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Chapter 12

Activated Carbon Treatment

INTRODUCTION

Activated carbon adsorption is the most effective and reliable water treatment process available for the removal of a broad spectrum of organic substances dissolved in water.¹ In surface waters about 94 percent of the organics commonly present are adsorbed on carbon.² In groundwater supply sources, both natural organics and man-made organic contaminants are also generally amenable to carbon treatment. Because of this wide range of applicability and the effectiveness of this method of treatment, the use of activated carbon adsorption will be increasingly important in the future. When organics that are not readily adsorbed constitute a water quality problem, other treatment may be used in place of carbon, or carbon usage may be supplemented by other processes such as air-stripping. (More detail is provided in References 3 through 7.)

PAST PRACTICES

In the past, the principal reason for the use of activated carbon treatment was to control taste- and odor-causing organics. This was mainly for aesthetic rather than public health purposes. To control tastes and odors in water, the carbon dosage requirements are low and the necessary contact times short. This set of circumstances permitted the application of powdered activated carbon (PAC) rather than granular activated carbon (GAC). The use of PAC was advantageous because in most cases it could be used with no changes or additions to existing treatment facilities other than installation of the powdered carbon storage and feed equipment. Contact time was provided in existing settling basins, and the spent carbon was removed in existing rapid sand filters and disposed of along with the settling basin sludges.

RECENT DEVELOPMENTS

Over the past 15 years there has been a tremendous proliferation in the number, variety, and quantity of complex organic chemicals used for agricultural, industrial, and domestic purposes. Many of these substances eventually find their way into sources of public water supply. Even in very low concentra-

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1030
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tions many of these compounds have toxic, carcinogenic, mutagenic, or teratogenic properties that may produce long-term insidious health effects in water consumers. (These chemicals are discussed in greater detail in References 8 and 9.)

Development of this extensive, bewildering array of new synthetic organic chemicals has been paralleled by the development of new sophisticated and extremely sensitive equipment that can detect and measure very minute concentrations of these synthetic organics in water. Monitoring capability has progressed rapidly from parts per million to parts per billion, parts per trillion, and beyond. Some chemists predict that the day may not be far away when it will become possible to detect individual molecules of substances in a water sample.

One surprising result of this new-found ability to detect trace quantities of organics in water is that examination of well water supply sources has revealed the universal presence of naturally occurring organics such as aldehydes, ketones, terpenes, humic compounds, and other substances. Some of these materials, as well as some organic pollutants in well water, may react with chlorine to form trihalomethanes and other undesirable chlorinated hydrocarbons in drinking water. This potentially hazardous situation has been the subject of much recent concern for public health officials and water consumers. (Chapter 14 discusses trihalomethane formation and control measures.)

CURRENT TREATMENT TRENDS

As already discussed, both natural and synthetic organics in water are for the most part adsorbable on activated carbon. However, compared to requirements for taste and odor removal, dosage and contact times are much greater. This difference in carbon removal efficiency dictates the use of granular rather than powdered activated carbon. When granular activated carbon is used for taste and odor control, it is possible to add a shallow bed (1 foot or less) of GAC on top of an existing sand filter, or to substitute a properly sized and graded bed (24 to 36 inches) of GAC in lieu of the fine media in a rapid sand filter, with satisfactory results. However, experience has demonstrated that such shallow beds of GAC generally are not suitable for removal of natural or synthetic organics for other control purposes. Deeper beds and longer contact times are necessary for economic, efficient removal of these trace materials. The majority of new installations will be separate deep-bed GAC contactors. The contactors may be located in the treatment process train, either ahead of or following plant filters. When GAC contactors are located after the filters, they will be either downflow or an upflow-downflow series configuration in order to avoid the leakage of carbon fines that is common to all upflow carbon beds. (Treatment trends also are discussed in References 10 through 14.)

When GAC contactors are located ahead of filters, they may be either upflow or downflow. The use of upflow GAC contactors makes it possible to take advantage of countercurrent flow principles that may make more efficient use of the carbon. Generally speaking, GAC empty bed contact times of from 15 to 45 minutes will be required for most installations. The time to be provided for a particular supply depends upon the characteristics and concentrations of the organics to be removed and the other properties of the water to be treated.

Most water treatment plant installations of GAC will involve the construction and use of on-site reactivation facilities. One exception would be small plants using less than 200 pounds of carbon per day (91 kg/d), which could economically use carbon on a once-through, throwaway basis. Another would be plants that use between 200 and 1,500 pounds per day (91 and 681 kg/d) of GAC. Such plants might consider central off-site carbon reactivation if the cost of hauling would permit economical operation.¹⁵

Trihalomethanes

GAC may be used in either of two ways for trihalomethane (THM) control. It can be used directly for removal of trihalomethanes, or it can be used indirectly to remove the precursors. In either case, good to very good removal is technically feasible. When the GAC is fresh, removal is nearly complete, but toward exhaustion, breakthrough begins. Loading is proportional to influent concentration. THM's containing bromine are adsorbed better than chloroform. (Removal of trihalomethanes is described in Chapter 14 and in References 16 through 18.)

Alternate to GAC for THM control. It is generally more economical to replace the use of free chlorine with an alternate disinfectant (such as ozone, chlorine dioxide, or chloramines) rather than to use GAC to remove THM's or their precursor organics.¹⁹ The major disadvantage of doing this is the lack of any precursor removal. Also, the alternate disinfectants may produce undesirable oxidation products other than THM's in the water. Further, ozone does not produce a residual for distribution system protection; chloramine is a weaker disinfectant than free chlorine; and chlorine dioxide has chlorite and chlorate as inorganic by-products, anionic species whose health effects are currently unknown.²⁰

Volatile Organics

Volatile organic chemicals occur in both untreated and treated drinking water. Significant concentrations are more likely to be found in well waters than in surface waters. The potential health effects and acceptable limits of these substances in drinking water are of current concern, but these issues may

not be resolved for some time. In the meantime, research is under way to determine what degree of volatile organic removal is achievable so that water utilities can better assess the options of providing treatment or developing a new source. Volatile organics can be removed by aeration or adsorption on GAC or synthetic resins, or combinations of these processes, as described in detail in Chapter 15. Data are being developed on the effects of strong oxidants such as ozone and the reverse osmosis process in removing volatile organics. Boiling tap water for 5 minutes can also be effective for removing most of these organic compounds. In regard to the removal of volatile organics by aeration, the question has been raised of whether or not the exhaust gases create a problem. The evidence gathered to date on this subject indicates that the likelihood of creating an air pollution problem by aerating solvent-contaminated drinking water is remote.²¹

PRINCIPLES OF CARBON ADSORPTION

Activated carbon removes organic contaminants from water by a process of adsorption that results from the attraction and accumulation of one substance on the surface of another.²²⁻²⁵ In general, the chemical nature of the carbon surface is of relatively minor significance in the adsorption of organics from water and is secondary to the magnitude of the surface area of carbon available. Hence a high surface area is the prime consideration in adsorption. Granular activated carbons typically have surface areas of 2.44 to 6.84 million sq ft/lb (500 to 1,400 m²/g). Activated carbon has a preference for organic compounds and, because of this selectivity, is particularly effective in removing organic compounds that may cause taste and odor problems in water supplies. In addition to the taste and odor problems, trace concentrations of organics in drinking water supplies may have adverse health effects over the long term, as discussed in more detail in Chapter 15.

