

A Primer on Aquarium Filtration

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Filtration is fundamental to maintaining a healthy aquarium environment and, unfortunately, it is an aspect of the hobby that is, at best, poorly understood and, at worse, fraught with unmitigated nonsense. Filtration is the removal, or separation, of one or more substances from one or more other substances. There are three basic types of filtration that apply to the aquarium: mechanical, biological, and chemical.

Mechanical filtration is the removal of solid or undissolved particulates from suspension in water by passing the water through some type of mesh or porous mass. The particles are removed from the water either by a simple sieving effect or impaction on the filter medium. The size of the particles removed can range from larger than a grain of sand to smaller than bacteria or viruses. Two mechanisms are involved in mechanical filtration: the screening effect, or the removal of particles simply because they are too big to pass through the pores of a filter, and the depth effect, or removal or entrapment of particles smaller than the pores of the filter by impaction through tortuous channels and cavities. With most methods of mechanical filtration, such as with polyester pads, sand, gravel, etc., the principal mechanism is the depth effect. Some pressurized systems use pleated cartridges with membranes that utilize primarily the screening effect. I will wait to compare the relative merits of these systems until we have considered the dynamics of aquarium filtration or recirculation.

Biological filtration is the removal of both undissolved and dissolved substances (the latter are called "solutes") by biological consumption or biological conversion of a toxic solute to a less toxic or harmless solute. Biological filtration (primarily nitrification) is absolutely essential to the maintenance of any long-term closed system aquarium. The biological filter is easily established by seeding a mechanical filter bed with a nitrifying bacterial source, such as ocean or pond water, gravel from an established aquarium, or a commercial product. The required ammonia can be supplied with a hardy fish or simply the metered regular addition of ammonia as ammonium hydroxide or other ammonium salt.

I have had good experience establishing the biological filter in a reverse mode by the addition of sodium nitrite to establish the Nitrobacter population first and then the addition of ammonia to establish the Nitrosomonas. The bacteria are not fussy about their source of ammonia or nitrite, so that it is really not necessary to jeopardize a fish to establish the cycle. The main advantage of this reverse cycling (not to be confused with reverse flow) is the avoidance of the Nitrobacter inhibition by excess ammonia that ordinarily takes place in establishing a cycle. This ammonia inhibition of Nitrobacter is the main cause of cycle delays and failures.

Chemical filtration is the removal of solutes (dissolved substances) from solution by retention on a medium through physical-chemical interaction of solute and adsorbent. There are three basic properties of solutes that can be utilized to remove them from solution: molecular size, net charge, and polarity. Separation by molecular size should not be confused with mechanical filtration: mechanical filtration involves undissolved substances, while chemical filtration involves dissolved substances (solutes). In the aquarium, solutes are dissolved in one common substance, the solvent water. Water is a small polar molecule with no net charge. Examples of small solutes include all the cations and anions of dissolved salts, small metabolites such as amino acids, sugars, and fatty acids. Examples of large solutes are proteins, peptides, starches, some fats, and added polymeric conditioners.

Any ionizing substance is a good example of charged solutes, such as salts, acids, and bases. Uncharged solutes are covalent compounds with no ionizing groups, for example, water, sugars, starches, alcohols, ketones, and aldehydes. Charge and polarity are easily confused, but they are not equivalent. Charge refers to a net negative or positive charge that is not internally balanced. Polarity refers to the possession of balanced charged zones. Sodium is a positively charged ion, but it is not polar; water has no net charge, but it has a positive and negative zone and is, therefore, polar. In an electrical field, charged solutes migrate to, and collect at, the pole of opposite charge; polar substances do not migrate, but only orient their zones towards the

poles of opposite charge. Another important distinction is that polar are always polar, but charged can become uncharged, as for example, with a change in pH. A good example of this in the aquarium is ammonia. Free ammonia is an uncharged polar substance, but, with decreasing pH, more and more free ammonia ionizes to the ammonium ion, a still polar but now also positively charged substance: $\text{NH}_3 \leftrightarrow \text{NH}_4^+$. See Fig. 1 for some illustrations of these concepts.

Just as there are three general types of physical-chemical properties that permit the separation of solutes, so, also there are three types of filtrants or filtration media: (1) molecular sieves that separate on the basis of size; (2) ion-exchangers that separate on the basis of charge; and (3) adsorbents that separate on the basis of polarity. While a given filtrant may belong to one of these three types, it is not unusual for two or all three processes to be going on.

