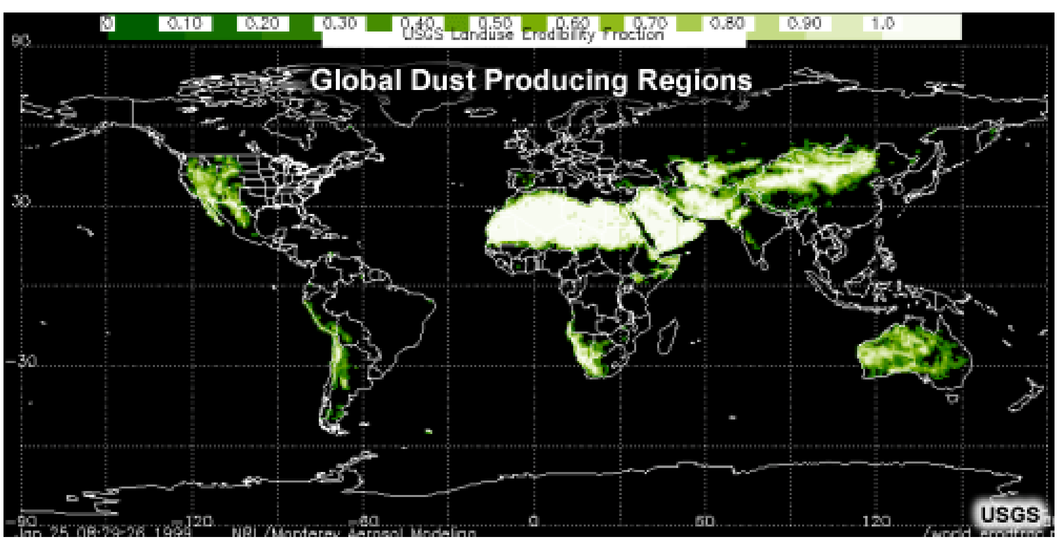


Figure 3-30. Areas of the World that have High Dust Concentration
(COMET Program)

Contaminants

There are three typical conditions that exist in the desert: clean air, dust haze, and sand storms. Table 3-4 describes the contaminant sizes and levels which can be experienced during these three events. Dust is the main contaminant in the desert for these conditions. This can be sand or other fined grained material such as desert pavement. Desert pavement is the layer of large stones left on the floor of the desert as shown in Figure 3-31. While these stones are not harmful in their solid state, they can easily be broken by human or animal traffic and crumbled into fine particles. These particles can range from large (500 microns) to very fine (sub micron size). Due to the lack of vegetation and protection of the ground dust from the wind, more dust can be lofted into the air than in other environments. This leads to a high concentration of dust.

Table 3-4. Typical Desert Conditions

Condition	Contaminant Level, ppm	Average Contaminant Level, ppm	Particle Size, Microns
Sand Storm	3 - 118	59	5 - 15
Dust Haze	0.15 - 3	1.5	1 - 3
Clean Air	0.15	0.15	0 - 1

Large amounts of dust combined with high winds can be a formula for transporting the dust from these environments to the surrounding areas. As discussed in Section 3.3.2.3, turbulent air activity will keep the dust aloft, and the wind can transport the dust far away from the source. Areas upwind of the local site should be checked for potential dust sources. The closer a site is to a possible dust source, the more likely the source will affect and impact the gas turbine filtration. For example, a dust track five miles away will most likely not have much effect. However, a dust track only 500 feet away could be of importance. Also, the closer a gas turbine installation is to a dust source, the higher potential for larger particles and higher concentration, since the dust has not had as much time to settle out.

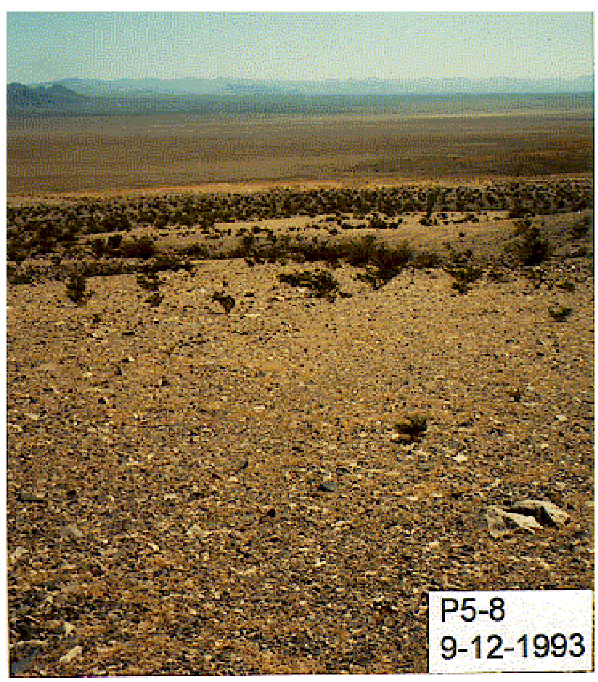


Figure 3-31. Desert Pavement
(US Army Corp of Engineers)

There are several seasonal winds around the world that are recognized and given names. These winds not only carry dust through the local area, but also far distances to other locations. In North Western and Western Africa, the Harmattan wind, which is a northeasterly wind, blows during November and March. This wind reduces visibility to as little as 50 meters with a yellow haze and blurs the horizon. It can cover large areas of coastal waters reaching as far as the Cape Verde Islands. The Shamal wind blows through the Iraq and Persian Gulf during the summer. This hot and dry wind whips up sand and reduces visibility to a few 100 meters. The summer wind in Australia near Victoria and New South Wales is the Brickfielder or Bricklayer. This wind is caused by the movement of tropical air from the north and carries clouds of dust and hot temperatures.

One of the most common dust storms is a Haboob, as shown in Figure 3-32. This wall of dust can travel up to speeds of 50 mph and be as tall as 3000 ft. This type of dust storm can travel for up to three to four hours and is most commonly seen in Southern United States, the Middle East, and Africa. Often after the wind has died down, a dust haze can remain for several days.

The Central Mediterranean will experience a strong southerly wind named Scirocco. It is hot, dry, and dusty, and passes over the North African coast. This wind can also travel across the Mediterranean to the Southern part of Europe, bringing warm, humid, and dusty air. In February to May, the Chamsin/ Khamsin, a hot, dry southerly wind, blows over Egypt to North Eastern Africa and Saudi Arabia. All of the winds and dust storms mentioned above, can easily plug the filtration system with large erosive dust.

Figure 3-32. A Texas Haboob
(COMET Program)

The filtration systems in deserts are usually solely designed for dust removal. However, some desert locations experience periods of dense fog and high humidity. This is especially true for deserts near a coastal region. The moisture can collect on the surface of cartridge filters on self-cleaning systems and cause the dirt to form a cake on the filter. This cake of dust can significantly reduce the effectiveness of filtration and pulse cleaning. If fog and high humidity are present at the desert type site, then this should be considered for the filtration system.

Filtration System

Dust loads in the desert can range from mild (low wind) to fairly high (dust storms). Conventional non-self-cleaning filtration systems can quickly become loaded and require frequent filter change outs. Also, high pressure losses can trigger a shutdown if they become excessive. In order to avoid the constant maintenance and labor required for changing filters out, a self-cleaning system is needed. Filtration systems without self-cleaning filters have proven to be more expensive due to the labor cost and maintenance required with filter replacements.

Inertial separators can be used as a first defense for the gas turbine. They are effective at removing the large dust particles (greater than 10 microns), but have low efficiency for small particle removal. It should be noted that inertial separators are not typically used with modern inlet filtration systems. The advent of pulse cleaning systems reduced the need for the solid particle inertial separators. High efficiency cartridge filters are used with a pulse cleaning systems. The pulse cleaning systems are very effective, especially during a sand storm. They keep the pressure loss below acceptable levels by constant cleaning without any interaction of the gas turbine operator. This allows the gas turbine to continue to operate at an optimal performance even during adverse conditions. However, the use of the pulse cleaning system should be cautioned. If the environment has high humidity, fog, or moisture (near a coastal desert) or contaminants with sticky particles (such as pollen), the particles will cake on or stick to the cartridge filter elements and cannot be removed with the air pulses. Some levels of moisture and sticky particles can be tolerated, but the filters must then be replaced in order to regain the original condition with new clean filters. If moisture is present due to fog or high humidity, then an additional stage with a coalescer and vane axial separator should be considered. Pulse cleaning systems have a higher initial cost than conventional filtration systems, but the benefits of their use in high dust or desert environments outweighs this through reduced maintenance and labor costs.

3.3.4.2 Arctic Application

The arctic environment is highly influenced by prevention of ice buildup and formation and removal of snow. This environment is characterized by lengthy periods of time with temperatures below 32° F (0° C) and with snow and freezing rain. The locations considered to be arctic may also be classified as another type of environment during the year. This depends on the seasonal changes. It may be necessary to implement another environment's filtration scheme for part of the year and then an arctic system for the cold season.

Contaminants

Ice buildup on the filtration system or inlet to the gas turbine is the main concern in an arctic environment. Ice forms primarily in two ways. The first is the most obvious; through ingestion of snow or freezing rain. The frozen precipitation accumulates on filtration system components and forms blocks of ice. Arctic snow is typically dry due to low ambient temperatures, but wet snow can also occur. Wet snow is more detrimental to an inlet system, since it has a sticky capability. If ingested, it can easily accumulate on inlet components. Snow falling with little wind does not present much of a threat to the gas turbine engine. However, blowing snow can cause quick ice accumulation.

The second method of ice buildup is depression of cool humid air in the inlet system. When the air velocity increases across areas of the inlet system, the pressure decreases, which causes a simultaneous decrease in temperature. Any moisture in the air can freeze and collect on inlet system components. This type of ice formation can occur on the filters, inlet ducting, or even at the bell mouth of the gas turbine.

The moisture can be due to ice fog, ice crystals in humid air, and cooling tower drift. Ice fog or freezing fog is composed of fine ice crystals that are suspended in the air. When these crystals contact a solid surface, they will freeze and build up ice. Ice fog typically starts to form, when the temperature of the air drops below -15° F. Another type of ice that will buildup in the same manner is hoar frost. Hoar frost is produced from water fog or small water particles suspended in the air.

Cooling towers often release many water aerosols. These aerosols can form fog clouds or ice crystals and be ingested by the gas turbine. Some cooling tower manufactures have options for minimizing the formation of these aerosols. Also, the plant could be laid out to minimize the drift of cooling tower aerosols to the gas turbine inlet. Ice fog has been seen to have a more severe and faster effect than blowing snow. The submicron aerosols in fog or the air are often not captured by the filters, and ice builds up in the gas turbine inlet. The ice reduces the surge margin of the compressor by decreasing the inlet pressure of the compressor. Also, pieces of ice can break off and be ingested by the turbine causing FOD if the ice accumulates past the filtration system. Aeroderivative engines are the most susceptible to this due to their higher temperature depression, lighter compressor blading, and lower surge margin than heavy duty turbines.

During the summer in some arctic environments, there will be insect swarms. This event usually only last a few weeks, but can affect the operation of the gas turbine by plugging the filters. Insect screens should be included in the filtration system to minimize insect ingestion.

Filtration Systems

There are three primary components of the filtration system for the arctic environment: initial weather hood or weather louvers, anti-icing system, and filters. The weather hoods are designed in order to mitigate the ingestion of snow or freezing rain. The weather hoods have a large entrance area which promotes a lower upward velocity. The velocity should be a maximum of 250 ft/min. This decreases the likelihood that snow will be pulled upwards into the filtration system. The dry crisp snow in the arctic environments makes the use of inertial separators possible. These can be used as a first stage snow filtration for the system but may be troublesome in areas with heavy snow. The design or layout of the surrounding equipment near the inlet should be considered carefully. Wind deflecting structures can adversely affect the operation of the filtration system if not placed correctly. Insect screens on hinges are used at the inlet to the filtration system to minimize the effect of insects during the summer months.

Anti-icing systems are often used in the arctic environment. These are primarily used if inlet compressor icing is a concern. These systems use the mixing of the cold inlet air with heated air to prevent icing. The heated air is re-circulated from a compressor bleed or the exhaust of the gas turbine. The compressor bleed is the most common. Since air is being removed from the gas turbine, there are power losses to the gas turbine operation. This depends on how much bleed air is taken from the compressor exit. It is possible to see up to a 5% efficiency loss when using the compressor bleed air for anti-icing. These systems protect the inlet to the filtration system, but must be used with a high efficiency filter in order to have a complete protection system for the gas turbine. There are alternate systems which use a hot water source for anti-icing. Even with anti-icing protection, alarm switches should be installed on the filtration system to warn operators if there is an excessive pressure loss due to ice build-up.

After the inlet weather protection and anti-icing is a bank of high efficiency filters. Conventional non-self-cleaning filtration is susceptible to icing. Pulse cleaning or self-cleaning systems have been found to be effective in preventing ice buildup. These systems are able to remove the ice through reverse air pulses in the system. Large amounts of air are required for the pulses to effectively remove the ice; therefore, it is recommended that a dedicated air compressor be installed for the pulse cleaning system. The self-cleaning filters operate well in the arctic environment, since the snow is usually very dry and crisp. However, if any moisture is present due to elevated temperatures, the filters can quickly become loaded and have elevated pressure losses. Wet or damp filters should never be installed in any filtration system in the arctic environment. This is especially true in freezing weather. The moisture in these cartridges will freeze partially or completely clogging the filter. If small contaminants are present in the local environment, then high efficiency filters should be installed downstream of the self-cleaning filters or anti-icing systems.

The inlet filter housing should be elevated to minimize the ingestion of snow or freezing rain. Consideration should be given to the expected height of snow during the winter months. The inlet to the filtration system may be an adequate distance above the ground during the warm months, but may be near the top of snow drifts after the snow has built up.

3.3.4.3 Tropical Application

Between the band Tropic of Cancer and Tropic of Capricorn along the equator are the tropics. This area is characterized by hot climate, high humidity, monsoons, high winds, and insect swarms. Due to the extensive vegetation, there is not much erosion concern. It is considered a low dust environment. The area has little seasonal variation with the exceptions of periods of intense rainfall. Typhoons, dust, insects, and the remoteness of systems in the tropics should be considered when choosing the correct system.

Contaminants

The main contaminants in this area are water, insects, and salt (if the location is near a shoreline). Dust is minimal, since the overgrown vegetation protects the ground dust from winds. Off course, there are always exceptions to this. If the gas turbine is installed in a construction site, then the dust levels will be higher than normal. Also, unpaved roads can contribute to the dust in the environment. Pollen can be an issue. Salt will be present in aerosol form due to the high humidity and moisture present.

Insects are a common problem. Large moths live in the area and occur in large quantities, particularly during their breeding periods. One moth that is common to India and South East Asia is the Swift moth (Hepralidae). This moth can grow to have a wing span of 6 inches and has been reported in one night to lay up to 1200 eggs. Moths are attracted to lights which often surround gas turbine installations. Also, the pull of the air to the gas turbine inlet draws the moths onto the insect screens. The moths can quickly cover the insect screens and block the airflow to the gas turbine. In some instances, this can cause the gas turbine to trip. Moths confine themselves to a few miles inland.

The effect of rainfall cannot be ignored in gas turbine operation. The filtration system must be able to handle frequent rain storms. The humidity or moisture in the air is always high. During the rainy season, the humidity tends to stay constant throughout the day. The other times of the year, the humidity reaches its lowest point during the hottest part of the day and is the highest at night. The tropics have high winds which cause “horizontal” rain. This phenomenon makes the use of weather hoods less effective.

Filtration System

The filtration systems for tropical environments are specifically built to handle large amounts of rain. Weather hoods are used as a primary defense. Extended area insect screens are used for blocking insects. These screens have a lower air velocity (in the range of 260 ft/min) which allows the insects to move away from the screens. This prevents obstruction of the inlet air flow. This is followed by a mix of pre-filters, coalescers, and vane separators. The water removal system must be designed in order to handle the highest expected water ingestion. If this is not done, then water will be able to travel farther downstream in the inlet filtration system. Any pre-filters or high efficiency filters used should be selected to prevent water travel through the filter. If water is allowed to penetrate the filter, then it can absorb the capture soluble contaminants and transport them through the filter into the gas turbine. This can have detrimental effects if salt is being removed from the air stream. These filters should also be selected for the expected contaminants such as pollen and road dust.

The high temperature in combination with the high humidity leads to the formation of mold fungus and corrosion. The sustained hot and humid environment makes this an accelerated process. Corrosion can quickly spread and damage any non-protected inlet components. Therefore, it is essential that all metal inlet parts be made of corrosive resistant materials or coated with corrosion protection. Carbon steel has been used unsuccessfully in the tropics. Constant maintenance on the painted surfaces leads to high cost and many labor hours. Also, the use of shot blasting to remove old paint adds a contaminant which the gas turbine inlet system is not necessarily designed to protect against. Stainless steel is almost exclusively used for inlet ducting and components, especially if salt is present.

3.3.4.4 Rural Countryside Application

The rural countryside is a diverse environment. Depending upon where the gas turbine is located in this environment, it can be subjected to hot, dry climate, rain, snow, and fog throughout the year. The majority of the year there is a non-erosive environment with low dust concentrations in the range of 0.02 to 0.1 ppm (0.01 to 0.05 grains per 1000 ft^3). The area can be near a local forest or be near agricultural activities.

Contaminants

The contaminants in this environment vary depending on the season. Throughout the year, insects and airborne particulate will need to be filtered. If the gas turbine is installed near an agricultural area, then during plowing and harvesting season, the concentration of dust will increase. During plowing, insecticides and fertilizers will be airborne. At harvest, the particles or grains from cutting plants down will be lofted into the air. The particles that travel to the gas turbine are relatively small (less than 10 microns), unless strong winds are present to carry large particles. Gas turbines near forests may not have as high dust concentration. The foliage of the forest will protect the ground dust from being lifted by the wind. With the change in season, snow, rain, fog, pollen, airborne seeds, and insects will be present. This climate has one of the most diverse filtration requirements as compared to other environments.

Filtration Systems

These systems are typically comprised of three stages: weather hood, pre-filter, and high efficiency filter. The weather hood protects the filters farther downstream from rain and snow. They also minimize the amount of dust entering the filtration system. Insect screens are used, especially if insects are present in swarms during parts of the year. The pre-filter is used to remove any erosive dust present in the air. The pre-filter also protects the high efficiency filter from being overloaded too quickly.

The high efficiency filter removes the smaller particles. If the gas turbine is installed near an agricultural area, the filter engineer may consider a self-cleaning system. This type of system would be beneficial during plowing or harvest season when the air has a high erosive dust concentration. A self-cleaning system can also be beneficial in an area with a dry, cold climate during the winter season. It can effectively prevent ice from forming on the filter elements and influencing the gas turbine operation.

