See it. Control it.

Defining the Environment Before Deploying a Filtration Solution

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ABSTRACT

Filtration solutions are often deployed without accurately understanding the contamination challenges of the environment to be protected. This is usually done to either implement a solution as quickly as possible, or to minimize cost by using pre-defined and readily available off-the-shelf solutions. However, this approach neither assures an efficient contaminant removal nor does it optimize cost of ownership. An inexpensive filter changed out often may be more expensive than getting a tailored, more expensive solution that lasts much longer.

The approach promoted here is the *See it. Control it.* paradigm, where "seeing" means measuring the contamination first in order to characterize the environment, and "controlling" means implementing a filter solution that is tailored to that specific environment. Instead of formulating a filter solution that provides equal amounts of adsorbents for different contaminant classes, we suggest adjusting the adsorbents such that they match the actual environmental challenge, as determined by accurate measurements.

Contamination control concepts detailed in this paper are specifically for filters removing gas-phase air contamination and particles, but apply equally to any other type of filtration, such as the purification of liquids, solids, or slurries.

To arrive at the best characterization of the environments to be protected, an accurate and specific measurement technique needs to be applied. For gas-phase evaluation, qualitative or semi-quantitative methods are unsuitable to do so (e.g., corrosion strips or micro balances).

To measure actual concentrations as well as contaminant identification, ISO 17025 accredited lab services should be used, which are found competent for specific analyses of specific environments for specified concentration ranges. Such gas-phase contaminant concentrations can range from 100s of parts per million in odor problems to single digit parts per trillion in cleanroom environments as per ISO standard 14644-8. For particle contamination, the ISO standard 14644-1 defines ranges 1 through 9, laying the foundation for MERV, HEPA, and ULPA filter ratings for their removal.

In order to choose a suitable filter solution, the contaminants, their types and ranges, as well as concentrations need to be defined first. The paper demonstrates this concept, as well as solutions and guidelines for best practices, along with a real-world case study, but also outlines some limitations to the concept.

INTRODUCTION

Many filtration solutions are deployed without accurately understanding the contamination challenges of the environment to be protected, either because no measurement has been performed at all, or only qualitative evaluation methods like corrosion strips or inexpensive particle counters were used to define the state of contamination. In addition, many filter providers prefer to offer a few off the shelf products, rather than customizing the solution, in order to keep inventory and lead times low.

However, with sustainability becoming a strategic goal for many industrial operations, filter lifetime, cost of ownership, and minimized waste streams are focal points of procurement and installation services. More importantly, processes, products, and humans need to be better protected from contamination impact. Just like one would never use a simple MERV filter for a process needing ULPA filtration, one should not use a basic, off the shelf chemical filter with unknown capacity and removal efficiency for gas-phase contaminants.

Filter performance as well as lifetime can be optimized by characterizing the environment to be protected first, and then building a filtration solution to match that environment. The measurement data would provide an accurate evaluation, the filter solution would then be tailored to match those analytical results. This is the most scientific, data-driven way to air filtration.[1]

CONCEPTS

The *See it. Control it.* Paradigm

There are three basic approaches to any problem solution. The least effective is the reactive way, when no action is taken until a problem occurs. This is also the most dangerous type, as any process or product is left unprotected, but it has been the most common approach to many industries. A more effective solution is the predictive way, when an attempt is made to predict how a process or product behaves if and when a problem arises, with potential or at least partial solutions already in place or at hand. However, this approach may not be optimized and may be costly if deployed where not needed. The most effective way is the proactive or prescriptive approach, when potential scenarios for interruptions or impacts are anticipated, with solutions in place to prevent them from happening, or to minimize the impact if any one metric is not fully effective. The progression from reactive to proactive approach is what the IEEE *International Roadmap for Devices and Systems* recommends (IRDS)[2] for the management of industrial processes.

One such proactive approach is to choose the best filtration solution to any air contamination scenario. Rather than using off the shelf products that might be inexpensive and quickly available, the Entegris model suggests to define the contamination first by characterizing the environment to be protected, and then finding or creating the most suitable solution for that specific environment.