Activated carbon can be made from a variety of materials such as coal, wood, nut shells, and pulping waste (see below). Activated carbon made from wood is normally termed charcoal and was the first type of granular carbon to find its way into municipal water treatment.

Granular carbons made from coal are hard and dense, and can be pumped in a water slurry without appreciable deterioration. Hydraulic handling of carbon allows dust-free loading and unloading of filters. Coal-derived granular carbons are well suited to water treatment because the carbon wets rapidly and does not float, but conforms to a neatly packed bed with acceptable pressure drop characteristics. Also, the carbon is quite dense, and thus makes available more adsorption capacity in any given filter volume. Much of the surface area available for adsorption in granular carbon particles is found in the pores within the granular carbon particles created during the activation process.

The major contribution to surface area is located in pores of molecular dimensions. A molecule will not readily penetrate into a pore smaller than a certain critical diameter and will be excluded from pores smaller than this; thus, molecules are "screened out" by pores smaller than a minimum diameter that is a characteristic of the adsorbate and is related to molecular size. Furthermore, for any molecule of the adsorbate and is related to molecular size. Furthermore, for any molecule of the adsorbate and is related to molecular size. Furthermore, for any molecule of the adsorbate and is related to molecular size can exist only in pores that the molecule can enter.

Figure 12-1 illustrates this concept for the case in which two adsorbate molecules in a solvent (not shown) compete with each other for adsorbent surface. Because of the irregular shape of both pores and molecules and also by virtue of constant molecular motion, the fine pores are not blocked by the large molecules but are still free for entry by small molecules. As a contributing factor, the greater mobility of the smaller molecule should permit it to diffuse ahead of the larger molecule and penetrate the fine pores first. The forces of attraction between the carbon and adsorbing molecules are known to be greater, the more similar the adsorbing molecules are in size

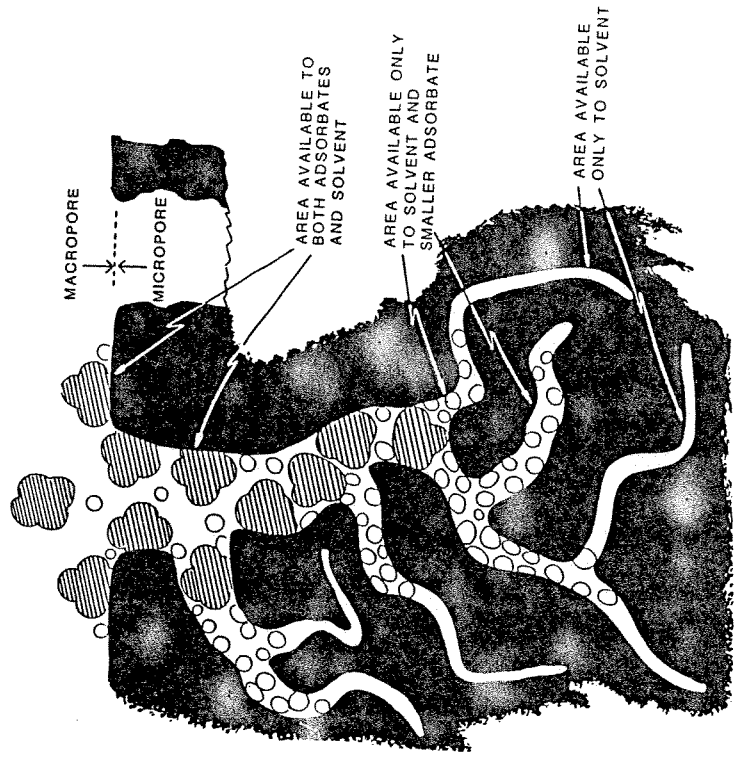


Fig. 12-1. Concept of molecular screening in micropores. (Courtesy of Calgon Carbon Corp.)

to the pores. The most tenacious adsorption takes place when the pores are barely large enough to admit the adsorbing molecules. The smaller the pores with respect to the molecules, the greater the forces of attraction. The pores cannot be so small, however, that the adsorbing molecules find it difficult to enter, or the adsorption for those molecules will be greatly reduced. The pore structure of activated carbons is extremely important in determining their adsorptive properties.

MANUFACTURE OF GRANULAR CARBONS

Activated carbons can be made from a variety of carbonaceous raw materials. Generally, the process consists of selection of an organic raw material, dehydration and carbonization, and, finally, activation to produce a highly porous structure. Raw materials that have been used to produce activated carbons include wood, lignin, nut shells, coal, lignite, peat, bagasse, sawdust, and petroleum residues. Granular carbons prepared from coal generally have the best physical characteristics (specifically hardness and density) for use in water treatment filters or contactors. The better grades of powdered carbons are made from lignin and lignite. The dehydration and carbonization step is usually accomplished by the slow heating of the raw material in the absence of air. Sometimes a dehydrating agent such as zinc chloride or phosphoric acid is used. The activation step may be carried out with chemicals in the solid or liquid state, or by using mixtures of gases. The more modern techniques use mixtures of oxidizing gases such as steam, air, and carbon dioxide.

Activated carbons are usually classified according to their physical state (e.g., powdered or granular) and their use (e.g., water grade, decolorizing, liquid phase, or gas phase). Granular carbons are those materials that are greater in particle size than approximately 150 mesh, whereas powdered carbons are those that are smaller in particle size.

Characterization of Granular Carbons

The important characteristics of a carbon must be expressed in terms of both adsorptive characteristics and physical properties. The adsorptive capacity of a carbon can be measured to a fair degree by experimentally determining the adsorption isotherm in the system under consideration. Simple capacity tests such as the Iodine Number or the Molasses Decolorizing Index also may be used as a measure of adsorptive capacity. (Further details are presented in References 26 through 30.)

The adsorption isotherm is the relationship, at a given temperature, between the amount of a substance adsorbed and its concentration in the surrounding solution. If a color adsorption isotherm is taken as an example, the adsorption isotherm would consist of a curve plotted with residual color in the water

as the abscissa, and the color adsorbed per gram of carbon as the ordinate. A reading taken at any point on the isotherm gives the amount of color adsorbed (at equilibrium conditions) per unit weight of carbon, which is the carbon adsorptive capacity at a particular color concentration and water temperature. In very dilute solutions, such as water supplies, a logarithmic isotherm plotting usually gives a straight line.