Molecular sieves can be visualized as multiple mazes with openings of varying sizes. As solutes pass by these mazes, those that are small enough to enter do so and become trapped. Occasionally, some solutes find their way out, but more enter than leave. Eventually, however, the mazes fill up and it becomes easier to find a way out until just as many leave as enter.

Ion-exchange is a process where an ionized solute present in large numbers or with a strong charge takes the place of another ion that is attached to a matrix.

Adsorption is a process where polar solutes become attached to polar surfaces and non-polar solutes are

pushed and held against non-polar surfaces by surrounding polar substances (water). Usually, polar and charged substances are hydrophilic (attracted to water) and non-polar and uncharged substances are hydrophobic (repelled by water). Since water is the solvent in all aquarium filtration, hydrophobic solutes are removed more easily by adsorption. As solutes become progressively hydrophilic, removal becomes

more and more dependent on molecular sieving and opposite charge effects, including ion-exchange. Of the three processes, the most important for aquarium filtration is adsorption, followed by ion-exchange. Molecular sieve action is usually an integral aspect of both adsorption and ion-exchange, and is a limiting factor for both types of filtrants. Because the action of most chemical filters tends to be mixed rather than exclusively one process, it is best to look at specific filtrants rather than process types.

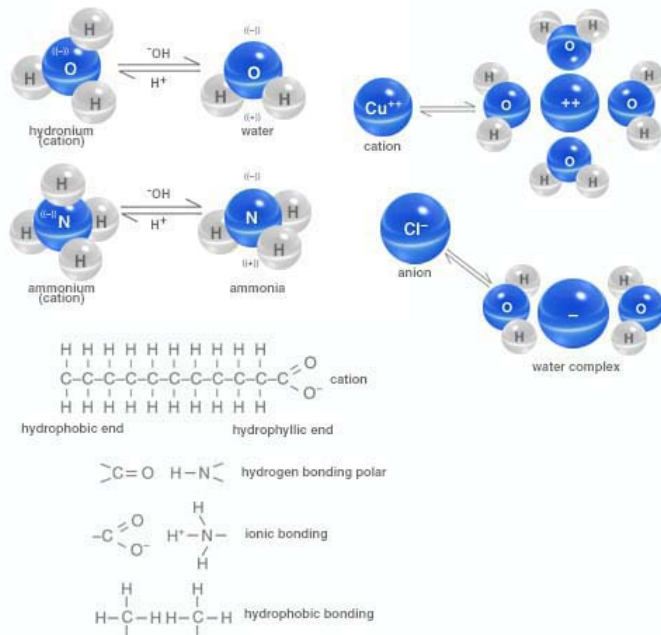


Fig. 1. Fundamental structures of aquarium biologicals associated with ionic, hydrophilic, hydrophobic, and polar attractions useful in filtration

CARBON. Activated carbon is prepared by carbonizing coal, wood, bone, nut shells, or other organic material at 900°C , then activating with steam, air, or carbon dioxide at $800^\circ\text{--}900^\circ\text{C}$. This treatment drives out hydrocarbons, increases surface area, and develops porosity. Differences in adsorption characteristics are due to these treatments and the addition of inorganic salts such as zinc, copper, phosphate, sulfate, and silicate before activation. Caustic and acid washes are also frequently used to both change adsorption characteristics and to remove soluble materials.

In the aquarium, activated carbon removes relatively non-polar or hydrophobic organic solutes from the polar solvent water. Charged solutes such as ionized salts are repelled by carbon and not adsorbed. Water

is strongly polar and is poorly retained by carbon. The more non-polar or hydrophobic, or the less soluble in water, the solute is, the more strongly is it retained on carbon. Many metabolites, such as amino acids, are retained only at a certain pH, called the isoelectric point, where the solute has no charge. If the pH changes, the substance acquires a charge and is released by the carbon. Proteins and peptides tend to be strongly retained because they have many non-polar side chains. If the carbon is rich in zinc or copper it will retain ammonia and other amines through complex formation. Although ionizing salts are repelled by carbon, some heavy metals such as copper, mercury, and zinc are retained by carbon under alkaline conditions. Some carbons are rich in insoluble phosphates, carbonates, silicates, or oxides, and these carbons have a relatively high capacity for polar and positively charged groups. Carbons that have not been acid-washed have more of these polar groups than acid-washed carbons, but also contain more soluble contaminants, such as metals and carbonates, which can cause toxicity and pH problems, particularly in freshwater aquaria.