The most important aspect of controlling gas-phase contamination and implementing AMC filters is to define the contamination state of the environment to be protected. The measurement of both type and concentration of gases establishes this and enables the creation of an optimized filter solution for that particular application. The *See it. Control it.* approach is what this paper recommends. We See the contamination through air analysis with the Entegris Analytical Services laboratory, which provides accurate gas phase analysis for any environment from the parts per million (ppm, 10^{-6}) to the parts per trillion (ppt, 10^{-12}) level.

We can then *Control* the environmental contamination more easily, as the filtration solution can be tailored exactly to that environment's challenges and needs, as defined by the measurements. Some environments have an unusual mix of AMC classes. To prevent one portion of the filter being used up faster than others, Entegris adjusts adsorbent mixes such that all adsorbents last about the same amount of time, based on the measurements of AMC in that environment.

WHAT IS THE INKJET CARTRIDGE EFFECT?

The idea of this approach is to avoid what we call the "inkjet cartridge effect", referring to old style inkjet cartridges that held three equal amounts of magenta, yellow, and cyan inks, but typically drained cyan first, forcing to discard a significant amount of yellow and magenta inks when replacing the cartridge. Applying our approach to this, we would determine first how much cyan, magenta, and yellow is typically used up in a given amount of time, and then adjust the ink amounts accordingly such that all three are used up at about the same time (Figure 1).

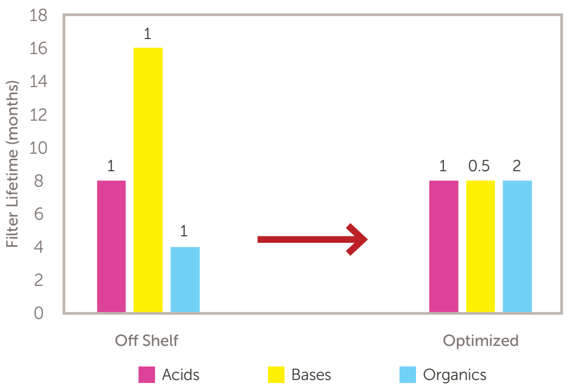

Figure 1. The inkjet cartridge effect for AMC filters visualized. The bars indicate filter lifetime in months for the respective contaminant classes (example: acids, bases, organics), the relative adsorbent ("ink") amounts are indicated as numbers above each bar. Equal adsorbent amounts yield different lifetimes. Equal lifetime is achieved by using different adsorbent amounts.

For real world filter scenarios, commercial environments usually attempt to remove acidic, basic, and organic contaminants from air streams. Each of those classes has their own adsorbent for optimized removal but each also has different concentrations in any environment.

The most common and economical filter type for these applications is the combined adsorbent filter, which contains a mix of all adsorbents in one set of (usually pleated or V-bank formed) media. Adjusting adsorbent amounts for an equalized lifetime of all contaminant classes is simple, if the measurements are available. However, each contaminant class may also have different priorities or importance for the application and in some cases, lifetimes may become secondary to the priority of removing one contaminant class more efficiently.

For particulate contamination, one should not only determine the overall particle count, but also the size distribution to determine impact on the process. Larger particles are easy to remove with low rating MERV filters, but more advanced processes might need HEPA and ULPA rated filters for best protection. Even those might still leave large numbers of very fine particles in the nanometer range to impact high technology processes. An understanding of these dependencies is important to prevent unrealistic filter expectations.

FILTER PERFORMANCE

Gas-Phase Filters

For gas-phase filters, the most critical performance characteristics are removal efficiency (RE) and capacity or remaining lifetime (RL), but also pressure drop (not to mention parameters that are not performance related, such as size, weight, materials, and sustainability, amongst others). Removal efficiency is defined as:

$$RE = \left(1 - \frac{Downstream}{Upstream}\right) \times 100(\%)$$

Equation 1.

Where *Downstream* and *Upstream* are the contaminant concentrations downstream and upstream of the filter. Removal efficiency can then be tracked over time to determine a practical end of life.

For particle filters, removal efficiency actually increases over time (the filter slowly clogs up), but pressure drop also increases because of that. That will eventually exceed a value that can be efficiently handled by the air flow system.

