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Particles

This section describes the physical nature, origins and behavior of particles.

PARTICLES

SOURCES

Particles can be produced by many different sources. *Inert* (nonliving) particles usually arise from the rubbing of one item against another, such as the dust produced when you saw through a piece of wood. Humans shed lots of inert particles, as in the continuous sloughing off of dead skin. Electric motors give off particles where the commutator is rubbed by wire brushes. Plastic disintegrating slowly in ultraviolet light sheds particles in a light breeze. *Viable* particles are living microorganisms such as bacteria, viruses and fungi. Humans shed large quantities of viable particles.

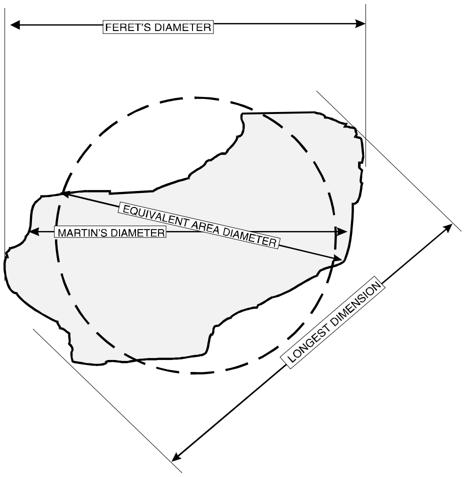
Particles can be classified as *organic* (arising from living matter, though not necessarily alive themselves) or *inorganic* (arising from matter that was never alive). A dead skin cell is an inert organic particle. A protozoan is a viable organic particle. A grain of copper dust is an inert inorganic particle.

SIZE

Particles are small. In the context of contemporary manufacturing methods, the smallest particles are so small that they cannot be considered contamination, and therefore will not be discussed in detail. These smallest particles *per se* are many times smaller than an atom, and are called subatomic particles. Leptons, muons, quarks, nutrinos, and an ever-growing number of tiny particles populate the realm of the subatomic. The branch of science dealing with these particles is called particle or high-energy physics.

The next larger family of particles are atoms. Next in size are molecules, or groups of atoms. These are still too small to be considered industrial microcontamination.The particles we are interested in range in size from well under a micron (abbreviated *µm*, 1/1000 of a millimeter) to about 100 microns (1/10 of a millimeter.) Particles larger than this can be seen with the naked eye. Particles smaller than this (approximately 0.01µm) are of little or no consequence to modern manufacturing processes, as was noted above.

There are several different ways to measure a particle. The diagram below shows the standard dimensions that are employed to describe a particle. A sphere is shown in dashed lines representing a PSL (polystyrene latex) particle, which is a man-made particle used to calibrate particle counters and test filters.



The scientific term for each type of measurement is shown above. Each is useful in different contexts, especially in microscopy.

Some particles can change in size. Take, for example, a viable organic particle like a *paramecium*. A paramecium is a microorganism that, like most animals, is made mostly of water. If the paramecium becomes *desiccated* (dries up) it will be much smaller than it was when it was *hydrated* (full of water). For more information on particle size, see the box on the next page.

Why is the size of a particle of interest to a manufacturer? Depending on the clean process, particles in a particular size range may be of interest because they could do specific kinds of damage to the process. If you are buying a filter, you need to know how small the pores in the filter media need to be.

MATERIAL

Particles can be made of any substance and can be organic or inorganic in origin. Metals, plastics, fibers, animals, sea salt, smoke, fumes and dust are all examples of particle sources. Virtually anything can generate particles under the right circumstances. In a cleanroom, the most prolific particle generators are usually the people who work inside, shedding skin cells, breathing, sneezing, etc.

To put these items in perspective, a typical human hair is about 50µm -150µm in diameter.

Particle	**Approximate size**
Metallurgical dust and fumes	0.01µm to 100µm
Atmospheric dust	0.01µm to 5µm
Flu Virus	0.07µm
Pollen	7.00µm to 100µm
Sneeze particles	10.00µm to 300µm

BEHAVIOR: HOW DO PARTICLES ACT?

Particles exhibit certain tendencies. They move through the air (and other fluids) by means of *diffusion* and *ballistic forces*, and they accumulate on surfaces through gravity and *electrostatic adhesion*. In liquids, particles may adhere to air bubbles, cling to the walls of a duct or container, or agglomerate into a larger mass.

MOVEMENT

Diffusion

If red dye is dumped into a bucket of clean water, the entire bucket of water eventually turns a uniform red color. This spreading-out action is called *diffusion* and takes place even when a gas or liquid seems to be still. Particles suspended in a fluid (liquid or gas) are moved by several forces: currents, thermal variation and Brownian motion.

Currents: Currents are the laminar (smooth) and turbulent (rough) movements of a fluid. Currents are a result of pressure differences, with the fluid always moving from an area of higher pressure to an area of lower pressure. Particles suspended in a laminar flow tend to remain in that part of the fluid. In air, a lateral (side-to-side) movement is called *advection*; a vertical (up and down) movement is called *convection*.

Thermal variation (thermophoresis): Temperature differences in a fluid contribute to currents, particularly convective (vertical) currents. Warming a fluid will also increase Brownian motion. This causes the molecules to be more energetic, and consequently they collide more frequently and are farther apart. This is why warm air is less dense than cold air and tends to rise.

Brownian motion: Air is chock-full of particles, ranging from visible dust to non-visible gas molecules, that are continually colliding and bouncing off of each other (and into other particles). The same thing is true of liquids. Over time, brownian motion results in a more-or-less random distribution of particles. The distance a particle can travel in a straight line before it bounces off another particle is its *mean free path.*

Ballistic Forces

Particles can be ejected from a tool or process causing them to move against the prevailing air flow. This is one reason that particles are seldom found in a truly random distribution.

ADHESION

There are several ways a particle can be taken out of its free (diffused) state. These primary adhesive forces are *electrostatic adhesion, agglomeration, accretion*, and *friction.*

Electrostatic adhesion**:** Particles can carry static electricity the same way a balloon rubbed against your hair can. This can cause particles to be attracted and stick to a surface that carries the opposite charge.

Agglomeration**:** In liquids, particles tend to agglomerate around (stick to) gas bubbles.

Accretion**:** Particles can stick to each other. This can be the result of electrostatic adhesion or other “sticky” forces. Under certain conditions, it is common for two particles to stick together forming a *doublet.*

Friction**:** A particle can get caught on a rough surface where the movement forces are not strong enough to dislodge it. This mechanism, along with electrostatic adhesion, is the basis for most types of filtration.

MOVEMENT AND ADHESION CYCLE

Diffusion and adhesion coexist in a continuous cycle, such that a particle circulates, is trapped, breaks free, circulates, etc. Because of this *the number and size of particles in a given fluid volume is always changing*. This is important, as we will see later in our discussion of particle detectors.

Environments

This section describes the use of specialized environments and filtration to control the effects of particles on production.

ENVIRONMENTS

Many of our modern, high-technology industrial practices demand cleanliness. Specifically, they demand an absence of particle contamination.

Let's look at a more concrete example. Take semiconductors, commonly referred to as "microchips." A microchip is a flat piece of silicon on which very small *traces* (flat wires) are etched, forming transistors and other components. This allows the manufacturer to create a very tiny electronic circuit.

Some traces are so close together (0.3µm apart) that a particle laying across two of them would cause a short circuit. Because of this, the manufacturer would want to filter out any particles in the air that are 0.3µm or larger. Particles smaller than this are not big enough to cause a short circuit.

Also, microchips are multi-layered devices, each layer being extremely thin. The result of this is that, for manufacturing purposes, a microchip's effective surface area is equal to the length times the width times the number of layers, compounding the likelihood that a stray particle could shut the whole thing down. The semiconductor maker has to manage the production environment to eliminate particle contamination.