Aside from the chemical nature of the carbon surface (non-polar), the major factor in carbon filtration is actually molecular sieving. Carbons can be looked upon as sponges or mazes with large openings that lead successively to smaller and smaller channels with smaller and smaller openings. The capacity and, to some extent, the adsorptive characteristics of a given carbon depend on its surface area and pore volume. Surface area refers to the internal surface of the carbon particles. The more channels inside the carbon, the greater the surface area. Pore volume

refers to the amount of emptiness inside the carbon. The greater the surface area, the greater is the capacity; and the greater the pore volume, the greater is the efficiency. There is a working limit of about 0.7 ml/cc for pore volume, since increasing pore volume also increases the fragility of the carbon. Increasing the surface area without increasing the pore volume results in diminished mean pore size (fewer large channels and more small channels), which, in turn, limits entrance to the carbon to progressively smaller solutes. The ratio of surface area to pore volume, then, is a valuable guide to the mean pore size: the greater the ratio, the smaller the pore size.

Several ways of grading carbon include surface area, iodine number, molasses index, and carbon tetrachloride activity, but none of these are, in themselves, meaningful for evaluating adsorbents for the specific use of aquarium water purification. The best measure of an adsorbent is the ratio of total surface area (TSA) to pore volume (PV). To facilitate interpretation, total surface area should be expressed in square meters per cubic centimeters (m^2/cc) and pore volume in milliliters per cubic centimeters (ml/cc). If these are reported on the basis of weight (grams) instead of volume (cc), then the density in grams per cubic centimeters (g/cc) must also be reported. Unfortunately, with few exceptions, sources of aquarium carbon do not provide these valuable figures. While there are only five manufacturers of carbon in this country and all commercial aquarium carbons come from one of these, all these sources supply numerous grades of carbon from very economical water treatment grades to expensive pharmaceutical grades. Not all aquarium carbon vendors provide the best carbon for the application; many provide the carbon with the best profit margin.

My study of carbons for the purification of aquarium water indicates that the better carbons have a TSA of 450 to 550 m^2/cc and a PV of 0.45 to 0.60 ml/cc with a TSA/PV ratio of 700 to 1000. Carbons that have not been acid-washed have better buffering ability for marine aquaria and greater retention of polar and charged solutes. Acid-washed carbons, however, are safer for fresh water and, with poor grades of carbon, the acid-washed versions are safer for marine aquaria as well. Given a choice, the acid-washed version of a particular carbon is usually preferable. Generally, the better carbons are prepared from bituminous coal. Acceptable carbons can be prepared from nut shells, wood and bone. Paper mills waste and other organic waste carbons are not acceptable. Some carbons are not truly activated carbons, but mere charcoal or, worse, just ground-up coal. If the TSA of a carbon is reported in units other than those used here, it is possible to convert the units for comparison by recognizing that:

$1 m^2 = 1.2 yd^2 = 10.8 ft^2$; $1 cc = 0.06 in^3 = 0.0338$ fluid oz; and $1 g = 0.035$ oz. If the TSA is given on the basis of weight and the dry density is not given, then directly comparable figures are not possible, but, gen-

erally, a good carbon should have a TSA of at least 1000 m²/gram and the better carbons have a TSA of about 1500 m²/gram. The PY should be at least 0.4 ml/cc.

Since an important consideration with carbon adsorption is surface area, it might be surmised that powdered carbon is better than granular carbon. This, however, is not the case, since the surface area that is important is the internal surface area, not the external. Diminished particle size only increases external surface area, and, by comparison to the total surface area, the gain in surface area from smaller particles is relatively slight. The choice of particle size, then, is not governed by surface area considerations. The particle size of choice should permit unimpeded and uniform flow through the carbon and allow rapid penetration of solute into the inner network of the carbon particle. The optimum size that satisfies these requirements is about the size of a pinhead, 0.5-1.5 mm or 1/32-1/16 in. (10-40 mesh). Smaller sizes impede flow while larger sizes produce non-uniform flow and retard penetration of solute into the carbon

matrix. With a carbon about the size of a pinhead, nearly 90% of the available surface area will be utilized before exhaustion; but with a carbon about the size of a small pea (5-8 mm), only about 40% of the available surface area will be utilized before exhaustion, due to the inability of solutes to penetrate the carbon particle.