The filter housing, ducting, and components are normally constructed of carbon steel. There are typically not corrosion concerns in these areas. A protective paint coat is applied to the system for weather protection. Stainless steel may be used if the area is near a dry salt bed or near a source which expels corrosive type contaminants.

3.3.4.5 Large City Application

Large cities can experience all the types of gas turbine degradation: corrosion, erosion, and fouling. Contaminants from many different sources ensure the requirement of a multi-staged filtration system.

Contaminants

All different types of weather can occur throughout the year in a large city. The amount of contaminants varies throughout the season as discussed above for the rural countryside. One example is salt or grit that is laid down on icy roads during the winter. The city also has smog and pollution. These can also be seen in the countryside due to high winds, but are much more concentrated in the city. Some other considerations for large cities are noise issues and vandals.

The dust concentration of the area can range from low amounts to high amounts (0.018 to 8.6 ppm). It is dependent on what is installed near the inlet system. If the gas turbine is near power plants or other industrial facilities, then there will be hydrocarbon aerosols in the air. Also, sooty and oily dust particles can be present from the exhaust of the local industrial plants or even exhaust from vehicles. In heavy industrial areas, corrosive gases and soot emitted from nearby exhaust stacks will be present. If the large cities are positioned near the ocean, then the effects of salt also come into play.

These environments are extremely dependent on what is located near the gas turbine installation. Each location should be evaluated for what contaminants are present and must be removed. This evaluation should look at the full year and consider the seasonal changes of the area.

Filtration System

The system has a multi-stage approach with specific filters installed for the local contaminants. Weather hoods are used the majority of the time due to the changing weather conditions with seasons. This protects the system from rain, snow, and windy conditions. The filtration system is composed of a pre-filter and a high efficiency filter. The pre-filter removes the larger erosive particles. The high efficiency filter is typically of the non-self-cleaning type with rectangular filters or cartridges filters. The self-cleaning systems are not used due to the sticky aerosols present in the air. If freezing conditions are expected, then an anti-icing system is included. Urban/ industrial areas typically do not have airborne particulate concentrations that warrant the use of self-cleaning filtration systems, but self-cleaning systems are used successfully in these areas, when these are in regions of heavy snow and minimal sticky particles.

The filter housing is generally constructed out of carbon steel with a protective coating. If there is a high concentration of corrosive gases, dust, or salt, then stainless steel may be used. The filtration system is designed to prevent compressor fouling, but this still usually occurs to some extent. Scheduled compressor washing may be used to restore the compressor's performance after an allocated amount of degradation has occurred. The gas turbine inlet is oriented and fitted with a silencer in order to control the noise emitted to the surrounding communities.

3.3.4.6 Industrial Area Application

Many gas turbines are installed in heavy industrial areas. These locations can be in any of the environments discussed above, but they have additional concerns. There are several emission sources in an industrial location which contribute to the contaminants which must filtered out.

Contaminants

The most prevalent contaminant in industrial areas is contaminants from exhaust stacks. These can be in the form of particles, gases, and aerosols. Many of the particles emitted by the exhaust stack are in the submicron size range. These size particles are difficult to filter and can collect on compressor blades and cause fouling. The gases emitted in the exhaust can contain corrosive chemicals. For example, exhaust gases from fossil fuel plants has SO_x which contains sulfur. Sulfur is one of the corrosive components that can lead to hot corrosion in the turbine section. Gas cannot be removed by mechanical filtration. Aerosols also present a challenge. These are typically on the submicron size and difficult to filter. Many of these aerosols are sticky, and when they are not removed by the filters, they stick to compressor blades, nozzles, and other surfaces. One example of this already mentioned in this guideline is the compressor blade fouling due to oil vapors. An example of this is shown in Figure 2-6.

Industrial locations can also experience contaminants that are not typically seen, unless near a localized source. Some examples of these are dust from mining operations, sawmills, foundries, and other industrial facilities. Also, if the gas turbine is near a petrochemical plant, the air may be contaminated with specific chemicals. These chemicals could be harmless, but they also could have corrosive properties.

One example of a unique emission source in an industrial location is shown in Figure 3-33. This figure shows a bag filter and a turbine blade at a soda ash plant. The initial filtration installed for this facility only had one stage of filtration which was not able to handle the limestone dust that was prevalent in the air. As a result, the turbine blades were damaged several times during the initial operation.

Figure 3-33. Bag Filter and Turbine Blade at Soda Ash Plant

Filtration System

One commonality between all industrial locations is that the inlet of the filtration system is subjected to the local plant emissions. This condition typically requires a more robust high efficiency filtration system to remove fine particles that are entrained in the air. One way to reduced the amount of emissions that are ingested into the inlet is to direct the inlet air flow away from these emission sources. Several recommendations in regards to the inlet placement and site layout are discussed later in Section 3.3.5.

Even so, there are still some emissions that are ingested by the turbine. Additional filter elements should be included in the filtration system to address these emission particles. For example, if the industrial location is near an open coal storage site, then the gas turbine should have pre-filters and high efficiency filters to remove the coal dust that is in the air.

One contaminant that is often in the air at industrial locations is sticky aerosols. These aerosols can be from oil vapors from lubrication systems or unburned hydrocarbons emitted from exhaust stacks. These aerosols are very difficult to remove from the air and often lead to blade fouling. High efficiency filters should be used to minimize the aerosol's effect on the gas turbine, but a compressor washing scheme is needed to keep the compressor blades clean and to minimize the effects of fouling on gas turbine performance. Gas turbine washing is discussed in more detail in Section 4.5.

3.3.4.7 Other Applications and Considerations

There are several other local emission sources that can affect the operation of the gas turbine. If the sources discussed below are located near where the gas turbine is installed, then their effect needs to be considered in the design of the filtration system.

Winter Lake Effects

At locations with large lakes, in early winter the temperature of the water may be above the temperature of the air. The water evaporates into the air and forms snow or ice-crystals creating snow storms. Large quantities of snow may fall in a period of a few hours. The locations which are affected by this are dependent on the distance from the shoreline, time of year, lake temperature, wind direction, and wind strength. To minimize snow or ice ingestion, the gas turbine inlets should be positioned such that they are not in the direction of the prevailing winds in late autumn and early winter. More information on protection in arctic type environments can be found in Section 3.3.4.2.

Inland Dry Lake Beds

Dry lakebeds are a potential source of alkali salts. They can be found in dry desert climates. The salt is present as solid particles. The salt particles captured by the filters can be a problem in wet seasons or in the presence of high humidity if the filters are not design to prevent water penetration. Section 3.3.3 has more information on the effects of salt and how it is removed.

Inland Salt Lakes

These tend to have the same effects as the seawater does at coastal environments. A few distinct differences are that there will be less aerosol generated due to wave action, and the higher saline concentration of the water will increase the salt in the air due to evaporation. Section 3.3.3 has more information on the effects of salt and how it is removed.

New Emission Sources

During the life of the gas turbine, there is the likelihood that a new emission source will develop. This could be nearby construction activity, change in local industrial activity, or change in agriculture activity. These should be considered in the protection of the gas turbine and their effects on life and performance.

3.3.5 Site Layout

The layout of the site where the gas turbine is installed can have a significant effect on the type and amount of contaminants that need to be removed from the inlet air. This has been mentioned in several of the environmental type discussions above, but is summarized here for completeness. Listed below are general recommendations. Gas turbine manufacturers may have their own set of guidelines for placing the gas turbine.

- When installing other combustion type equipment, such as a diesel engine, near the gas turbine, the exhaust of the equipment should be directed away from the gas turbine inlet. This reduces the possibility of the exhaust gas entering the gas turbine inlet system. This exhaust can contain unburned hydrocarbons or corrosive gases.

- Cooling towers can be a major source of aerosol drift. Cooling towers are open to the atmosphere and, therefore, release aerosols into the air due to agitation from cross winds and the flow of the water down the tower. The water in the cooling tower also contains water treatment chemicals that could be detrimental to the gas turbine. The drift of aerosols from a cooling tower is confined within a few hundred feet. If possible, the gas turbine inlet should be positioned away from cooling towers and placed upstream of the prevailing wind direction to minimize the aerosol drift. CFD can be a useful tool to model how the wind will carry aerosols over to the gas turbine inlet. This will help the filter engineer to properly place the gas turbine to minimize cooling tower drift effects. Figure 3-34 shows an example of cooling tower aerosols drifting into the inlet of the gas turbine.

Figure 3-34. Aerosols Drifting from Cooling Tower to Gas Turbine Inlet
(Courtesy of Camfil Farr)

- Pressure relief valves are installed on many gas lines and equipment to protect the equipment in case of an over pressurization event. The vents to these relief devices should be directed away from the gas turbine inlet. Release of any hydrocarbon could result in high concentration ingestion at the filtration system. The filters at the inlet to the gas turbine do not remove gas phase contaminants.

- Piping connections on gas, fluid, or steam lines will generally leak after some time. The leaks at these connections can impact the filtration system. Piping should be routed away from the inlet in order to prevent this influence.

- Lube oil vents should be directed away from the inlet to prevent oil vapor ingestion.

- The exhaust of the gas turbine should be directed away from the inlet of the gas turbine. Carbon smoke and hydrocarbon fumes released at the exhaust could lead to accelerated fouling of the compressor blades. If the compressor blades are fouled, then the performance of the gas turbine will be reduced.

- The gas turbine inlet system should not be directed toward or installed near any exhaust stacks. These exhaust stacks release chemical exhaust and unburned hydrocarbons which can lead to compressor fouling and corrosion.

- Avoid placing the inlet near gravel or dirt roads. The dust thrown into the air from vehicle traffic and wind can be carried into the inlet of the gas turbine.

    - If the gas turbine is operated during construction activities, consider adding more robust filters to remove the excess dirt that will be ingested.

- Direct the inlet away from any open storage of coal, salt, or other grainy particles. The wind can carry the smaller grains from the storage area into the inlet of the gas turbine.

3.3.5.1 Temporary Filters

In many of the applications discussed above, temporary or seasonal conditions are mentioned As gas turbines become more advanced and more sensitive to the inlet air quality, it becomes more important to address these conditions.

In order to address seasonal changes, the expected conditions must first be defined. During the design phase, the air quality at the site where the gas turbine is going to be installed should be monitored for at least one year. This will provide the filter engineer with information about which contaminants they can expect in each season. Also, the filter engineer should map out any potential construction, agricultural, or dust-generating projects that will occur in the first five to ten years of the life of the gas turbine. Combining the expected contaminants will allow the filter engineer to develop a more holistic approach to their inlet filtration.

Currently, the majority of the filtration systems installed have a fixed filtration system. The number of stages, types of filters, and level of filtration remain constant throughout the operation. If the future site for the gas turbine is expected to have high variability in the type of contaminants experienced (temporary or seasonal), the filter engineer may consider a filtration system which allows the use of many different filters. This would then allow the filtration system to be adapted to the current conditions.

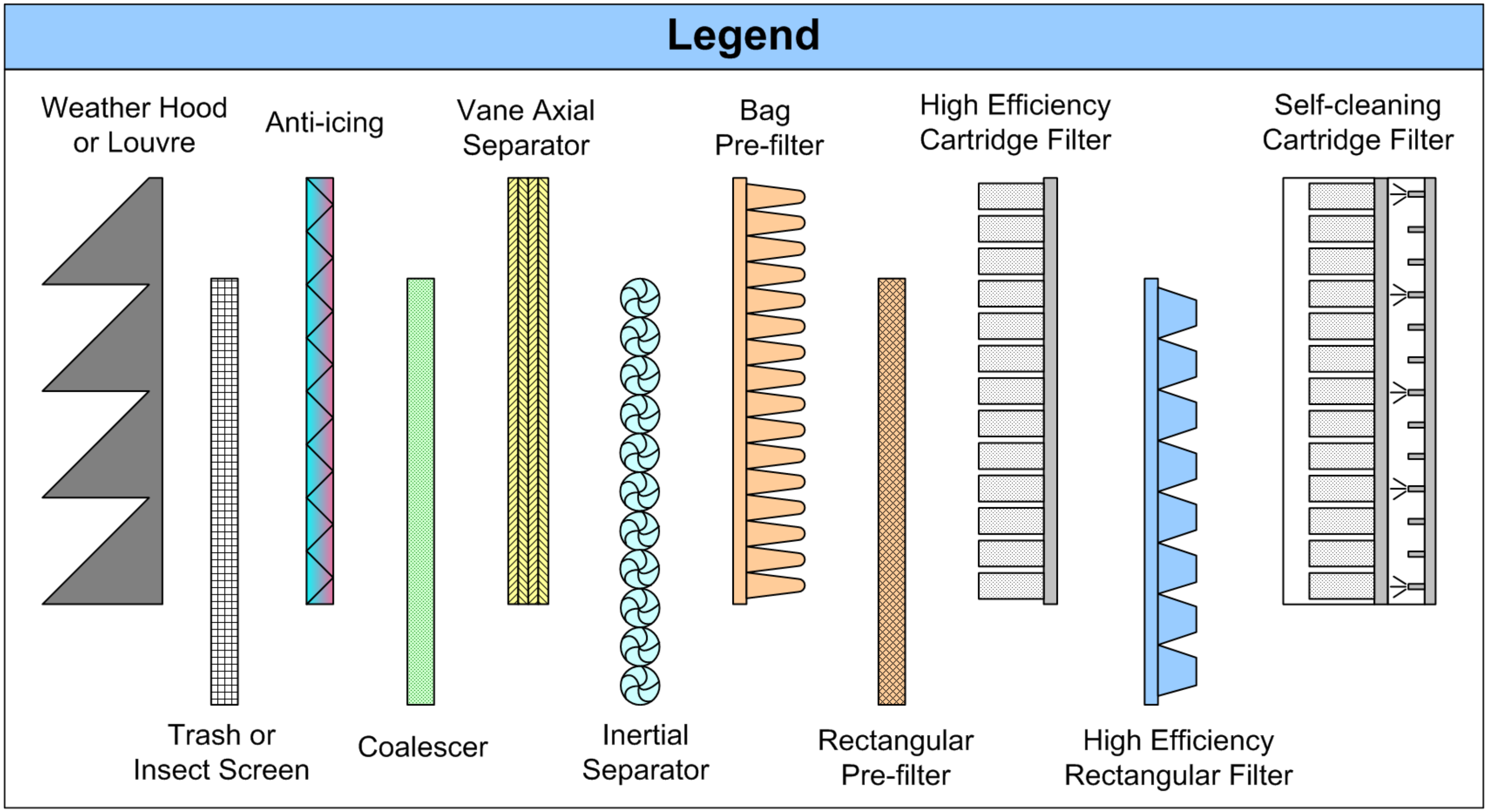
3.3.5.2 Summary

Many different applications are discussed above for gas turbine inlet filtration systems. Table 3-5 provides a summary of the various applications discussed including their common contaminants and what filtration systems are typically employed to remove the contaminants. Figure 3-35 through Figure 3-38 display graphical representations of typical systems for each of these environments. The filter engineer should be cautioned that these arrangements may not be suited for their application. A filtration system could be used at a location that represents only one type of environment or that encompasses multiple environments. For example, a gas turbine may be installed in a large city that has a arctic winter and is near a coast. For this location the contaminants in large cities, arctic, and coastal environments should be considered. A thorough review of the existing contaminants at the gas turbine site should be used to determine the required inlet filtration scheme.

Table 3-5. Summary of Filters Required for Various Applications

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
Arctic	Ice	Anti-icing system, self-cleaning filters
	Insects	Insect screens
	Snow	Weather hoods, self-cleaning filters
	Summer dust	Pre-filter and/or high efficiency filter
Tropical	Water (rain)	Weather hoods, vane separators, coalescers
	Insects	Insect screens
	Pollen	Pre-filter and/or high efficiency filter
	Salt (near ocean)	Pre-filter and/or high efficiency filter
Rural Countryside	Water (rain, snow, fog)	Weather hood
	Agricultural dust	Pre-filter and/or high efficiency filter, self-cleaning filters
	Pollen, ground dust, seeds	Pre-filter and/or high efficiency filter
	Leaves	Trash screen
	Ice	Anti-icing
Large Cities	Water (rain, snow, fog)	Weather hood
	Agricultural dust	Pre-filter and/or high efficiency filter, self-cleaning filters
	Pollen, ground dust, seeds	Pre-filter and/or high efficiency filter
	Leaves	Trash screen
	Ice	Anti-icing
	Soot, pollution, exhaust fumes	High efficiency filter

Environment	Contaminant	Filtration
Industrial Locations	Water (rain, snow, fog)	Weather hood
	Ice	Anti-icing
	Cooling tower aerosols	Coalescer
	Ground dust, pollen	Pre-filter and/or high efficiency filter
	Leaves	Trash screen
	Hydrocarbons, soot, exhaust	High efficiency filter