Another example may be drawn from the pharmaceutical industry: A *parenteral* (injectible) drug must be free of particles that could block a blood vessel, causing a stroke (interruption of blood supply to part of the brain) or necrosis (interruption of blood supply to tissue). The drug maker, like the microchip maker, has to manage the production environment to eliminate particle contamination.

CONTROLLING PARTICLE CONTAMINATION

There are three ways to control particles:

- Eliminate existing particles in the manufacturing environment
- Prevent or restrict the importation of new particles into the process environment
- Prevent the generation of new particles by the manufacturing process

FILTRATION

Particles are eliminated by *filtration*. In filtration, the particle-containing medium is passed through a filter with holes large enough for the medium's molecules to pass, yet too small to allow the particles through. A filter accumulates particles during its service life, and is typically replaced before it is *saturated* (completely full of particles), though some filter media can be *purged* (cleaned) and reused.

There are two steps to filtration; directing the particles to the filter and catching them in the filter. Directing particles to the filter is the more difficult part of filtration. In section one we discussed the factors involved in particle migration; now think about them in the context of a typical manufacturing facility. Such a facility has an enormous number of particle traps, a great deal of surface area and many sources of contamination. The optimal method of particle management is to preserve laminar flow wherever possible, in the hope that as many particles as possible can be swept through the filter. However, it is not always possible to preserve laminar flow.

Filter media have become very sophisticated and are made of synthetic fibers, porous plastics or ceramics. There are two air filtration standards in current use:

> *HEPA filtration (High Efficiency Particulate Air)* is the industry standard for ultraclean or ultrapure manufacturing environments. HEPA filters typically remove 99.99% of particles that are equal or greater in size to the filter specification, usually 0.3µm. HEPA filtration is often an integral part of an *HVAC* (Heating/Ventilation/Air Conditioning) system.
>
> *ULPA filtration (Ultra Efficiency Particulate Air)* removes 99.9995% of the particles that are equal or greater in size to 0.12µm, and is used where ultraclean process environments are required.

Previously, the filter would be examined with a microscope to count and measure particles. Today, this activity is often performed by sophisticated instrumentation. Particle counting will be discussed later in this guide.

CLEANROOMS

Modern "clean" process environments often must be so clean that it is impractical to simply filter the air in the factory. Separate environments called *cleanrooms* have been developed to keep particle contamination at known, controlled levels. Cleanrooms are designed to maximize laminar flow and minimize particle traps. In the most efficient facilities, filters are installed in the ceiling and air returns are installed in the floor. This results in the cleanest environment possible, and minimizes the number of particles that are carried from one place to another by advection.

Other cleanroom techniques include the wearing of protective gowns, caps, overshoes and gloves. In the cleanest environments, personnel wear space-suit-like outfits. Cleanroom apparel is an important step in microcontamination control, because people are prolific particle generators.

Minienvironments

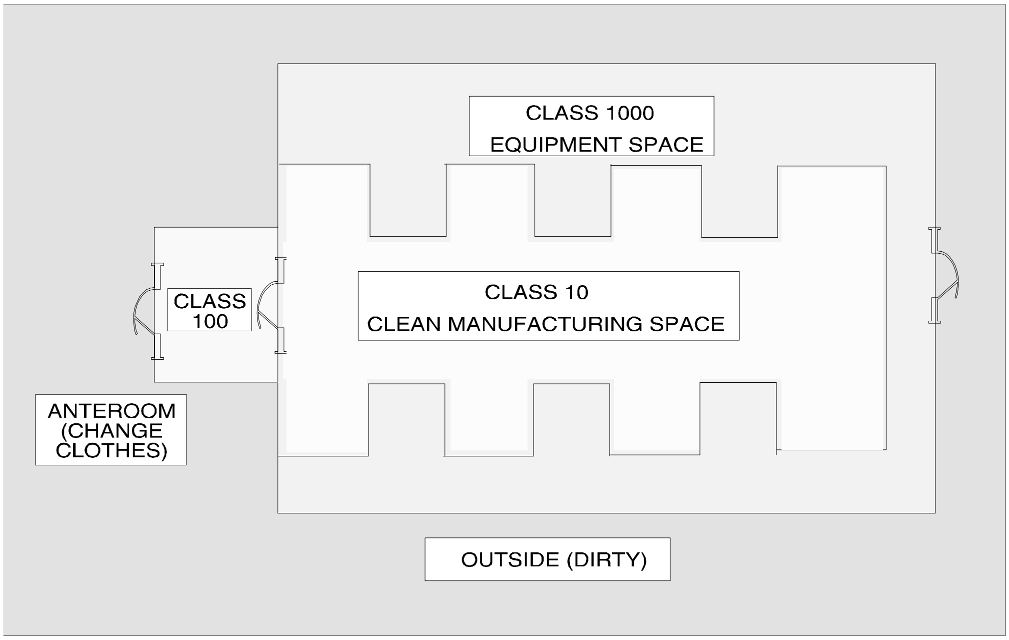
A recent trend has been to use minienvironments, which are in essence small cleanrooms with internal robotic arms or integral rubber gloves. Minienvironments are significantly less expensive than cleanrooms, and their use is growing. In some cases it is possible to install a minienvironment in a lower grade cleanroom instead of building a new facility, saving a great deal of money.

Classification of Cleanrooms and Minienvironments

Federal Standard 209 establishes standard classes of air cleanliness for cleanrooms and clean zones based on specified concentrations of airborne particulates. A "Class 100" cleanroom has no more than 100 particles larger than 0.5µm in any given cubic foot of air. A "Class 10" cleanroom would be ten times cleaner than a Class 100 cleanroom. There is also a Standard Industry (SI) system that is less intuitive (see following page).

Standards for Cleanrooms

In 1984 the Institute of Environmental Science and Technology drafted IES-RP-CC-006-84-T, "Testing Clean Rooms" a scheme for cleanroom evaluation.



TYPICAL CLEANROOM LAYOUT

The items included are measurement techniques for:

- airflow velocity and uniformity
- filter integrity
- airflow parallelism
- cleanroom recovery time
- airborne particle counting
- particle fallout rate
- cleanroom pressure and contaminant induction rate
- lighting and noise levels
- temperature and relative humidity
- vibration

The National Environment Balancing Bureau (NEBB) expanded this standard and offers a third-party certification program. While the program provides useful information, NEBB is not required for cleanroom certification.

Cleanroom Evaluation and Certification

Cleanrooms are certified after construction or significant physical changes. Certification guarantees that the facility has met the requirements for a statistically valid maximum concentration of specified-size airborne particles. A cleanroom can be certified in any of three different stages:

1. *As built*: A cleanroom certified "Class *X* as built" means that the classification was established with the cleanroom fully constructed and ready to use, but without equipment or personnel in the room.
2. *At rest*: A cleanroom certified "Class *X* at rest" means that the classification was established with the equipment installed and operating (or operable, as specified) but without personnel within the facility.
3. *Operational*: A cleanroom certified "Class *X* operational" means that the classification was established with the room in normal operation, with equipment and personnel performing their normal functions within the facility.

Deposited Particles

Cleanroom certification schemes generally do not require that the surface deposition of particles be evaluated—they only evaluate free air. This is a critical issue, because deposited particles may have the greatest impact on manufacturing processes.

In order to verify particle deposition, it is necessary to collect deposited particles on a *witness plate*, a clean, flat object that is known to be free of particles, and is similar in material and characteristics to the item upon which particles are deposited (for example, if you make ABS plastic products, you should use ABS plastic witness plates). Several witness plates are placed throughout the cleanroom, and after a set period of time are collected and the deposited particles are counted. The counting may be done by means of optical microscopy or surface analysis particle counter.