In this connection, a useful formula is the Freundlich equation, which relates the amount of impurity in the solution to that adsorbed, as follows:

$$\frac{x}{m} = kC^{1/n} \quad (12-1)$$

where:

x = amount of color adsorbed

m = weight of carbon

$\frac{x}{m}$ = amount of color adsorbed per unit weight of carbon

k and n are constants

C = unadsorbed concentration of color left in solution

In logarithmic form:

$$\log \frac{x}{m} = \log k + \frac{1}{n} \log C \quad (12-2)$$

in which $1/n$ represents the slope of the straight line isotherm. Detailed procedures for establishing the experimental conditions and conducting and interpreting isotherm adsorption tests are presented elsewhere.^{31,32}

From an isotherm test, it can be determined whether or not a particular purification can be effected. The test will also show the approximate capacity of the carbon for the application, and provide a rough estimate of the carbon dosage required. Isotherm tests also afford a convenient means of studying the effects of pH and temperature on adsorption. Isotherms put a large amount of data into concise form for ready evaluation and interpretation. Isotherms obtained under identical conditions using the same test solutions for two test carbons can be quickly and conveniently compared to reveal the relative merits of the carbons.

For some applications, it is not necessary to know the complete adsorption isotherm to determine the best carbon for a particular application or to specify the most appropriate carbon. In these cases, it is possible to use simple capacity

Table 12-1. Typical Granular Carbon Specifications.

ITEM	UNITS	VALUE
Total surface area	sq ft/lb (m ² /g)	(860-1500)
Bulk density	lb/cu ft (kg/m ³)	26 (421.5)
Particle density, wetted in water	(g/cc)	1.3-1.4
Effective size	(mm)	0.8-0.9
Uniformity coefficient	(mm)	1.9 or less
Mean particle diameter	(mm)	1.5-1.7
Iodine Number		850 Min
Abrasion Number		70 Min
Ash	%	8 Max
Moisture	%	2 Max

tests such as the Iodine Number or Molasses Decolorizing Index as an appropriate measure of adsorptive capacity.

The Iodine Number is the number of milligrams of iodine adsorbed per gram of carbon when in equilibrium, under specified conditions, with a solution of 0.02 N iodine concentration.^{31,32} The Iodine Number is an approximate measure of the adsorptive capacity of a carbon for small molecules such as iodine. The Molasses Decolorizing Index is, roughly, a measure of the adsorptive capacity of the carbon for color bodies in a specified molasses solution, compared to a standard carbon. The Molasses Decolorizing Index is a measure, therefore, of the adsorptive capacity for large molecules such as color bodies.

The physical properties of granular carbons that are important in performance include resistance to breakage, particle size, and degree of dustiness. For measuring resistance to breakage there are empirical tests such as the

Table 12-2. Comparison of Coal and Granular Carbon As Filtration Media.

	VALUES FOR		FILTRASORB*	
	HARD COAL MEDIA	8 X 30 MESH**	8 X 30 MESH**	14 X 40 MESH**
Real density, g/cc	1.5-1.6	2.1	2.1	2.1
Particle density in water, g/cc†	—	1.5-1.6	1.5-1.6	1.5-1.6
Effective size				
Single media filters	0.5 mm	—	—	0.5 mm
Multi-media filters	0.8 mm	0.8 mm	0.8 mm	—
Uniformity coefficient	Less than 1.75	1.9 or less	1.9 or less	1.7 or less

* Coal-based granular activated carbon, products of Calgon Corporation.

** U.S. Sieve Series.

† The pores of the activated carbon filled with water.

Table 12-3. Typical Size Distribution of Granular Activated Carbon.

Sieve Size U.S. Standard Series	8 X 30 MESH		14 X 40 MESH	
	Larger than No. 8—max %	Larger than No. 14—max %	Larger than No. 8—max %	Larger than No. 14—max %
Smaller than No. 30—max %	3	—	—	3
Smaller than No. 40—max %	—	1	—	—
Mean particle diameter (mm)	—	1.6	—	0.9

Abrasion Number and the Hardness Number. Particle size is determined by a screen analysis, from which the mean particle diameter and effective size can be calculated. Density is simply the weight per unit volume of the carbon. Typical specifications of a granular carbon suitable for water treatment applications are given in Table 12-1.

For incorporation in filter and contactor design, carbon particle size distribution is important. If the carbon is to replace anthracite coal in a dual-media filter, it should have similar filtration characteristics and similar backwashing characteristics to the coal. Fortunately, as shown in Table 12 2, commercial carbons are available with characteristics that are similar to anthracite coals used as filter media. The typical size distribution of a commercial carbon is shown in Table 12-3.

The headloss through granular carbon is a function of the carbon size, the depth of the carbon layer, the hydraulic throughput rate, and the water temperature. Figure 12-2 presents the headloss data for some commercial carbons in downflow service as filter media following backwashing. The backwash characteristics are shown in Fig. 12-3.

DEVELOPING DESIGN BASIS FOR WATER TREATMENT WITH ACTIVATED CARBON

Historical Use of Activated Carbon in Water Purification

Powdered Carbon. Powdered activated carbon (PAC) has been used successfully for more than 50 years to remove taste and odor from public drinking water supplies.^{33,34} Except for particle size, this PAC is often identical to the GAC used in wastewater treatment. In 1930, Hassler reported that PAC was being used in more than 150 municipal water treatment plants.³⁵ In this type of use, PAC dosages usually are in the range of 1 to 5 mg/l, although dosages as high as 20 to 30 mg/l have been used in some places for short periods of time when taste and odor problems were severe. PAC'

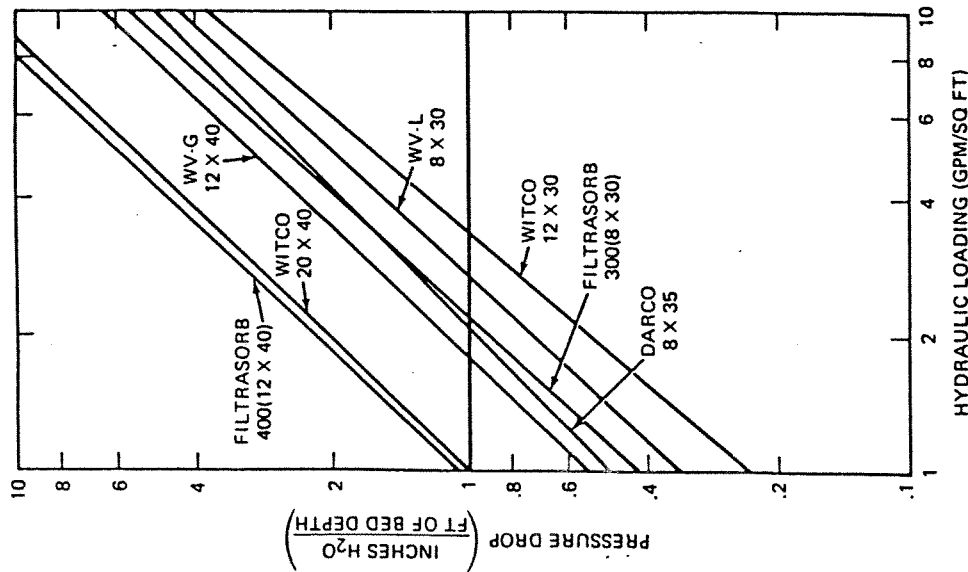


Fig. 12-2. Pressure drop vs. hydraulic loading.

is commonly used on a one-time, throwaway basis, with no attempt at recovery or reuse.