Note: Air flows from left to right

Figure 3-35. Legend for Filtration System Graphics

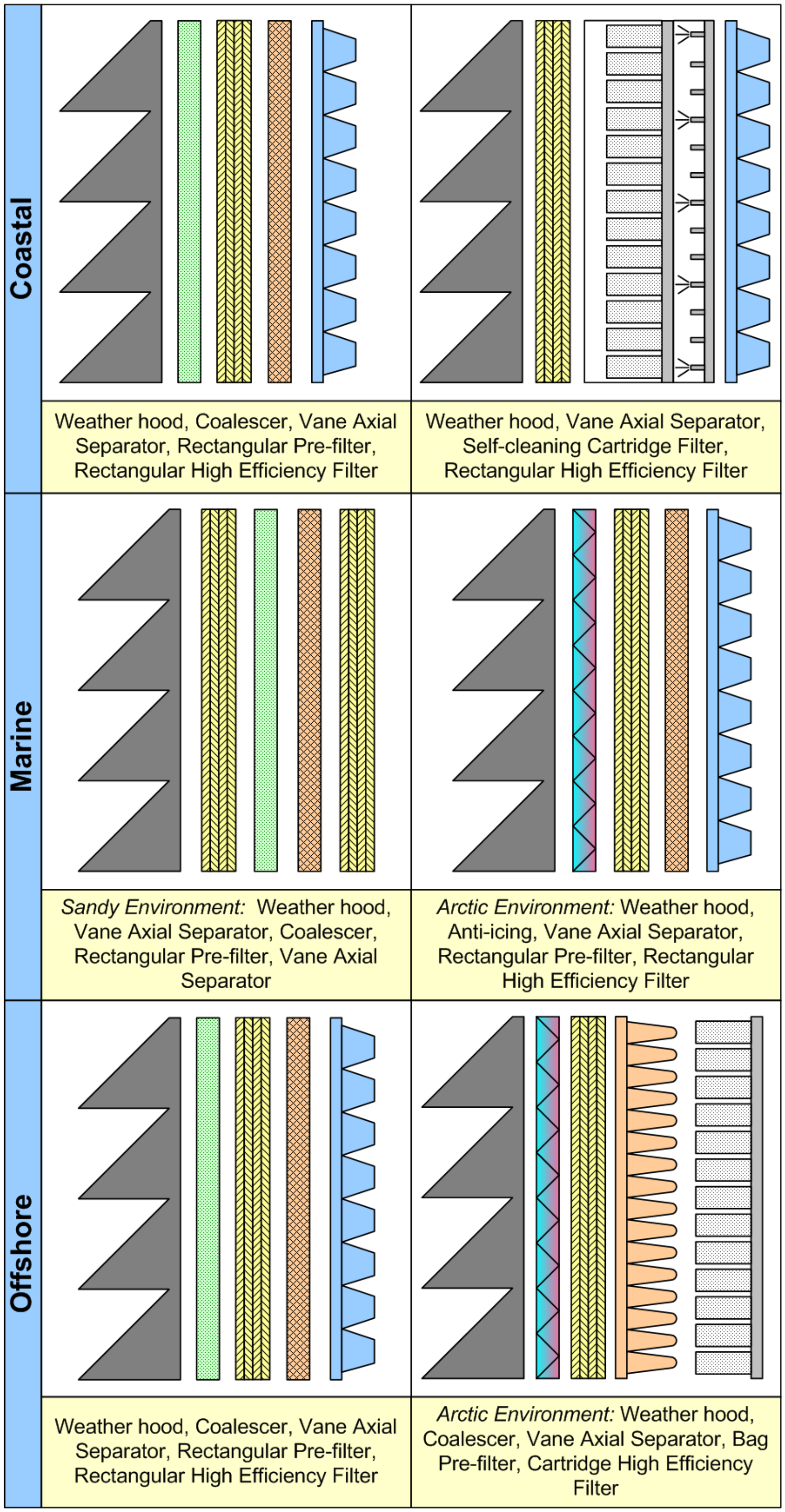


Figure 3-36. Typical Filtration Systems for Coastal, Marine, and Offshore Environments

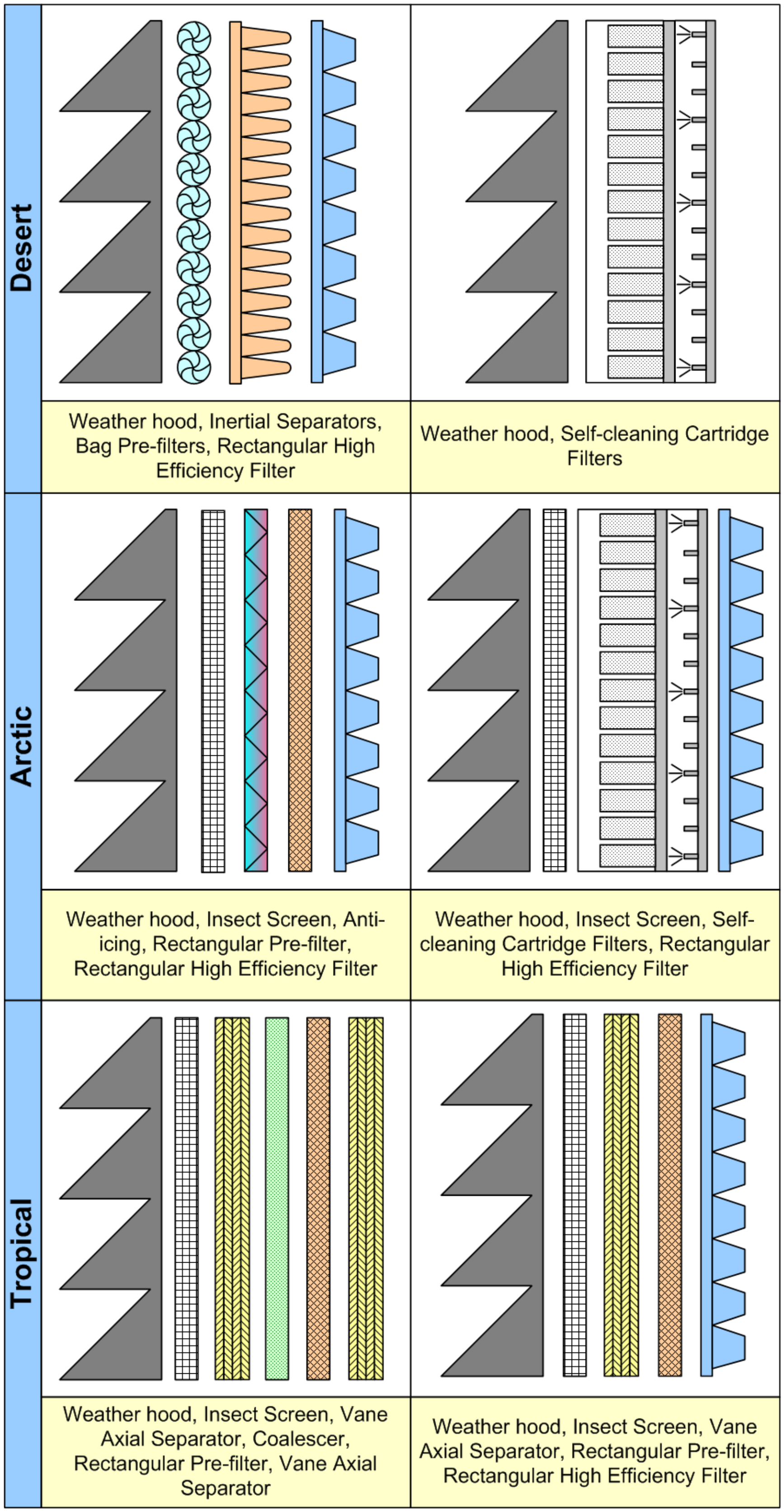


Figure 3-37. Typical Filtration Systems for Desert, Arctic, and Tropical Environments

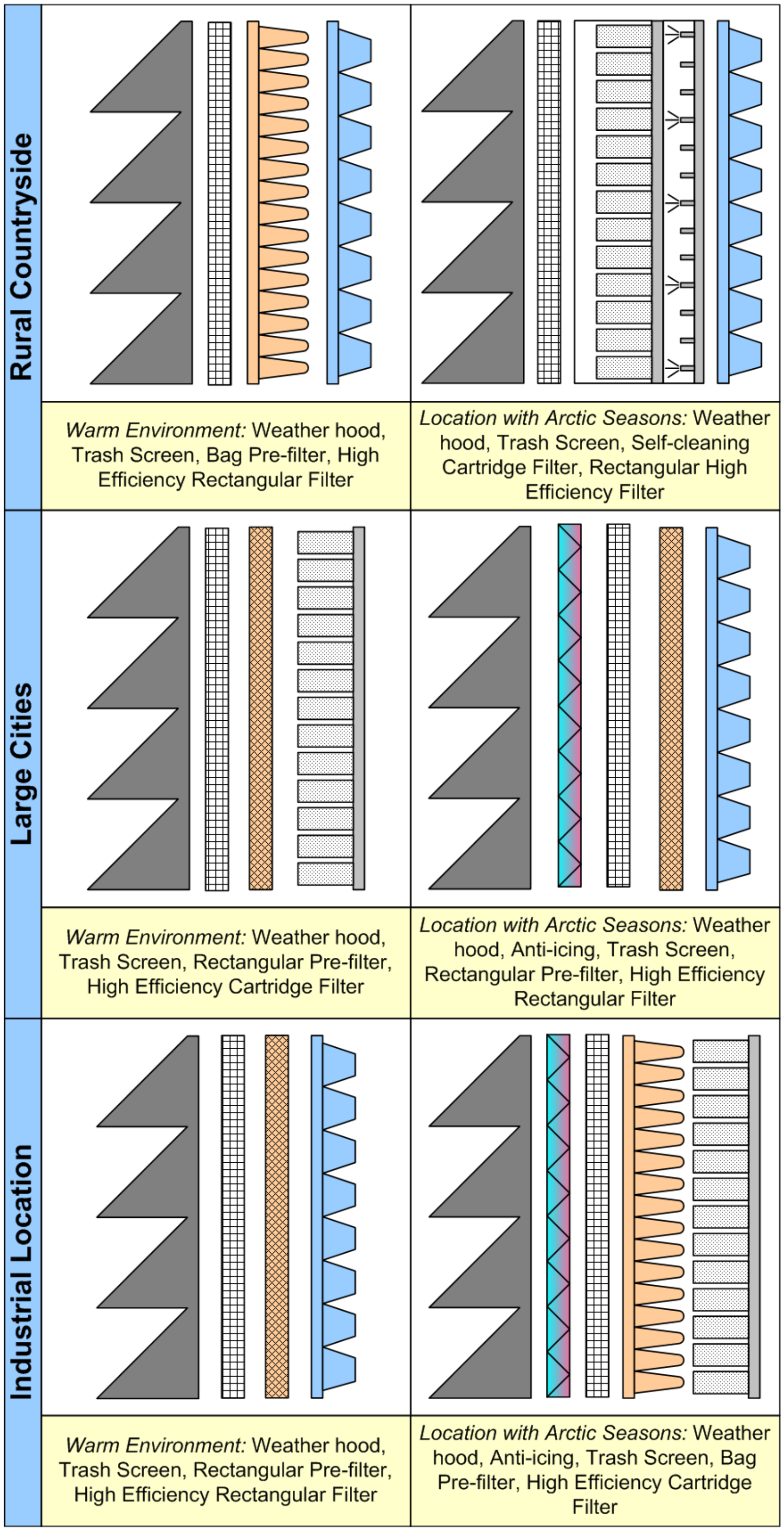


Figure 3-38. Typical Filtration Systems for Rural Countryside, Large Cities, and Industrial Locations

3.3.6 Site Evaluation

As discussed previously, there are several different types of environments where a gas turbine can operate. Also, there are many possible local, seasonal, and temporary contaminants that can be present. Therefore, each gas turbine installation site has a unique make-up of contaminants. When selecting the inlet filtration system, this make-up should be determined. This includes determining what contaminants and how much are present at the site. Once this information is known, the types of filters needed and filtration efficiency required can be established.

This section provides guidance on evaluating the site where the gas turbine will be installed. A site evaluation questionnaire which can assist in this process is provided in Appendix A. The first step in this process is to define which type of environment that gas turbine will be installed in. From this, a list of possible contaminants can be assembled. Next, the site and surrounding areas should be evaluated for local contaminants. This can be confirmed through a visual survey of the area for any localized emission sources. Sources that should be noted vary from dirt roads, local agricultural sites, nearby industrial plants, or local vegetation. Many typical localized sources are discussed above in Section 3.3.

In the United States (US), the Environmental Protection Agency (EPA_{US}) samples airborne particles periodically at some 4000 locations. The air analysis results can be useful in determining what contaminants are present at the installation site. Results of the surveys are published on the EPA_{US}'s website at the Technology Transfer Network – Clearinghouse for Inventories & Emission Factors website. This data can be accessed by any member of the public, and the data has the yearly emission levels in counties throughout the United States. The emissions are broken into various categories including SO_x, CO_2, various other gases and chemicals, and particulate matter emissions. The particulate matter is divided into five categories: PM10-PRI, PM10-FIL, PM25-PRI, PM25-FIL, and PM-CON. Emissions in the PM10 category are in size range of 2.5 to 10 microns. The PM25 category is for particles less than 2.5 microns in size. The EPA_{US} does not track emissions larger than 10 microns. The PRI represents the primary emissions. This is the sum of the filterable and condensable emissions measured. FIL indicates that these emissions can be filtered from the air. CON is an indication that the emissions are condensable. The CON category is only associated with fuel combustible sources.

While a visual survey and the EPA_{US} data will provide a general list of contaminants, an air survey may be required. This is especially true for sites that do not have local data available. This survey would need to take periodic samples at the gas turbine installation site. These samples can be analyzed for the type and quantity of contaminants present. Air quality of air sampling consultants and labs can complete this type of study. Also, the filter engineer can complete the survey themselves with proper air quality measuring equipment. The EPA_{US} has a list of several air quality monitoring equipment which follows the 40 CFR Part 50 methods listed on the EPA_{US} Technology Transfer Network – Ambient Monitoring Technology Information Center webpage.

The filter engineer must remember that the local contaminants can vary with season. The site should be surveyed several times a year. This will provide a complete list of the contaminants and contaminant levels that can be experienced. Meteorological data can provide insight into the weather experienced at the site. This data can be used to determine if anti-icing protection is required or how rigorous the water removal system needs to be. The US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) monitors and publishes meteorological data from thousands of sites across the nation. This information can be retrieved from the NOAA website. The majority of these sites monitored are at airports and military bases. It should be noted that even with this data, the localized meteorological conditions can vary from those reported at the weather stations, especially if the site is far away from the station or in a location with significant elevation changes (i.e. in the mountains).

Once all the existing contaminants and seasonal patterns are documented, the filter engineer should consider future contaminant sources. If the site where the gas turbine will be installed is undeveloped, then future contaminants could include dirt roads during construction, emissions from future exhaust ducts, and water drift from cooling towers. Also, the local surrounding area may have agricultural expansions. This would introduce more grains and particulate matter during the harvest or growing season. Some of the future contaminants can be anticipated based on published development plans for the surrounding area.

If the information described above is collected, then the contaminants that are expected to be experienced at the site can be quantified. With this information, a proper inlet filtration system can be designed.

3.4 Filtration System Life Cycle Cost Analysis

When selecting a filtration system, the filter engineer is burdened with deciding the level of quality they want their system to achieve. This includes the efficiency of filtration, the particle size to be filtered, the amount of maintenance that will be needed to maintain the filtration system, what rate of degradation is acceptable for the gas turbine, the required availability and reliability of the gas turbine, what type of washing scheme will be used (online, offline, or a combination of both), and cost of the filtration system. The cost impact of each of the items mentioned can be quantified. A Life Cycle Cost (LCC) analysis provides a convenient means to compare different filtration system options quantitatively.

This section covers the inputs that should be considered for the LCC analysis for a filtration system. It also provides methods to calculate the cost impact for each input. The basic formulas for the LCC analysis are also discussed.

3.4.1 Basics of Life Cycle Cost Analysis

A LCC analysis is a useful tool that is often used to compare various design options for a new equipment installation. It can also be used to compare the cost of leaving an existing system as is, or implementing retrofits. This type of analysis focuses on the overall or lifetime cost of a system. It is a tool that estimates the total cost to purchase, install, operate, maintain, and dispose of equipment. This analysis can assist in determining the best design options which will minimize the overall cost of a system.

It is important to include initial cost in the analysis, but it is just as important to include operation and maintenances cost. The operating and maintenance cost over the life of a piece of equipment can have a more significant effect, especially if a poorly designed system is chosen. An LCC analysis can help to determine which system configuration can minimize lifetime costs. Some of the costs that are typically considered are shown below. Examples of how this would apply to filtration systems are provided in parentheses. The terms in brackets will be used in an equation below.

- Initial cost (filters, filtration system, spares filters, instrumentation) [NPV_{init}]
- Installing and commissioning costs (labor, cost of installation equipment (such as cranes), shipping costs) [NPV_{inst}]
- Energy costs (pulse system for self-cleaning filters) [NPV_{ener}]
- Operating costs (labor, inspections) [NPV_{oper}]
- Maintenance (replacing filters, repairing system, labor for maintenance) [NPV_{main}]
- Downtime (replace filters, complete offline water washes, anything outside of normal shutdowns for other maintenance) [NPV_{down}]
- Gas turbine effects (degradation, performance loss) [NPV_{GT}]
- Decommissioning and disposal (disposal of filters) [NPV_{disp}]

In a LCC analysis, estimates are provided for each cost component of the system. An inflation rate can be applied to the costs which will occur later in the life of a system (such as ten years from the installed date). Once these cost are established, they are brought back to present value using Equation 3-2. The Net Present Value (NPV) term represents the value of the cost in present terms. *A* is the value of the cost in the year it occurs. The term *i* is the discount rate and *n* is the year the cost occurs in. If there is a price increase (inflation) or decrease, then this can be accounted for by using Equation 3-3. The term *e* is the increase or decrease in price.

$$NPV = A(1+i)^{-n} \tag{3-2}$$

$$NPV = A(1+(i-e))^{-n} \tag{3-3}$$

Projected costs over the lifetime of the system cannot be combined directly when calculating the LCC, because the funds spent at different times have different values to the investor. The discount rate, *i*, is used to bring the costs to present terms, where they can be directly added together, and is defined as the rate of return that is used to compare expenditures at different points in times. For example, the investor would be equally satisfied to have one amount received earlier and the other amount received later (Europump and Hydraulic Institute).

If a cost occurs yearly, the NPV of the total recurring costs can be calculated with Equation 3-4. If inflation or price escalation is considered in the analysis, the NPV of the total recurring cost can be calculated with Equation 3-5.

$$NPV = \frac{A}{i}\left(1-[1+i]^{-n}\right) \tag{3-4}$$

$$NPV = A\left(\frac{1+e}{1-e}\right)\left(1-\left[\frac{1+e}{1+i}\right]^{n}\right) \tag{3-5}$$

The NPVs must be determined for each cost. Then the cost will be added together to obtain the total NPV or LCC cost. This addition is shown in Equation 3-6 with each cost from the list discussed above.

$$\begin{aligned} NPV_{total} &= NPV_{init} + NPV_{inst} + NPV_{ener} + NPV_{oper} + NPV_{main} + NPV_{down} \\ &\quad + NPV_{GT} + NPV_{disp} \end{aligned} \tag{3-6}$$

The NPV can be calculated for several different system configurations. The NPV values are directly comparable between systems. For equipment installations, the NPV will often be a negative value unless the profits/ revenues from the process are included. Having a negative value (when not including profits/ revenues) is acceptable. In this case, the result of the analysis would indicate that the least expensive system to install, operate, and maintain is the one with the lowest negative value. For example, a system with an LCC of -$1000 would be chosen over a system with an LCC of -$5000. If the profit/ revenue is included in the analysis, the system chosen would be one with the highest positive value. If the profit/ revenue is included, but the analysis still produces a negative value, this is an indication that the overall cost of the system is higher than the expected profits/revenue.

3.4.2 Gas Turbine Inlet Filtration System Considerations

The purpose of the inlet filtration system is to remove contaminants that could have detrimental effects to the gas turbine. Therefore, the operation and performance of the gas turbine based on the level of filtration must be considered. There are several questions that should be asked when considering the gas turbines operation for the life cycle analysis.