Airborne particle concentration limits for different cleanroom classes:

CLASS NAME		**CLASS LIMITS (MAXIMUM PARTICLE CONCENTRATION)**									
SI	**English**	**0.1µm**		**0.2µm**		**0.3µm**		**0.5µm**		**5.0µm**	
		(m^3)	**(ft^3)**	**(m^3)**	**(ft^3)**	**(m^3)**	**(ft^3)**	**(m^3)**	**(ft^3)**	**(m^3)**	**(ft^3)**
M1		350	9.91	75.7	2.14	30.9	0.875	10.0	0.283		
M1.5	1	1,240	35.0	265	7.50	106	3.00	35.3	1.00		
M2		3,500	99.1	757	21.4	309	8.75	100	2.83		
M2.5	10	12,400	350	2,650	75.0	1,060	30.0	353	10.0		
M3		35 000	991	7,570	214	3,090	87.5	1,000	28.3		
M3.5	100			26,500	750	10,600	300	3,530	100		
M4				75,700	2140	30,900	875	10,000	283		
M4.5	1,000							35,300	1,000	247	7.00
M5								100,000	2,830	618	17.5
M5.5	10,000							353,000	10,000	2,470	70.0
M6								1,000,000	28,300	6,180	175
M6.5	100,000							3,530,000	100,000	24,700	700
M7								10,000,000	283,000		

Particle Detection

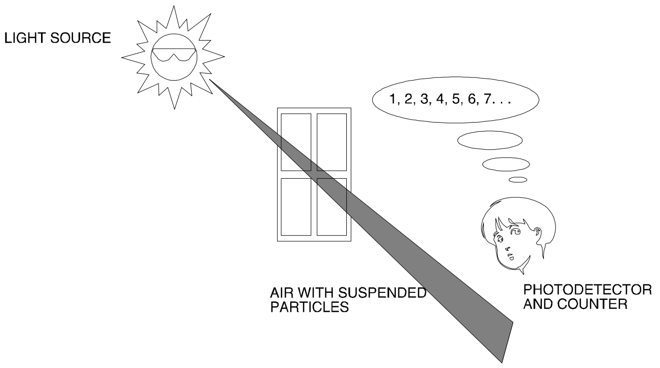
This section describes the most common methods of detecting, counting and measuring particles, and the technology of optical particle counters.

PARTICLE DETECTION

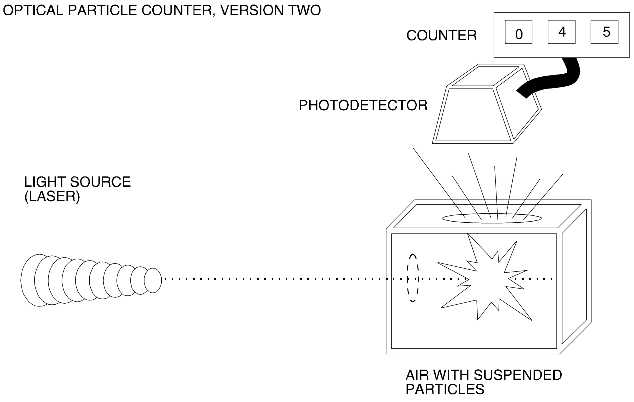
The certification of a cleanroom is an ongoing process. The air quality must be monitored to ensure that the filtration system is working properly and that no unknown particle generators exist.

In the early days of clean manufacturing processes, test filters were examined with a microscope to determine the number and size of the particles that were being removed from the air. Sometimes the person counting the particles could tell what the particles were made of (e.g., copper dust). Microscopy is still the best way to learn certain things about contamination, but is limited by the fact that it is a postcontamination assessment technique.

OPTICAL PARTICLE COUNTER, VERSION ONE



OPTICAL PARTICLE COUNTER, VERSION TWO



In the mid-1950s, the first particle counting machines were invented. These devices made it possible to monitor particle contamination levels during the manufacturing process, allowing quick responses when contamination levels got too high. This increased productivity.

OPTICAL PARTICLE COUNTERS

Most people are familiar with the sight of dust in a sunbeam. Four things are necessary for this: sunlight (to illuminate the dust), dust (to reflect the sunlight), air (to carry the dust), and your eye (to see the dust, or more specifically to see the light reflected by the dust). An optical particle counter (OPC) uses the same principles, but refines them to maximize its effectiveness. In modern particle counters, a laser light source is used, the viewing volume is controlled, and a high-sensitivity photodetector is employed to detect light that the particle scatters.

THEORY OF OPERATION

How a Typical Laser Optical Particle Counter Works
A generic laser optical particle counter consists of five major systems:

1. *Laser light source and optics:* A laser is the preferred light source because its light is a single wavelength (and therefore it is one color—typically red or infrared for particle counters). The first lasers were ruby rods, which were replaced by glass tubes filled with a gas or mixture of gases. Helium-Neon lasers (HeNe, pronounced “heenie”) are the classic example in particle counters. Solid state laser diodes are now the most widely used laser because of their smaller size, lighter weight, and longer MTBF (*Mean Time Between Failures).*

2. *Viewing volume:* The viewing volume is simply a chamber where the laser is aimed. The sample medium (air, liquid, or a gas) is drawn into the viewing volume, where the laser is shined on the medium and any light *scattered* (reflected) by particles is detected by the photodetector.

3. *Photodetector:* The photodetector is an electric device that is sensitive to light. When laser light is scattered, any light that strikes the photodetector causes the photodetector to emit an electric pulse. An amplifier converts the pulse to a control voltage. Larger particles scatter more light, and make bigger pulses.

4. *Pulse height analyzer:* Pulses from the photodetector are sent to a pulse height analyzer. This is a

device that sorts pulses into various size groups, called *bins*.

5. *Black box:* The black box looks at the number of pulses in each bin and turns that into particle data people can use. A computer is often used to display and analyze data.

OBSERVATIONS REGARDING LASER PARTICLE COUNTERS

Observation #1

Particle counters do not directly count particles. They count flashes of light scattered by particles (or shadows cast by backlit particles). This is important, because the amount of light a specific particle scatters or eclipses can vary with several factors, including:

The shape of the particle: Particles in the real world are seldom the smooth, spherical latex particles used to calibrate a particle counter. If that particle floats through the viewing volume sideways, it will scatter a different amount of light than if it went through lengthwise.

The albedo (shininess) of the particle: Some particles are more reflective than others and cause more light to be scattered onto the photodetector. The photodetector produces a larger pulse, and the particle counter thinks it is a bigger particle than it really is. Conversely, some particles are less reflective and trick the particle counter into thinking a smaller particle has passed through the viewing volume.

Observation #2

Particle counters don't count every particle in the room. In fact, depending on the room size, a particle counter in one minute of counting will look at only 1/60000 of the total air in a five thousand square foot cleanroom with a twelve-foot high ceiling. That's only 0.0000166%. In an hour, it will count sixty times that, or 0.001% of the total volume of air/gas/liquid. Because of this, particle counters must be used to provide a statistically valid sample of the air in a cleanroom (or the liquid in a tank, or the gas in a cylinder.) A statistically valid air sample is a sample that is representative of the average air in the rest of the room. Although this sounds simple, problems can arise since particles are never truly diffused (evenly distributed throughout the container, whether the container is a room or a bottle). They tend to stay in laminar flow, they tend to accumulate inside turbulent flow, they tend to stick to surfaces, and they tend to rise in warm air and hang around near the ceiling. Cleanrooms are designed to minimize these particle traps, but they can seldom be eliminated completely.

TYPES OF PARTICLE COUNTERS

There are several varieties of particle counters currently available. The primary differences are related to the medium in which particles are suspended: air, liquid, gas, vacuum or if the particles are deposited on a surface.