If specifications of a carbon are not available or if you do not want to bother with all those numbers and calculations, what should you look for in a carbon? First, is it the right size? That should be pinhead size. Avoid the more common, convenient, and prevalent larger sizes. What is the appearance of a rinsed, but dry, particle? If it is dull, flat black, this indicates a fairly porous particle. If it is relatively shiny or glossy black, the carbon is relatively non-porous and should be avoided. What happens when you put it in water? If it floats or is buoyant and takes several hours to fully wet, making a hissing sound as it does, that indicates a porous, air-filled, hydrophobic carbon. If it sinks relatively quickly and emits little or no air or hissing sound, avoid it. What about on the shelf? Compare weights and volume. Select the carbon that takes up the most volume for a given weight. The better carbons are more porous (less dense), which means that

for a given volume, they weigh less. Carbon's action is a consequence of its surface area and volume, not its weight. It is inconsistent to buy or sell carbons by weight alone.

POLYMERIC ADSORBENTS. These adsorbents are synthetic porous molecular sieves based on styrene or acrylic polymers with controlled non-polar to polar surface properties. They function in essentially the same way as carbons and the operating optimum TSA, PV, ratio and particle size are the same as for carbons. Their TSA range from about 300 m²/cc to 500 m²/cc with PY ranging from about 0.4 to 0.6 ml/cc. The TSA/PV ratio ranges from 700 to 850. Strictly speaking, only uncharged adsorbents should be considered polymeric adsorbents. Several synthetic adsorbents available for aquarium use are not uncharged, but are in fact ion-exchangers and they will be considered separately. By comparison to carbons, polymeric adsorbents generally have a less efficient porous structure, but more effective surface properties and more predictable adsorption of polar as well as non-polar solutes. Although the overall capacity of these adsorbents is less than that of carbon, they have strong affinity for some solutes of importance that are not retained by carbon. Organic acids and both organic and inorganic nitrogen compounds are good examples. Overall, carbon is superior, but there is a sound basis for using both polymers and carbons together. Polymeric adsorbents are usually white to tan, dull, and have the shape of small beads about the size of a pinhead. It is also possible to manufacture them as fibers.

ION-EXCHANGERS. There are several types of ion-exchangers. There are mineral or natural exchangers and synthetic exchangers. The mineral exchangers are, like carbon, molecular sieves, but have much less TSA, only about 5-50 m²/cc. These exchangers are zeolites, kaolins, or other type of clays. They have limited exchange capacity and are poorly defined; consequently, they have limited application. They probably would not be used at all, were it not for being very economical. Chemically, they are mixtures of aluminum, magnesium, zinc, and other metal silicates. The ion-exchange property is primarily due to surface oxygen of the silicate, making this material primarily a cation exchanger, usually exchanging ammonium ions from water for sodium or calcium ions on the exchanger. Some also have very limited anion exchange capacity.

These mineral exchangers are not suitable for salt water use, because the high salt content would render them ineffective and would tend to release toxic metals into the water. These exchangers are promoted commercially mainly for removal of ammonia from fresh-water aquaria. If you have noticed a physical similarity between your ammonia absorbent and kitty litter, the similarity is not accidental. These exchangers also have limited adsorptive capacity for polar charged groups.

Synthetic exchangers are defined as either anion or cation exchangers and are available as either microporous or macroporous types. The microporous types have only very small pores that admit only small inorganic ions. These have been used for many years to deionize water or soften water for household use. In the aquarium, however, proteins, bacteria, colloids, and other large solutes quickly plug up or "foul" the micropores of this type of exchanger and render it useless. The macroporous types are molecular sieves with TSA ranging from 25 to 506 m²/cc with PV ranging from 0.2 to 0.6 mi/cc. These macroporous exchangers are much more resistant to fouling than microporous types. There are four types of macroporous exchangers: strong anion, weak anion, strong cation, weak cation. Without getting overly technical, the main difference of importance for aquarium use between strong and weak exchangers is that only the strong exchanger is a true exchanger in that it will split off its counterions and generate and adsorb corresponding counterions from solution. Weak exchangers are not true exchangers in that they only adsorb already existing free ions without actually generating any ions themselves.

