Pall Corporation

Scientific & Technical Report WER 5300

Principles of Filtration

Filtration. Separation. Solution.SM

Principles of Filtration

Introduction

Filters play an important role in any industrial society. Filtration is the separation of particles from a fluid (liquid or gas) by passage of that fluid through a permeable medium.[1] When the particles represent a significant proportion of the fluid, the process may be described as bulk solids collection. When the particles represent only a very small proportion of the total (0.01% or less), the process is called fluid clarification.

In most cases, Pall filters are used to remove particles ranging in size from fractions of a micrometer to 40 plus micrometers. The smallest pencil dot that can be seen by the unaided eye is approximately 40 micrometers in diameter. For those who think in terms of the metric system, a micrometer is 1 / 1000 of a millimeter which is approximately one twenty-fifth of an inch. To translate directly into inches,

one micrometer = $\frac{\text{inch}}{25{,}400}$ = 0.000039 inches.

"Micron" is the commonly used shortened form for micrometer, and its symbol is µm.

See References at end of paper.

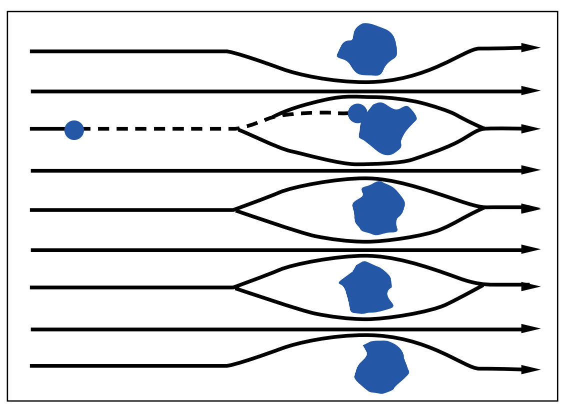
Filtration Processes

Suspended solids are separated from fluids via three mechanisms: inertial impaction, diffusional interception and direct interception. While these mechanisms of filtration are operable, the relative importance and role of each changes. Both inertial impaction and diffusional interception are much less effective with liquids than with gases. Since the density of a particle will typically be closer to that of a liquid than to that of a gas, deviation of a suspended particle from the liquid flow line is much less, and thus *impaction* on the structure of the medium is less likely. Moreover, impaction in many systems is not followed by adhesion of the particles to the surface of the filter medium. Diffusional interception in liquids occurs to only a very limited extent because Brownian Motion is not nearly as pronounced in liquid suspensions as in gaseous suspensions.

1. Inertial Impaction

Particles in a fluid stream have mass and velocity and, hence, have a momentum associated with them. As the liquid and entrained particles pass through a filter media, the liquid stream will take the path of least resistance to flow and will be diverted around the fiber. The particles, because of their momentum, tend to travel in a straight line and, as a result, those particles located at or near the center of the flow line will strike or impact upon the fiber and be removed. Figure 1 illustrates this process. The fluid stream, shown as solid lines, flows around the filter fibers while the particles continue along their path, shown as

Figure 1 Inertial Impaction



dashed lines, and strike the fibers. Generally, larger particles will more readily deviate from the flow lines than will small ones. In practice, however, because the differential densities of the particles and fluids are very small, deviation from the liquid flow line is much less and, hence, inertial impaction in liquid filtration plays a relatively small role.

Figure 2
Diffusional Interception

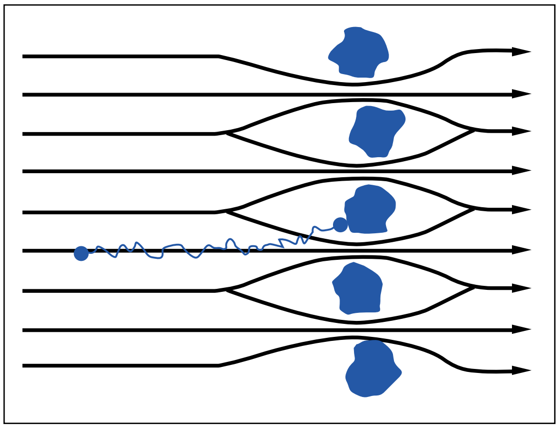
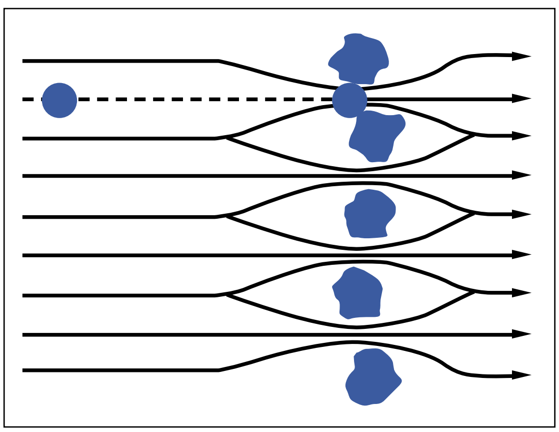


Figure 3
Direct Interception



2. Diffusional Interception

For particles that are extremely small (i.e., those with very little mass), separation can result from diffusional interception. In this process, particles are in collision with the liquid molecules. These frequent collisions cause the suspended particles to move in a random fashion around the fluid flow lines. Such movement, which can be observed microscopically, is called "Brownian Motion." Brownian Motion causes these smaller particles to deviate from the fluid flow lines and, hence, increase the likelihood of their striking the fiber surface and being removed. Figure 2 shows the particle flow characterized by Brownian Motion and impacting the filter fibers. As with inertial impaction, diffusional interception has a minor role in liquid filtration. This results because of the inherent nature of liquid flow which tends to reduce the lateral movement or excursions of the particle away from the fluid flow lines.

3. Direct Interception

While inertial impaction and diffusional interception are not as effective in liquid service as in gas service, direct interception is equally as effective in both and is the desired mechanism for separating particles from liquids. In a filter medium, one observes not a single fiber, but rather an assembly of a large number of such fibers. These fibers define openings through which the fluid passes. If the particles in the fluid are larger than the pores or openings in the filter medium, they will be removed as a result of direct interception by the holes. Figure 3 portrays this removal mechanism. Direct interception is easily understood in the case of a woven wire mesh filter with uniform pores and no thickness or depth; once a particle passes through an opening, it proceeds unhindered downstream. Yet such a filter will collect a very significant proportion of particles whose diameter is smaller than the openings or pores of the medium. Several factors that help account for this collection are outlined below and illustrated in Figure 4.