- What are the availability and reliability requirements?
- What type of environment is the gas turbine operating in?
- Is lost performance an issue (as it relates to lost product and engine fouling)? What is an acceptable rate of degradation of the gas turbine performance?
- Will the turbine be operating at full load, part load, or varying load?
- Is a spare gas turbine unit available, and how are they operated in relation to one another?
- How much power margin is built into the gas turbine?
- How often are the turbines operated? What is the value of daily operation?
- What pressure loss on the inlet system is acceptable?
- What type of washing scheme will be used for the gas turbine? How often should it be performed?
- Will the washing be online or offline? If offline, how much downtime is associated with this?
- Is maintenance possible on the filtration system? How often can maintenance be conducted?
- What is the cost of fuel for the gas turbine?
- What is the disposal cost of selected filters?
- Is the system operated in a remote or dangerous location?

The answers to each of these questions can be quantified so they can be input into the LCC analysis. The items are reviewed in more detail below with guidance on how to quantify them in terms of dollars.

3.4.2.1 System Initial and Maintenance Costs

One of the main costs considered by companies when purchasing a filtration system for their gas turbines is the initial cost. This is should be included in the analysis in the first year. A cost estimate can be obtained from the filtration system manufacturer or the gas turbine packager. Another cost which is important to consider for the system is the recurring or maintenance costs. One example of this type of cost is the price for replacement filters. The cost of the filters on the new system is lumped into the system purchase price, but when the filters are replaced, the company will need to purchase a new set. The cost of filters has a range of values depending upon what they are designed to remove from the air, their material of construction, their efficiency, the number of filters required, and their estimated life span.

Depending on the type and construction of the inlet system, there may be other maintenance activities that need to be performed throughout the life of the system. If carbon steel is used for construction of the housing, it will need to be repainted after a certain number of years in order for the housing to maintain corrosion resistance. If a self-cleaning filtration system is used, there will be maintenance associated with the pulse jet system. Also, there will be a labor cost for installing replacement filters in the system. Any maintenance costs (labor and materials) that are required for the filtration system need to be included in the LCC analysis. These costs should be included in the year they are expected to occur.

3.4.2.2 Availability/ Reliability

The availability of a gas turbine is how often the gas turbine is available to operate on a yearly basis. This term is usually reported in a percentage form. For example, a gas turbine with 85% availability can be operated 7446 hours a year (out of 8760 hours). The availability is associated with any scheduled maintenance or other activities that lead to gas turbine downtime that are expected to occur. Reliability is a close relative to availability. It is how often the gas turbine can operate on a yearly basis. It is also expressed as a percentage. The reliability is associated with the ability of the different components and systems of a gas turbine to operate a specified number of hours out of the year. If the gas turbine can operate all 8760 hours of the year without a failure or event that causes a shutdown, then it can be considered to be 100% reliable. However, if a failure or event occurs where the gas turbine has to be shut down, then the reliability will be less than 100%. Often reliability and availability are presented as one integral value. The individual reliability and availability percentages are not necessarily calculated.

The type of inlet filtration system that is used has a direct effect on the availability and reliability of the system. If the filtration system allows a large amount of contaminants into the turbine, then the reliability may decrease. This occurs because there is a higher chance of failure due to fouling, corrosion, and erosion. However, a more rigorous filtration system may required more downtime for filter replacement. This could cause the availability to decrease since the gas turbine will not be available to operate as often.

When comparing two different systems, the important consideration is the availability and reliability difference between the two options. During the design and selection of a gas turbine system, the availability and reliability are usually specified. The filtration system is expected to operate to this level. The difference that will be realized from one filtration system to the next is the difference in the amount of downtime required for maintenance and the possibility of a failure or event due to air quality related issues. For example, filter System A may require the gas turbine be shutdown every 10,000 operating hours for 12 hours to replace the high efficiency filters, while System B does not require shutdowns since it has a pulse jet or self-cleaning filtration system. There is a significant difference in the initial cost of these systems, but the availability of the second system will be higher than the first system. The difference between the availability of these two systems can be quantified by the cost of the downtime for System A.

The cost of downtime is quantified by the loss of production. If the gas turbine is driving a generator, then the lost production could be the loss of revenue due to electricity sales or the cost of the power purchased from another source since the power cannot be provided by the generator set. If the gas turbine is driving a gas compressor on a transmission line, the lost production may be the loss of revenue due to a reduction in the flow of gas. Equation 3-7 shows how the electricity production loss can be calculated. P is the power of the gas turbine in kW, t_{down} is the downtime required to replace the filters in hours, and C_{kWh} is the cost or sale price of the electricity in dollars per kWh. This formula can be used to calculate the loss of production for other maintenance activities and possible failures. A failure would also have additional cost to repair or replace the components that failed. Maintenance activities would have added cost for labor and parts.

$$A = P * t_{down} * C_{kWh} \qquad (3\text{-}7)$$

It should be noted that filter change outs are often completed during scheduled downtime for the gas turbine. If this is the case, then the downtime for filter change out does not necessarily have to be included in the cost. However, it is important to keep the calculations consistent between different system options. If the downtime cost is included for one system, then it should be included for all the systems being considered.

The expected reliability and availability of a system is used in some of the other calculations for the life cycle cost analysis. One example of this is for any recurring costs that depend on the number of hours the system has operated. For example, a filtration system may require the prefilters to be changed out every 2000 hours. If the gas turbine has 90% availability, then the filters would need to be changed out 3 times in one year. If the gas turbine had 100% availability, then the filters would need to be changed out 4 times in one year. Of course, if the number of hours the gas turbine operates is lower than the availability, then it would be used for the calculation.

3.4.2.3 Gas Turbine Degradation

Over time, the performance of the gas turbine (efficiency, power output, heat rate) will degrade. A typical degradation rate is 1.5% in one year with frequent online and offline washing. This rate will increase with poor filtration or an inadequate washing plan. The gas turbine will also have a reduced performance with increases in the pressure loss across the inlet filtration system. Each of these effects must be balanced to obtain the optimal filtration system.

When comparing two systems during an initial design phase, the systems typically are not vastly different in terms of expected degradation rate. They will most likely be very similar in their performance, but have different maintenance and operational schemes. In this case, the degradation rate for both cases would be equal. However, when comparing a new state-of-the-art filtration system to one that is going to be replaced, the degradation rate may not be equal. If this is the case, then the loss of performance over the time period of the analysis due to degradation should be calculated in order to include this in the LCC analysis. Also, if the LCC analysis is being conducted to compare a filtration system with a low efficiency to a high efficiency system, then the degradation rate may be different.

There are two ways that the degradation can be included in the analysis. The simplest method is to calculate the total power loss for the first year. This would then be included as a recurring cost each year in the analysis. However, a gas turbine continually degrades with time and may have less or more losses in the later years. Water washing schemes are implemented so that some of the performance can be regained, but the performance cannot be brought back to 100%. Therefore, the degradation in the second or third year will not necessarily be equal to the degradation of the first year. The degradation can be evaluated on a yearly basis for the LCC analysis, but this task can be time consuming. The first approach mentioned provides a quick conservative method for calculating the cost of degradation.

The cost due to degradation includes two different factors: the lost production cost or sale price of electricity and the cost of additional fuel required to run at full load. The cost due to percent reduction in power output (the cost of electricity sale price or purchase price) is calculated with Equation 3-8. *D* is the degradation rate in percent and *a* is the availability or percentage of time the gas turbine will be operating. The one-half is included in the equation, because the degradation in the equation is an average of the degradation over one year's time.

$$A = \frac{1}{2} * P * D * 365 * 24 * a * C_{kWh} \tag{3-8}$$

The cost of degradation due to increased fuel flow is express as a reduction of heat rate as shown in Equation 3-9. *LHV* is the lower heating value of the fuel, *HR* is the heat rate of the gas turbine, and C_{scf} is the cost of each standard cubic foot of fuel gas. The total cost for degradation is calculated by adding the results of Equation 3-8 and 3-9 together.

$$A = \frac{1}{2} * \left(\frac{1}{LHV} \right) * HR * D * P * 365 * 24 * a * C_{scf} \tag{3-9}$$

3.4.2.4 Gas Turbine Compressor Washing

Gas turbine compressor washing is used to restore the performance of a turbine after the compressor has been fouled with the local contaminants (oil, salt, hydrocarbon, and other deposits). There are two types of washing that are done: online and offline (or crank) washing. Online washing is carried out while the gas turbine is operating. This type of washing is only effective if it is done frequently. Online washing in itself does not provide adequate cleaning for a gas turbine, since it only reaches the first few stages of blades. It should be used in conjunction with offline cleaning. The online washing extends the amount of time between offline washes. Offline washing or crank washing is completed when the gas turbine is shut down and cooled down. Shutting the gas turbine down can take from 12 to 36 hours, depending on the size of the turbine. This time is lost production, but it is necessary to ensure the gas turbine is cleaned and the performance is restored.

The online and offline washing frequencies are determined based on the type and amount of contaminants expected. Filtration systems which remove a larger amount of fouling type contaminants can decrease the frequency of washing needed. The length of times between online and offline washes is best determined through experience on gas turbine systems at the location where it will be installed. However, it is possible, that gas turbines at the same location may have different washing protocols due to localized contaminants (dusty roads, spray from cooling towers, hydrocarbons from exhaust stacks).

In the LCC analysis, the online washing scheme itself (if frequent enough) will not have much influence on the final NPV comparison. However, if the online washing will not be performed on a frequent basis over the life of the turbine, then there is a potential for a higher degradation rate and possible failures due to blade deterioration. These effects should be included in the analysis. A proposed offline washing scheme should be included in the LCC operational costs. The two main items that should be included for offline washing are the lost production due to downtime for the wash and the expected increase in performance of the turbine. The lost production can be calculated using Equation 3-7. The expected increase in performance with washing or the minimization of the yearly degradation rate should be included with the calculations completed using Equations 3-8 and 3-9.

3.4.2.5 Pressure Loss

The performance of the gas turbine directly correlates to the pressure loss across the filters. For 1 inH2O of inlet pressure loss, it can be estimated that there will be a 0.5% reduction in power output and a 0.1% increase in heat rate (2009 Gas Turbine World Handbook). When a filter is installed, it has a prescribed pressure loss. This can be measured during operation, but is usually reported by the filter manufacturer in their literature. Over time while the filter is in operation, the pressure loss increases. Ideally, once the pressure loss reaches a certain limit, the filter is either replaced (non-self cleaning system) or pulsed cleaned (self-cleaning system). The pressure loss limit is dictated by the maximum allowable pressure loss for the filtration system and the recommended replacement or cleaning pressure loss from the filter manufacturer. The pressure loss across a filter typically increases in a non-linear fashion. An example of a non-linear filter loading curve is shown in Figure 3-39. The shape of this curve depends on the type of filter.

Since the increase of pressure loss across the filtration system has a negative impact on the gas turbine performance, it should be considered in the LCC analysis. The cost of the pressure loss can be estimated using Equations 3-10 and 3-11. Equation 3-10 calculates the cost of pressure loss over the life of the filter due to gas turbine power degradation and Equation 3-11 estimates the additional fuel cost due to heat rate increase. The relationship stated above for pressure loss and power reduction and heat rate increases (1 inH2O correlates to 0.5% reduction in power and 0.1% increase in heat rate) was used to construct the equations.

$$A = 0.0025 * P * C_{kWh} * (dp_2 + dp_1) * t_{filter} \qquad (3\text{-}10)$$

$$A = \frac{0.0005}{LHV} * HR * P * C_{scf} * (dp_2 + dp_1) * t_{filter} \qquad (3\text{-}11)$$

In order to calculate the cost of pressure loss, a filter loading curve must be defined. Equations 3-10 and 3-11 assume a linear increase in pressure overtime. The dp_2 and dp_1 terms are the end and beginning pressure losses of the filters and t_{filter} is the life or loading interval of the filter. Non-linear curves can also be used to calculate the cost of pressure loss. If non-linear loading curves are used, the average pressure can be found by integrating the pressure loss over the expected life or loading interval of the filter element. Then the $(dp_2 + dp_1)$ term in Equations 3-10 and 3-11 would simply be replaced by twice the calculated average pressure. Figure 3-39 shows an example of the integration of a non-linear pressure curve. The total cost of the pressure loss across the filter is then a result of Equations 3-10 and 3-11 added together.

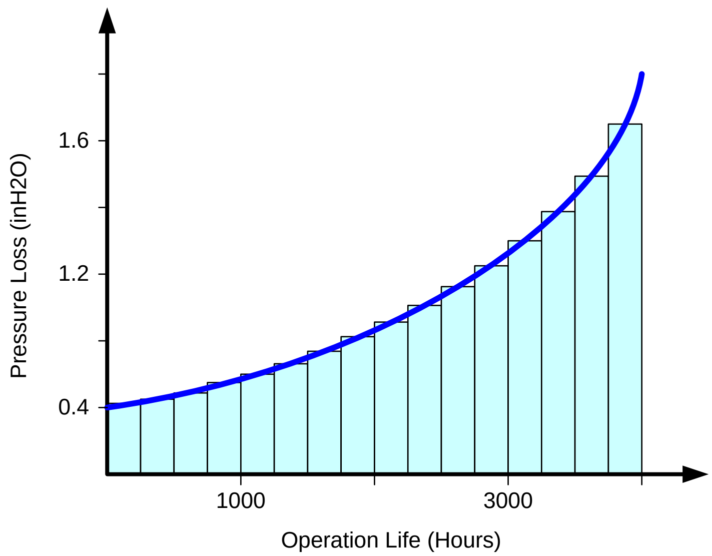


Figure 3-39. Example of Integration of Non-Linear Filter Loading Curve

The costs calculated above are a recurring cost. These costs should be included in the analysis for each time the filters will be changed out or pulse cleaned. For example, if the filters are changed out or pulse cleaned twice a year, then the cost above would be included twice in each year. If the filtration system has multiple stages with different change out/cleaning intervals, then the cost can be calculated for each stage of filtration.

3.4.2.6 Failure Costs

Every gas turbine system is built with the intention to have the highest reliability and no failures. With poor inlet filtration or infrequent compressor washing, the possibility of a failure increases. These types of events are nearly impossible to predict during the design phase. If the gas turbine is already installed and operating, there may be previous event history that can be used to predict these events. These events could include blade failure due to pitting or corrosion, failure of filtration system components, surge of compressor due to distorted blades from erosion or fouling and many others. Potential events due to inlet air quality or the filtration system should be considered in the LCC analysis. Costs that should be included in the event are downtime (Equation 3-7), labor (Equation 3-12), materials for repair/ replacement, and services required for repair. The event costs should be included in the year the event is anticipated to occur.

3.4.2.7 Labor Costs

With any maintenance activity or event that occurs with the filtration system and gas turbine, there is a labor cost. This cost may be covered by the plant's operating budget. If contractors are used for the work, then this may be an additional cost to the plants budgeted operating costs. It can easily be included in the LCC analysis. Equation 3-12 can be used to estimate the total labor cost for each maintenance activity and event that occurs. C_{labor} is the cost of labor per hour per person in year zero of the analysis, *hr* is the time required for the maintenance activity, *N* is the number of personnel involved in the activity, and *e* is the inflation rate for labor costs.

$$A = C_{labor} * hr * N * (1+e)^n \qquad (3\text{-}12)$$

3.4.2.8 Summary of Costs

Different costs which should be considered in a filtration system LCC analysis are described above. These costs are summarized in Table 3-6. The calculations and equations above gave values for the actual cost in the year it occurs. In order to complete the LCC analysis, each of these costs needs to be brought back into present terms. Equations 3-2 through 3-5 are used to do this with the discount rate. Once this calculation is completed for all the costs, they can be added together to obtain to total NPV for the filtration system. The NPV for various systems can be directly compared.

Table 3-6. Summary of Cost that are Considered in an LCC Analysis of a Gas Turbine Inlet Filtration System

Description	Costs Included	Cost Estimate Source	When Cost Occurs
Purchase Price	- Initial price of system	- Filter vendor - Gas turbine packager	First year
Maintenance	- Filter replacement - Filter disposal - Auxiliary system maintenance	- Filter vendor - Past experience - Calculated: Labor cost, Production loss for maintenance	Recurring (based on frequency of each activity)
Availability/ Reliability	- Include in costs that depend on number of hours gas turbine operates	- Expected operating hours based on required downtime - Past experience with reliability of system	Yearly
Gas Turbine Degradation	- Loss of power due to degradation (recoverable and non-recoverable) - Increase in fuel costs due to degradation	- Calculated: Cost of power loss, Cost of added fuel	Yearly
Compressor Washing	- Downtime associated with offline cleaning - Performance of gas turbine with specified washing scheme	- Downtime estimate from gas turbine manufacturer or past experience - Calculated: Cost of downtime (loss of power or production or cost of purchasing electricity) - Include performance predictions in gas turbine degradation calculation	Recurring (based on planned washing frequencies)
Pressure Loss	- Loss of power due to pressure loss of filtration system - Increase in fuel costs due to pressure loss of filtration system	- Calculated: Cost of power loss, Cost of added fuel	Recurring (depends on expected filter life or cleaning interval)

Description	Costs Included	Cost Estimate Source	When Cost Occurs
Failures or Events	- New equipment or materials required for repair/replacement - Labor to make repairs/replacement - Services required for repairs/replacement - Production loss due to failure/event	- Cost estimates for repair/replacing failed parts - Cost of services required (cranes, disposal of old equipment, etc) - Calculated: Labor costs, Cost of downtime	When failure or event is expected to occur based on past experience

3.4.3 Example LCC Analysis

An example LCC analysis is presented in Appendix B. The calculations use the equations which are presented in the sections above, and each equation used is indicated. All costs and assumed values are included in the example.

4. FILTER OPERATION AND MAINTENANCE

Selecting the air filtration is only part of the effort required to maintain clean air at the inlet of the gas turbine. The inlet filtration system must also be operated carefully and maintained in working condition. Even the best air filtration systems cannot prevent the effects of poor maintenance. Open man doors, damaged filter material, holes and rips in the flexible duct transitions, non-functional water traps, and incorrect filter cleaning procedures can dramatically reduce the effectiveness of the filtration system. Carrying out effective maintenance and condition and performance monitoring of an inlet filtration system can limit both recoverable and non-recoverable degradation of the gas turbine. Several recommendations are listed below that will help the filter engineer maintain an adequate filtration system.