Ion-exchangers have valuable uses in the aquarium, particularly for fresh water. A mixture of strong anion and strong cation exchangers will effectively produce soft water of slightly acid pH as well as remove ammonia (ammonium) and other ionic metabolites. Weak exchangers will also produce soft water and at a controlled pH. Customized stable fresh water can easily be attained by the intelligent use of ion-exchangers.

With salt water, the high sodium, chloride, calcium, magnesium, and sulfate content quickly equilibrates with strong exchangers and renders them virtually useless as ion-exchangers. Macroporous types, however, retain their usefulness for organic removal. Weak

exchangers have limited but useful applications. These exchangers can be used to effectively remove heavy metals and to remove acids. Acid removal with weak exchangers significantly promotes good pH control. Weak anion exchangers are amines and are very effective in removing copper, including many types of chelated copper, turning blue as copper is complexed to the exchanger.

Most ion-exchangers available commercially for aquarium use are clays for fresh water use, usually, but not always, restricted to ammonia removal. There are a few sources of microporous strong exchangers for softening water. The possibilities for ion-exchange in fresh-water aquaria of aquarists have not been adequately or intelligently explored. The use and recommendations for ion-exchangers in salt water are at best confused. The combined use of carbons, polymeric adsorbents, and judicious selection of ion-exchangers results in improved water quality, which, in turn, leads to more colorful, healthier, more active fish and invertebrates than is otherwise possible. Appetites are more aggressive and one mixed blessing is the comparatively unimpeded or uninhibited growth.

Synthetic ion-exchangers are usually beads about pin-head in size ranging in color from tan or off-white to dark brown. Microporous exchangers are usually translucent and shiny, while macroporous exchangers are opaque and dull. Anion exchangers are usually off-white to tan, while cation exchangers tend to be gray or brown to dark brown.

BOTTOM FILTRATION. Although bottom filtration is primarily biological, considerable chemical activity is also involved, at least in the marine aquarium. The principal component of bottom filtration in the marine aquarium is magnesium carbonate in one form or another, either as dolomite, crushed oyster shell, or crushed coral. This material behaves as a cation exchanger and polar adsorbent, not unlike the zeolites used in fresh water. The principal recognizable chemical action of magnesium carbonate is the removal of heavy metals, including trace elements such as copper and vanadium. Many organics, including proteins, amino acids, vitamins, and

medications are also adsorbed to, magnesium carbonate, although the capacity is very limited. The adsorbed material is eventually attacked biologically.

Carefully controlled experiments show that a surprising amount of ammonia is retained on the surface of magnesium carbonate. This is also eventually attacked biologically.

AMMONIA ABSORBERS. Ammonia removal is so important to aquarium maintenance that it warrants separate attention. Unquestionably, the best long-term route to ammonia removal is biological filtration. There are, however, numerous products available to aquarists to supplement the action of biological filtration. To look at these products intelligently, it is necessary to understand ammonia, the solute. Ammonia, as already indicated in Figure 1, is a covalent polar compound, not unlike water, which ionizes in aqueous solution to the positively charged ammonium ion. The interconversion of ammonia and ammonium is a reaction at equilibrium, and, with increasing pH, ammonia is favored, while, with decreasing pH, ammonium is favored. If an absorber removes one of the forms, then the equilibrium is shifted in that direction and all the ammonia is eventually consumed.

Removal of ammonia as an uncharged polar compound requires a very strong polar adsorbent, since the environment is water and, likewise, strongly polar. Some polymeric adsorbents are able to do this, but only to a very limited extent, and more so in salt water than in fresh water. The polar solvent water competes very effectively with ammonia for polar adsorbent sites, and the polar interactions between ammonia and water are effective in eluting ammonia from the adsorbent.

Removal of ammonia as the ammonium ion calls for an ion-exchange process and ion-exchangers can do this effectively in fresh water. Even these exchangers, however, have limited capacity and once the available sites are saturated no further adsorption can take

place. Ammonium ions, however, are not strongly held by ion-exchangers and the addition of

even relatively small quantities of salts, as is frequently done in fresh-water aquaria, dramatically decreases the ability of ion-exchangers to remove ammonium. Under ideal conditions, the best synthetic ammonia absorber has a capacity of about 60 mg of ammonia per ml of absorber. For a 10 gallon aquarium, this translates into a capacity of 1.5 mg/Liter (ppm) for each ml of absorber. For a 10 gallon aquarium, about 50-200 ml of absorber would generally be used, giving a total capacity of 75-300 ppm of ammonia. This is a cumulative capacity and once attained the absorber will be saturated and no longer function, unless regenerated. The addition of as little salt as 5

teaspoons per gallon will cut capacity by more than 50%. Zeolite absorbers have about 1/4 to 1/5 the capacity of synthetic absorbers. Zeolites are easily recognizable as dusty, white to tan granules, similar to kitty litter. Synthetic absorbers are dustless, tan to brown beads or fibers.