- In the real world most suspended particles, even if quite small when viewed from some directions, are irregular in shape and, hence, can "bridge" an opening.
- A bridging effect can also occur if two or more particles strike an opening simultaneously.
- Once a particle has been stopped by a pore, that pore is at least partially occluded and, subsequently, will be able to separate even smaller particles from the liquid stream.
- Specific surface interactions can cause a small particle to adhere to the surface of the internal pores of the medium. For example, a particle considerably smaller than a pore is likely to adhere to that pore provided the two surfaces are oppositely charged. Moreover, it is sometimes not necessary that they be oppositely charged. A very strong negatively charged

filter surface can cause a positive charge to be induced on a less strongly charged negative particle. There can also be other types of interactions such as "hydrogen bonding."

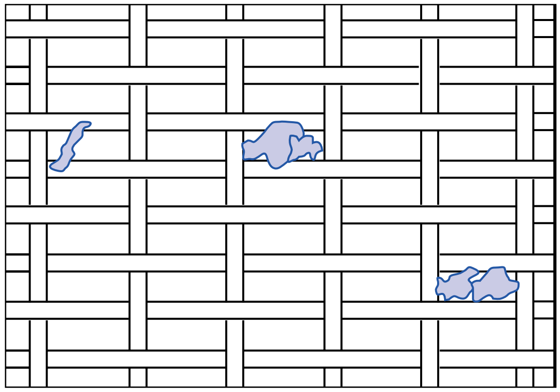


Figure 4
Removal Mechanisms for Particles Smaller Than the Pores of the Medium

Direct interception can also obviously occur in filters in which the pore openings are not uniform but instead vary in size (but within carefully controlled limits) throughout the thickness of the filter medium, resulting in a tortuous flow path. Filters of this type include membranes,[2] Pall's HDC® II medium, Pall's Ultipor® glass fiber filters, and cellulosic paper filters.

Membrane filters like screen-type filters collect particles smaller than their absolute removal rating by the four means previously mentioned. However, the fact that the medium contains pores smaller than the absolute removal rating size further enhances the possibility of particles smaller than this rating being removed from the fluid stream by direct interception.

4. Particle Release Under "Impulse" Conditions

We have established that there are numerous methods by which a filter can collect particles smaller than its absolute removal rating. Under certain conditions, a portion of these finer particles can be released and pass downstream. For example, if a wire mesh screen filter has collected particles smaller than its pore openings at a low, steady rate of liquid flow, and the flow rate is then increased many fold, some of these smaller particles will probably be released downstream. To test for such release, "impulse" (rapidly varying) flow conditions can be deliberately set up, and particles so released collected downstream by a finer filter for counting and inspection.

Even if the buildup in pressure is gradual and not that great, release of collected particles is likely to occur if the structure of the medium is such that the pore dimensions can enlarge. Those commercially available filters prone to this type of malfunction are the so-called "wound" and similar fibrous types in which numerous poorly supported fibers are present which move as pressure builds.

To summarize, every type of filter will collect particles finer than its absolute rating, and under extreme impulse conditions such finer particles may release. Filters in which the structural portions of the medium are free to move in response to increased pressure are particularly prone to this occurrence, and they may even release downstream particles larger than their pore size.

In a well designed filter, particles larger than the pore size do not pass downstream of the medium. The most successful approach to zero particle release is achieved by using a filter medium in which the pores will not enlarge under pressure and in which the thickness is sufficient so that in normal service substantially all the incident particles are collected in the first tenth to fifth of the thickness, leaving the rest available to stop undersize particles which may be released from the upper layer on impulse.

5. Aids to Liquid Filtration

It is possible to supplement the three principal mechanisms of filtration, and to enhance a filter's effectiveness in removing particles from a liquid. Several methods will be discussed briefly.

A. Electrostatic Deposition

Most particles carry a negative charge. The fibers of the medium often carry charges that can affect both particle removal efficiency and/or particle retention efficiency of the filter. It is possible, therefore, to enhance the particle capture mechanisms of a filter by inducing a desired charge (usually positive) on the fiber.[3] Figure 5 illustrates a typical particle-fiber interaction based upon differences in zeta potential. The particle has a negative surface charge associated with it resulting from a double ionic layer formed on the particle surface. The clear circles are positive ions while the dark circles are negative ions. The filter media has an induced positive zeta potential which can then promote particle adherence.

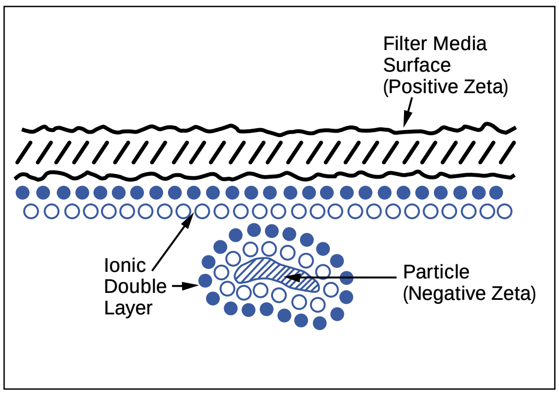


Figure 5
Zeta Potential Particle-Fiber Interaction

The intensity of charge of both the particle and the fiber is important. In general, as the charge intensity increases and particle size decreases, capture efficiency will increase. The obvious effect of a charged filter surface is the ability to remove very fine sized particles by a medium having relatively large pores, very often at low pressure drops and high dirt holding capacity.

One must use great caution when seeking to aid the filtration of liquids through electrostatic deposition, however. A charge is often unstable and influenced by pH of the contacting fluid, the passage of ionized gases, radiation, time, humidity, and the deposition of charged particles. Consequently, predictability of particle capture efficiency is poor and should be determined empirically.

B. Flocculation

Very fine size particles are difficult to filter. One way to enhance filterability is to cause them to "clump" together to form larger particles that are easier to filter and usually produce filter cakes which result in less pressure drop and, in consequence, an increase in throughput. Flocculation of particles by the addition of polyelectrolytes (long chain molecules with many positive and negatively charged ionic points along the chain length) to the fluid system is a common practice. Polyelectrolytes (e.g., soluble starches, gelatin, and derivatives of polyacrylates) attach themselves to many oppositely charged particles in the liquid causing their agglomeration and increasing their settling rate. They should be selected empirically for each fluid process. Figure 6 summarizes the basic flocculation process.