4.1 Installation

After selecting the appropriate filtration system, the next part of ensuring optimal air filtration is a proper installation. Several recommendations are listed in Section 3.3.5 about where the filtration system inlet should be placed. If the filtration system inlet is not placed in an optimal location, then additional contaminants can be experienced that could potentially lead to blade fouling, erosion, or corrosion. It is important that the inlet to the filtration system is elevated above the ground. Elevating the filter housing moves the inlet further away from ground dust which prolongs the filter's life. Also, in arctic locations, the filtration system inlet should be placed well above the average snow drift height for that location. If not, then the closeness of the inlet and top of snow drifts can increase the amount of snow ingested by the gas turbine.

During and after installation is complete, all sealing surfaces of the inlet filtration system should be inspected. If there is a poor seal on the system, especially downstream of the filters, then unfiltered air can pass into the turbine, which negates the purpose of the filtration system. Some of the locations that should be inspected are: filter frame to filter housing seals, seals at any ducted joints on the filter housing (especially downstream of the filters), and seals on the blown-in doors and inspection ports.

If carbon steel housing is used for the filtration system, then all exposed surfaces need to be painted to delay corrosion of the housing. After the painting is complete, all surfaces should be inspected to ensure they are fully covered. After the system is assembled at the installation site, all bolted connections should be cleaned and painted.

During the filter selection process, the filters for the system are chosen based on the expected type and level of contaminants during operation. Even with a thorough and detailed contaminant analysis, there is the possibility of unexpected contaminants or higher levels of contaminants that anticipated. A few months after installation and operation, it is useful to take samples of deposits off the inlet guide vanes and first stage of compressor blades. This can help to determine if there are any contaminants that are not being filtered out by the filtration system. A chemical analysis can be used to identify the individual components that make up the deposits on the blades. It is important to identify any sodium, acids, potassium, vanadium, and lead since these can lead to corrosion which permanently damages the compressor and turbine blades. If these are found in the blade deposits, the filtration system should be adapted to improve the filter efficiency for these individual constituents.

Another important item to note during the post installation and start-up inspection is the amount of deposits on the blade. Even if the deposits are not corrosion agents, thick deposits on the blades will decrease the gas turbine performance. If thick deposits are occurring, then the current filtration system should be evaluated for improvements. Also, a more frequent compressor washing scheme should be considered. However, all contaminants removed from the blades with washing will travel downstream to later stages and can be re-deposited.

If the new gas turbine is going to be installed near an existing gas turbine, then the contaminants experience in the existing gas turbine can be used to develop the inlet filtration system for the new gas turbine. Before selecting the new filtration system, a filter from the existing system should be removed and evaluated for the type of contaminants which are captured. Also, deposit samples from the inlet guide vanes and compressor blades of the existing turbine should be taken. The results from each of these evaluations can provide the type of contaminants that can be expected on the new installation.

4.2 Instrumentation

The life of a filter for a gas turbine is monitored with the pressure loss across the filter. Filter manufacturers provide values of pressure loss across the filter when it is installed and also after it is fully loaded. The pressure loss across the filters should be monitored continuously. This provides the filter engineer with a time history of the filter's life. This can be valuable in determining if there are any factors which are affecting the filters performance. For example, the time history may show a sharp increase in pressure loss one morning when fog is present. This indicates that the filters are made of material which does not perform well with moisture. Also, poor performance of the gas turbine during that time may be attributed to the increased filter pressure loss.

The pressure loss measurement also tells the filter engineer when it is time to replace or clean the filters. If the filter is not replaced or cleaned once it is fully loaded or has reached its maximum allowable pressure loss, then this will cause decreased performance of the gas turbine. An increase of 50 Pa (0.2 inH2O) in pressure loss can result in a 1% decrease in gas turbine power output. It is important to follow manufacturer's recommendations and replace or clean the filters once they reached the maximum allowable pressure loss. If this recommendation is ignored, then the performance of the gas turbine will suffer due to decrease power output and ingestion of harmful contaminants. The filter should also be replaced if there is a sudden increase in pressure loss and if it has been verified that this increase is not caused by an obvious obstruction of the air intake.

The pressure loss is an integral measurement on self-cleaning systems. This measurement is used to determine when it is time to pulse clean the system. The pressure change across several filters is measured continually. In self-cleaning systems it is important to measure the pressure of the air which is used for pulse cleaning. If the pressure is too low, the filters will not be cleaned and the pressure loss will increase.

Differential pressure gauges or pressure switches are used to measure the filter pressure loss. These measurements are recorded and reported by the site's control system. Both high pressure and low pressure events should be set to alarm in the control system. High pressure events are indication of the filters being fully loaded or entrained with moisture. Low pressure events can indicate a tear or material failure of the filter fiber media or severe leakage through the various seals in the filtration system. Shutdown alarms and switches should be used in case the pressure loss becomes excessively high. Lastly, it may be beneficial to place alarms on the inspection ports or doors on the filter housing (which are downstream of the filters) which could allow unfiltered air to enter the gas turbine if left open. These will help to ensure that only clean air enters the gas turbine.

4.3 Filter Replacement, Cleaning, and Inspection

As mentioned above, it is important that the filters be cleaned or replaced once they are fully loaded with dust particles and reached a specified pressure loss. It is highly recommended that filters be changed out when the gas turbine is <u>not</u> running. High efficiency filters <u>should not</u> be changed out when the gas turbine is running. When the gas turbine is operating, the pressure change across the filters and suction holds them in place. To remove the filters while the gas turbine is operating, these forces would need to be overcome by the technician. Also, when the filters are being removed, they can release dust into the air. If the gas turbine is operating, this dust will be ingested by the turbine or collected by downstream filters. During gas turbine shutdowns, the filter should be removed in such a way as to minimize the amount of dust re-entrained in the air.

Two stage non-self cleaning filtration (pre-filter and high efficiency filter) systems have an operating life in the range of 5,000 to 10,000 hours. It is common maintenance practice to replace the pre-filters on two stage systems multiple times (ex. 2 to 3 times) for each high efficiency filter change out. Also, some pre-filters can be cleaned 10 to 15 times before they are replaced. Fiber type filter should not be cleaned. Washing metal filters is an acceptable practice. It should be noted that the filter will not have the same filtration efficiency after it has been cleaned. The filtration efficiency after the filter is cleaned will be lower than the original filtration efficiency when the filter was new. Filters should be primarily cleaned with water. A soft detergent may be used on some filters. The filter engineer should consult with the filter manufacturer to determine the possibility and proper methods to clean the pre-filters. High efficiency filters should not be cleaned and should be disposed of at the end of their useful life or when they start to show signs of degradations. Degradation can be caused by heat, UV rays, and FOD.

Self-cleaning systems are automated systems which clean themselves when the pressure change across the filters reaches a specified level. This is completed through reverse air pulses. The filters in these systems are surface loaded filters, so dust does not accumulate within the filter itself. This feature combined with the cleaning air pulses allows these filters to have long lives. However, if these filters start to show signs of degradation or when cleaning becomes ineffective, then they should be replaced. Self-cleaning filters typically have an operating life in the range of 1-2 years.

Filters are most often replaced when they reach the specific pressure loss level and are fully loaded. However, some filters are used in environments with a low amount of contaminants and may take several years to become fully loaded and reach the specific pressure loss. Filter media ages with time and should be replaced if there are signs of degradation. If filters do not reach their final pressure drop or show signs of degradation after three years then they should be replaced. Filters can be stored for a maximum of three to five years if they are left in a controlled environment with dry and heated conditions. The filter manufacturer should be consulted to determine the actual operation and storage life of the filters being used.

There are several filters which are designed to prevent water penetration. These are used in environments where high humidity and high amounts of moisture are present (marine, offshore, coastal, and tropical environments). When the filters are installed, their water rejection capability is intact. However, over their life the water rejection capability degrades. This is due to filter loading, ageing due to heat and UV rays, and collecting specific contaminants (such as hydrocarbons). At some points, it may be possible for water to leach through the filters. This water can collect soluble contaminants and transport them through the filters into the gas turbine. Experience has shown that the water penetration can occur when the filters approach the maximum allowable pressure drop. Therefore, filters in wet environments may need to be replaced before they reach their maximum pressure drop in order to minimize the water and contaminants which enter the gas turbine inlet due to the filter's water rejection degradation.

As discussed in Section 3.3, each environment is unique; therefore, the filters useful life will also be unique at each installation site. It is discussed above that the pressure loss across the filter is the most common method to monitor a filter's life. However, several special cases have been presented that indicate that pressure loss does not cover all the aspects which can cause a filter's performance to degrade overtime. It may be beneficial for the filter engineer to test several sample filters from the inlet filtration system at different intervals during the filter's useful life. These tests should include testing the filter's strength, determining the filter's water rejection performance, measure the amount and type of contaminants on the filters, and assessing how the filter has aged. The tests will provide the filter engineer with an assessment of how the filters are performing in the filtration system. The results can be used to determine if different filters should be installed or when the filters need to be replaced. This type of testing program can help ensure that the degradation of the gas turbine is minimized due to air quality issues.

There are several inspections which should be completed on the filtration system in order to verify that it is and stays in good condition. The water level in the drain traps and flexible connections in the draining system should be visually inspected on a weekly basis. The seals between ducting joints should be visually inspected on a monthly basis. Any defects identified in these inspections should be fixed in a timely manner. Also, the filters themselves should be visually inspection when possible. During a visual inspection, fully loaded or damaged filters can be identified. These filters should then be replaced.

When the gas turbine is shutdown and the filters are replaced, the filtration system should undergo a detailed inspection. All structural seals and flexible connections in the drainage system should be inspected. The drainage points should be checked to ensure they are functioning properly. Pre-filters and high efficiency filters which are not being replaced should be inspected for any tears or rips. The seals between the filters and holding frames should be checked for leakage. The filtration system housing and vane separators should be checked for contamination and cleaned if necessary. If any anomaly is identified during the inspection, it should be corrected before gas turbine start-up if possible. Also, when the gas turbine is shutdown it is beneficial to take borescope pictures of the inlet guide vanes and first stage compressor blades before any washing takes place. If pictures are taken at an identical location each time the unit is shutdown, the fouling rate can be monitored. The fouling rate can help determine the frequency of compressor washings and if the filtration system needs to be modified to remove specific contaminants.

4.4 Maintenance Scheduling

Operation with a fully loaded filter affects the gas turbine performance and can cause elevated contaminant ingestion. The elevated contaminant ingestion can lead to permanent degradations effects such as erosion or corrosion. Filters should be replaced based on the filter's condition and loading.

There are several ways that filters replacement is scheduled. Changing out filter elements is typically based on calendar or running hour intervals. In this type of scheduling scheme, it is assumed that a filtration system will see a steady increase in pressure loss across the filter elements based on measured filter contamination level or deterioration of the filter's performance. However, the degradation rate of the filter elements will depend on type and level of contaminants present. Other activities near the gas turbine such as grit blasting or painting may drastically affect the degradation rate of the filter elements. Replacing the filters based on time intervals does not take other effects into consideration.

Excluding time maintenance scheduling, the next most common method to determine when a filter needs to be replaced is based on the pressure loss across the filter. The filter is monitored for pressure loss and replacement is considered when the filter reaches a pre-determined pressure loss level that is recommended by the manufacturer. This monitoring scheme does not take into account the face velocity of the filter or the moisture that is present in the filter. If the gas turbine is operated at part load, the velocity across the filters is reduced. This in turn causes a reduction in the pressure loss across the filter. Liquids in the filter will change the filter resistance to air flow (pressure loss) and may cause some of the contaminants captured in the filter to be released downstream.

If the filter maintenance scheduling is going to be planned based on time intervals (calendar and running hours), the first several filter changes outs should be monitored closely or based on pressure loss. This will provide the filter engineer a relationship between the pressure change and the number of operating hours. They can then use this to better estimate when the filters will be replaced in their scheduling. Also, the filter engineer should take note of any debris events near the gas turbine inlet (such as grit blasting, painting, etc…). If these events occur, then the filter replacement can be scheduled at an earlier date in order to avoid operating with fully loaded filters. It should be noted that if different filters (upgraded or new style) are installed in the filtration system, then the replacement schedule should be adjusted based on their filtration efficiency and expected life.

During the life of the gas turbine outside of normal maintenance scheduling, there are typically several regular overhaul intervals. When the gas turbine is being overhauled, the filters should be replaced. This is true, even if the filters have not reached the end of their life. If the filters are replaced, when the gas turbine is restarted, it can operate with the minimum pressure loss at the inlet. Also, the gas turbine will not have to be shut down shortly after start-up to replace filters due to them being fully loaded.

4.5 Water Washing

Water washing is a method of cleaning the gas turbine between overhauls that renews some of the performance that is lost due to degradation from contaminants which is not removed by the filtration system. There are two types of water washing: offline (also referred to as crank) or online. Online washing is the most convenient since it can be conducted while the gas turbine is in operation. However, offline washing provides a more rigorous clean and removes some of the fouling that online washing cannot remove. A gas turbine should have a cleaning plan that includes both online and offline washing. The frequency of washes depends on the amount and type of contaminants which are entering the gas turbine. A higher frequency of online washes will delay the time between offline washes. If a gas turbine cannot be shutdown very often for offline washing, then it may be necessary to have very frequent online washings to keep the performance of the gas turbine at acceptable levels.

Online washing nozzles are typically installed near the inlet guide vanes (IGV). The nozzles are positioned so they have full coverage of the IGVs. This type of washing is only effective in the IGVs and first and second stage of the compressor. However, this is where a large part of the contaminants will collect, so the washing is still effective. One disadvantage of online washing is that any distilled water sprayed into the gas turbine will be carried downstream to the compressor and turbine. So the contaminants captured in the water can be re-deposited on the later stages of the compressor and in the combustor and turbine sections.

Offline washing is a more rigorous process than online washing. Detergent is used instead of distilled water to remove the contaminants. In this type of washing, it is important to vary the speed of crank, droplet size, IGV settings, and pressure on the water line in order to ensure the detergent is traveling to the farthest compressor stages to remove the maximum amount of fouling. Once the gas turbine has been cleaned with the detergent, it is important that the compressor is completely washed with distilled water. This will remove any excess detergent or contaminants that did not drain. This part of the process requires multiple cycles to fully clean the compressor. The water drain from the compressor may visually seem to be clean after a cycle or two. However, the resistance of the water should be checked and compared to clean distilled water. Once these resistances are fairly equal, the washing is complete.

5. FILTER TESTING

The performance tests of filters are essential for the use of filters with gas turbines. The tests provide information related to filtration efficiency, pressure loss across the filter, effects of various contaminants (aerosols, different size particles, etc.), and dust holding capacity. There are standards which provide a rating system for filter comparison. The performance of the filters is important during the selection process. The test results help the filter engineer determine which filter should be used for their application. The filter engineer should be careful when comparing the filter's stated performance to the application. Each filter is tested to a specific condition (flow rate, particle sizes, types of particle, humidity, temperature, etc.). The performance results from the test only correlate to this condition. The filter will have a different performance if one of these conditions is not the same.

There are four different standards which are used to determine the performance of the filters for gas turbines. These standards were developed for HVAC applications, but they are still used for gas turbines. The standard used in the United States is ASHRAE 52.2: 2007. The standards used in Europe are EN 779: 2002 and EN 1822: 2009. Each of these test standards is unique in test set-up and performance results. The details of the performance tests described in each of these standards are reviewed below. Also, the useful results and benefits of each standard are discussed. These test standards that exist do address many aspects of the performance of filters. However, there are some effects that are not included in the tests. These primarily include the effects of moisture and salt. At the end of this section, additional considerations for filter testing are discussed.

5.1 ASHRAE 52.2: 2007 – Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size

The ASHRAE 52.2: 2007 standard was developed around 1990, when it was realized that there was a need for particle size efficiency and a test standard for higher efficiency filters. Research was funded in order to develop the procedures outlined in the standard today. This standard addresses two important characteristics of filters: the ability of the device to remove particles from the airstream and the resistance of airflow through the filter. The rating system employed by this standard is the Minimum Efficiency Reporting Value (MERV).

The testing in this standard focuses on testing of fine particles. The filtration efficiency is found for three different particle size ranges: 0.3 to 1 microns, 1 to 3 microns, and 3 to 10 microns. Virtually any air filter can be tested with this standard provided that it fits within a test section. However, it is recommended that electronic filters not be tested with this standard. This is due to the fact that the dust used in the test is very conductive carbon, and it may cause electrical shorting, thus reducing or eliminating the effectiveness of the filter. The end result will be a lower MERV. Also, the standard mentions the effects of filters with an electrostatic charge. If the charge is left on the filter during the performance test, the actual efficiency during operation when the charge is lost will be different than the measured efficiency. If possible, the filter's performance should be measured without the charge present.

5.1.1 Test Set-up

The test set-up for an ASHRAE 52.2: 2007 test has many components. This set-up is designed to have control on some conditions of the inlet air. The test section is designed for flow rates from 472 to 3000 cfm. The test section can either be a straight or U-shaped test duct. Figure 5-1 shows an example of a U-shaped test duct. This configuration is typically used to minimize the length of space needed for the test duct.