The principal benefit of PAC in water treatment is to remove taste and odor. In some waters, PAC may also remove color or organics that otherwise would interfere with coagulation or filtration. During its widespread use by waterworks for more than 50 years, no harmful effects have been reported.

Granular Carbon. Altogether, 46 water treatment plants in the United States are now using GAC (AWWA, 1979). In these plants, GAC is used

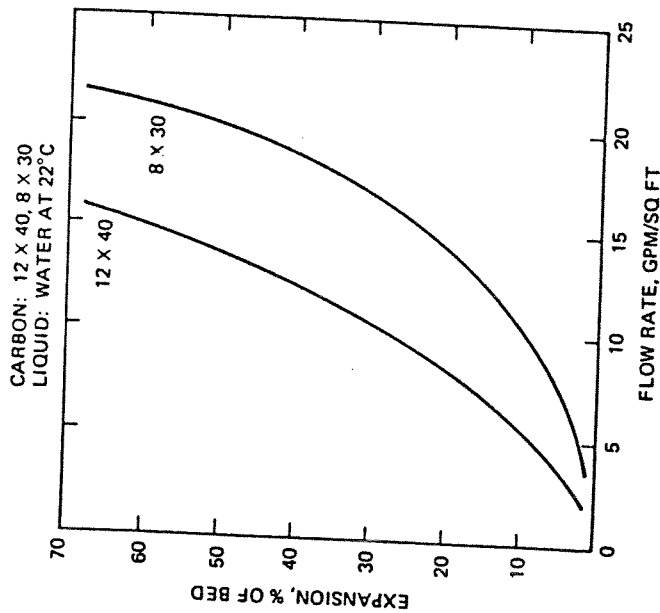


Fig. 12-3. Expansion of carbon bed at various flow rates. Carbon: 12 X 40, 8 X 30; liquid: water at 22°C.

to control taste and odor in drinking water. At the plants in Hopewell, Virginia and Davenport, Iowa, however, other benefits have been observed by the American Water Works Service Co., especially the reduction of trihalomethanes in finished water. Historical uses of GAC are discussed in References 36 through 42 for specific cases.

Because there has been no need for on-site reactivation of carbon, few useful data are available for estimating the costs involved in organics removal.

Recently, Manchester, New Hampshire installed a fluidized bed in its water plant for on-site GAC reactivation. Capital costs are available from EPA and the city, but operating and maintenance costs will not be forthcoming until more data are accumulated.

Cincinnati, Ohio has completed pilot testing of GAC adsorption and on-site regeneration. At this writing, the associated consulting firms of Malcolm Pirnie and Culp/Wesner/Culp are designing a 175 mgd (662.4 MI/d) post-filtration GAC contacting and regeneration facility for the City Water Works in Cincinnati. This is the subject of a special discussion that follows later, in this chapter.

Use of GAC in Food and Drink Processing and in Other Industries

There are more than 50 carbon reactivation furnace installations in the United States, serving many of the largest GAC users in the country. Included are seven large sugar refiners and nine large corn syrup refiners that use GAC for decolorizing their food products. The list also includes 15 industries that use GAC to remove organics from wastewater discharges and 19 cities that use GAC in the advanced treatment of their wastewaters.

GAC has also been used for many years in industrial water purification and in the production of soft drinks, pharmaceuticals, fats and oils, and alcoholic beverages. From 1935 to 1960, the utilization of decolorizing grades of GAC increased from 11,000 to 60,000 tons per year (9,977 to 54,420 metric tons/y) (API, 1969).

Extrapolating GAC Experience in Municipal Wastewater Reclamation to Water Treatment

South Lake Tahoe. The first plant-scale use of GAC in a municipal wastewater treatment plant was at South Lake Tahoe, California, in 1965. This plant has operated continuously since that time and now has 19 years of operating experience with GAC; the GAC system has processed more than 14 billion gallons (53 Gl) of pretreated municipal wastewater. The reclaimed water COD ranges from 10 to 30 mg/l. The South Tahoe installation was a United States Environmental Protection Agency (EPA) demonstration plant. For 3 years, EPA funded the collection of very detailed and complete plant operating data and cost information.⁴³

Except for a few months in 1977-1978 when some carbon was reactivated off-site during an emergency, all carbon has been reactivated at the plant with the use of a multiple-hearth furnace. Carbon losses in reactivation have averaged about 8 percent. This means that all of the original carbon has now been replaced by makeup carbon. More significantly, plant experience has now verified the results of bench-scale tests of reactivation (made in 1963)—tests indicating that the GAC could be maintained at or near full adsorptive capacity by means of thermal reactivation until the carbon was eventually all replaced by making up losses from attrition and burning. It has been demonstrated that the GAC has a service life of at least 12 cycles of reactivation under actual full-scale plant operating conditions.

At South Tahoe, the carbon furnace refractories were all replaced after 10 years of service. In 1977-1978, owing to maladjustment of the burners in the reactivation furnace, excess oxygen was present during reactivation of a considerable volume of GAC. This carbon was overburned and suffered a dramatic loss (over 50 percent) in adsorptive capacity. Fortunately, it was possible to fully restore the adsorptive capacity of the carbon in one pass

through the furnace, once the burners were readjusted properly. During this emergency, some off-site reactivation of GAC was necessary. This is the only major difficulty encountered in 18 years of operation of the GAC system. Corrosion of the exhaust gas scrubber has been something of a problem, especially when breakpoint chlorination has been practiced before GAC adsorption. Exhaust gas scrubbers should be fabricated from 316 SS (stainless steel) where such corrosive conditions prevail. Also the 50 psi (344.5 kPa), 304 SS carbon column inlet and outlet screens are being replaced by 100 psi (689 kPa), 316 SS over a period of years because of corrosion and mechanical distortion. The average service life of the original screens will probably exceed 15 years by the time all are replaced.

Other Wastewater Installations. Water reclamation plants constructed at the Orange County Water District (Water Factory 21), California;^{44,45} the Upper Occoquan Sewer Authority, Virginia; and the Tahoe-Truckee Sanitation Agency, California, have the same configuration as the South Tahoe Plant both in respect to the type of GAC facilities provided and the high degree of pretreatment afforded. All of these plants operate successfully with few GAC system problems. As might be expected with second- and third-generation designs, these later plants embody some minor improvements over the original South Tahoe installation, although there are no major changes.

Although there are many other successful applications of GAC in advanced waste treatment (AWT) plants, the experience with GAC in AWT in some places has, unfortunately, been poor. These failures in AWT applications have not stemmed from deficiencies in the basic GAC processes or in organics adsorption and thermal reactivation, but, rather, from mechanical problems.