In everyday practice, the polyelectrolyte is dissolved and a very small quantity is added to a much larger volume of the suspension of solids to be flocculated. Agitation must be optimum for the system – sufficient to disperse the polyelectrolyte but not too strong as to rupture the flocs. Continued agitation can decrease the flocculation and increase the amount of "haze" present. Air pressure, or a non-shearing pump is preferred for moving the flocculated material to the filter so as not to cause deflocculation. Recirculation of the suspension should also be avoided for the same reason.

Whether or not a polyelectrolyte can be used in a filter process depends on its performance, cost, and adulterating effect.

Figure 6 Flocculation Process

The Use of Polyelectrolytes, Large Molecules with Multiple Ionic Sites of Different Charge Than the Zeta Potential of the Particle, Which Actually Binds Particles Together to Form Aggregates.

TYPE	STRUCTURE
CATIONIC	$[\text{-CH-}]_n$ | ⊕N(R)$_3$
ANIONIC	$[\text{-CH-}]_n$ | C // \\ O ⊖ O
NONIONIC	Both Types of Charge With Overall Neutrality

C. Filter Aids

The ease with which fine size particles can be removed from a liquid stream can also be increased by the addition to the suspension of small amounts of filter aids. This is known as a "body feed" or "body aid," and should not be confused with precoat filtration where filter aid is first deposited on a filter and the suspension then caused to flow through. As in the case with flocculation, the purpose of the filter aid is to achieve the desired cake permeability.

Perhaps the most commonly used filter aid is diatomaceous earth, which consists of the sedimentary deposits of fossilized diatoms. The diatom skeletons have a wide variety of shapes, and it is this property which enables them to produce filter cakes of high permeability. Other filter aids include perlite (an igneous rock formed by the quenching of molten volcanic lava in water), carbon, and cellulose.

Filter aid filtration is not common in fluid clarification but, when used, is often found upstream of cartridge filtration. Cartridge filters are used as "trap" filters downstream of precoat filters to capture any filter aid which may "bleed" past the filter medium.

Filter Types

In recent years it has become increasingly common to classify filters and filter media as either "depth type" or "surface type." Unfortunately, filter manufacturers have been unable to agree upon an "official" definition of the terms. As a result, much misunderstanding is encountered in the field on this subject. The purpose of this section is to separate fact from fiction respecting this matter.

1. Non-Fixed Random Pore Depth Type Media

Non-fixed random pore depth type media depend principally on the filtration mechanisms of inertial impaction and/or diffusional interception to trap particles within the interstices or spaces of their internal structure. Examples of this type of media are felts, woven yarns, asbestos pads, and packed fiberglass. Such filters are constructed of non-fixed media of a thickness sufficient to trap particles in a given size range on a finite statistical basis.

As noted earlier, release of collected particles is likely to occur if the structure of the medium is such that pore dimensions can enlarge as the pressure drop increases. Also, every type of filter will collect particles finer than its pore size but under impulse conditions these finer particles are more likely to be released by a filter whose pores can enlarge.

This is always a problem with non-fixed random pore depth type media. Such media contain many tortuous passages, and there are many paths through which fluid can flow. Naturally, the small passages become blocked first, resulting in more and more flow being taken by the large passages. Since the structure of the medium is not an integral one, increased pressure on the large passages can cause the medium to separate, thereby widening the passages. It should be obvious that channeling of this nature adversely affects the performance of the filter.

Non-fixed random pore depth type filters depend not only on trapping but also on adsorption to retain particles. As long as the dislodging force exerted by the fluid is less than the force retaining the particle, the particle will remain attached to the medium. However, when such a filter has been onstream for a length of time and has collected a certain amount of particulate matter, a sudden increase in flow and/or pressure can overcome these retentive forces and cause the release downstream of some of the particles. This unloading will frequently occur after the filter has been in use for some time and can give the false impression of long service life for the filter.

Furthermore, most non-fixed random pore depth type filters are subject to media migration. This means that parts of the filter medium become detached and continue to pass downstream contaminating the effluent (fluid that has passed through the filter). Media migration is also sometimes incorrectly taken to include release of "built-in" contamination – for example, dust and fibers picked up by the filter during its manufacture.

2. Fixed Random Pore Depth Type Media

Fixed random pore depth type filters consist of either layers of medium or a single layer of medium having depth, depend heavily on the mechanism of direct interception to do their job, and are so constructed that the structural portions of the medium cannot distort and that the flow path through the medium is tortuous. It is true that such filters retain some particles by adsorption as a result of inertial impaction and diffusional interception. It is also true that they contain pores larger than their removal rating. However, pore size is controlled in manufacture so that quantitative removal of particles larger than a given size can be assured. Moreover, by providing a medium with sufficient thickness, release of particles collected that are smaller than the removal rating can be minimized, even under impulse conditions.

3. Surface Type Media

In the strict definition of the term, a surface or screen filter is one in which all pores rest on a single plane, which therefore depends largely upon direct interception to separate particles from a fluid. Only a few filters on the market today (for example; woven wire mesh, woven cloth, and a membrane filter manufactured by Whatman Nuclepore) qualify as surface filters.

Naturally, a surface or screen filter will stop all particles larger than the largest pore (provided, of course, the structure of the medium is an integral one). While particles smaller than the largest pore may be stopped because of factors previously discussed (bridging, etc.), there is no guarantee that such particles will not pass downstream. Woven wire mesh filters are currently available with openings down to 8 micrometers.

4. Summary of Filter Types

Upon reviewing the above information, it should become apparent that classifying filters as depth or surface is meaningless. Nearly all filters exhibit "depth" when viewed under a microscope.

A more meaningful classification of filters is as follows:

- Non-fixed random pore depth type with pores whose dimensions increase at high pressure ("wound," low density felted).
- Fixed random pore depth type with pores which do not increase in size at high pressures (most membrane filters, including Pall's Nylon 66 and Ultipor® membranes, Pall HDC® II polypropylene, Ultipor glass fiber, and Epocel® epoxy impregnated cellulose filters).
- Screen Type (woven cloth or screens).