Aerosol: The most common particle counters are used to measure contamination in a HEPA-filtered cleanroom.

Liquid: Liquid particle counters are used for everything from drinking water to injectible drugs to transmission fluid to hydrofluoric acid. Some liquid particle counters require an accessory called a *sampler*, which draws a precise volume of liquid and passes it through the particle counter at a specified rate; other counters are simply attached to a pressurized source.

Gas: Some particle counters are designed to count particles suspended in a gas. Gases can be inert or volatile and may be dry (anhydrous) or have water vapor suspended in them.

Vacuum: Some activities performed during semiconductor fabrication occur under vacuum. Particles generated by the fabrication tools and materials are measured with specially-designed particle counters.

Surface: Semiconductors have to be free of surface contamination before the next layer can be added. Optical components, such as lenses and mirrors, have similar requirements. Surface analysis particle counters use lasers to create a kind of topological map of a surface, showing the location, size and shape of particles.

Atmospheric/Meteorological: Particle counters are used to examine atmospheric contamination, in applications like pollution control or weather studies. Some of these instruments measure water droplets, ice crystals or condensation nuclei.

VARIANT TECHNOLOGIES OF PARTICLE COUNTERS

There are several technological variations that can be used in the design of a particle counter. These are dictated by the kind of particle counter, and the task to which it will be applied.

Scattering vs. Extinction

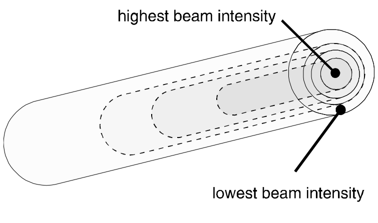
Scattering particle counters measure the amount of light reflected by a particle traversing the beam. *Extinction* particle counters backlight the viewing volume and measure the shadows particles cast on the photodetector.

Volumetric vs. In-Situ

Volumetric particle counters look at all the media that is sampled. *In-Situ* (a Latin phrase meaning ‘in position’) particle counters look at only a small portion of the media that is sampled.

Monitor vs. Spectrometer

As we mentioned before, the intensity of laser light is not uniform throughout the beam. The center of a laser beam is more intense than the edges. *Monitors* use the full width of the laser beam to count particles. *Spectrometers* use only the center of the laser beam. This means that spectrometers are more precise in their ability to measure the size of a particle, because a particle that passes through the edge of the viewed volume scatters as much light as a particle that passes through the center. Depending on the application, a monitor or a spectrometer may be appropriate.



Choosing Between Monitors and Spectrometers:
For a given light intensity, a small particle scatters a small (dim) amount of light and a large particle scatters a large (bright) amount of light.

The intensity of a laser beam is distributed in a bell curve or Gaussian distribution, i.e., it is brightest in the center. (A discussion of Gaussian distribution is presented later in this guide).

Particles that pass through a laser beam do not feel any obligation to keep to the center of the beam. In the ideal world when a particle passes through a laser beam, the flash of light is dim at first when the particle enters the edge of the beam, then brightens as the particle crosses the beam’s center, and then dims again as the particle passes through the far edge of the beam and exits the viewing volume. In the real world, however, particles are just as likely to transit the edge of the beam, resulting in a dim flash.

Unless the “viewed” portion of the laser—the part that is visible to the photodetector—is limited to the center of the beam, it is impossible for the pulse height analyzer to determine if a small electrical pulse was a dim flash caused by a small particle transiting the bright center of the beam or a large particle that only crossed the edge of the beam. Thus, the ability of the particle counter to accurately measure the size of a particle is limited.

Particle *spectrometers* use focusing or masking techniques to limit the viewed portion to only the center of the beam. A spectrometer has a smaller sample volume and flow rate, but provides specific particle sizing data. A spectrometer is the preferred instrument to analyze problems or conduct studies such as filter element testing with a monodispersed particle challenge.

There are plenty of applications where the precise size of a specific particle is of no consequence. For those applications, a particle *monitor* (which views the complete beam) is appropriate. For any given particle size sensitivity, a monitor has a higher flow rate and sample volume. It is the preferred instrument for multipoint monitoring of a dionized (DI) water system or plant and its associated piping system.

CONDENSATION PARTICLE COUNTERS (CPC) AND NONVOLATILE RESIDUE MONITORS (NRM)

All automated particle counting techniques are minimum-sensitivity-limited. The optical techniques discussed thus far cannot detect particles that are smaller than some minimum diameter at which the amount of light scattered by a particle generates a signal that is smaller than the background noise level of the "dark" signal (when no particles transit the laser beam).

There is a method wherein the particles are "grown" to a larger diameter that is sufficient to be detected by the particle counter. A condensation particle counter (CPC) contains a reservoir of volatile liquid such as butyl alcohol. The sample air flows through a warm chamber where alcohol vapor mixes with the sample air. Next, the sample air and alcohol vapor flow through a cold condensing chamber, and the alcohol vapor becomes super-saturated and condenses upon the particles. Particles as small as .01µm will be surrounded by a microscopic droplet of alcohol; typically, all the particle/alcohol droplets will end up at about 1-2µm - a size that is easily detected.

The CPC must be designed so that all excess alcohol diffuses against the walls of the condensing chamber rather than becoming droplets that would add to the particle counts. As with optical particle counters, CPCs with very small minimum detectable particle diameters are more complex and require more maintenance.

One may think that it is always better to count the smallest particles possible, so why not always use CPCs? There are some disadvantages to a CPC vs. an OPC. Someone must periodically refill the alcohol reservoirs, butyl alcohol has an unpleasant odor and non-butyl alcohol CPCs use a fluorocarbon liquid that is expensive. A tipped-over CPC will spill and have no data output until the flooded parts return to normal. In many environments (Class 1,000 or dirtier), a CPC would detect so many particles that it could not count fast enough, and the data would be quite erroneous. Also, unlike an OPC, a CPC cannot report particle size information. Since all particles will grow to the same diameter when using a CPC, it can only report that a particle was detected—it cannot determine what size the detected particle was.

NRMs: Liquids and CPC

The CPC techniques used to increase the sensitivity of aerosol counters also have liquid applications. A nonvolatile residue monitor (NRM) uses an atomizer to turn the sample fluid into droplets. The droplets pass through a heated drying column where each droplet evaporates to leave behind an agglomerate particle of residue material. Dissolved salts, small organic matter and certain inorganic materials such as colloidal silica are invisible when dissolved in liquid and so are undetectable with liquid OPCs. But when the liquid carrying these materials evaporates, the leftover matter appears. This matter is "grown" to a detectable diameter in the CPC.

Of course, as with other forms of optical particle counting an NRM cannot report the chemical makeup of the detected material. Nevertheless, with proper trend analysis NRM data can be used to alert operators to rising amounts of contamination that cannot otherwise be detected without extraordinarily expensive and slow laboratory tests such as atomic absorption spectrometry. NRMs can be extremely useful in, for example, a deionized water plant. Huge savings can be realized by not prematurely replacing filter elements. Carefully scheduling DI bed back-washes can also help reduce product production downtime.

USING PARTICLE COUNTERS

In order to effectively employ a particle counter, it must be handled, installed and used correctly. By doing so, you ensure that the instrument is working correctly and that you are taking statistically valid samples.

Particle counters are not like most of the equipment on your bench. Because a particle counter looks a little bit like an oscilloscope, people tend to treat them like oscilloscopes. But particle counters just are not as simple as most other electronic devices, and they are much more sensitive to environmental stresses like vibration, RMI (radiomagnetic interference), extremes of heat and cold, and dirt. Particle counters are high-performance electronic instruments.