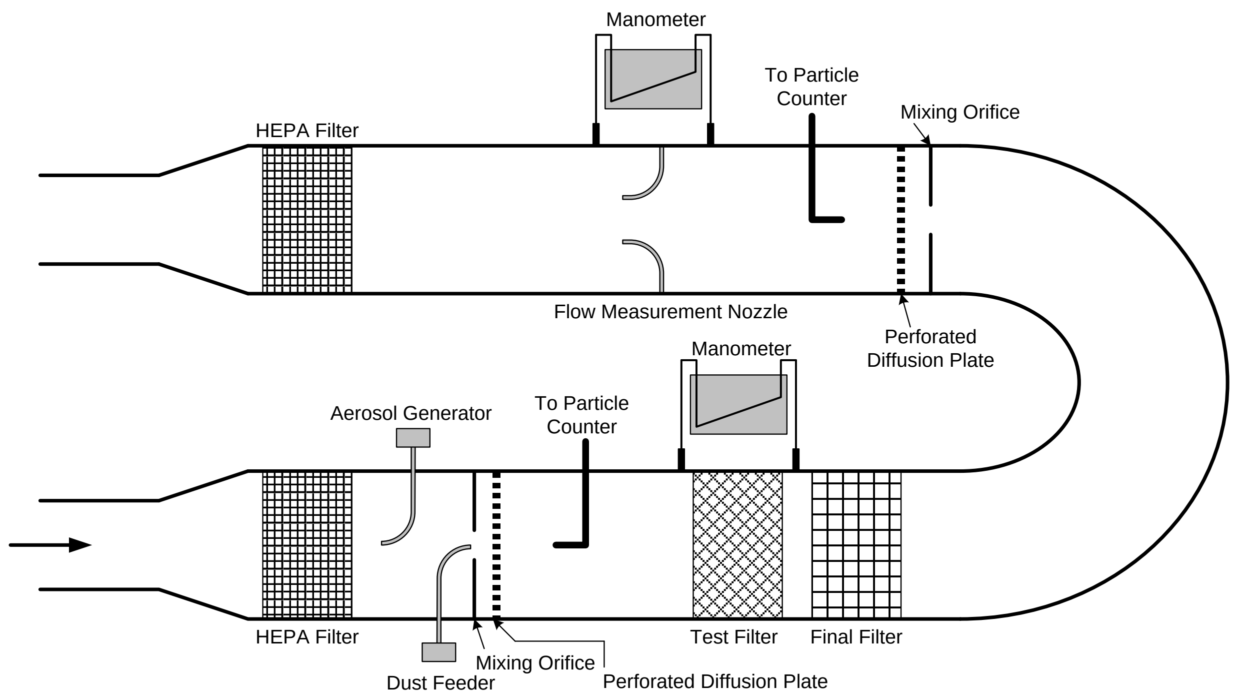


Figure 5-1. Schematic of ASHRAE 52.2: 2007 Test Set-up

The test section is required to be under a positive pressure according to the standard. This means that the test section must be at the discharge side of the blower. The inlet to the test section where the blower discharges is indicated by an arrow in Figure 5-1. The air coming into the test section is required to be either indoor air or re-circulated air. Both of these air sources allow better control of the inlet air quality. The test section can be exhausted either outdoors or indoors (for recirculation). The temperature of the air entering the test section is required to be between 50 and 100° F. The relative humidity must be within 20 to 65%. A HEPA filter is installed upstream of the test section to provide further control of the quality of air entering the test section. The HEPA filter will remove any fine particles which can cause anomalies in the test results. If the air is re-circulated and discharged indoors, a HEPA filter is placed at the outlet of the test section. This allows the re-circulated air to be well conditioned before it returns to the inlet of the test duct.

Two types of test particles are used for the efficiency measurements. The first is ASHRAE test dust. The test dust is comprised of 72% fine Arizona test dust, 23% powder carbon, and 5% cotton liners. This test dust is used to load the filters to different dust loading conditions. A mixing orifice and perforated diffusion plate are used to ensure that the particles are even distributed when they reach the test filter. Loading of the filter will be completed at a minimum of four intervals during a single test. The intervals will occur when the filter's pressure loss has reached one-quarter, one-half, and three-quarters of the prescribed final filter pressure loss. This allows the loading of the filter over its expected life span to be simulated.

The weight arrestance of the filter is also measured throughout a test. There are several definitions of filtration efficiency as discussed in Section 3.1.2.2 of this guideline. In order to avoid confusion of which efficiency is being referenced, this standard gives a unique name to the measured mass filtration efficiency; the "weight arrestance." The weight arrestance is defined as being the ability of the filter to remove the test dust from the test air. The weight of the test dust fed and the weight of the dust passing the test filter during a time interval are measured. Arrestance is the percentage of the dust captured by the test filter. This value is calculated with Equation 5-1. The variable $A_{52.2}$ is the arrestance in percent, W_d is the weight of the dust passing the test filter, and W_u is the weight of the dust fed. W_d is a combination of the dust collected by the final filter (after the test filter, see Figure 5-1) and any dust gathered from the bottom of the test section.

$$A_{52.2} = 100 * \left(1 - \frac{W_d}{W_u}\right) \qquad (5\text{-}1)$$

The weight arrestance efficiency measurement does not provide any information related to particle size efficiency. During the loading of the test filter with ASHRAE test dust, the final filter as shown in Figure 5-1 is included in the test set-up. This filter must be able to capture 98% of the test dust released into the test section. During the dust loading, the aerosol generator is not producing aerosols and the particle samplers (indicated with "To particle counter" in Figure 5-1) are sealed off so test dust cannot plug the sample tubes.

The second test particle used is laboratory-generated polydispersed solid-phase (dry) potassium chloride (KCl) particles. This is commonly referred to as the test aerosol. The particles generated for this test are in the range of 0.3 to 10 microns. A typical distribution of the particle sizes is shown in Figure 5-2. The actual distribution of the test aerosol will depend on the aerosol generator used for the test. This test aerosol was chosen for this standard because it is easy to generate, has a low cost, is commonly available, and is benign to health.

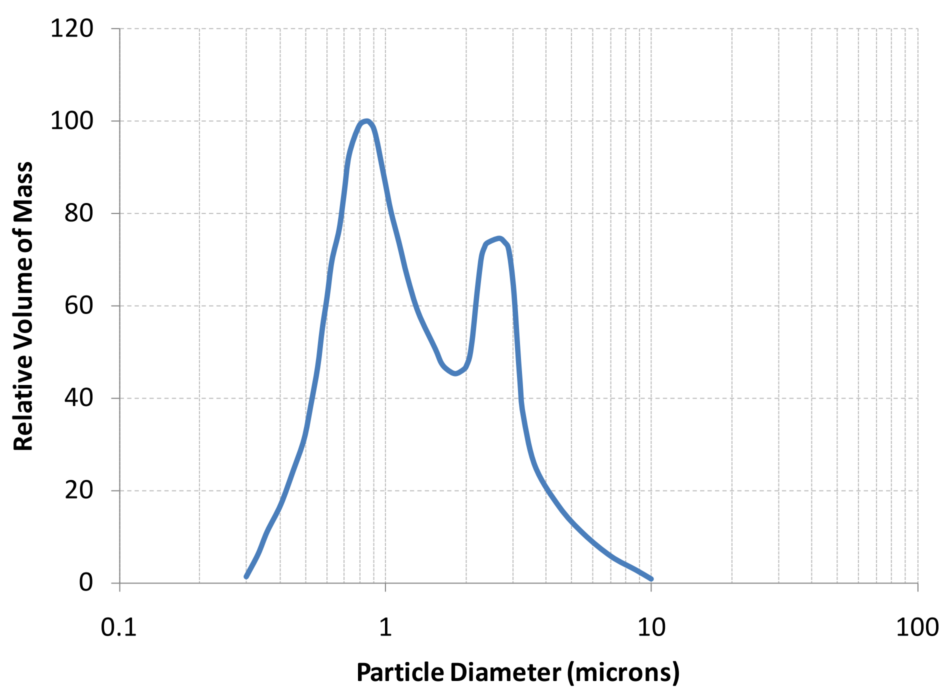


Figure 5-2. Typical Aerosol Distribution for ASHRAE 52.2: 2007 Test

The KCl test aerosol is used to determine the particle size efficiency. The particle size efficiency is determined at each loading interval during a test. For this test, the aerosol is generated with the aerosol generator as shown in Figure 5-1. The mixing orifice and perforated diffusion plate ensure that the aerosols are distributed evenly throughout the test duct section. The final filter is removed for the aerosol particle size efficiency test. The particle size efficiency is determined by the difference in the concentration of particles upstream and downstream of the test filter. A particle counter is used to measure and count the test aerosol particles in 12 size ranges at both locations. These size ranges are listed in the standard. The particle sample port (labeled as "to particle counter" in Figure 5-1) is designed to collect and transport a representative sample of the test aerosol to the particle counter. It should be noted that during the particle size efficiency test, no ASHRAE test dust is released into the test chamber. Only the KCl aerosols are generated.

A test following the ASHRAE 52.2: 2007 standard uses several sensitive measurement devices. Also, many parts of the test system need to be validated to ensure that they are within an acceptable range in order to minimize the error in the final test results. Therefore, ASHRAE 52.2: 2007 requires several qualification tests for the test set-up. These tests include qualifying the air velocity uniformity, aerosol uniformity, downstream mixing of the aerosol, overload tests of the particle counter, 100% efficiency test, correlation ratio test, aerosol generator response time, duct leakage test, particle counter zero test, particle counter sizing accuracy, radioactivity of the aerosol neutralizer, dust feeder airflow rate, and final filter efficiency. The standard provides guidance on how the test should be conducted and the criteria for the test results.

5.1.2 Test

Tests following the ASHRAE 52.2: 2007 standard should be conducted at the specified air flow rate (within 472 to 3000 cfm) and up to a defined final filter pressure loss. If these values are not specified for the test filter, then the test will be conducted at a face velocity of 492 fpm and with a specified final filter pressure loss of 1.4 inH2O. The air flow rate for the test must be maintained throughout a test. Before the dust loading and particles size efficiency test is conducted, the pressure loss (or resistance) across the filter is measured at four air flow rates: 50%, 75%, 100%, and 125% of the test air flow rate. Once this is completed, then the efficiency testing of the filter begins.

The efficiency (particle size efficiency and weight arrestance) of the filter will be measured at a minimum of six points during a test: when the filter is new and unloaded, when either 30 g of test dust is loaded into the filter or the pressure loss has increased 0.04 inH20 from initial resistance (whichever comes first), at the three pressure loss intervals during the test (one-quarter, one-half, and three-quarters of the final filter pressure loss), and after the filter is fully loaded and reached its final pressure loss. The list below details a typical timeline for a filter test.

1. Measurement 1
2. Load Interval 1 – Either 30 g of dust is loaded in filter or pressure loss is increased 0.04 inH2O
3. Measurement 2
4. Load Interval 2 – Filter pressure loss has reached one-quarter of final filter pressure loss
5. Measurement 3
6. Load Interval 3 – Filter pressure loss has reached one-half of final filter pressure loss
7. Measurement 4
8. Load Interval 4 – Filter pressure loss has reached three-quarters of final filter pressure loss
9. Measurement 5
10. Load Interval 5 – Filter has reached final filter pressure loss
11. Measurement 6

At each measurement interval (indicated by "Measurement #", a weight arrestance and particle size efficiency measurement are taken. During each loading interval, the final filter is installed and the ASHRAE test dust is released into the test duct.

5.1.3 Results

The weight arrestance of the filter at each load interval is determined as described in above. The particle size efficiency is calculated for each of the 12 particle size ranges at each loading interval using the test aerosol results. The penetration is calculated from the ratio of test aerosol particles counted upstream and downstream of the filter with Equation 5-2.

$$P_{52.2} = \frac{Downstream\ Particle\ Concentration}{Upstream\ Particle\ Concentration} \quad (5\text{-}2)$$

The observed penetration, $P_{52.2}$, is corrected with the correlation ratio to find $\overline{P}_{52.2}$. The correlation ratio is established from the ratio of the downstream and upstream particle counts without the test filter installed in the test duct at the flow rate that the filter will be tested at, before testing the filter. The ratio corrects for any differences in the sampling and counting of the test aerosols by the particle sampling and counting system upstream and downstream of where the test filter will be installed. The particle size efficiency (PSE) is calculated for each particle size range with Equation 5-3.

$$PSE = \left(1 - \overline{P}_{52.2}\right) * 100\% \quad (5\text{-}3)$$

Even though the efficiency is calculated for each of the 12 size ranges measured, the final results are reported for three broad size ranges: 0.3 to 1 micron, 1 to 3 micron, and 3 to 10 micron. These ranges are referred to as E_1 (0.3 to 1), E_2 (1 to 3), and E_3 (3 to 10). The efficiency report for each size range is the minimum efficiency measured across all six test intervals and particles sizes in that range. Figure 5-3 shows an example of finding the minimum efficiency for each size range. The particle size efficiencies for each measurement and load interval are plotted. The division of each range is indicated. The circles indicate the location of the minimum efficiency for that particle size range.

The minimum particle size efficiency, weight arrestance, and final pressure loss of the filter are used to determine the Minimum Efficiency Reporting Value (MERV) rating of the filter. The MERV ratings range from 1 to 16 in the standard. There are some publications that discuss a MERV rating up to 20, but the ASHRAE 52.2: 2007 standard does not define the efficiencies for above a MERV 16 rating. The filter performance results shown in Figure 5-3 would indicates that the filter has a rating of MERV 10. The large black circles indicate the average composite minimum efficiencies for each particle size range. The value ranges for each MERV rating are included in the ASHRAE 52.2: 2007 standard and in Table 3-2 in Section 3.1.2.2 of this guideline. The MERV value only provides information related to the particle size efficiency of the filter. It does not provide any information related to the dust loading capacity, life of the filter in an actual operation, or operation of filter in a wet environment.

5.2 EN 779: 2002 – Particulate Air Filters for General Ventilation – Determination of the Filtration Performance

There are two primary filtration standards in Europe that address testing and specifications for air filters. The first which addresses the coarse and fine particulate filters is EN 779: 2002. The filters tested under this standard should have an initial efficiency of less than 98% with respect to 0.4 micron size particles. The standard describes the tests that are required to determine the average efficiency and average arrestance of the filters. These values are used to determine the classification of the filter which is outlined in the standard. The performance results obtained when following this standard cannot alone quantitatively be applied to predict performance in service regarding efficiency and lifetime predictions. However, the results do offer a baseline comparison between filters. In addition to performance testing specifications, the standard also provides additional requirements for the filter. This includes general recommendations on mounting frame suitability and how to mark the filter with its classification.

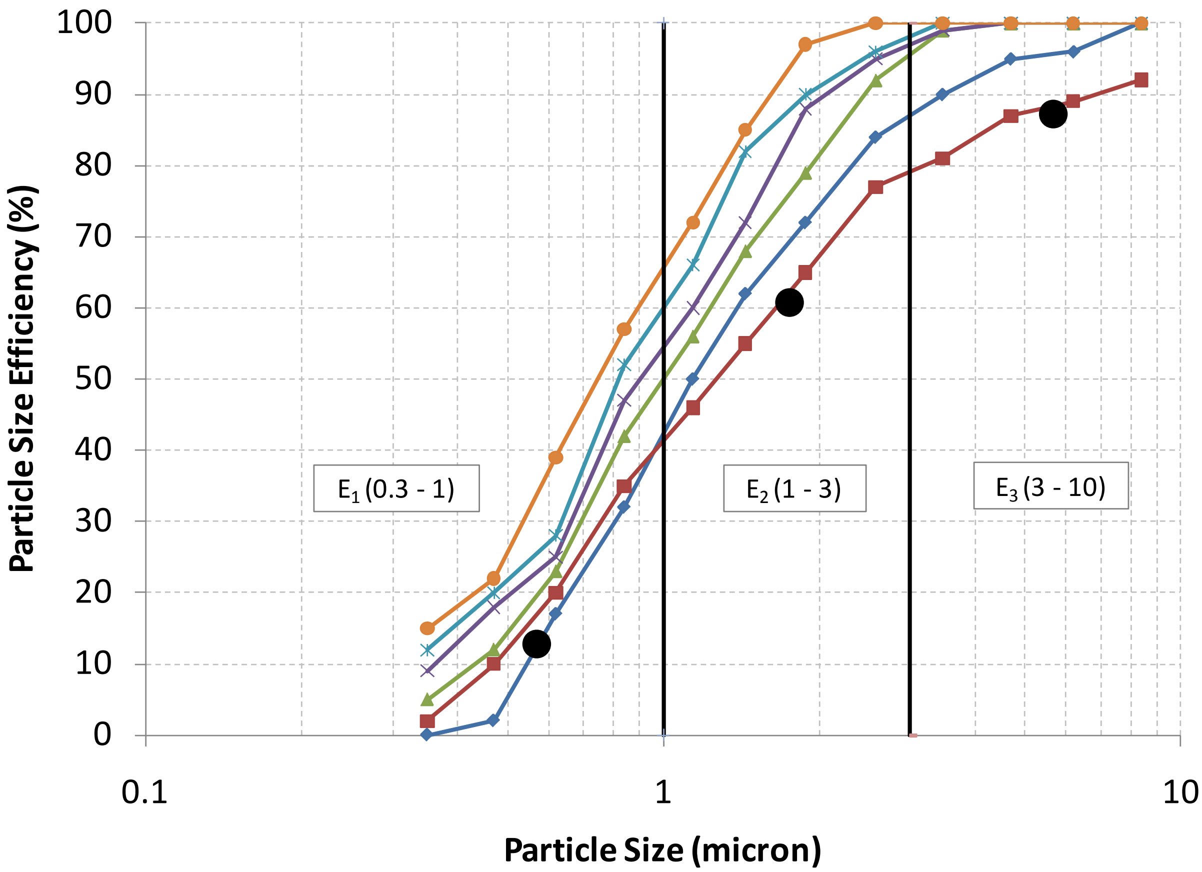


Figure 5-3. Particle Size Efficiency Graphed with Average Minimum Composite Efficiencies Indicated in Each Particle Size Range

5.2.1 Test Set-up

The objective of the test described in EN 779: 2002 is to determine the average filtration efficiency and average weight arrestance of a filter. This is accomplished with a test set-up as shown in Figure 5-4 and two types of test particles. The test is conducted at flow rates from 509 to 3,178 cfm (0.24 m^3/s to 1.5 m^3/s). This standard addresses the electrostatic charge that some filters will have when they are new. This charge will make the initial filtration efficiency higher. However, when the charge is lost, the filtration efficiency can degrade. For filters with an initial charge, the standard recommends testing the filter with and without the charge. This will provide efficiency results for both situations.

The test set-up shown in Figure 5-4 has many components that are also used on the ASHRAE 52.2: 2007 test. The test section starts with a HEPA filter with a minimum classification of H13. This filter is used to remove any particles entering the test duct. The air supplied to the test section can be taken from indoors, outdoors, or re-circulated. Also, the exhaust of the duct can be discharged to the indoors, outdoors, or be re-circulated. If the air is discharged indoors or re-circulated, it is recommended that another HEPA filter be installed on the outlet side of the test duct. This is shown as optional in Figure 5-4. The air is required to have a relative humidity of less than 75%. There are no temperature requirements on the inlet test air. However, some of the test instrumentation may have their own temperature requirements that need to be followed.