The fixed random pore depth type filter is superior for most purposes when compared with the screen type. It combines high dirt capacity per unit area with both absolute removal of particles larger than a given size and minimum release of collected particles smaller than this rated size under impulse conditions.

Non-fixed random pore depth type filters have no absolute ratings, are subject to media migration, and unload particles very badly on impulse. Comparison of dirt capacity between fixed pore and non-fixed pore depth types is meaningless because the nominal removal ratings of non-fixed pore depth type filters bear little relationship to their behavior in service.

If it matters little whether a filter is surface type or depth type, how should one judge filters? Only two questions should concern the filter user. Is the filter subject to unloading, channeling, or media migration? If so, then for most applications it's probably unwise to use the filter. If not, then look to the second question: Can the manufacturer guarantee that the filter will reliably remove all particles that should be removed from the fluid in question, and is the filter safe to use?

Removal Ratings

Various rating systems have been evolved to describe the filtration capabilities of filter elements. Unfortunately, there is at the moment *no generally accepted rating system* and this tends to confuse the filter user. Several of the systems now in use are described below.

1. Nominal Rating

Many filter manufacturers rely on a Nominal Filter Rating which has been defined thusly by the National Fluid Power Association (NFPA): "An arbitrary micron value assigned by the filter manufacturer, based upon removal of some percentage of all particles of a given size or larger. It is rarely well defined and not reproducible." In practice, a "contaminant"[4] is introduced upstream of the filter element and subsequently the effluent flow (flow downstream of the filter) is analyzed microscopically. A given Nominal Rating of a filter means that 98% *by weight* of the contaminant above the specified size has been removed; 2% by weight of the contaminant has passed downstream. Note that this is a gravimetric test rather than a particle count test. Counting particles upstream and downstream is a more meaningful way to measure filter effectiveness.

The various tests used to give non-fixed random pore depth type filters a Nominal Rating yield results that are nebulous if not misleading. Typical problems are as follows:

A. The 98% contaminant removal by weight is determined by using a specific contaminant at a given concentration and flow. If any one of the test conditions are changed, the test results could be altered significantly.

B. The 2% of the contaminant passing through the filter is not defined by the test. It is not uncommon for a filter with a Nominal Rating of 10 µm to pass particles downstream ranging in size from 30 to over 100 microns.

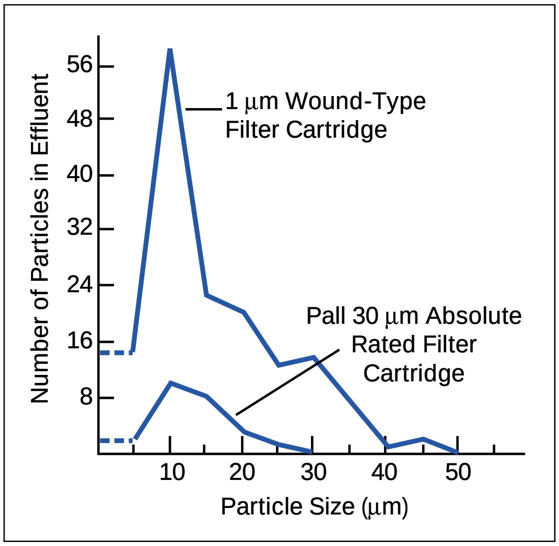
C. Test data are often not reproducible, particularly among different testing laboratories.

D. Some manufacturers do not base their Nominal Rating on 98% contamination removal by weight but instead on a contamination removal efficiency of 95%, 90%, or even lower. Thus, it often happens that a Pall filter with an Absolute Rating of 10 µm is actually finer than a competitive filter with a Nominal Rating of 5 µm. Always check the criteria upon which a competitor's Nominal Rating is based.

E. The very high upstream contaminant concentrations used for such tests are not typical of normal system conditions and produce misleading high efficiency values. It is common for a wire mesh filter medium with a mean (average) pore size of 17 µm to pass a 10 µm nominal specification. However, at normal system contamination concentrations, this same filter medium will pass *almost all* 10 µm size particles.

One cannot, therefore, assume that a filter with a Nominal Rating of 10 µm will retain all or most particles 10 µm or larger. Yet some filter manufacturers continue to use *only* a Nominal Rating both because it makes their filters seem finer than they actually are, and because it is impossible to place an Absolute Rating on a non-fixed random pore depth type filter. Figure 7 compares a 1 µm nominal rated wound type cartridge to a Pall 30 µm absolute rated cartridge. The graph shows that the effluent stream from the 1 µm nominal cartridge contains particles up to 50 µm in diameter while the effluent stream from the 30 µm absolute rated cartridge contains no particles larger than 30 µm.

Figure 7 Comparison of Filter Cartridge Removal Ratings



2. Absolute Rating

The NFPA defines Absolute Rating as follows: "The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. It is an indication of the largest opening in the filter element." Such a rating can be assigned only to an integrally bonded medium (such as Pall's fixed pore depth media or sintered metal media).

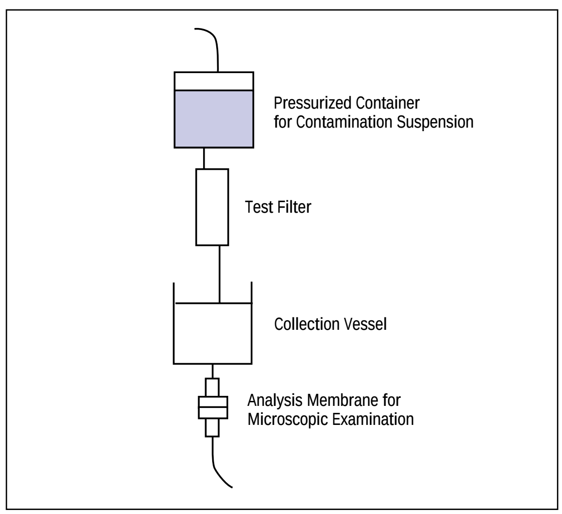
The original test and term for the Absolute Filtration Rating was proposed by Dr. Pall, founder of Pall Corporation, in the mid-1950s. It was considered by the Filter Panel of SAE Committee A-6 and with minor changes subsequently adopted.