DYNAMICS OF AQUARIUM FILTRATION. The most useful vantage from which to examine

aquarium filtration is efficiency, which is defined as percent impurity removal per unit of time. A complex interaction of interdependent factors, depicted in Figure 2, govern the efficiency of aquarium filtration.

Any factor which results in an increase in the volume that must pass through the filter decreases efficiency, while any factor that increases throughput increases efficiency. However, since many factors do both, the net result of changing any filtration variable is not usually as obvious as might be supposed.

The most obvious, but also the most overlooked, factor is recirculation, which causes clean or filtered water

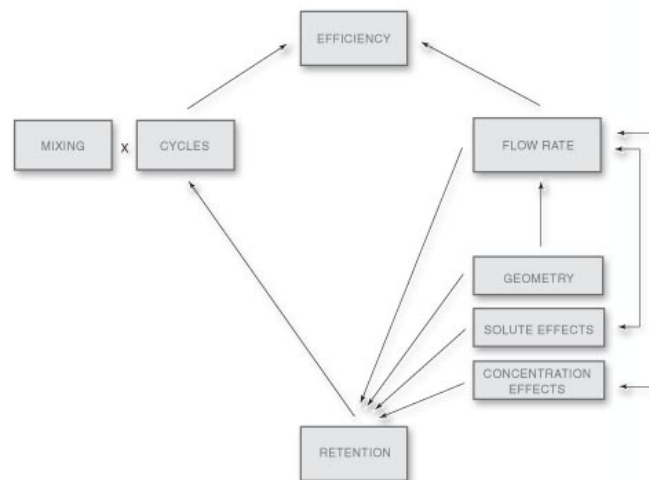


Fig. 2. Inter-relationship of factors influencing the efficiency of aquarium filtration

issuing from the filter to be continuously mixed with the relatively less clean or unfiltered in the aquarium. The mathematics of recirculation are similar to compound interest, except the percent change is

negative. Assuming a filter totally removes all of a given impurity, that is, it retains 100% of an impurity of the water passing through the filter, no mixing at all would require that 100% of the total volume of water pass through the filter to remove all available impurity; a 50% mix would require that 332% of the water pass through to remove all of the impurity; a 90% mix would require 437%; a 99% mix would require 458%; and continuous mixing, the actual situation with aquarium filtration, would require 460%. Put differently, recirculation is a constant that decreases aquarium filtration efficiency by increasing by a factor of 4.6 the cycle frequency, or the number of aquarium volumes, that must pass through the filter to effect 99% impurity removal.

The factor that has the most influence on efficiency is retention, the percentage of impurity concentration retained on the filter medium or removed from the passing water. Figure 3 shows the percentage of total volume, or number of cycles, that must pass through a filter to achieve 99% impurity removal at different % retentions. Since 100% retention is a rare exception, it is clear that the combination of low retention and recirculation requires very

Figure 3

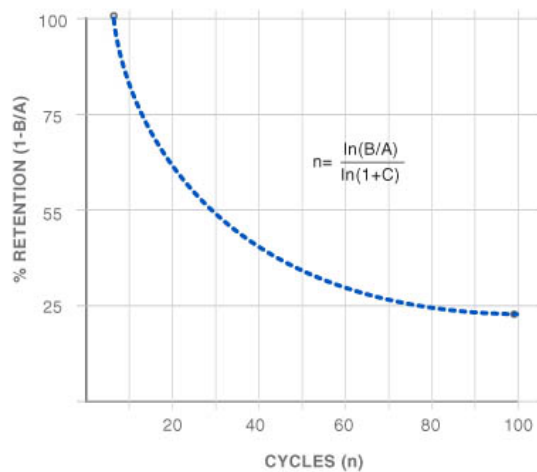


FIGURE 3. The effect of retention on the number of cycles of aquarium volume required to attain 99% removal of a solute. A = original concentration of impurity; B = unremoved or new concentration of impurity; C = retention; n = number of cycles of total volume of aquarium content.

large volumes of water pass through a filter for effective removal of impurities.