Operational Problems. In discussing the operational problems encountered with GAC systems, those problems associated specifically with sewage treatment must be distinguished from general problems that might be encountered with any type of GAC system. Many problems with GAC in wastewater treatment will not occur in water purification. For example, in water treatment, few or no problems could be expected with excessive slime growths, hydrogen sulfide gas production, or corrosion from adsorbed organics released during carbon regeneration. Other operational problems include GAC bed losses and desorption of adsorbed compounds.^{46,47}

Some of the types of problems encountered with GAC systems in wastewater treatment include:

- Inadequate carbon transfer and feed equipment.
- Undersized supply and transfer lines.

- Failure to provide for air venting from backwash lines with destruction of contactor bottoms and disruption of GAC.
- Failure to house automatic control systems or otherwise protect them from the weather.
- Inadequate means for continuous, uniform feed to the reactivation furnace, resulting in temperature fluctuations, inconsistent reactivation efficiency, and wasted energy.
- Location of furnace and auxiliary drive motors in areas of very high ambient temperature (e.g., above the top of the furnace).
- The use of nozzles in filter and carbon contactor bottoms, which produced major failures in carbon systems just as they have for many years in water filtration plants. Their use is risky.
- The use of air-assisted backwash of carbon contactors.

Common problems related to wastewater treatment that do not apply to water purification have been growth of biological organisms in the carbon contactors and development of anaerobic conditions with the production of corrosive hydrogen sulfide. Both of these problems have been successfully circumvented by providing adequate flow through the columns or frequent backwashing. Failure to provide adequate pretreatment has caused column clogging and mudballs with the need for more frequent backwashing.

Corrosion has been a problem with some of the GAC systems. The furnace system, transfer piping, and storage tanks are susceptible components. Many operations require frequent replacement of the rabble arms and teeth, and replacement of the hearths every few years. At one installation, titanium or ceramic-coated rabble teeth were no more resistant to corrosion than stainless steel teeth. In one case, the corrosion problem in the furnace was solved by eliminating the use of auxiliary steam during reactivation. In another case, corrosion was linked to fluctuating temperatures in the hearths caused by irregular feed to the furnace and frequent startup and shutdown. These problems can be partially remedied by better operation and avoided by better engineering design.

In several industrial applications, the wastewater itself has been highly corrosive. In these cases, the contactors have been subject to corrosion. At Spreckles Sugar, the epoxy linings in the columns must be replaced every 3 years; Republic Steel also replaces its column linings on a regular basis. This kind of corrosion would not be expected in water treatment plants.

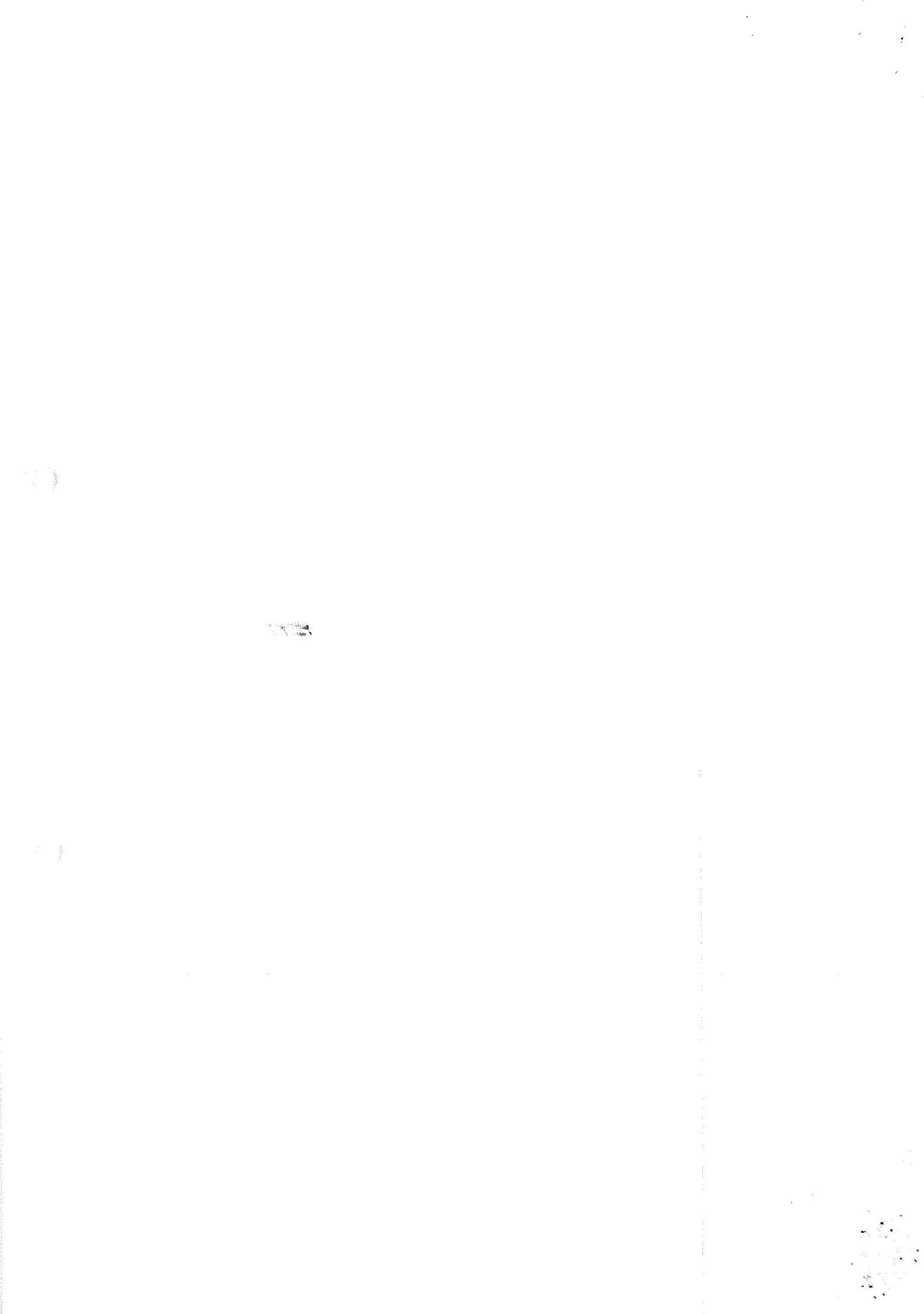
By properly applying the best current engineering design knowledge and practices for GAC systems, these rather serious problems might be avoided. When waterworks engineers apply GAC to produce high-quality drinking water, they should make the most of the experiences of the consultants for industry and wastewater agencies.

Extending Wastewater Treatment Experience to Water Treatment Systems. Caution must be observed in extrapolating GAC cost data from operating industrial installations and municipal wastewater treatment plants to the design of waterworks. The purpose for using GAC in each of these types of applications is generally the same—to remove organics. There are important differences, however. In industry, the GAC serves to remove a rather narrow band of organics—color molecules—from a viscous liquid. In wastewater treatment, the GAC removes (with or without biological activity) a broad spectrum of organic substances from water, as measured by BOD, COD, and TOC. In water treatment, the objectives of GAC treatment are not completely defined at this time, but for raw waters with color or taste and odor problems, using GAC unquestionably improves the drinking water from an aesthetic standpoint. In many cases, the cost of GAC may be warranted for these purposes alone. For the great number of water systems without color or taste and odor problems, the main concerns with respect to organics are the health effects from prolonged periods of ingesting trace quantities of possible carcinogens.