One point that confuses users of absolute rated filters is that when measuring downstream contamination, contaminants larger than the pore size indicated by the Absolute Rating are invariably found. At first glance, this would seem to cast doubt on the very concept of an "absolute" rating. However, one must realize that it is impossible to take effluent samples, transfer them, run the test, or wash out a newly manufactured filter without adding a quantity of contaminants. Even a new filter is contaminated when it is removed from its packing! All of this is called "background contaminant" and before running any test an experienced laboratory will have determined the amount of such contamination in its test setup. A test will be invalidated if the background contamination count is above established limits.

There are several recognized tests for establishing the Absolute Rating of a filter. What test is used will depend on the manufacturer, on the type of medium to be tested, or sometimes on the processing industry. In all cases the filters have been rated by a "challenge" system. A filter is challenged by pumping through it a suspension of a readily recognized contaminant (e.g., glass beads or a bacterial suspension), and both the influent and effluent examined for the presence of the test contaminant.

Such challenge tests are destructive tests – i.e., the challenged filter cannot be used thereafter in actual service. Consequently, integrity tests for for filters have been established which are non-destructive and correlate with the destructive qualification challenge test. In other words, if the test filter was successfully integrity tested by the non-destructive test, that would mean it would pass the destructive challenge test. However, after passing the integrity test, the filter element can be placed in service and will provide the user with the results claimed by the filter manufacturer.

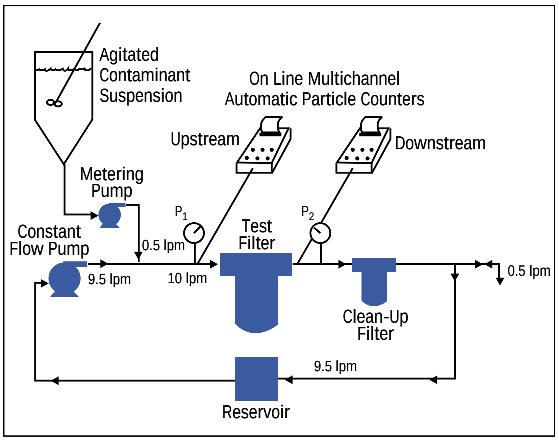
Figure 8 Schematic Representation of Glass Bead Challenge Test Apparatus



3. Glass Bead Challenge Test

One method of establishing the Absolute Rating of a filter is the Glass Bead Challenge Test as depicted in Figure 8. A suspension of glass beads (all lying within a specific size range) is passed through a filter and collected downstream on an analysis membrane. Glass beads are used because their spherical shape makes them easy to differentiate from background contamination that may be generated during the test. Those glass beads which pass the filter are then examined under a microscope to determine the largest spherical glass bead passed. This will establish the filter's Absolute Rating.

Figure 9 Schematic Representation of Single Pass Beta (β) Test Apparatus



4. Beta (β) Rating System

While absolute ratings are clearly more useful than nominal ratings, a more recent system for expressing filtration rating is the assignment of Beta ratio values. Beta ratios are determined using the Oklahoma State University, "OSU F-2 Filter Performance Test." The test, originally developed for use on hydraulic and lubricating oil filters, has been adapted by Pall Corporation for rapid semi-automated testing of filters for service with aqueous liquids, oils, or other fluids.

The Beta rating system is simple in concept and can be used to measure and predict the performance of a wide variety of filter cartridges under specified test conditions.

The basis of the rating system is the concept of titer reduction. If you measure the *total particle counts at several different particle sizes,* in both the influent stream and effluent stream, a profile of removal efficiency emerges for any given filter. Figure 9 shows a single pass Beta test apparatus.

The Beta value is defined as:

$$\beta = \frac{\text{Number of particles of a given size and larger in the influent}}{\text{Number of particles of a given size and larger in the effluent}}$$

Percent removal efficiency at a given particle size can be obtained directly from the β value and can be calculated as follows:

$$\text{\% Removal Efficiency} = \frac{\beta - 1}{\beta} \times 100$$

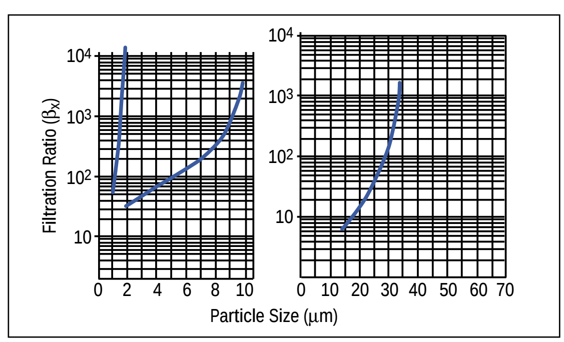
The relationship between β values and percent removal efficiency is illustrated below.

β	% Removal
1	0
2	50
10	90
100	99
1000	99.9
5000	99.98
10000	99.99
100000	99.999

Usually a β = 5,000 can be used as an operational definition of an absolute rating.

The β values allow the comparison of removal efficiencies at different particle sizes for different cartridges in a meaningful manner. Figure 10 illustrates typical Beta curves for three different cartridges. Beta curves are part of all Pall published literature.

Figure 10 Typical Beta (β) Curves



Among the more important factors that must be taken into consideration when choosing a filter for a particular application are the size, shape, and hardness of the particles to be removed, the quantity of those particles, the nature and volume of fluid to be filtered, the rate at which the fluid flows, whether flow is steady, variable and/or intermittent, system pressure and whether that pressure is steady or variable, available differential pressure, compatibility of the medium with the fluid, fluid temperature, properties of the fluid, space available for particle collection, and the degree of filtration required. Let us now examine how some of these factors affect filter selection.

1. Nature of Fluid

The materials from which the medium, the cartridge hardware, and the housing are constructed must be compatible with the fluid being filtered. Fluids can corrode the metal core of a filter cartridge or a pressure vessel, and the corrosion will in turn contaminate the fluid being filtered. Thus it is essential to determine whether a fluid is acid, alkali, aqueous, oil or solvent based, etc.

2. Flow Rate

Flow rate (the units of measure of flow rate are given as volume per unit time – e.g., ml/min., or liters/hr., or gallons/min.) is dependent on two general parameters, pressure [P] and resistance [R]. Flow rate depends directly on pressure and inversely on resistance. Thus, for a constant [R], the greater the pressure, the greater the flow. For a constant [P], the lower the resistance, the greater the flow.

Pressure can come from any number of sources and is usually expressed as pounds per square inch (psi). All other factors being equal, if the pressure on a fluid is increased, then the flow rate of that fluid will increase.