For AMC filters, removal efficiency is highest in the beginning and then decreases over time. Pressure drop does not appreciably change over time (AMC filters do not remove particles except for large dust). The RE curve over time follows a typical 'S' shape (essentially an inverted break-through curve, Figure 2):

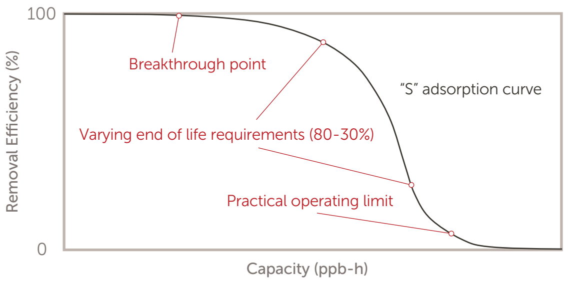

Figure 2. AMC filter capacity curve. Removal efficiency is largest early on, then decays in S-shape over time. Practical end of life values depend on application.

Instead of using filter capacity values such as gram of contaminant per gram of adsorbent, we suggest a more user-friendly capacity term is the product of contaminant concentration (in parts per billion, ppb, 10^{-9}) and time (in h), expressed as ppb-h. Using this figure, an end user can measure the actual concentration in the application space, average that over time, and then plug it into the above curve to determine capacity in hours. An added benefit is that this process specific average does not have to be revealed to the filter manufacturer.

Filter performance characterization is guided by international standards. ISO standard 10121 describes test methods for air filtration media in part 1 and for devices in part 2.[3]

Particle Filters

For particle filters, the performance of a filter can be measured with the $\log_{10}$ reduction value (LRV), which is the ratio of the levels of contamination before and after the filter process.

$$LRV = \log\left(\frac{Challenge}{Filtrate}\right)$$

Equation 2.

Where *Challenge* and *Filtrate* are the upstream and downstream amounts of particles (in any one size class). An LRV increment of 1 corresponds to a reduction in concentration by a factor of 10.

Reporting this particle filter efficiency is usually standardized as a percentage of specific particle size ranges being removed. The Minimum Efficiency Rating Value (MERV), Efficiency, High Efficiency or Ultra Low Particle Air filter ratings (EPA, HEPA, ULPA) provide these classifications. MERV ratings 1 through 16 are described by ASHRAE standard 52.2-2017.[4] The HEPA standard was first defined by the US Department of Energy, but is now regulated by ISO standard 29463[5] and provides classification (part 1), statistics (part 2) and test methods for flat sheet media (part 3), leakage (part 4) and full-size filters (part 5). This standard also covers the ULPA classification, which was a gradual improvement of HEPA filters, but without known origin.

In contrast to gas-phase filters, particle filters can become more efficient over time, they slowly clog up. However, particle removal happens through three basic principles: sieving occurs when the particle is larger than the filter fiber pores. Many particles, however, are smaller than the pores, but still get adsorbed through electromagnetic (or chemical) surface interaction after attaching to the media through inertial impaction or gravitational settling, direct interception and diffusional interception, the latter two being the primary mechanisms. Those particles may get mobilized again if the pores are sufficiently clogged up and average flow rate increases through the remaining pores, causing break-through and reduction of the LRV.

In addition, as the filter pores close up, pressure drop increases and, with it, energy consumption. Both energy consumption and potential break-through will determine practical filter lifetime.

When is a filter exhausted and needs to be replaced?

The practical end of life depends on the minimum filter removal efficiency that still provides the application with a benefit and maintains the maximum contaminant concentration that the application can tolerate. This is a value that needs to be determined by observing the application and monitoring concentrations.

For particle filters, this is a straightforward exercise, as in most cases, only the pressure drop needs to be monitored and filter life be cut off when the HVAC system's capability is exceeded. However, to prevent fine particles from breaking through as filter clog up happens, occasional measurement of particle counts will prevent exceeding the filter's capacity, but this measurement frequency is less critical than with gas-phase filters. Pressure drop is usually readily available from the air handling system, and flow capability is well defined for air handlers and fan filter units.