Public health officials and waterworks managers still disagree as to whether potential health risks due to the presence of minute traces of organics in drinking water are sufficient to warrant the cost of GAC treatment. A major concern is that the potentially harmful organics in drinking water have not all been identified at this time, and many of those that have been tagged as suspect have widely different adsorptive characteristics. Some adsorb readily on GAC, while others do not.

GAC loading rates at exhaustion of adsorptive capacity vary widely among the different potentially hazardous organics. This affects the length of service life of GAC before carbon reactivation or replacement is necessary—a determining factor in GAC treatment costs. Similarly, the reactivation times and temperatures for thermal reactivation of GAC saturated with different organics also differ, and not all are known at this time. Again, this has an important bearing on GAC treatment costs. Because of the widely varying adsorptive and reactivation characteristics of trace organics on GAC in water supplies, pilot plant tests of both adsorption and reactivation are mandatory prelude to treatment system design.

Over a period of years, perhaps general, average design parameters will emerge from the results of pilot plant studies and demonstration projects; but this time is not yet at hand. Once the GAC design parameters for water treatment have been established from pilot tests for a particular water source, then the knowledge and experience from other GAC installations in industry and wastewater plants can be put to good use. Carbon dosages, GAC contact times, and spent carbon reactivation times and temperatures can be determined. Contactor sizes can be calculated, and furnace sizes and fuel



requirements can be estimated. Transport facilities for GAC in water treatment can be the same as for other types of GAC installations, provided the differences in quantities and possible differences in the viscosities of carbon slurries due to any slime growth are taken into account. Also, with the GAC design parameters pinpointed as a result of pilot plant studies, construction costs can be accurately estimated based on the costs of existing installations in AWT and industry. The estimates cannot, however, be based on a flow basis; rather, they must be based on adsorption and reactivation data applicable to each specific installation.

Selecting the most economical number of contactors for a water system of a certain size involves the same principles as are used for other systems. Because of shipping regulations, factory-fabricated contactor vessels are generally limited to about 12 feet (3.7 m) maximum diameter. For large-capacity installations, a small number of field-erected steel vessels or poured-in-place concrete vessels may be economical.

Because upflow contactors provide all of the advantages of countercurrent operation with respect to carbon savings, they are favored for most types of service. The exception is water treatment. In this case, downflow is used because the discharge of carbon fines in the effluent (a characteristic of upflow columns) is avoided.

Cost estimates must be evaluated on the same basis as all other estimates of construction cost; there is no reason why they should be more or less accurate than estimates made for the rest of the treatment plant. Fifteen percent is generally accepted as an allowable difference between costs estimated from construction plans and the best bid received from the contractors. With good pilot plant data and with proper application of cost data from existing GAC installations, preliminary cost estimates for GAC treatment of public water supplies should be accurate enough for planning purposes. (Cost data for GAC systems are included in Chapter 30.)

The extrapolation of wastewater treatment experience with GAC to the design of water treatment systems is a task for trained, experienced, engineering professionals.

DESIGNING GAC ADSORPTION AND REACTIVATION SYSTEMS FOR WATER TREATMENT

The following discussion is devoted to some of the procedures and details for developing the design basis and costs for GAC water treatment systems. Criteria are obtained from pilot plant test results and information from full-scale applications. (Further information on the design and costs of GAC adsorption and reactivation systems may be found in References 48 through 55.)

GAC System Components

Systems utilizing GAC are rather simple. In general, they provide for the following system components:

- Carbon contactors for the water to be treated for the length of time required to obtain the necessary removal of organics.
- Reactivation or replacement of spent carbon.
- Transport of makeup or reactivated carbon into the contactors.
- Transport of spent carbon from the contactors to reactivation or hauling facilities.

These facilities are discussed in more detail later in this section.

Pilot Plant Tests

Despite the simplicity of GAC systems, laboratory and pilot plant tests are needed to select the carbon and the most economical plant design for both water and wastewater treatment projects.⁵⁶⁻⁵⁸ Pilot column tests make it possible to:

- Determine treatability.
- Select the best carbon for the specific purpose based on performance.
- Determine the required empty bed contact time.
- Establish the required carbon dosage that, together with laboratory tests of reactivation, will determine the capacity of the carbon reactivation furnace or the necessary carbon replacement costs.
- Determine the effects of influent water quality variations on plant operation.

During pilot testing, the influence of longer carbon contact times on reactivation frequency can be measured. These measurements allow costs to be minimized through a proper balance of these two design factors.

Design of Pilot GAC Columns

Detailed information, including a list of materials, on the design and construction of pilot GAC columns is presented elsewhere, as are descriptions of the analytic methodology for monitoring pilot column tests.⁵⁹ Also included are:

- Data on the adsorbability of various organic compounds.
- Data on the performance of GAC in their removal.

- Information on the use of multiple-hearth, infrared, fluidized-bed, and rotary kiln furnaces for reactivation of spent GAC.
- Example calculations for balancing added costs of increased contact time versus savings (if any) from less frequent reactivation.

Frequency of Reactivation

One of the principal differences in costs for GAC treatment between water and wastewater is the more frequent reactivation required in water purification due to earlier breakthrough of the organics of concern. In wastewater treatment, GAC may be expected to adsorb 0.30 to 0.55 lb COD/lb carbon (0.30 to 0.55 kg/kg) before the carbon is exhausted. From the limited amount of data available from research studies and pilot plant tests (mostly unpublished), it appears that some organics of concern in water treatment may break through at carbon loadings as low as 0.05 to 0.25 lb organics/lb carbon (0.05 to 0.25 kg/kg). The actual allowable carbon loading or carbon dosage for a given case must be determined from pilot plant tests. Costs taken from wastewater cost curves, which are plots of flow in mgd versus cost (capital or operation and maintenance costs), cannot be applied directly to water treatment. Allowance must be made in the capital costs for the different reactivation capacity needed, and in the operation and maintenance costs for the actual amount of carbon to be reactivated or replaced.

Because the organics adsorbed from water generally are more volatile than those adsorbed from wastewater, the increased reactivation frequency due to lighter carbon loading may be partially offset, or more than offset, by the reduced reactivation requirements of the more volatile organics. The times and temperatures required for reactivation may be reduced, owing to both the greater volatility and the lighter loading of organics on the carbon. (Removal of VOC's is discussed in Chapter 15.)

From the limited experimental reactivations to date, it appears that reactivation temperatures may be less than the 1650 to 1750°F (899 to 954°C) required for wastewater carbons. The shorter reactivation times required for water purification carbons may allow the number of hearths in a multiple-hearth reactivation furnace to be reduced. Also, less fuel may be required for reactivation. These factors must be determined on a case-by-case basis.