Viscosity is the resistance of a fluid to the motion of its molecules among themselves; in other words, a measure of the thickness or flowability of a fluid. Water, ether, and alcohol have low viscosities; heavy oils and syrup have high viscosities. Viscosity affects resistance directly. If all other conditions remain constant, doubling the viscosity in a filter system gives twice the original resistance to flow. Consequently, as viscosity increases, the pressure required to maintain the same flow rate increases. Centipoise is the unit of measurement comparing the viscosity of a fluid with that of water which has a viscosity of 1 centipoise at 70°F/21°C.

3. Temperature

The temperature at which filtration will occur can affect both the viscosity of the fluid, the corrosion rate of the housing, and filter medium compatibility. Viscous fluids generally become less viscous as temperature increases. If a fluid is too viscous, it may be advisable to preheat the fluid and to install heater bands in the filter. Thus, it is important to determine the viscosity of a fluid at the temperature at which filtration will occur.

High temperature also tends to accelerate corrosion and to weaken the gaskets and seals of filter housings. Very often disposable filter media cannot withstand high temperatures, particularly for prolonged periods of time. It is for this reason that one must often choose porous metal cleanable filters.

4. Pressure Drop

Everything a fluid passes through or by contributes resistance to the flow of that fluid in an additive fashion. The pressure losses due to flow of the fluid through the tubing, piping, etc., couples with the pressure loss through the filter to produce resistance.

Resistance to flow through a clean filter will be caused by the filter housing, cartridge hardware, and the filter medium. For a fluid of given viscosity, the smaller the diameter of the pores or passages in the medium, the greater the resistance to flow.

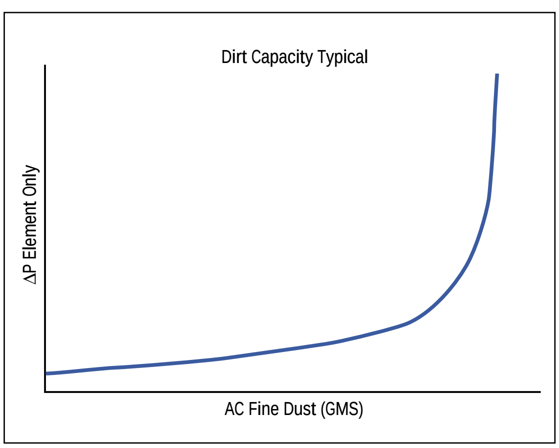
When a fluid meets resistance in the form of a filter, the result is a drop in pressure downstream of that filter, and the measurement of the pressure drop across the filter is called the differential pressure or ΔP. Thus, for all practical purposes the terms pressure drop, differential pressure, and ΔP are synonymous.

The more resistance a filter medium offers to fluid flow, the greater the differential pressure at constant flow. Since flow is always in the direction of the lower pressure, the differential pressure will cause fluid to flow. Thus, it is differential pressure that moves the fluid through the filter assembly and overcomes resistance to flow.

In the preceding discussion it was tacitly assumed that the fluid was completely free of particulate contamination. But in reality there will always be some particles present in a system. As the filter does its job, particles will be stopped by and partially occlude or block the pores or holes of the filter medium, thereby increasing resistance to flow and ΔP.

In choosing a filter, therefore, one must provide for sufficient pressure source not only to overcome the resistance of the filter, but also to permit flow to continue at an acceptable rate as the medium plugs so as to use fully the effective dirt holding capacity of the filter. *If the ratio of initial clean pressure drop through the filter to total available pressure is disproportionally high, unacceptable flow will quickly result even though the medium's capacity for collecting dirt has not been exhausted.*

Figure 11
Cartridge Pressure Drop vs. Dirt Capacity



When this occurs, the proper solution is usually to increase pump capacity or gravity head or, as an alternative, to reduce clean pressure drop by increasing filter size.

Filter cartridges exhibit an exponentially increasing pressure drop vs. dirt capacity curve as shown in Figure 11. Usually, the capacity of the filter is mostly consumed before the sharp increase in pressure drop. Consequently, the available system pressure source should be at least sufficient to overcome the pressure drop (ΔP) at the knee of the curve so as to utilize most of the dirt holding capacity of the filter medium.

Maximum allowable cartridge pressure drop is the limit beyond which the filter might fail structurally should additional system pressure be applied to maintain adequate flow. This limit is always specified by the filter manufacturer.

In choosing a pressure source, one must take into consideration the resistance to flow of the filter – both constant resistance components (filter housing and element hardware), and the variable resistance components (filter cake and medium). As filtration proceeds at constant flow, there will be an increase in pressure drop made up of a constant component and an increasing variable component. Eventually, the increasing pressure drop component becomes so large as to either clog the filter and stop flow or to structurally damage the filter. Enough pressure drop should be available to satisfy both components at least to filter clogging.

If a pressure head exists downstream, as for example in an elevated receiver, this must be overcome without limiting the available pressure drop for the filter. In such cases a check valve should be installed downstream of the filter to prevent reverse pressure from damaging the cartridge.

As noted above, the pressure drop across the filter assembly can be reduced by increasing the size of the assembly. This is usually an economical approach for continuous processing since the increase in total throughput is often more than linear with respect to the cost of the larger number of filter cartridges in the larger assembly (see below).

5. Surface Area

It should be clear from the above discussion of pressure drop that the useful life of a filter relates to its dirt capacity, defined in the NFPA glossary as "The weight of a specified artificial contaminant which must be added to the influent to produce a given differential pressure across a filter at specified conditions." While dirt capacity can be measured using any consistently reproducible contaminant, ACFTD is most often employed for this purpose.[5]

The life of most screen and fixed pore depth type filters is greatly increased as their surface areas are increased; in fact, the ratio *can be* as much as the square of the area ratio! To understand why this is so, let us look at *two filters of identical medium* (thus subject to the same pressure drop limit) which pass the same fluid at the same flow rate.

The first filter has a surface area of 5 sq. ft. and collects a filter cake .005″ thick (128 µm) in a 24-hour period. After 24 hours most of the pores are plugged; the pressure drop is 75 psi; and the useful life of the filter has been exhausted.