Four factors directly effect retention: geometry, flow rate, solute-adsorbent effects, and concentration effects. Poor geometry is without a doubt the principle cause of low retention and consequent low filtration efficiency characteristics of too many aquarium filters. The two most common geometry defects are tubing locations that allow leakage around the filter medium, and low filter bed heights. Filtration requires a minimum bed height of about 1 cm, and the deeper the bed the better. Deeper beds are more retentive because they minimize leakage, they increase contact time, and each progressive layer behaves as a series of separate filters rather than a parallel of separate filters.

There are three basic filter geometries: the box filter, the cartridge filter, and the canister filter. The box filter is characterized by a relatively small surface area with limited flexible bed depth. Disposable "cartridges" for box filters impose, in addition, a fixed and shallow bed depth. Box filters also generally have several locations for by-passing (leakage) the filter medium around flow tubes or cartridges. Cartridge filters are characterized by relatively large surface areas with fixed shallow bed depths, and, therefore, are more retentive as sieve filters than as depth filters. Canister filters have small surface areas, but deep beds. Both

Figure 4

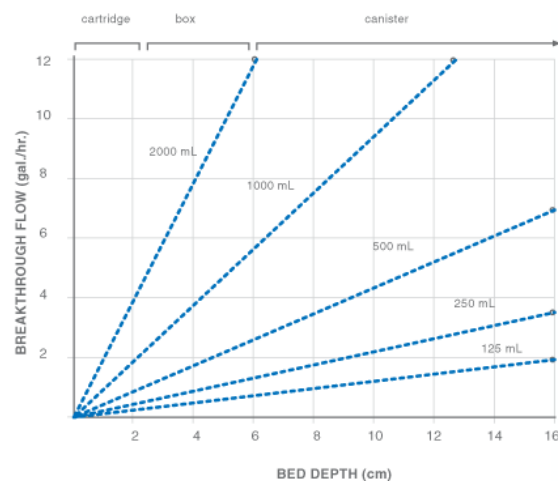


FIGURE 4. The effect of bed depth and filter material volume on breakthrough flow. The filter type identification at top of chart indicates the general ranges in which these filters operate.

Figure 5

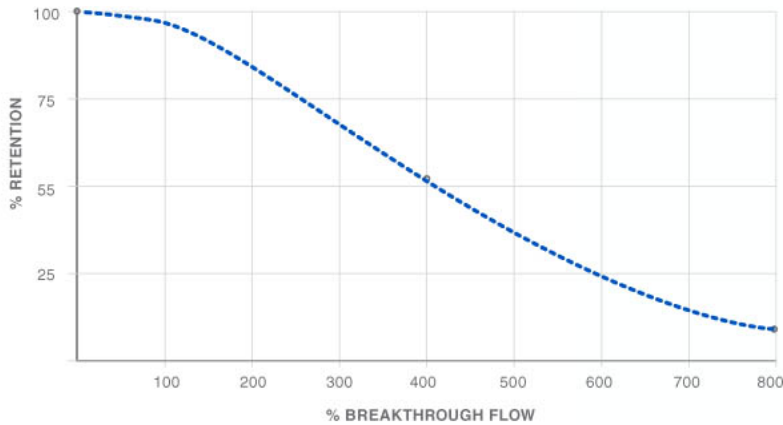


FIGURE 5. The effect of flow rate (expressed as breakthrough flow) on the retention of a hypothetical solute capable of being totally retained..

cartridge and canister filters have insignificant by-pass or leakage.

Retention of solutes on a filter medium is directly proportional to the volume or quantity of that medium, and, for a given amount of medium, is proportional also to the bed depth. Figure 4 shows the effect of bed depth on the break-through flow rate for representative volumes of filter medium.

Break-through flow is the minimum flow, expressed as volumes of the filter medium, at which solutes leak through the medium. It is evident that canister filters, with their deep beds, have remarkably more retention than either box or cartridge filters. The break-through flow can be determined empirically with dye solutions. It can also be approximated by calculation:

Break-through flow (gal/hr) = $dcm(0.009)cc$ where d is the depth of the filter bed in cm and cc is the volume of filter medium. The volume of various filters can be calculated as follows: box volume

(cc) = $lcm \times wcm \times dcm$ cartridge volume (cc) = $[h\pi r^2]e - [h\pi r^2]i$ canister volume (cc) = $d\pi r^2$

where l is length, w is width, h is height, d is depth, r is radius. For box and canis-

ter filters, $d = h$; for cartridge filters, d is equal to distance between external and internal walls. All dimensions should be in cm. Typically, the break-through flow rate for a small box filter equipped with a disposable cartridge is about 2 gal/hr; for a cartridge filter, about 10-12 gal/hr; and for a canister filter, about 100-140 gal/hr.