Guidelines for Handling Particle Counters

Unpacking: Most particle counters are manufactured and packaged in a cleanroom. Do not remove the plastic bag the particle counter is wrapped in until the instrument is in the environment where it will be used, especially if it is to be used in a cleanroom. This will minimize the amount of airborne dirt and moisture that can contaminate the optical surfaces. It is also important that you read through the manual *before* you attempt to install the instrument.

Installation: Place the particle counter on a clean, level, flat surface near a source of grounded, conditioned AC power. Avoid placing the instrument in an electrically noisy environment (with lots of voltage spikes from electric motors, relays, transformers, etc.) Electrical noise can cause false particle counts.

Storage: If you ever store your particle counter, wrap it in a plastic bag (before removing it from the clean environment, if it is installed in a cleanroom), seal the bag, and label it with masking tape. Your label should show the type of particle counter, the date and reason it was stored, the serial number and the calibration due date. That way, you can ship it off for recalibration without repackaging it.

Store your particle counter at room temperature (around 70°F/21°C) on a sturdy shelf in a vibration-free environment where it is not likely to be inadvertently damaged by people moving it to get at something else.

Unit file: You should consider keeping a file that shows the date the unit was placed in service, the date recalibration is due, the amount of time it is used, the date any preventive maintenance (optical cleaning, etc.) is performed, any mishaps and any unusual performance noted by operators.

Particle counters need routine maintenance. A typical item is cleaning the optical surfaces. Over time, optical surfaces accumulate dirt that can scatter laser light. This can result in diminished sensitivity and/or false particle counting. To avoid this, follow the instructions that came with your particle counter. On most instruments, cleaning must be performed by the user. Be very careful to follow the directions exactly. If you are unsure of what you are doing, do not proceed. Contact the manufacturer for further instructions.

APPLICATIONS OF PARTICLE COUNTERS

This section describes how to use particle counting equipment and accessories to collect useful information about particles. Before we begin, there are a few concepts common to all particle counters that are useful to know.

Trend Tracking

Once a filtration system is in place and the manufacturing environment is as clean as practically possible, the further reduction of particle contamination is problematic. Fortunately, it is seldom useful to know how many particles are in a room. Particle counters are useful for trend analysis. That is, they watch for gradual or sudden changes in the amount of contamination in an environment. This can tell the operator if there is a filtration problem, or a tool or process is dirty, or if someone left a door or a valve open.

There are more sophisticated applications for particle counters. These will be discussed later, under the heading for each type of particle counter.

Statistically Valid Sample

This concept was discussed earlier, but bears repeating because it is so important. A statistically valid sample is a sample of particle-containing media that is similar in particle content and physical characteristics to the rest of the media.

Data Normalization

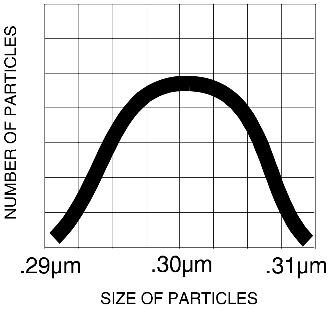
A particle counter draws the sample medium in at a constant flow rate. It then counts the particles in the medium. Because of this, there are two ways to examine the data collected by the particle counter.

Raw counts: The total number of particles counted in a particular size channel is called a raw count. Raw counts do not relate particle counts to sample volume, and thus do not provide a picture of how dirty the sample medium is. This data is useful in some applications, as well as in calibrating the instrument.

Normalized counts: Normalization is the formatting of data to make it useful by giving it context. In particle counting, the total number of particles counted by the particle counter divided by the sample volume is a normalized count.

Bell-Curve Distribution *(Gaussian Distribution)*
Particles in the real world seldom fall neatly into 0.30000µm size bins. Most of what we call 0.3µm particles, in fact, are either a little bigger or a little smaller than 0.3µm. We call 0.3µm the *nominal size* of the particle because it is convenient (instead of calling them, for example, "0.2547µm to 0.3582µm size particles"). The amount that a particle is different from the nominal size is the *variance*. (And the variance is the square of the *standard deviation*).

If you were to precisely measure a number of particles at a nominal size of 0.3µm and then were to graph the results, the graph would look like this:



On this graph, most of the particles are pretty close to 0.30µm. Particles slightly larger or smaller than 0.30µm are fewer in number. Particles that are much larger or smaller than 0.30µm are fewest in number. In a particle counter, particles that fall off the curve end up in the next higher or lower size bin. This is called a *bell-curve* (or *Gaussian*, or *normal)* distribution.

Hardware and Accessories

The following section describes the different kinds of particle counters and their associated hardware and mentions some specific applications or uses for each type of particle counter.

HARDWARE AND ACCESSORIES

Aerosol Particle Counters

Aerosol particle counters are used to detect and measure particle contamination in air. Their typical application is to observe particle contamination trends in clean environments, such as cleanrooms or microenvironments. In addition to room air monitoring, aerosol particle counters can be used to monitor airborne particles inside a large tool.

Another common application is filter efficiency monitoring, where air is sampled immediately before entering and immediately after exiting the filter. The number of influent counts (air going into the filter) is compared to the number of effluent counts (air coming out of the filter). The particle counter can be set up such that a sudden decrease in filter efficiency triggers an alarm.

As with all particle counters, aerosol counters are most effective when they are used to detect changes in contamination trends.

Channel sizes for aerosol particle counters range from 0.05µm at the smallest to several hundred microns at the largest. The number of channels and the size range of each channel may be factory preset or software-controllable, depending on the make and model of particle counter.

One typical application of an aerosol particle counter is to place it on a shelf in a cleanroom and set it to trigger an audible alarm if the level of contamination rises above a preset level. Recall that to take a statistically valid sample, you should sample several points around the room. This can be done by:

- Aerosol Manifold (described below)
- Moving the particle counter from place to place
- Demonstrating that a statistically valid sample can be taken at a single location

Aerosol Manifolds

It is possible for a single aerosol particle counter to take samples of air from many different locations by means of an *aerosol manifold*. An aerosol manifold is a device, usually controlled by the particle counter, that has several incoming air hoses (from the locations where air is sampled) and one outgoing air hose (to the particle counter). The manifold sends the air from one incoming hose at a time to the particle counter. Careful manifold design is necessary to avoid cross-contamination and particle loss in the transport tubes.

Isokinetic Probes

In order to take an accurate sample, an *isokinetic probe* is used at the end of a sample tube. The isokinetic probe captures a sample from moving air (or any fluid) at the same velocity the air is moving. This allows an accurate normalized particle count to be made. Probes that do not capture a fluid while preserving free velocity are said to be *anisokinetic*.

High Pressure Diffuser

A high pressure diffuser adapts an aerosol particle counter to analyze inert pressurized gases.

Environmental Probe

This device measures temperature, relative humidity, room air pressure, air velocity, etc. This data is transmitted to the particle counter and/or the FMS (Facility Monitoring System, discussed later).

Portable Aerosol Counter

This small particle counter that is used to pin-point contamination sources in a cleanroom. They use an isokinetic probe at the end of a hose, and often emit different-pitch tones (like a Geiger counter or metal detector) corresponding to different particle concentrations.

Liquid Particle Counters

Liquid particle counters are used to count particles in almost every kind of liquid, from water to hydrofluoric acid to petrochemicals to injectible drugs. They are often used to monitor filter efficiency or as quality control devices in batch sampling applications.

Liquid Samplers

A liquid sampler is a device that draws a precise volume of a liquid and delivers it at a specific rate to a liquid particle counter. Liquid samplers are often used when unpressurized liquids need to be handled.

Correctly used liquid samplers can prevent *cavitation* or the creation of bubbles. Bubbles are a problem because they can accumulate particles (agglomeration), and because they can be erroneously counted as particles themselves.