GAC Contactors

Selection of the general type of carbon contactor to be used for a particular water treatment plant application may be based on several considerations, including economics and the judgment and experience of the engineering designer.^{60,61} The choice generally would be made from three types of down-flow vessels:

1. Deep-bed, factory-fabricated, steel pressure vessels of 12-foot (3.66-m) maximum diameter might be used over a range of carbon volumes from 2,000 to 50,000 cu ft (56 to 1,400 m³).
2. Shallow-bed reinforced concrete, gravity-filter-type boxes may be used for carbon volumes ranging from 1,000 to 200,000 cu ft (28 to 5,600 m³). Shallow beds probably will be used only when short contact times are sufficient or when long service cycles between carbon regenerations can be expected from pilot plant test results.
3. Deep-bed, site-fabricated, 20- to 30-foot (6.1- to 9.1-m)-diameter, open concrete or steel, gravity tanks may be used for carbon volumes ranging from 6,000 to 200,000 cu ft (168 to 5,600 m³), or larger.

These ranges overlap, and the designer may very well make the final selection based on local factors, other than total capacity, that affect efficiency and cost.

As previously mentioned, the current design trend in retrofitting existing water treatment plants with new GAC adsorption facilities is to provide separate, post-filtration, downflow contactors.^{62,63} Contactor flow rates are usually 3 to 7 gpm/sq ft (7.32 to 17.08 m/h), and GAC bed depths are normally 2.5 to 15 feet (0.76 to 4.57 m). A direct linear relationship between contact time and carbon bed performance has been found in full-scale plant tests and concurrent small column tests. Carbon performance at a given contact time has been found to be unaffected by variations in hydraulic loading rates in the 2 to 10 gpm/sq ft (4.88 to 24.4 m/h) range. Thus, in terms of adsorption only, contact time is the governing criterion, and not surface loading rate within the ranges of practicality.

When the granular carbon bed is functioning as both a turbidity removal and an adsorption unit, there may be reasons to limit the bed depth and flow rate parameters to remove turbidity effectively and to backwash the filter properly. If GAC is to be effective in turbidity removal, it must be hard enough to withstand vigorous backwash agitation. At the same time, it should be dense enough to expand during the backwash cycle and to settle quickly for immediate resumption of filtration. As discussed earlier, coal-based granular carbon possesses approximately the same density and filtration characteristics as anthracite, and has found increasing use in the water field.

Particle size of the carbon, in addition to contact time, should be considered carefully as a design factor. Reduction of particle size for a given set of flow conditions is a means of increasing adsorption rates and thereby improving adsorption performance. Reduction in particle size to improve adsorption must be consistent with other significant factors such as headloss and backwash expansion. The length of the filter run in an adsorption-filtration bed would also be a problem, if too small a particle size were chosen.

Where existing rapid sand filters are being converted to adsorption-filtration

units, the permissible depth of the carbon layer will be limited by the freeboard available in the existing structure. Adequate space between the carbon surface and the backwash trough bottoms should be available to permit at least 30 percent expansion of the carbon layer.

The AWT experience with GAC contactors may be applied to water purification if some differences in requirements are taken into account. The required contact time must be determined from pilot plant test results. Although contactors may be designed for a downflow or upflow mode of operation, and upflow packed beds or expanded beds provide maximum carbon efficiency through the use of countercurrent flow principles, the leakage of some carbon fines (1 to 5 mg/l) in upflow carbon column effluents makes downflow carbon beds the preferred choice in most municipal water treatment applications. At the Orange County Water Factory 21, upflow beds were converted to downflow beds to correct a problem with escaping carbon fines. This full-scale plant operating experience indicates that leakage of carbon fines is not a problem in properly operated downflow GAC contactors.

Single beds or two beds in series may be used. Open gravity beds or closed pressure vessels are permissible. Structures may be properly protected steel or reinforced concrete. In general, small plants will use steel, and large plants may use steel or reinforced concrete.

Sand in rapid filters has, in some instances, been replaced with GAC. In situations where contact times are short and GAC regeneration or replacement cycles are exceptionally long (several months or years), as may be the case in taste and odor removal, this may be a solution. However, with the short cycles anticipated for most organics, conventional concrete-box-style filter beds may not be well suited to GAC contact; deeper beds may be more economical in first cost and provide more efficient use of GAC. Beds deeper than conventional filter boxes, or contactors with greater aspect ratios of depth to area, provide much greater economy in capital costs. The contactor cost for the needed volume of carbon is much less. In water slurry, carbon can be moved from contactors with conical bottoms easily and quickly, and with virtually no labor. Flat-bottomed filters of a type that require labor to move the carbon unnecessarily add to carbon transport costs. The labor required to remove carbon from flat-bottomed beds varies considerably in existing installations from a little labor to a great deal, depending upon the design of the evacuation equipment.

For many GAC installations intended for precursor organic removal or synthetic organic removal, specially designed GAC contactors should be installed. Contactors should be equipped with flow-measuring devices. Separate GAC contactors are especially advantageous where GAC treatment is required only seasonally because the contactors then can be bypassed when they are not needed, possibly saving unnecessary exhaustion and reactivation of GAC.

Tremendous cost savings can be realized in GAC treatment of water through proper selection and design of the carbon contactors. The design of carbon contactor underdrains requires experienced, expert attention.

Carbon Contactor Underdrains

Although good proven underdrain systems, such as Johnson screens and Leopold block, are available, often they are not used, and there have been numerous underdrain failures due to poor design. Earlier underdrain designs have failed in many installations for conventional filter service, and they continue to be misapplied to GAC contactors as well as filters.

GAC Reactivation or Replacement

Spent carbon may be removed from contactors and replaced with virgin carbon, or it may be reactivated either on-site or off-site. The most economical procedure depends on the quantities of GAC involved. As already discussed, for larger volumes on-site reactivation is more economical. For small quantities of carbon, replacement or off-site reactivation will probably be most economical.

Carbon may be reactivated thermally to very near virgin activity. Carbon burning losses may, however, be excessive under these conditions.

Experience in industrial and wastewater treatment indicates that carbon losses can be minimized (held to 8 to 10 percent per cycle) if the activity of reactivated carbon (as indicated by the Iodine Number) is held at about 90 percent of the virgin activity. To remove certain organics, there may be no decrease in actual organics removal despite a 10 percent drop in Iodine Number.

Thermal Reactivation Equipment

GAC may be reactivated in a multiple-hearth furnace, a fluidized-bed furnace, a rotary kiln, or an electric infrared furnace. Spent GAC is drained dry in a screen-equipped tank (40 percent moisture content) or in a dewatering screw (40 to 50 percent moisture) before being introduced to the reactivation furnace. Dewatered carbon is usually transported by a screw conveyor. Following thermal reactivation, the GAC is cooled in a quench tank. The water-carbon slurry may then be transported by means of diaphragm slurry pumps, eductors, or a blow-tank. The reactivated carbon may contain fines produced during conveyance; these fines should be removed in a wash tank or in the contactor. Maximum furnace temperatures and retention time in the furnace are determined by the amount (lb organics/lb carbon) and nature (molecular weight or volatility) of the organics adsorbed.



Off-gases from carbon reactivation present no air pollution problems provided they are properly scrubbed. In some cases, an afterburner may also be required for odor control.