The break-through flow rate is not usually the optimum operating flow rate. As is evident from Figure 3, large volumes of water must pass through the filter for effective removal of impurities. For this to happen in a timely manner, it is usually necessary to sacrifice some absolute retention for overall timely removal. Figure 5 shows the effect on retention of increasing the flow rate beyond the break-through flow rate. Figure 6 re-draws the data from Figure 3 against unit time where unity is defined as the time required to clear 99% impurity at break-through flow rate. This type of plot shows the effect of the interaction of retention and flow rate on filtering efficiency.

For example, the plot shows that filtration at 100% break-through rate is no more effective than filtration at 340% that rate. The overall optimum is about 200%

Figure 6

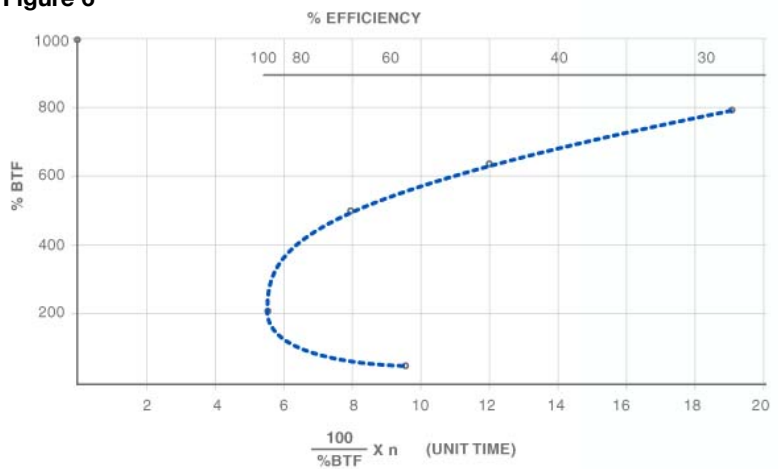


FIGURE 6. A redrawing of information from Figures 3, 4, and 5 to show the effect of flow rate (expressed as a % of the breakthrough flow) on efficiency by plotting against a unitized time scale. The chart shows that filters function well anywhere between 50-600% of their breakthrough flow, but the maximum efficiency is attained at about 200% of the breakthrough flow.

of the break-through flow. The plot shows that flow rate can be increased up to about 400-500% of the break-through rate without seriously sacrificing efficiency. Beyond that, however, increased flow rate begins to have consequential negative effects on filtration efficiency. Typically, this limit is about 10 gal/hr for box filters, 60 gal/hr for cartridge filters, and 700 gal/hr for canister filters. Both box and cartridge filters generally are operated well beyond this maximum, while canister filters are operated well below this maximum. Canister filters, in fact, are operated very closely to their optimum, generally around 150 gal/hr.

Solute-adsorbent effects are relatively complex and have already been discussed, but, in general, hydrophilic solutes are adsorbed at hydrophilic sites and hydrophobic solutes at hydrophobic sites. Carbons and polymeric adsorbents are more hydrophobic than hydrophilic. Synthetic ion-exchangers are more hydrophilic than hydrophobic. Some gel-type adsorbents are more hydrophilic than hydrophobic.

Concentration of solutes affects solute adsorption in a manner which is predictable from mass action considerations. The greater the concentration of solute, up to a limit characteristic of the capacity of the adsorbent, the more readily is it adsorbed. As the solute concentration drops, the rate of removal drops proportionately.

These principles of filtration dynamics have been worked out primarily for chemical filtration, but they apply, generally, to any type of aquarium filtration, with the exception of mechanical filtration by sieving action. In that case, the depth of the filter bed is of little importance and external surface area becomes paramount. For mechanical filtration by sieving action, cartridge filters are unexcelled. For all other types of filtration, including mechanical depth filtration, biological filtration, and chemical filtration, the canister filter is clearly superior. Box filters, as they currently exist, with their poorly placed tubing, small volumes, and shallow bed depths, are remarkably inefficient.