Liquid samplers can also reduce or eliminate *effervescence* (bubbling) by compressing the bubbles out of a liquid.

Viewing Modules

Viewing modules for liquids are analogous to those for vacuum particle counters. They allow liquids to be checked for particles without diverting the flow.

Corrosives and Plumbing

In order to count particles suspended in a liquid—especially a corrosive liquid—it is important to choose a particle counter with wetted surfaces that will not dissolve or release toxic gas when the corrosive liquid contacts them.

Particle Measuring Systems (PMS) uses several different optical materials and plastics for the wetted surfaces of liquid particle counters.

Optics:

Fused Silica: a material similar to glass, fused silica is compatible with most chemicals except hydrofluoric acid.

Sapphire: compatible with most chemicals used in the semiconductor industry, including hydrofluoric acid.

Magnesium Fluoride: compatible with most chemicals except ammonium fluoride and hydrogen peroxide.

Plumbing:

PVDF: a plastic used in many sample cells. It is not recommended for long-term use with acetone.

PFA Teflon*:* a plastic used in some sample cells. PFA Teflon is porous to some chemicals. Other materials include *Teflon, KalRez,*(an extremely expensive O-ring material) and *Kel-F.*

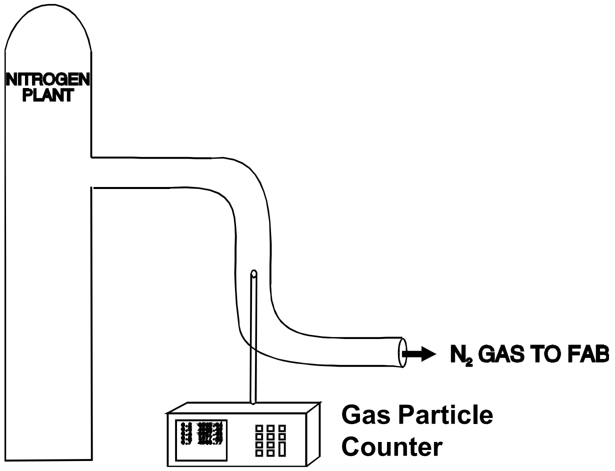
Chemical Compatibility

Before you put any chemical into a liquid particle counter, make sure that (a) the chemical is compatible with the wetted surfaces of the particle counter, liquid sampler, and all accessory plumbing (including the tool plumbing); and (b) that the chemical will not react with any chemical residue from the previous sample.

GAS PARTICLE COUNTERS

Gas particle counters are used to determine the purity of various gases, both inert and corrosive. A gas particle counter is a sort of specialized aerosol particle counter that counts particles under pressure. Some can be used at cylinder pressures; others are suitable for (reduced) line pressures.

Acquiring and analyzing representative samples of gas can be difficult. Common sampling challenges in semiconductor factories include hooking-up the particle counter to the gas supply. Typically, a large plant outside the chip fabrication (fab) facility purifies nitrogen and pumps it to the fab through large-diameter stainless steel pipes.



There are not many particles in semiconductor gas, and the effects of gravity and diffusion can make it hard to capture statistically-valid samples of the few particles that are present. The drawing above shows a gas particle counter mounted below the main nitrogen supply pipe; the sample tube captures gas from the center of the stream—thus avoiding the "boundary layer” at the edge of the flowing gas and providing a more representative sample than would be acquired if the particle counter were simply connected to a tee in the pipe. Usually, additional particle counters are placed near points-of-use, as a final check on gas quality.

PMS field personnel have often encountered gas analysis systems consisting of a homemade high pressure diffuser connected to an aerosol particle counter. High pressure diffusers manufactured by PMS contain many proprietary features that have evolved after prolonged efforts to analyze ultra-clean gas. Almost none of the homemade diffusers work at all. Their failure to zero-count when sampling filtered gas, and the randomness of the particle counts are all problems PMS designers had to overcome before high pressure diffusers were ready to market.

When deciding whether to use a high-pressure gas particle counter or an aerosol counter with high-pressure diffuser (HPD), consider the cost of the gas (HPDs consume more gas than is analyzed), the desired sample flow rate, instrument size, particle size/ instrument sensitivity and local data display options (consult with your particle instrument sales representative).

VACUUM PARTICLE COUNTERS

Vacuum particle counters are used in manufacturing processes that take place under vacuum (in the absence of air or gas); semiconductor manufacturing is the most common example.

Viewing Modules
In order not to break vacuum, it is necessary to count particles non-invasively in the vacuum environment. To accomplish this, a viewing module is installed in the tool plumbing. The viewing module has windows that allow a laser to pass through the viewing volume and also allows scattered light to reach the photodetector. Typically, the viewing module mounts between the process chamber and the pump. Some vacuum particle sensors can be mounted in-situ, that is, directly inside the process environment.

Vacuum particle counters provide the users of “process tools” with valuable data that allows them to plan cleaning of the tools, optimize certain tool operations, and possibly reduce the cost of operating the tools by limiting the number of disposable “witness wafers” used.

SURFACE ANALYSIS SYSTEM

Surface particle counters are designed to measure particle contamination when particles are deposited on a flat surface, such as a silicon wafer substrate, high-precision mirror, precision optical coating, liquid crystal display or witness plate. Surface particle counters are the most demonstrably accurate of all particle counters, because they are capable of counting the same number of particles on a test wafer repeatedly. It is impossible to conduct this test with any other particle counter.

A typical surface particle counting system consists of the particle counter, a robot and a clean environment. The robot takes a component from the manufacturing process and places it in the surface analysis particle counter. The particle counter scans the component and creates a sort of topographical map of the surface, showing the size, shape and number of particles deposited on the surface. The robot then removes the component from the particle counter and places it on the appropriate shelf, which depends on the amount and location of particles that were detected.

Data Integration

This section describes how particle detection and
control technologies work together to manage microcontamination.

DATA INTEGRATION

FACILITY MONITORING SYSTEMS

A facility monitoring system (FMS) is used to allow all of the particle counters, samplers, manifolds, environmental sensors and other microcontamination assessment equipment to communicate with each other and with a central monitoring station. This allows the collection and analysis of particle data, and the correlation of particle counts with events, like a door or valve opening, or a filter failure or a flow reversal in a duct.

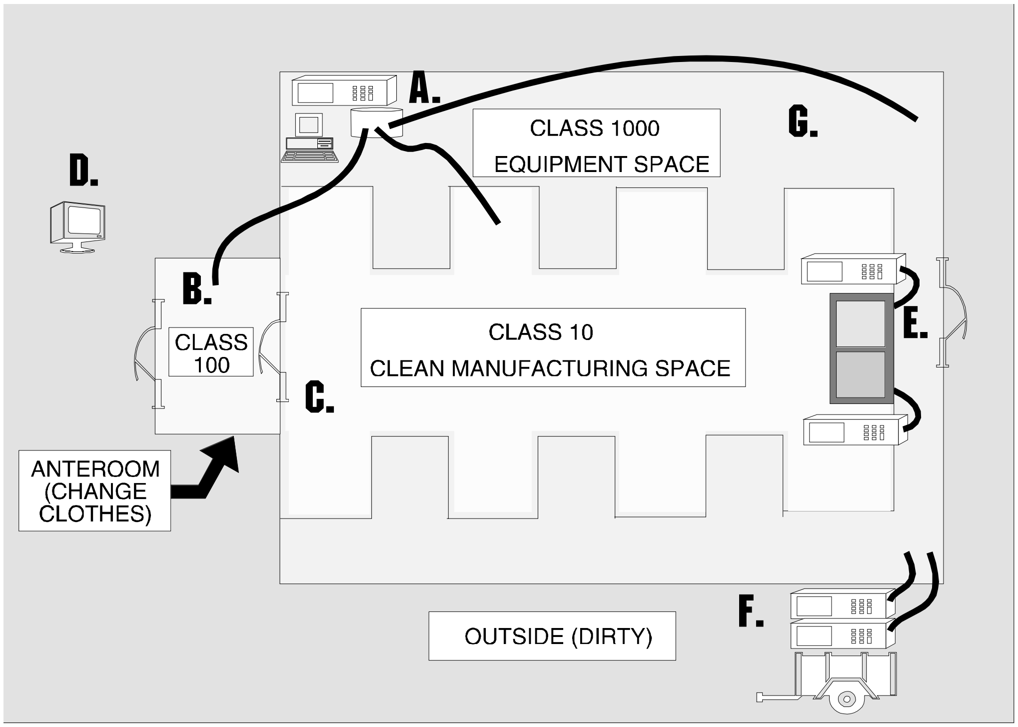
FMS is usually controlled by a computer with special software that allows the operator to observe the system in action. The computer can be configured to trigger alarms, generate reports and analyze data.