MERV filters are typically changed out every 3 – 12 months. Whereas HEPA and ULPA filters can last five or more years, life span depends on flow rate and air particle loading. Filter changeout needs to be determined by flow impact and energy needed to maintain that.

For chemical filters, the initial removal efficiency for AMC may not be 100% and largely depends on parameters like the adsorbent amount, the adsorbent efficiency, flow rate, and temperature. Practical end of filter life for any one AMC filter application is defined as the point where ambient contaminant concentration can no longer be maintained at the desired maximum level that is safe for the application.

Typical AMC filter lifetimes are weeks to years, depending on application, filter design, and desired or required removal efficiency. Two of the primary impact parameters are AMC challenge concentrations and air flow rate. Higher concentrations use up available active adsorbent sites faster and higher flow rate reduces residence time on the adsorbent and with that, the overall removal efficiency. Figure 3 shows a typical performance curve for the removal of organic contaminants for two flow scenarios, low flow at 0.5 m/s face velocity and high flow at 2.5 m/s, using the same filter media.

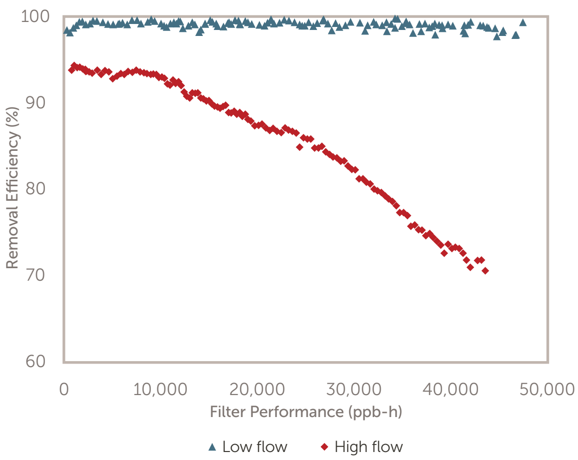

Figure 3. AMC filter performance as a function of flow rate. Notice how high flow not only significantly diminishes the lifetime, but also the initial removal efficiency.

How to optimize filter lifetime?

The *See it. Control it.* approach helps to define and understand individual applications and put analytical as well as filter performance results into proper context by characterizing contaminants, their concentrations, the filter's removal efficiency, and lifetimes and considering process impact. This leads to minimizing cost of ownership and maximizing the performance with optimized filtration solutions.

In addition, monitoring contaminants over time not only defines the application's contamination state better, but also reveals gradual environmental changes, which may require filter solutions to be adjusted to that change. Having a commercial analytical service to measure AMC or particles onsite, accurately, with individual contaminants and classes identified, and down to the lowest concentration levels for the given application is a critical necessity.

Measurement accuracy is important

The cost of analytical evaluation typically scales with performance. In order to get the required insight into the contamination state of a space, measurements must be specific, selective, and accurate. For gas-phase contaminants, corrosion strips, micro balances or other semi-quantitative means can be inexpensive, but are limited to qualitative answers at best. Such systems do not provide accurate concentrations or identification of contaminants. Meaningful gas-phase contamination should not only identify/speciate each contaminant, but also measure its concentration accurately.

Measurement accuracy needs a sufficient detection limit specific to any one application. Semiconductor plants that operate at ppt concentration levels cannot be characterized with a local laboratory specializing in EPA type ambient air quantitation at the ppm level. Likewise, a product sensitive to sub-micron particle intrusion and protected by ULPA filters cannot be characterized with inexpensive particle counters that are made for PM 2.5 monitoring.

Contaminant detection limits should be determined statistically, not as a signal to noise ratio, unless it is a continuous method. Online monitors, which can provide a data point every few minutes or hours enable the calculation of averages and meaningful standard deviations, which can then be used as a definition of detection limits. Older approaches used 20 or more data points collected in one hour and simply calculated the signal to noise ratio, multiplied that by 2 or 3 to determine detection limits.