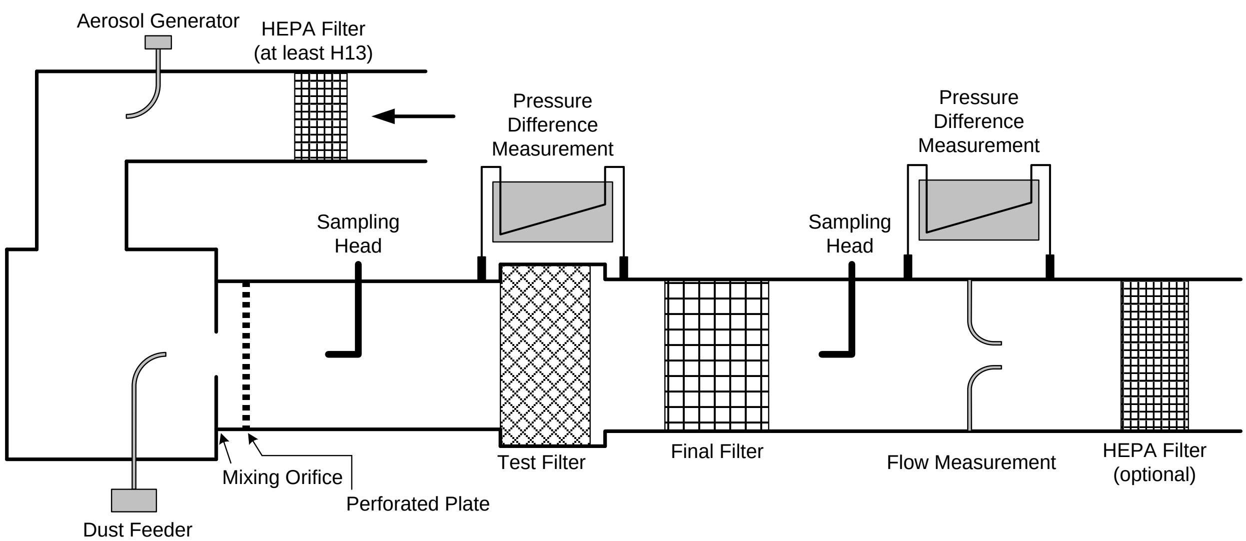


Figure 5-4. Schematic of EN 779: 2002 Test Set-up

There are two test particles used for the EN 779: 2002 test. The first is the test aerosol. This aerosol is Di-Ethyl-Hexyl-Sebacate (DEHS) liquid aerosol. This non-soluble, colorless, odorless aerosol is used to determine the particle size efficiency of the filter in the size range of 0.2 to 3 microns. There are several advantages of using DEHS: it is a neutral test aerosol that can be injected into the test section with or without a charge, and it is a liquid aerosol. The determination of particle size of spherical liquid aerosols using an optical particle counter is more accurate than when using solid non-spherical test particles. Directly after the inlet HEPA filter is the aerosol generator. The aerosol generator is placed in the duct such that the aerosol will be dispersed and mixed to create a uniform concentration upstream of the filter. During the particle size efficiency tests when the aerosol is being released, the mixing orifice and diffusion plate should be removed to minimize turbulence at the filter face.

An optical particle counter is used to determine the number and size of the aerosol upstream and downstream of the filter. This counter is required to a have a size detection range of at least 0.2 to 3 microns with a minimum of 5 size intervals. The aerosols are transported to the counter through the sampling head and tubing (indicated as “Sampling Head” in Figure 5-4). These sampling tubes are designed in order to minimize the particle loss in the sampling lines. If possible, the sampling losses should be made equal for both upstream and downstream sampling lines. This will minimize the error of reported particle count and sizes. When the particle size efficiency tests are not being conducted, the sampling heads should either be sealed off or removed from the test section.

The second test particle is the test dust or loading dust. This dust is used to obtain information about the dust holding capacity and weight arrestance. Two different types of dust are used for loading the filters. For the coarse filter tests (classification of G, the classification is reviewed in Section 5.2.3) the standard ASHRAE test dust is used. This is the same test dust used in ASHRAE 52.2: 2007. For fine filters (classification F) the test dust is ISO-12103-1. This is commonly referred to as Arizona road dust. It consists of mainly silica particles ranging in size from 1 to 80 microns. The size distribution (volume distribution) is skewed to the smaller particles. The test dust is released from the dust feeder as shown in

Figure 5-4. A mixing orifice and diffusion plate are included in the test set-up to ensure that the dust is evenly distributed throughout the test section once it reaches the filter face. When test dust is being released into the test section, a final filter is installed. This filter should be able to collect at least 98% of the dust released into the test section and should not lose more than 1 g of dust due to humidity variations.

After the dust feeder section and upstream sampling head is the test filter. Virtually any air filter can be tested in this test set-up, but it should be able to fit within the test section dimensions. The pressure difference is measured across the test filter. The standard previously discussed (ASHRAE 52.2: 2007) recommend the use of a manometer for this measurement. However, EN 779: 2002 does not specify what pressure measurement device should be used. Whatever device is used must have an accuracy of at least +/- 0.008 inH2O (2 Pa) in the range of 0 to 0.28 inH2O (0 to 70 Pa). Also, the error must be within +/- 3% of the measured value.

The last component shown in Figure 5-4 is the flow measurement device. The flow is measured with standardized flow measurement devices in accordance with ISO 5167-1. Some examples of these devices are an orifice plate, nozzle, and venturi tube. The flow uncertainty should not exceed 5%.

The test set-up can operate on a negative or positive pressure. This means that the blower can be placed upstream or downstream of the test section. Both test set-ups have potential leak sources. A positive pressure system could leak the test aerosol and dust into the laboratory. A negative pressure system could have particles in the ambient air surrounding the test duct leak into the test section. Both of these situations can cause anomalies in the test results. In either case, the test duct should be sealed to minimize the amount of leakage into or out of the test duct.

There are several qualification tests required for the test set-up including air velocity uniformity in the test duct, aerosol uniformity in the test duct, particle counter sizing accuracy, particle counter zero test, particle counter overload test, 100% efficiency test, zero % efficiency test, aerosol generator response time, pressure equipment calibration, pressure drop checking, dust feeder air flow rate, and neutralizer. The procedures and criteria for each of these qualification tests are described in the standard. This standard also recommends maintenance and test set-up qualification intervals. Several of the qualifications tests need to be completed monthly, bi-annually, and annually.

5.2.2 Test

There are four tests which are conducted in an EN 779: 2002 test. The first is a filter pressure loss test. During this test it is recommended that any device inside the test duct that creates a pressure loss should be removed. This includes devices such as the aerosol injector, dust feeder, mixing orifice, diffusion plate, sampling heads, and final filter. The upstream and downstream HEPA filters should be left in the test duct in order to prevent ambient air particles from loading the test filter. The pressure loss across the filter should be measured at 50%, 75%, 100%, and 125% of the rated air flow. This should be measured before the filter is loaded with dust.

The second test is to determine whether or not the filter has an electrostatic charge. This should be conducted before testing begins. Details of this procedure are outlined in an annex in the standard.

The last two tests are the particle size efficiency and weight arrestance tests. These are conducted in conjunction with each other. The sequence of the test is very similar to the test described for ASHRAE 52.2: 2007. A typical test sequence is listed below. Several measurements are taken in between each loading interval. These are described in Table 5-1.

1. Measurement 1
2. Load Interval 1 –30 g of dust loaded in filter

3. Measurement 2
4. Load Interval 2 – Filter pressure loss has reached one-quarter of final filter pressure loss
5. Measurement 3
6. Load Interval 3 – Filter pressure loss has reached one-half of final filter pressure loss
7. Measurement 4
8. Load Interval 4 – Filter pressure loss has reached three-quarters of final filter pressure loss
9. Measurement 5
10. Load Interval 5 – Filter has reached final filter pressure loss
11. Measurement 6

Table 5-1. Measurements Taken During EN 779: 2002 Test (Table adapted from EN 779: 2002)

Stage	Parameter to be Determined			
	Particle Size Efficiency	Weight Arrestance	Dust Holding Capacity	Pressure Drop
Before dust loading	Yes	No	No	Yes
After 30 g of dust loaded	Yes	Yes	No	Yes
At each equal dust loading increment (minimum of 4)	Yes	Yes	No	Yes
After filter fully loaded and reached final pressure loss	Yes	Yes	Yes	Yes

In between each measurement interval is a loading interval. In the first interval, 30 g of dust are loaded into the filter. In the proceeding intervals, the filter is loaded at four equally spaced intervals. The pressures intervals listed above are merely recommendations and are not required. It is up to the filter tester to determine the intervals for loading the filter. However, a best effort should be made to ensure they are equally spaced across the filter loading. During the loading intervals, the test dust is released downstream, and the final filter is installed. The aerosol generator is turned off, and sampling heads are sealed.

5.2.3 Results

Three different results are calculated based on the measured values during the filter test. The first is the filtration efficiency. The filter's particle size efficiency is found from the ratio of the number of particles upstream and downstream of the test filter. Particles are counted multiple times at both locations. Equation 5-4 is used to calculate the particle size efficiency for one loading interval. The efficiency is an average of the summation of the efficiencies calculated for each data point collected.

$$E_i = \frac{1}{6}\sum_{j=1}^{6}\left(1 - \frac{2n_{j,i}}{N_{j,i} + N_{j+1,i}}\right) * 100\% \qquad (5\text{-}4)$$

The average efficiency is then calculated in each particle size range for all dust loading intervals using Equation 5-5. This is calculated by mass averaging each loading interval results. M_j is the total mass of dust released during the specified test interval, M_{total} is the total mass released during the test, and k is the number of dust loading intervals.

$$E_{m,i} = \frac{1}{M_{total}}\sum_{j=1}^{k}\left(\frac{E_{i,j-1} + E_{i,j}}{2} * M_j\right) \qquad (5\text{-}5)$$

After calculating the particle size efficiencies for the filter, the uncertainty of the efficiency results should be calculated. The EN 779: 2002 standard outlines a procedure for completing this calculation.

At each test interval, as discussed in Section 5.2.2, the weight arrestance of the filter is calculated. An average weight arrestance for the filter is found using Equation 5-6. The weight arrestance is mass averaged.

$$A_m = \frac{1}{M_{total}} \sum_{i=1}^{5} M_i * A_{m,i} \qquad (5\text{-}6)$$

The last value calculated from the test measurements is the dust holding capacity. This is calculated from the final pressure loss across the filter by multiplying the total mass of the dust fed by the average arrestance (A_m). The total mass of dust fed is corrected for any losses due to dust drop out in the test duct or leakage through duct joints.

After the values above are calculated, the filter classification can be determined. Filters are separated into four letter groups for classification: G, F, E, H, and U. G is the coarse filter group, F is the fine filter group, E is the EPA filter group, H is the HEPA filter group, and U is the ULPA filter group. EN 779: 2002 tests filters for performance in the G and F groups. The E, H, and U groups are tested under EN 1822: 2009 which will be discussed in Section 5.3. Each group has several numbers that are included after the letter. This number is selected based on the efficiency and arrestance results of the performance test. The efficiency and arrestance values used to classify filters are listed in Table 3-2.

The EN 779: 2002 standard states that filter should be tested at 2000 cfm (0.994 m^3/s) and up to a final filter pressure loss of 1 inH2O (250 Pa) or 1.8 inH2O (450 Pa) for G and F filters, respectively. Filters may be tested at conditions different than these. The rating of the filter not tested at standard conditions is still based on the values outlined in Table 3-2, but the conditions of the test must be reported in parentheses after the filter rating (e.g. G4 (0.7 m^3/s and 200 Pa)).

5.3 EN 1822: 2009 (Parts 1 through 5) – High Efficiency Air Filters (EPA, HEPA, and ULPA)

As mentioned above, the EN classification system includes four rating levels: G, F, E, H, and U. EN 1822: 2009 address the performance tests for the E, H, and U classification which includes EPA, HEPA, and ULPA filters, respectively. There are five parts of the EN 1822: 2009 standard which are listed below:

Part 1 – Classification, performance testing, and marking
Part 2 – Aerosol production, measuring equipment, and particle counting statistics
Part 3 – Test flat sheet filter media
Part 4 – Determining leakage of filter element (scan method)
Part 5 – Determining the efficiency of filter element

The measurements in this standard are based on particle counting methods. The efficiency is found with particle counts at the most penetrating particle size (MPPS). This efficiency is not a mass relationship, and a mass efficiency is not used in the standard. In ASHRAE 52.2: 2007 and EN 779: 2002 the arrestance is defined as a mass efficiency. The MPPS is the particle size in the range of 0.15 to 0.3 microns that has the lowest filtration efficiency. The small particle sizes allow the testing to be sensitive enough to evaluate ULPA filters.

5.3.1 Test Set-up

The objective of the EN 1822: 2009 test is to determine the filter efficiency and maximum penetration for the MPPS. This is accomplished with a test set-up similar to the one shown in Figure 5-5 and a test aerosol. The test aerosol is a liquid aerosol. This aerosol can be several different types: DEHS (same aerosol is used in EN 779: 2002), Di-octyl Phthalate (DOP) (this is used in a MIL-STD-282 test), or a low viscosity paraffin oil. The test aerosol can be monodispersed or polydispersed. If monodispersed particles are used for the test, then a particle counter which only counts the number of particles can be used for the test. A Condensation Nucleus Counter (CNC) is an example of a particle counter that could be used. However, a particle counter that measures the size of the particles will also need to be used. If the test is conducted with a polydispersed aerosol, then a particle counter which measures size of the particles and counts the particles is needed. An example of this is an Optical Particle Counter (OPC). Whichever counter is used, it needs to be able to measure or count particles in six size ranges across 0.15 to 0.3 microns for the test.

The aerosol generator should be capable of producing particles with a diameter that is the mean diameter of the MPPS. The size and concentration distribution of the aerosol should be constant over time. There are several pieces of equipment included in the aerosol generating system which ensure that the aerosol entering the test chamber is controlled. First the aerosol is created with the aerosol generator. Next the aerosol is passed through a conditioner. For example, the conditioner may be used to evaporate a solvent. Next, a differential electric mobility analyzer (DMA) may be used. This device is not required when polydispersed test aerosols are used. If a monodispersed aerosol is needed, then the DMA separates out a quasi-monodispersed for the test. After this, the charge of the test aerosol is neutralized. Lastly, the test aerosol is released in the test section. The location where the aerosol is released is designed to promote mixing and even distribution of the aerosol particles.

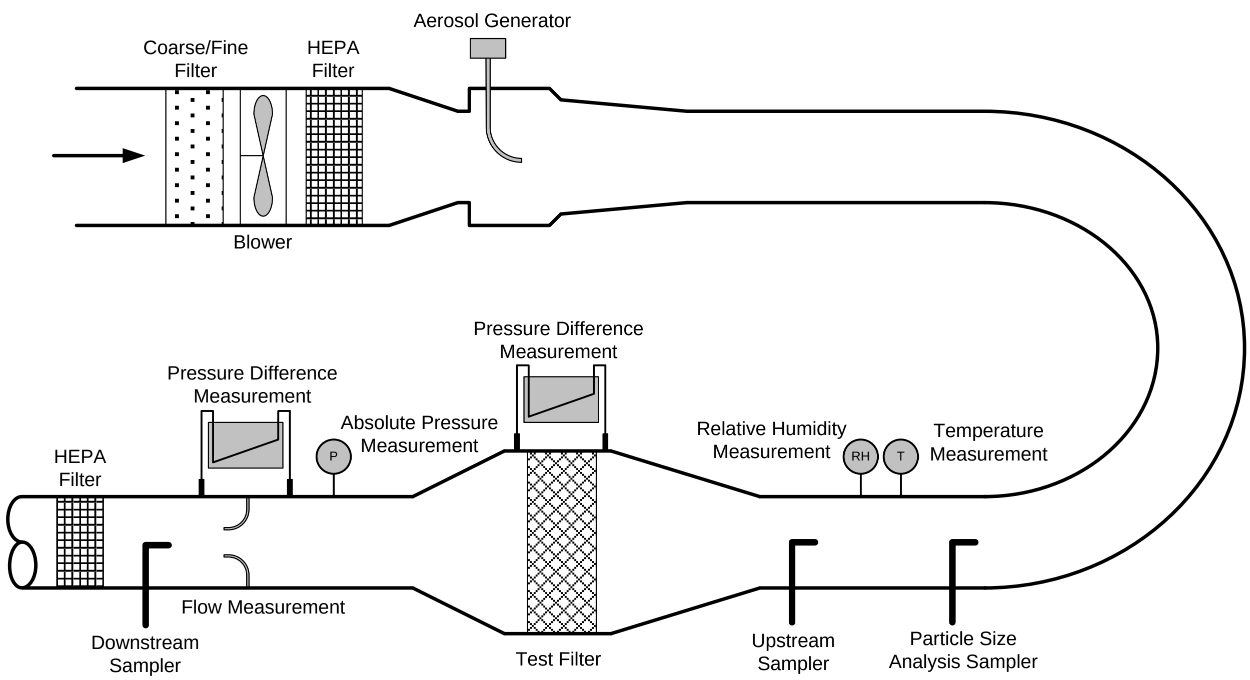


Figure 5-5. Schematic of EN 1822: 2009 Efficiency Test Set-up

The test should be conducted at the nominal flow rate for the filter. The standard does not require a specific flow rate for the test. The temperature for the test is limited from 64.4° F to 82.4° F (23° C +/- 5° C). The air temperature and test filter temperature should be the same. The relative humidity must be less than 75%. Both temperature and humidity should remain fairly constant over the duration of the test. There are filters installed upstream of the test section in order to ensure that the air entering the test section is clean. The inlet air is required to have a particle number concentration less than 9911 ft^{-3} (350,000 m^{-3}) when measured with a particle counter.

The test duct can have a circular or rectangular cross section. In the other test standards reviewed in this guideline, a rectangular test section is used. The test section can be tested at a positive or negative pressure. The configuration shown in Figure 5-5 has a positive pressure applied to the test section. If the blower is placed downstream of the test section (negative pressure), then the gas property measurements (relative humidity and temperature) should also be placed downstream of the test section. In case of either positive or negative pressure, a HEPA filter is to be placed on the inlet of the duct and on the exhaust of the test section.

In the test section, there are several measurements. The first measurements are the relative humidity and temperature. These measurements are made in order to ensure that the test air stays within the defined limits. The pressure change across the filter is measured with a pressure difference device. The standard does not give specific recommendations on the instrument that should be used for this measurement. Downstream of the filter, the absolute pressure is measured. Also, the volumetric flow rate is measured. The flow is measured with a differential pressure device in accordance with ISO 5167-1. Some examples of devices that can be used are orifice plates, nozzles, and venturi meters.

To measure the efficiency of the filter, a representative sample of the particles in the test air is captured by sample probes. These are placed upstream and downstream of the test section. These probes transport the sample to the particle counter. For all tests, the upstream sample probe is stationary. For the leakage test, the downstream sample probe traverses the filter exit face in order to measure the local penetration.

5.3.2 Test

An EN 1822: 2009 test is different from the tests described in ASHRAE 52.2: 2007 and EN 779: 2002. In the EN 1822: 2009 test, the filter is not loaded with dust at several intervals. Instead, the filter is tested in the new condition at several different particles sizes. These tests are used to determine the MPPS efficiency of the filter.