A sample manufacturing facility with cleanrooms, particle counters and FMS is shown here. An explanation follows.

A. FMS Computer and Software
Each particle counting device is connected to the FMS computer. The computer serves as a central control station for the particle counters and manifolds, and is a clearinghouse for the data that is collected. The FMS computer can analyze particle data, track particle trends and trigger local and/or remote alarms when preset conditions are met, such as maximum normalized particle counts, minimum temperature, maximum relative humidity, etc. Data can be displayed by remote computers that are connected to the FMS computer.

Aerosol Manifold and Particle Counter: This setup, along with isokinetic probes, is used to monitor the Class 10 and Class 100 cleanrooms along with the Class 1000 equipment space area. An aerosol manifold can be an economical way to monitor many different areas, or to monitor several points in the same area to ensure a statistically valid sample. Aerosol manifolds exhibit a certain amount of particle loss and inter-sample delay, and so are not suitable for all applications. Mixed air sampling can be used to continuously monitor the combined samples before they are sent to the large vacuum pump. This helps overcome the problem of multiplexed ("*muxed*") sampling; the delay between samples does not cause brief events to be missed.

B. Class 100 Cleanroom
Certain assembly, test and packaging operations are conducted in this environment, which is monitored by the aerosol particle counter and aerosol manifold associated with the hardware setup shown at location **A**.



C. Class 10 Cleanroom
Certain assembly, test and packaging operations require greater cleanliness than others. These highly-sensitive operations are conducted in this cleanroom. Monitoring is performed by the hardware setup shown at location **A.**

D. Remote Monitor
This device allows people outside the cleanroom to view particle counts.

E. Etching Acid Bath
In this part of the facility, an acid bath is used to etch the surface of the product. This acid and

its disposal are very expensive, and so the acid is filtered and reused as much as possible. Because of this, the facility manager has chosen to use two liquid particle counters and a corrosive liquid sampler to measure filter efficiency. The amount of particle contamination in the acid prior to filtration is compared to the amount of contamination after filtration, resulting in a measurement of filter efficiency. This helps determine when the filter needs to be replaced and also serves as an alarm if a hole should develop in the filter. It also can sound an alarm if the acid is too dirty to use.

F. HEPA Filter Efficiency Spot Check

An aerosol counter with an isokinetic probe has been mounted on a cart and is used to spot-check HEPA filter efficiency in the facility. Every filter is checked as part of a periodic inspection schedule.

TRANSPORTING PARTICLES THROUGH TUBING

Often it is convenient and sometimes unavoidable, to collect particles in one place and count them in another. This is accomplished by means of a tube or duct. When a sample medium is conducted from the sampling location to a particle counter by means of a tube, two things happen:

- some pressure is lost, and
- some particles adhere to the tubing.

Because of this, it is useful to be familiar with the following information:

Inside Diameter is the diameter of the inside of a round tube.

Reynolds Number is a composite figure that takes into account the shape of the tube, the viscosity of the fluid, the smoothness of the inside of the tube, the straightness of the tube, ambient air pressure, temperature and other factors that affect flow rate inside a tube.

Pressure Loss is the amount that air pressure decreases the farther the air has to travel in the tube. Thus, if air is pumped into a 7mm tube at 10psi, the air pressure at the other end of a 20 meter long tube is 8.6psi.

Gas Velocity is the speed at which gas travels through the line.

PARTICLE LOSS

The following graph depicts particle loss in semi-conductive polyester tubing, 3/8" inside diameter, using a Particle Measuring Systems' 3 CFM aerosol manifold flow rate:

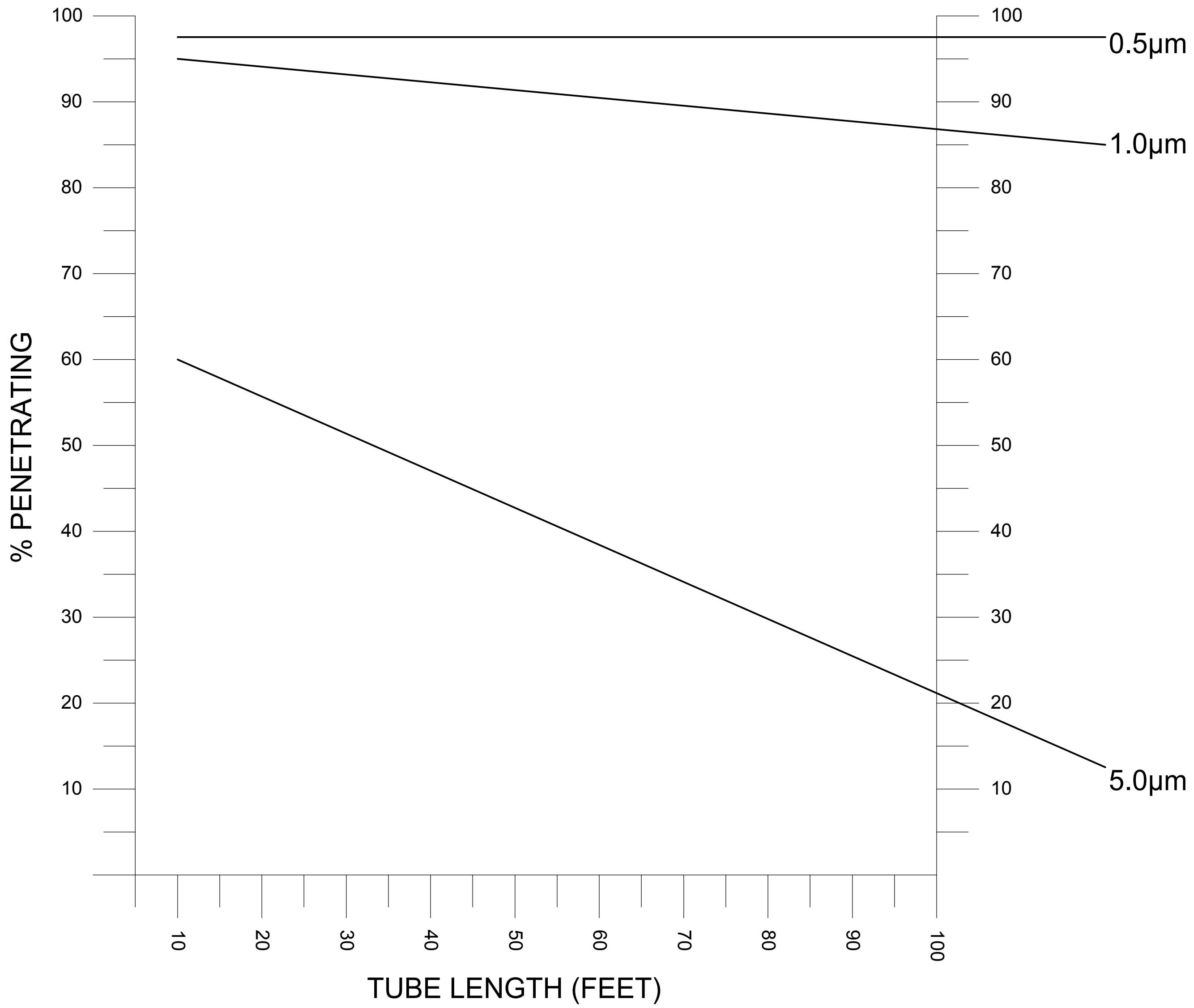
To minimize particle line loss, there are preferred aerosol transport line materials (in order of preference, based on particle loss):