However, the data frequency of offline grab samples such as water impinger samples or those using adsorption traps like Tenax™ or analyzers cycling through multiple sample ports for once daily data, is too low to calculate meaningful signal to noise ratios. In these cases, a statistical approach such as described in ISO standard 5725 should be used at the 99% confidence level.[6]

For best ambient contaminant evaluation, seeking lab services that are ISO 17025 accredited is advised, as this standard ensures competence for the provided services. Accredited methods specify the concentration regimes and contaminant types that can be tested, guaranteeing that the chosen method and service is suitable for the given environment or application.

Discussing the application

The installation and operation of a filter solution should not be disconnected from the vendor. Even though external services may be used for the installation, customer requirements as well as filter vendor guidelines and limitations need to be considered. Flow regimes, environmental parameters such as temperature, humidity and contaminant concentrations need to be well defined to ensure that the tailored solution applies to the actual environment.

Once installed, for most optimized operation, the filter vendor should be used for applications support and perhaps contaminant measurements. This will ensure that gathered data are put into applications context, and data or filter performance are realistically interpreted. This, in turn, will lead to learning and predicting filter changeout times, filter limitations, changes to the environment and other factors.

A CASE STUDY

A semiconductor customer wanting to utilize AMC filters followed the *See It. Control It.* model. As a first step, they characterized their cleanroom environment by measuring ammonia, a common contaminant that affects semiconductor circuitry, throughout the 40,000 square foot large space. Measurements were done in eight rows of four paths for a total of 32 measurement points. The premise was to find out how much the gas phase concentration of ammonia varied throughout the space. Surprisingly, concentrations varied substantially between 4 and 20 ppb of ammonia (Figure 4) for an average of about 18 ppb. A single measurement might have not defined that average sufficiently to install the best filter solution.

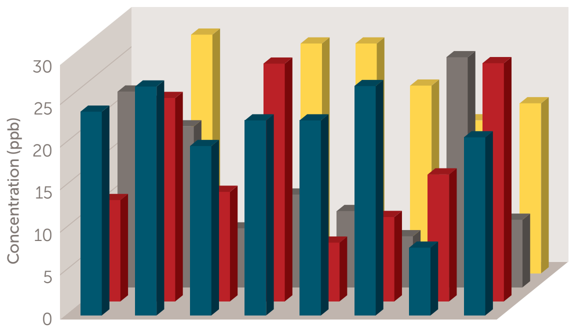

Figure 4. Concentrations of ammonia in ppb, measured throughout a large manufacturing space. A large variability could be observed despite a uniform air supply.

The second step then was to implement AMC filters for maximized removal of ammonia, while also reducing organic contamination in the same space. Once that filter media formulation was established, the customer used the performance curve of the filter as provided in the product sheet of the filter manufacturer, which shows removal efficiency of ammonia as a function of capacity (in ppb-h). This provides a reference point to calculate lifetime (Figure 5).

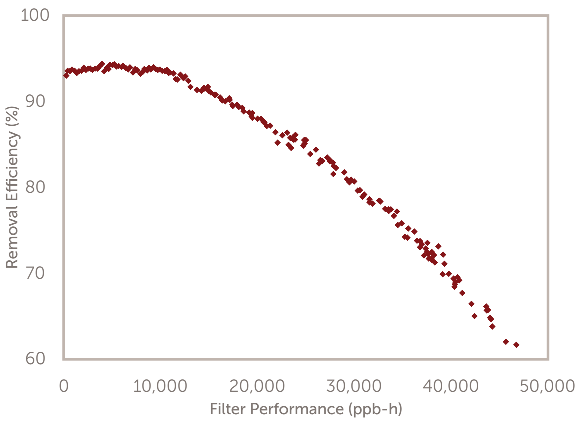

Figure 5. Filter performance curve for the removal of ammonia at high flow.

Once the filters were installed, the main activity was to monitor ammonia concentrations over time. As Figure 6 shows, the ammonia concentration successfully diminished as a function of the filter installation from an initial average of about 18 ppb to eventually level off at about 3.5 ppb. Any concentration below 4 ppb was considered safe for the process at the time. The reason why concentration did not drop to zero is the fact that human bodies – the employees of that plant – naturally produce ammonia and emit it to the surrounding air. The leveled concentration was an equilibrium between ammonia production and removal.