Let us then increase the surface area of the filter to 30 sq. ft. and calculate life. If a filter with a surface area of 5 sq. ft. collects a filter cake of .005″ in 24 hours, then at the same flow rate a filter of 30 sq. ft. will collect that same filter cake in x hours. Thus:

$$\frac{5}{24} = \frac{30}{x}$$

$$5x = 30 \times 24$$

$$5x = 720$$

$$x = 144$$

While the 30 sq. ft. filter has collected a filter cake of .005″ in 144 hours, its useful life will not be exhausted because the pressure drop will not have reached 75 psi (there are 6 times as many pores to plug: 30/5 = 6). Indeed, since flow rate per sq. ft. of filter area is in the ratio of 5/30, the pressure drop across the 30 sq. ft. filter will be 5/30 x 75 psi or 12.5 psi. If the 30 sq. ft. filter has a pressure drop of 12.5 psi in 144 hours, then it will have a pressure drop of 75 psi in x hours.

Thus:

$$\frac{12.5}{144} = \frac{75}{x}$$

$$12.5x = 75 \times 144$$

$$12.5x = 10{,}800$$

$$x = 864 \text{ hours}$$

The life of the 30 sq. ft. filter is therefore 36 times that of the 5 sq. ft. filter (864/24). If one calculates the square of the area ratio $(30/5)^2$ the answer is 36![6]

The benefit of opting for a filter assembly with a large surface area can be expressed as follows:

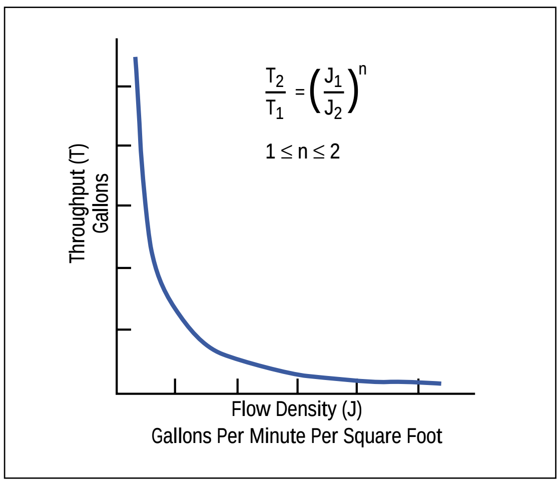
Let T = Throughput (gallons) for a filter with area, A, (sq. ft.)

Then $T_1 = T_2 \left(\frac{A_1}{A_2}\right)^n$

where n is equal to or greater than 1 and less than or equal to 2.

This relationship is expressed graphically in Figure 12. The curve shows that as the flow density (gallons per minute per square foot) decreases, the total throughput increases. If one assumes a con-

Figure 12 Filter Life vs. Flow Density



stant flow rate (gallons per minute), then the ratio of the flow densities simplifies to the ratio of the areas raised to the nth power which is exactly the relationship previously discussed.

The life extension factor (n) will approach two provided that:

- The filter cake is not compressible. If the filter cake is compressible, n will tend to be nearer to one.
- The collected cake does not become a finer filter than the medium itself (i.e., collect finer solids as it builds up). To the extent that the filter cake acts as a finer filter than the medium itself, n will tend to approach one.
- The solids collected are relatively uniform in particle diameter.

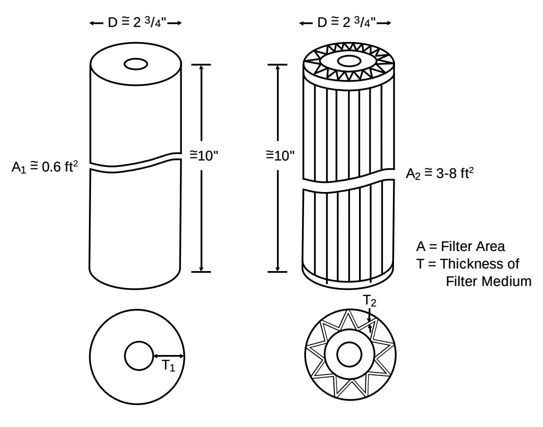


Figure 13
Schematic Representation of Pleated Structure Cartridge Design

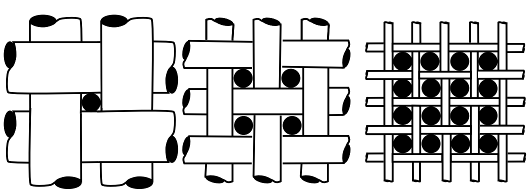


Figure 14
Void Volume vs. Fiber Diameter at Constant Pore Size

From the foregoing it is apparent that an increase in surface area will yield at least a proportional increase in service life. Under favorable circumstances, the ratio of service life may approach the square of the area ratio. In many, if not most cases, a filter user will save money in the long run by paying the higher initial cost of a larger filter assembly!

For example, let's assume an arbitrary cartridge cost of $1.00/square foot of effective cartridge surface area. Then, from the previous example, a 5 sq. ft. filter costs $5.00 while a 30 sq. ft. filter costs $30.00. Further, as calculated, the 5 sq. ft. cartridge lasts 24 hours while the 30 sq. ft. cartridge has a useful life of 864 hours. Therefore, the former requires 36 changeouts (864/24) as compared to the latter. In terms of costs, the filter user will be outlaying $180.00 (36 x $5.00) in cartridge costs as opposed to $30.00 for the 30 sq. ft. cartridge. This cost differential is exacerbated if one includes labor as well as other costs such as lost production time.

As the surface area is increased, a larger housing (container or pressure vessel) is required. There is, of course, a practical limit to housing size.

It is for this reason that Pall Corporation uses convoluted or pleated structures to provide large surface areas in small envelopes, thereby keeping housing size and cost to a minimum. Figure 13 is a schematic representation of a pleated structure cartridge design. The figure shows that for identical envelope dimensions (2-3/4″ x 10″), the pleated design provides for over 13 times the surface area.

6. Void Volume

Void volume,[7] or the open area of a medium, is always of great importance. All other factors being equal, the medium with the greatest void volume is most desirable because it will yield longest life and lowest initial clean pressure drop per unit thickness. Figure 14 illustrates the relationship between void volume and fiber diameter. As the fiber diameter decreases, the void volume increases, assuming constant pore size. Other factors, however, such as strength, compressibility as pressure is applied (which reduces void volume), compatibility of the medium with the fluid being filtered, cost of medium, cost of constructing that medium into a useable filter, etc., must all be considered when designing a filter for a particular application.