1. Stainless steel
2. Conductive polymer
3. Polyester
4. Vinyl (if plasticizer does not interfere)
5. Polyethylene
6. Copper
7. Glass
8. Teflon
9. Aluminum

Air pressure loss with distance at 3 cubic feet per minute (CFM):

Inside Diameter	Reynolds Number	**Pressure Loss** psi/meter	Gas Velocity m/sec
4mm	9150	0.98	40.35
5mm	7360	0.34	25.9
6mm	6130	0.15	18.0
1/4"	5780	0.11	16.0
7mm	5250	0.07	13.2
8mm (5/16")	4585	0.04	10.1
9mm	4070	0.02	8.0
3/8"	3865	0.016	7.2
10mm	3670	0.013	6.5

accretion (uh-kree'-shun) the



% PENETRATING
100
90
80
70
60
50
40
30
20
10
0.5µm
1.0µm
5.0µm
10
20
30
40
50
60
70
80
90
100
TUBE LENGTH (FEET)

Glossary

GLOSSARY

	tendency for particles to stick together.
aerosol	(air'-uh-sahl) a suspension of particles and water vapor in air.
agglomeration	(uh-glohm'-ur-ay'-shun) the tendency for particles to stick to a gas bubble in liquid.
albedo	(al-bee'-doh) the reflectivity or shininess of a particle.
anhydrous	(ann-high'-druss) lacking water; dry. C.f. *desiccated*
bin	(bihn) an electronic storage place for the electrical pulse generated by a photodetector; sometimes called a "channel."
brownian motion	(brow'-nee-un moe'-shin) the random movement of particles as they collide with each other.
cavitation	(cav-ih-tay'-shun) the formation of bubbles in a liquid, often related to the too-rapid filling of a sample syringe or the movement of a pump impeller.
class	(klahs) the quality of a cleanroom, expressed in the maximum number of 0.5µm particles per cubic foot (or meter, in the SI system); a class 100 cleanroom has no more than 100 0.5µm particles per cubic foot.
cleanroom	(kleen'-room) a manufacturing environment that is designed to minimize particle contamination by use of filters, protocols and design.
collimated	(call'-im-ay-tid) a beam of light focused such that the edges of the beam are parallel.
currents	(kur'-ints) movements of a fluid in a given volume.
desiccated	(dess'-ick-ay-tid) the state of having been dried out. C.f. *anhydrous*.
DI water	(dee'-eye' wah'-tur) de-ionized water; water from which an ion has been removed, making it an aggressive cleaning agent.
diffusion	(dye-fyoo'-zhun) the action whereby particles migrate from an area of greater concentration to an area of lesser concentration.
doublet	(dub'-let) a pair of particles that are stuck together.
electrostatic adhesion	(ee-lek'-tro-stat'-ik ad-hee'-zhun) the tendency of particles to stick to things as a result of static electricity.
extinction	(eks-tink'-shun) technique of particle counting based on backlighting the viewing volume and analyzing the shadows cast by particles.
Federal Standard 209	(fed'-rul stahn'-durd too' oh' nyne') a set of US Government regulations that defines how cleanrooms are classified; see *class*.

fluid	(floo’-ihd) any liquid or gas.
FMS	(eff’-emm’-ess’) Facility Monitoring System: a system of computer hardware, software and cables that allows all particle counting equipment in a facility to be monitored and controlled from a single location.
HEPA filter	(hep’-uh fil’-tur) High Efficiency Particulate Air filter.
hydrated	(high’-dray-tid) wet or moist. C.f. *desiccated*.
in-situ	(in-sit’-oo) a class of particle counter that looks at a small portion of the sample volume.
inert	(in-urt) nonliving; dead. C.f. *viable*
inorganic	(in’-oar-gahn-ik) not from an organic source (animal or vegetable).
laminar flow	(lahm’-inur) in fluids, a smooth, layered flow. C.f. *turbulent flow*.
laser	(lay’-zur) a device that generates high-intensity coherent light.
liquid	(lick’-wid) a fluid that is not gaseous or solid.
microcontamination	(my-crow-cuhn-tahm-in-ay-shun) particles that are detrimental to a manufacturing process.
minienvironment	(my-crow-in-vuy-run-mint) a miniature cleanroom.
micron	(my’-krahn) truncated form of the word *micrometer,* (my-crow-meter) unit of measure equal to 10^{-6} meter (1/1000 of a millimeter.) Symbol: µm. Incidentally, micrometer is not the same word as that used for calipers that are capable of very precise measurement, called a *micrometer* (my-crahm’-ih-tur)
monitor	(mahn’-ih-tur) a type of particle counter that uses the full laser beam width to count particles. C.f. *spectrometer.*
MTBF	(emm’-tee’-bee’-eff’) Mean Time Between Failures; the time in hours an electronic component or piece of equipment is likely to function before it breaks down.
normalization	(noar’-mul-eye-zay’-shun) the formatting of data to make it useful by giving it volume context.
organic	(oar-gahn’-ik) arising from living matter, either animal or vegetable. C.f. *inorganic*
particle counter	(pahrt’-ih-kul koun’-tur) a device that counts particles.
particles	(pahrt’-ih-kulz) very small pieces made of diverse substances.
photodetector	(foe-toe-dee-tek-tur) a device that detects light.

pulse height analyzer	(pulhs’ hyte’ an’-uh-ly’-zur) a device that measures electronic pulses. Abbreviation: PHA
raw counts	(raw kountz) particle counts that are not normalized.
RMI	(arr’-emm’-eye’) Radiomagnetic Interference, a common form of ambient electrical noise. Also called EMI, EMR.
scattering	(skaht-tur-ing) the reflection of light by a particle transiting a laser beam. One method of optical particle counting. C.f. *extinction.*
spectrometer	(speck-trohm’-ih-tur) a type of particle counter that uses only the center of the laser beam to count particles.
statistically valid sample	(stuh-tiss’-tik-lee vah’-lid sam’-pul) a sample whose particle content is representative of the (unsampled) rest of the volume.
thermal variation	(thurm’-ul vair-ee-ay’-shun) temperature irregularities in a volume of fluid that contribute to the fluid’s movement.
trend tracking	(trend trahk’-ing) the use of a particle counter to follow long-term trends in microcontamination within a given volume.
turbulent flow	(tur’-byoo-lint) nonsmooth movement of a fluid. C.f. *laminar flow*.
ULPA filter	(uhl-puh) Ultra Efficiency Particulate Air filter.
vacuum	(vack’-yoom) the absence of gas or liquid in a given volume.
viable	(vie-uh-bul) living. C.f. *inert*.
viewing module	(vyoo’-ing mahd’-yool) a device with windows that is installed in a conduit. This allows a laser beam to shine through it and a photodetector to measure the scattered light, allowing particle counting in sealed ducts and pipes.
volumetric	(vohl’-yoo-met’-rik) a type of particle counter that examines the entire sample.
witness plate	(witt’-niss playt) a test surface placed in a clean environment that collects particles for later measurement.