There are several different tests in a full EN 1822: 2009 filter evaluation. The first step is to measure the pressure loss across the filter in the unloaded condition. Next the efficiency is measured for six different particle size ranges. This efficiency is found at the nominal test velocity. As discussed above, a monodispersed or polydispersed aerosol can be used. If a monodispersed aerosol is used, then six different efficiency tests will need to be completed (one for each particle size range). Only one efficiency test is needed for a polydispersed aerosol, since the complete particle size range can be covered in the one test. The results of this test are plotted on a graph and the particle size for the minimum efficiency is found. Five different filter samples should be tested for minimum efficiency. The final minimum efficiency and particle size are the average of the results from all five tests. Figure 5-6 shows an example of the results from the initial efficiency test. In this test, the MPPS occurred at 0.15 microns.

Once the MPPS is determined, the leakage test can be completed. In this test, the local penetration across the filter is measured for the MPPS. This involved taking particle samples downstream of the filter across the full filter face. To accomplish this, a sampling tube will traverse the full filter surface. At each location (documented with coordinates), a sample of the particles is measured and counted, and the penetration is calculated. During this test, the particle size, concentration, and the air velocity are held constant. Also, the aerosols upstream of the filter are evenly distributed across the filter cross-section.

The last test of a filter evaluation is the efficiency test. The same test aerosol, MPPS, and nominal flow rate are used for this test. The efficiency can be determined in two ways. In the first method, stationary probes are installed upstream and downstream of the test. The downstream sampling probe must be installed downstream of a mixing section in order to ensure that the particles are evenly distributed across the test duct. The second method uses a probe downstream that traverses across the full filter face. This method is referred to as the scanning method and is the same method used for the leakage test. The results from the leakage test can be used for the calculation of the filter efficiency provided the particle count and size is measured continually throughout the leakage test.

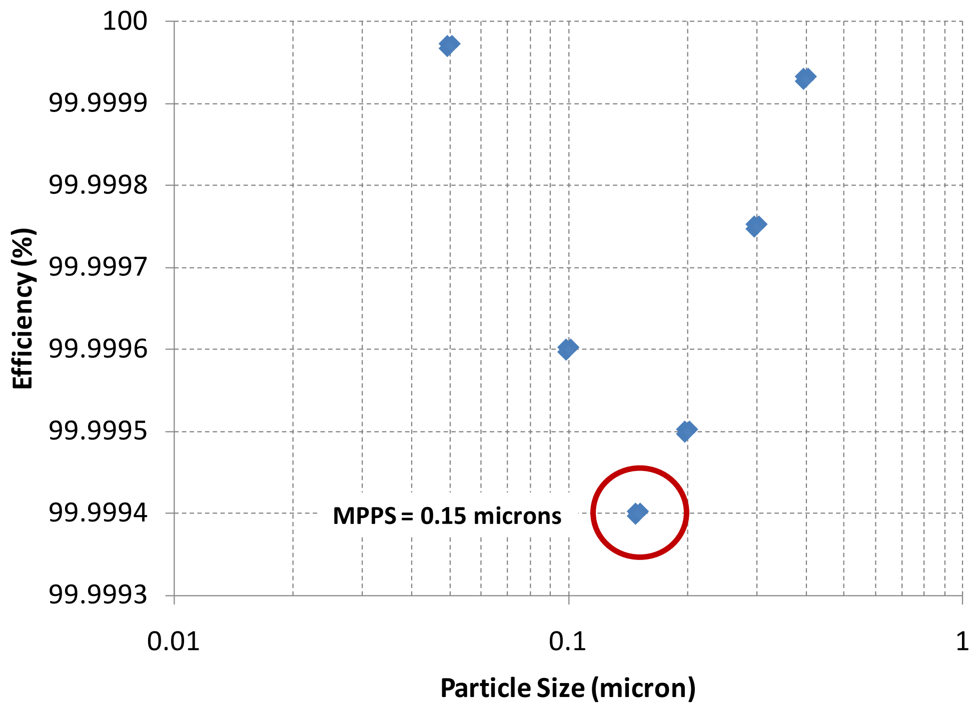


Figure 5-6. Example of Results from MPPS Efficiency Test

5.3.3 Results

There are several calculations that must be completed with the test results to evaluate the filter. As mentioned above, the MPPS particle size is determined by plotting the efficiency from the initial tests. The final MPPS and minimum efficiency is the arithmetic mean value for all test samples. The efficiency and penetration are calculated using the measured number of particles, particle size, flow velocity, and sampling time. These values are calculated for the leakage test and the efficiency test. The leakage test provides the local penetration and efficiency. The overall minimum efficiency and penetration are found from the efficiency test. Equations 5-7 through 5-10 below are used to calculate the efficiency and penetration.

$$E_{1822} = 1 - P_{1822} \tag{5-7}$$

$$P_{1822} = \frac{c_{N,d}}{c_{N,u}} \tag{5-8}$$

$$c_{N,d} = \frac{N_d}{\dot{V}_{s,d}\, t_d} \quad (5\text{-}9)$$

$$c_{N,u} = \frac{k_D N_u}{\dot{V}_{s,u}\, t_u} \quad (5\text{-}10)$$

The minimum efficiency is calculated with variations of the equations above using a 95% confidence interval. The calculation is completed for the MPPS. The filters are then classified with the minimum overall efficiency, maximum overall penetration, minimum local efficiency, and maximum local penetration. The efficiencies and penetration values used for classifying a filter are shown in Table 5-2. EPA, HEPA, and ULPA filters are assigned the letter E, H, or U, respectively, and a number. It should be mentioned that some EPA filters are used in gas turbine applications. HEPA and ULPA filters have not been used in the past for gas turbine inlet filtration. This is mainly due to the fact that gas turbines can withstand a low level of contaminants and ULPA level filtration is not required.

Table 5-2. Classification of EPA, HEPA, and ULPA Filters (Table from EN 1822-1:2009)

Filter Class	Overall Value		Local Value	
	Efficiency (%)	Penetration (%)	Efficiency (%)	Penetration (%)
E10	85	15	--	--
E11	95	5	--	--
E12	99.5	0.5	--	--
H13	99.95	0.05	99.75	0.25
H14	99.995	0.005	99.975	0.025
U15	99.9995	0.0005	99.9975	0.0025
U16	99.99995	0.00005	99.99975	0.00025
U17	99.999995	0.000005	99.9999	0.0001

5.4 Other Testing Considerations

In all the tests described above, the pressure loss across the filter was measured at several different air velocities. These results are useful for the filter engineer when selecting filters. Based on the operational air velocity of the new filtration system, the filter engineer can use the measured pressure loss (from the standards test) to estimate the expected pressure loss for the filtration system. Also, the pressure loss measurements during a test at different loading intervals can provide the filter engineer insight to how the pressure loss will change as the filter is loaded.

The ASHRAE test dust used for ASHRAE 52.2: 2007 and EN 779: 2002 tests is not representative of typical atmospheric dust. It has a much larger number of coarse particles than would be seen in a normal operation. As mentioned in Section 3.1.2.4, a filter loads differently with different size particles. Also, even though a filter may have good filtration efficiency for large particles, it will not necessarily have a high efficiency for smaller particles. Therefore, the weight arrestance measurements will not provide good estimates of the mass filtration efficiency or dust holding capacity of the filter during normal operation.

The ASHRAE 52.2: 2007, EN 779: 2002, and EN 1822: 2009 standards provide methods to measure the particle size efficiencies of the filters for particles on the lower micron and submicron scale. The results of each of these tests report the minimum efficiency measured. The minimum efficiencies do provide a good estimate of the expected filtration efficiency for the filter. Also, it is safe to assume that the filtration efficiency for larger particles (larger than the ones used during the test) will be better or meet the minimum efficiency measured. However, the results from these tests do not provide any valuable information related to the dust holding capacity or life of the filter. Also, there are several adverse conditions in actual operation which could cause the efficiency to deviate from the measured value.

One adverse condition that is not addressed in the filter testing is the effects of water. This can significantly affect the performance of the filter, especially if the filter is not designed to reject water. Water effects are discussed in more detail in Section 3.1.2.6. Also, soluble contaminants such as salt and exhaust gases (SO_x and NO_x) can affect the filters performance. Sticky particles such as pollen and unburned hydrocarbons can lead to deviations in the filtration efficiency. Lastly, uneven flow variations across the filter bank will affect the overall efficiency.

Since the conditions of the performance tests can vary significantly from the actual operation, the test results cannot necessarily be used to predict operational performance and the life of a filter in the actual application. Due to this, some filter manufacturers may conduct additional tests on their filters to address specific contaminants and conditions. These results are useful for the filter engineer when evaluating filters.

The primary advantage of the filter test standards is that they provide a method to compare and classify filters. The filter engineer can use the filter classification to select filters for their application. The results and rankings of the filters do provide a good estimate of the range of filtration efficiency that can be expected. For example, the standards clearly identify which filters can be used for coarse or fine particle filtration. However, the filter engineer should be cautioned when directly comparing filters based on classification. None of the test standards require a specific set of test conditions (temperature, relative humidity, air flow rate, and final pressure loss). Some of the conditions can strongly influence the test results. It is important that the test conditions are noted when comparing filters.

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APPENDIX A

SITE EVALUATION QUESTIONNAIRE

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GMRC Guideline for Gas Turbine Inlet Air Filtration Systems

Site Evaluation Questionnaire

The following information is intended to assist the filter engineer in determining the type and level of contaminants present in the location where the gas turbine will be installed. This information will help the filter engineer ensure that proper inlet filtration is used. If the amount and size distribution of particles are available, then this should be included in the information provided on this questionnaire

1. Environment (select all that apply)

___ *a. Coastal*

Contaminants
___ Salt ___ Cooling tower aerosols
___ Rain ___ Sea mist
___ Sand ___ Other: ______________

Distance from surf (miles) ______________

___ *b. Marine*

Contaminants
___ Salt ___ Sand
___ Rain ___ Sea mist
___ Ice ___ Hydrocarbons, soot, exhaust
___ Other: ______________

Size & weight limitations ______________
Location of gas turbine inlet ______________
Distance inlet is from ocean surface ______________
Minimum distance from shoreline ______________

___ *c. Offshore*

Contaminants
___ Salt ___ Cooling tower aerosols
___ Rain/sea mist ___ Hydrocarbons, soot, exhaust
___ Sand ___ Other: ______________

Size & weight limitations ______________
Distance inlet is from ocean surface ______________
Distance from shoreline ______________

___ *d. Desert*

Contaminants
___ Sand ___ Pollen/sticky substances
___ Salt ___ Fog, high humidity
___ Other: ______________

Frequency of sandstorms ______________

___ *e. Arctic*

Contaminants
___ Snow ___ Cooling tower aerosols
___ Insects ___ Ice
___ Other: ______________

Maximum snow drift height ______________

___ *f. Tropical*

Contaminants
___ Rain ___ Insects
___ Pollen ___ Salt
___ Other: ______________

Amount of anticipated rain fall ______________
Maximum rate of rainfall (in/hr) ______________

___ *g. Industrial Area*

Contaminants
___ Rain/Fog ___ Salt
___ Snow ___ Hydrocarbons, soot, exhaust
___ Ice ___ Cooling tower aerosols
___ Other: ______________

___ *h. Rural Countryside*

Contaminants

___ Pollen, seeds
___ Leaves
___ Snow
___ Ground dust
___ Rain/fog
___ Agricultural dust
___ Ice
___ Other: ____________________

Agricultural activities

Frequency of harvesting ________________________

Spray Irrigation ________________________

Soil preparation ________________________

___ *i. Large City*

Contaminants

___ Pollen, seeds
___ Leaves
___ Snow
___ Smog, pollution
___ Salt
___ Rain/fog
___ Agricultural dust
___ Ice
___ Hydrocarbons, soot, exhaust
___ Other: ____________________

___ *j. Other* ________________________

____

____

____

2. Local Contaminants

___ Mining operations
___ Foundries
___ Sawmills
___ Wallboard manufacturing
___ Petrochemical plants
___ Agricultural activities
___ Major highways (vehicle exhaust)
___ Drilling operations
___ Pollen and sticky substances
___ Winter lake effects
___ Inland dry lakebeds
___ Inland salt lakes
___ Other: ____________________
___ Particulate data available for location from EPA

3. Temporary Contaminants

___ Construction activity
___ Dirt roads
___ Grit blasting
___ Other: ____________________

4. Future Emission Sources

___ New nearby industrial facility
___ New construction at gas turbine facility
___ Agriculture development
___ Commercial development
___ Residential development
___ Other: ____________________

5. Site Layout

___ Near exhaust of combustion equipment (diesel engine, gas turbine, etc…)
___ In path of cooling tower aerosol drift
___ Near vent of pressure relief valve
___ Piping joints near inlet
___ Near lube oil vent
___ Near any exhaust stacks or flares releasing chemical exhaust and unburned hydrocarbons
___ Near gravel or dirt roads
___ Downwind of open storage of coal, salt, or grainy particles
___ Other: ____________________________

6. Weather

	Average	*Maximum*	*Minimum*	*Frequency*
Wind speed				
Wind direction				
Relative humidity				
Temperature				
Rainfall				
Snowfall				
Fog conditions				
Ice conditions				
Seasonal Changes				

___ Weather data available from NOAA

7. Additional Contaminant Sources

8. Other Additional Information

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APPENDIX B

EXAMPLE LIFE CYCLE COST ANALYSIS

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APPENDIX B

A life cycle cost analysis for a new inlet filtration is conducted below. This analysis is for a 25 MW gas turbine which is driving a generator to produce electricity for a small industrial plant. Any electricity that is not generated by the gas turbine has to be purchased from a power company for 0.06 USD/kWh.

Two filtration systems are compared for the gas turbine. The first system proposed only has one stage: pre-filters. The second filtration system has an additional stage with high efficiency filters. The high efficiency filters must be replaced once a year and require approximately 10 hours of downtime to replace. The pre-filters are replaced four times a year (for both systems), and the gas turbine is not shut down for their replacement. The gas turbine power is assumed to degrade at a rate of 5% per year, and the heat rate increases 1.7% per year with only the pre-filters. With the high efficiency filters included, the power degradation rate is reduced to 1.5% and the heat rate to 0.5%. The gas turbine with pre-filters and high efficiency filters is shutdown for compressor washings 4 times a year. The gas turbine with only pre-filters is shut down 10 times a year for compressor washing. The pressure loss rate for the high efficiency filtration system goes from 2 to 4 inH2O over one year. With only the pre-filters, the pressure loss is from 0.5 to 1.5 inH2O over one year. In both cases, it is assumed that FOD will occur on the IGV in the 8th year of operation. Also for simplicity, the availability/ reliability of the gas turbine is set at 100%. The life cycle cost of the filtration system is analyzed for a 15-year period with a discount rate of 10%.

Summary of Parameters:

Discount Rate = 10%
Analysis Time Period = 15 years
Availability/Reliability = 100%
Gas Turbine Power = 25 MW
Gas Turbine Heat Rate = 9952 Btu/kWh
Cost of Electricity = $0.06/kWh
Cost of Fuel = $0.007/scf
Gas Heating Value = 1030 Btu/scf

The life cycle analysis for each system is presented in Table B-1 and Table B-2. The system with only the pre-filters has a Net Present Value (NPV) of -$6,139,681. The system with the high efficiency filters and pre-filters has a NPV of -$4,545,060. The high efficiency filtration system has a $1,594,621 cost advantage over the pre-filter only system for a study period of 15 years.

Table B-1. Life Cycle Cost Analysis for System with Only Pre-Filters.

Description	Item Value	Cost		Year Occurs	Interval (years)	Equations	
		Actual Value (/year)	Present Value			Actual Value	Present Value
Purchase Price		-$100,000	-$100,000	0			
Maintenance							
Filter Replacement							
Pre-Filters (100 filters)	$50/filter	-$20,000	-$152,122	All	0.25		3-4
Inspections (2 hours every 2 weeks)	$80/hour	-$4,160	-$31,641	All	1	3-12	3-4
Gas Turbine Power Degradation	5%/year	-$328,500	-$2,498,597	All	1	3-8	3-4
Gas Turbine Heat Rate Increase	1.7%/year	-$125,902	-$957,624	All	1	3-9	3-4
Compressor Washing (10 offline washes/year)	15 hr/offline wash	-$225,000	-$1,711,368	All	1	3-7	3-4
Pressure Loss (full system in one year) - Power Degradation	dp_1 = 0.5 inH2O dp_2 = 1.5 inH2O	-$65,700	-$499,719	All	1	3-10	3-4
Pressure Loss (full system in one year) - Heat Rate Increase	dp_1 = 0.5 inH2O dp_2 = 1.5 inH2O	-$14,812	-$112,662	All	1	3-11	3-4
IGV Damage from FOD							
Failure Parts Cost		-$50,000	-$23,325	8			3-2
Labor Cost (20 hrs, 3 people)	$80/hour	-$4,800	-$2,239	8		3-12	3-2
Downtime	72 hrs	-$108,000	-$50,383	8		3-7	3-2
Total NPV	**-$6,139,681**						

Table B-2. Life Cycle Cost Analysis for System with Pre-Filters and High Efficiency Filters.

Description	Item Value	Cost		Year Occurs	Interval (years)	Equations	
		Actual Value (/year)	Present Value			Actual Value	Present Value
Purchase Price		-$200,000	-$200,000	0			
Maintenance							
Filter Replacement							
Pre-Filters (100 filters)	$50/filter	-$20,000	-$152,122	All	0.25		3-4
High Efficiency Filters (100 filters)	$100/filter	-$10,000	-$76,061	All	1		3-4
Downtime to replace	10 hours	-$60,000	-$456,365	All	1		
Inspections (2 hours every 2 weeks)	$80/hour	-$4,160	-$31,641	All	1	3-12	3-4
Gas Turbine Power Degradation	1.5%/year	-$98,550	-$749,579	All	1	3-8	3-4
Gas Turbine Heat Rate Increase	0.5%/year	-$37,030	-$281,654	All	1	3-9	3-4
Compressor Washing (4 offline washes/year)	15 hr/offline wash	-$90,000	-$684,547	All	1	3-7	3-4
Pressure Loss (full system in one year) - Power Degradation	dp_1 = 2 inH2O dp_2 = 4 inH2O	-$197,100	-$1,499,158	All	1	3-10	3-4
Pressure Loss (full system in one year) - Heat Rate Increase	dp_1 = 2 inH2O dp_2 = 4 inH2O	-$44,436	-$337,985	All	1	3-11	3-4
IGV Damage from FOD							
Failure Parts Cost		-$50,000	-$23,325	8			3-2
Labor Cost (20 hrs, 3 people)	$80/hour	-$4,800	-$2,239	8		3-12	3-2
Downtime	72 hrs	-$108,000	-$50,383	8		3-7	3-2
Total NPV	**-$4,545,060**						