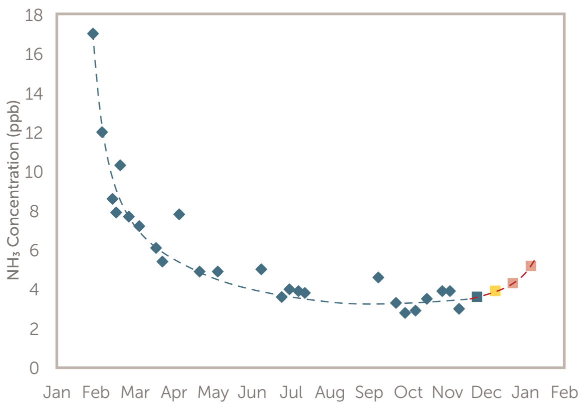

Figure 6: Manufacturing plant environmental ammonia concentration observed over time. Once concentrations exceed the safe threshold (red data), filters need to be changed out.

When the average concentration trend exceeded a set threshold, defined by the process sensitivity, and in this case 4 ppb, the contamination production exceeds its removal, and the filter no longer protects the process. That is the time when the filter needs to be changed. The important point here is that measurements need to be frequent enough to detect changes to avoid endangering the process, but also that there is a need to identify a trend, without relying on a single data point to make filter change decisions that could be very costly.

Iterating between that identified lifetime (in this case: about one year) and the performance curve of the filter will yield the targeted removal efficiency of the installation. At an average AMC challenge of 7 ppb (from measurements taken upstream of the filter) and the determined one-year lifetime (8700 hours) to filter exhaustion provides a value of about 60,000 ppb-h capacity. Plugging that into Figure 5 would provide an end of life removal efficiency of 50%. That is what the customer established as the future lifetime definition. For subsequent installations, they only measured filter removal efficiency occasionally, rather than weekly. Once the filters approached 50% RE, new filters were ordered for replacement.

Throughout this process, the customer worked with us to acquire analytical expertise to measure the contaminants, evaluate onsite filter performance and to put those data into context. Initially, the customer opted to replace filters more conservatively, as to not affect a very expensive production process. This caused a higher cost of ownership but, over time, and along with our guidance, continuous performance measurements and growing confidence in the solution, filter lifetime was extended until the threshold was determined below which the process was no longer affected. That eventually led to the maximum tolerable lifetime of the filter and with it, optimized cost of ownership.

It is that iterative process that needs to be carried out one time, before a simple end of life definition can be adopted for future changeouts.

LIMITATIONS

We have shown a practical approach to achieving optimized filter lifetime at minimized cost of ownership. Limitations to this paradigm apply if an industrial environment maintains many different spaces with very different contamination states. For example, a factory might have multiple assembly lines all using different chemicals, different amounts of employees with different air circulation flows. Creating solutions for each of these individual sub-spaces would lead to higher inventory, longer lead times, and higher cost for smaller purchase quantities and involved installation regimes. In these cases, purchasing a single filter for all environments might provide a better cost and lead time with simple inventory and installation routines, but will reduce applicability as the filters would be made to serve the least common denominator, instead of being optimizing for each sub-environment.

Another limitation is found in rapidly changing environments, where not only concentrations but also contaminant types change quickly over time. This would obsolete the best tailored solution quickly and demand a switch to a new solution in order to protect the process, increasing cost and not allowing to use filters to their designated end of life. The same limitation applies here to any solution that attempts to accommodate all contamination scenarios over time with less targeted contaminant removal.[7]

CONCLUSIONS

The *See it. Control it.* approach to contamination control is well suited to optimize a filtration solution for longest filter lifetime, best performance, and lowest cost of ownership.

Accurate and competent analytical characterization as well as optimized filtration solutions are both required segments for this approach.

We have shown how this applies to different filtration regimes, illustrated by a real-world case study.

Some limitations apply to this scenario, but for most practical purposes, it is a valid and useful tool for contamination control management.

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