7. Degree of Filtration

Naturally, the filter chosen for a given application must be able to remove contamination from the fluid stream to the degree required by the process involved. Once the size of the contaminants to be removed has been determined, it is possible to choose a filter with the particle removal characteristics needed to do the job. Choosing a filter with a pore size finer than required can be a costly mistake. Remember, the finer the filtration, the more rapid the clogging and the higher the cost!

Remember also that the filter selected must be able to retain particles removed from the subject fluid. As noted above, depth type filters of the type whose pores can increase in size as pressure is increased are subject to unloading. With surface type filters, or fixed random pore depth type filters, one selects a medium which will not change its structure under system-produced stress. For example, as system pressure rises to accommodate flow as filter cake builds, strands of woven wire mesh must not separate to produce a larger pore. Nor should the mesh rupture under the pressures possible in the system in question.

When it is necessary to support thin, membrane-type filters, attention must be given to the characteristics of the support material chosen. Support materials can react with the fluid, add significant resistance to flow, and cause poorer life.

8. Prefiltration

The purpose of a prefilter is to reduce overall operating cost by extending the life of the final filter. Extending final filter life may not in itself be sufficient to justify prefiltration; overall cost reduction is usually the principal consideration.

During 50 years experience with requests for prefiltration, it has been Pall's experience that most applications are better served by increasing final filter area rather than by providing a prefilter. This is because (as was shown in the previous section) increasing final filter area *always* yields a longer cycle and lower operating costs. Doubling the area of the final filter will result in two to four times the life. Since one-half to two-fold life increase due to prefiltration is typical, and four times very unusual, it may be seen that increasing the filter area usually yields better results. This approach also results in lower costs, requires less labor input, and permits operation with less power at lower pressure drop. Cost is less because one housing is used instead of two, and cost is further reduced because the larger filter installation has life in service which is proportionally larger than the increase in area. Clean pressure drop is reduced because of larger area, whereas a prefilter always increases pressure drop. Power required is reduced because pressure drop through most of the filtration cycle is lower.

In addition, increased final filter area always increases life at least in proportion, and often exponentially, while prefiltration often involves much cut and try experimentation, which is *not always* successful in the end. Even when the prefilter tests are successful, that success can be lost because the nature of the contaminants to be filtered changes with time.

Staged prefiltration, in which coarser but equal area absolute rated filters are arbitrarily selected to precede the final filter *can* also work – but in fact does so only rarely. This is not a recommended approach. However, if for some reason a final filter area increase is not feasible, the various Pall cartridges designated as prefilters can be tried using the grade of prefilter recommended by our literature.

Don't fall into the trap of always assuming that a final filter should always be preceded by a prefilter with an equal number of cartridges. Using a larger number of cartridges in a prefilter often results in substantially lower overall costs. For example, if the mode of operation is such that the prefilters are left onstream until clogged, then using two cartridges instead of one will increase life by more than two times, and possibly four to five times; this then results in lower operating cost, since more fluid is processed per cartridge.

Summary

This paper discussed the principles of filtration. The three capture mechanisms by which suspended solids are separated from fluids were examined and the conclusion reached that direct interception is the desired mechanism for separating particles from liquids, while inertial impaction and diffusional interception are more effective in gas filtration. In order to enhance the filter's separation effectiveness, it is possible to manipulate the particle/liquid/filter media system. Three such techniques were described. Because of the confusion over filter media classification, the paper compared and contrasted non-fixed random pore depth type media, fixed random pore depth type, and surface type media and explained why these classifications are more meaningful than simply a depth or surface classification. After characterizing the various types of filters that exist in the field today, it is necessary to examine their removal efficiencies. Three removal rating systems were analyzed including nominal rating, absolute rating, and Beta ratings. The paper concludes by considering the most important factors that a filter user must take into account when making a filter selection.

Footnotes

1 permeable medium – a material containing interconnected holes or pores, the presence of which permits passage of fluids.

2 except Whatman Nuclepore, which consist of straight through irregular and circular holes.

3 Filter Zeta Potential – a measurement of the electrical potential difference between a filter surface and the contacting liquid.

4 Standardized test dusts are classified from natural Arizona dust and are generally referred to as A.C. Fine and A.C. Coarse Test Dusts. A.C. Fine Test Dust (ACFTD) is commonly used to establish the Nominal Rating of filters less than 50 µm. For coarse filters (i.e., those greater than 50 µm) A.C. Coarse Test Dust is used.

5 Laboratory dirt capacity tests using ACFTD, or any other test contaminant, very often do not correlate with actual operating conditions in the field, and at best offer a rough guide to anticipated filter life. Also, dirt capacity tests between different types of media (e.g., wound or pleated paper) are not meaningful as they do not correlate to comparative actual field test results. No laboratory dirt capacity test now in use, or proposed for use, provides a meaningful index of filter life in service because life in service varies enormously depending on the nature of the actual contaminant, its state of suspension in the liquid, its size distribution, etc. Results also vary greatly depending on the viscosity and flow rate of the liquid. Meaningful data is obtained only from in-system tests.

6 The total pressure drop through a cartridge filter assembly is the sum of the pressure drops of the housing, the medium and the filter core. For simplification, this example does not take into account pressure drops through the housing or the filter core (the constant resistance components), and deals only with the variable resistance components. The proportion of the total pressure drop due to the constant resistance components will decrease as the size of the unit is increased, but this is a minor consideration.

7 Void volume is often confused with the term "porosity." Since porosity has been used in the industry to mean both percentage void volume and also pore size, we avoid use of the term.

Pall Corporation

Pall USA

888.873.7255 toll free in the USA
+01.516.484.0364 fax
FuelsandChemicals@pall.com email

Pall UK

023 9230 3303 phone
023 9230 2509 fax
FuelsandChemicals@pall.com email

Filtration. Separation. Solution.SM

Visit us on the Web at www.pall.com

Pall Corporation has offices and plants throughout the world in locations including: Argentina, Australia, Austria, Belgium, Brazil, Canada, China, France, Germany, Hong Kong, India, Indonesia, Ireland, Italy, Japan, Korea, Malaysia, Mexico, the Netherlands, New Zealand, Norway, Poland, Puerto Rico, Russia, Singapore, South Africa, Spain, Sweden, Switzerland, Taiwan, Thailand, United Kingdom, United States, and Venezuela. Distributors are located in all major industrial areas of the world.