Fluidized-bed and multiple-hearth furnaces are the simplest, most reliable, and easiest to operate for GAC reactivation. The infrared and fluid-bed units still have problems to be worked out.

It is necessary with all four types of furnaces to specify top quality materials to suit the conditions of service, and to see that these materials are properly installed. Corrosion resistance is important in the furnace itself and especially in all auxiliaries to the furnace. (More information concerning thermal reactivation equipment is offered in References 64 and 65.)

Required Furnace Capacity

The principal cost differences between GAC treatment of water and of wastewater may lie in the capital cost of the furnace and in the O&M cost for carbon reactivation. Water purification carbons typically are easier to regenerate (less time in furnace and lower furnace temperatures) and more lightly loaded (greater volume of carbon to be reactivated per pound of organics removed). Accurate estimates of GAC costs require knowledge and consideration of these two factors. It is not possible to use AWT cost curves based on mgd (ML/d) throughput or plant capacity to obtain costs for water treatment, unless the differences in reactivation requirements are taken into account.

Carbon Transport

The primary use of air or pneumatic transport of carbon is in bulk handling of makeup carbon. Once carbon is introduced into the adsorption-regeneration system, it is usually transported hydraulically in slurry form.

Handling characteristics have been experimentally studied by using water slurries of 12×40 mesh granular carbon in a 2-inch (50.8-mm) pipeline. The data indicate that a maximum of 3 lb carbon/gal (0.36 kg carbon/l) of water could be transported hydraulically, but that it is better to use a ratio of 1 lb carbon/gal (0.12 kg carbon/l). The velocity necessary to prevent settling of carbon is a function of pipe diameter, granule size, and liquid and particle density. The minimum linear velocity to prevent carbon settling was found to be 3.0 ft/sec (0.91 m/s). It is recommended that a linear velocity of 3.5 to 5.0 ft/sec (1.07 to 1.53 m/s) be used. Velocities of over 10 ft/sec (3.05 m/s) are objectionable because of carbon abrasion and pipe erosion. Carbon delivery rates are a function of pipe diameter, slurry concentration, and linear velocity. Data are shown in Fig. 12-4 and 12-5 for a 2-inch and a 1-inch pipe, respectively. Pressure drop data for various slurry concentrations and velocities in 2-inch (50.8-mm) pipe are shown in Fig. 12-6.

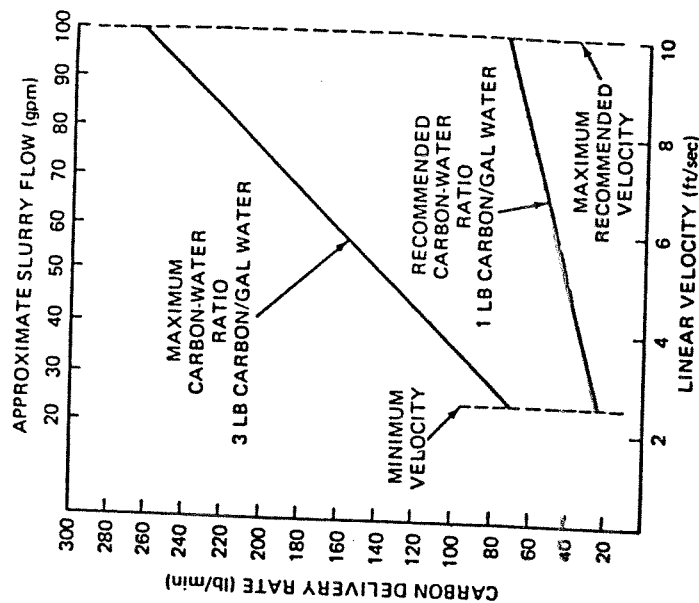


Fig. 12-4. Carbon delivery rate (2-inch pipe).

Pilot plant tests indicate that after an initial higher rate, the rate of attrition for activated carbon in moving water slurries is approximately constant for any given velocity, reaching an approximate value of 0.12 percent fines generated per exhaustion-regeneration cycle. This deterioration of the carbon with cyclic operation has been reported to be independent of the velocity of the slurry, within the recommended range of 3.5 to 5 ft/sec (1.07 to 1.53 m/s). Loss of carbon by attrition in hydraulic handling apparently is not related to the type of pump (diaphragm or centrifugal) used.

Carbon slurries can be transported by using water or air pressure centrifugal pumps, eductors, or diaphragm pumps. The choice of motive power is a combination of owner preference, turnaround capabilities, economics, and differential head requirements.

CARBON ADSORPTION ENHANCEMENT WITH OZONE

General

Depending upon water quality, ozone pretreatment ahead of GAC adsorption may increase GAC service life by 5 to 100 percent.⁶⁶ Under most circum-

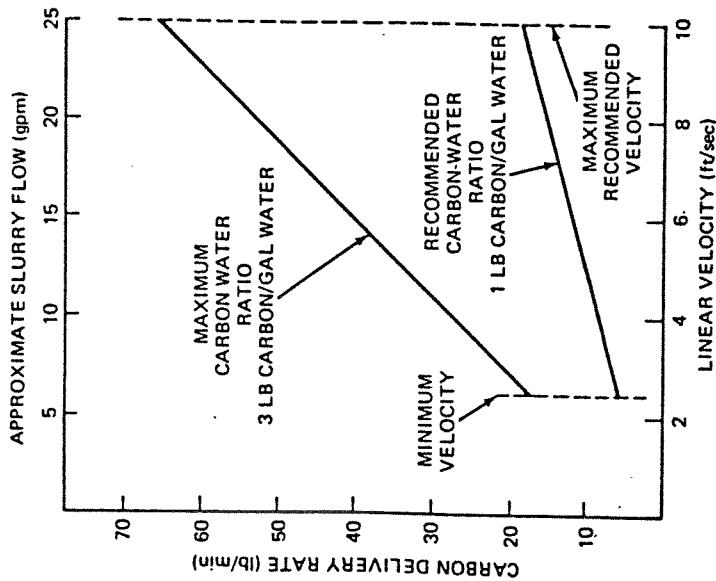


Fig. 12-5. Carbon delivery rate (1-inch pipe).

stances a 10 to 20 percent extension of carbon service life can be expected. Preozonation tests should be a part of all GAC pilot plant operations. Once the data are available on GAC savings, they should be compared to the cost of ozonation to determine the economics of providing ozone pretreatment.

Philadelphia Study

At Philadelphia, laboratory and pilot-scale studies were conducted to investigate the combined unit processes of oxidation by ozonation and adsorption by GAC.⁶⁸ In addition, the effect of chlorine and chlorine by-products on the ozone and GAC processes was investigated.

The study used Delaware River water previously treated by two coagulation/filtration plants: a full-scale plant operating with a 2 mg/l free chlorine residual and a 30,000 gpd (0.14 l/d) pilot plant operating without any disinfection. The rapid sand filter effluents from each were applied to parallel GAC and ozone/GAC systems. The GAC beds remained in service between 360 and 500 days.

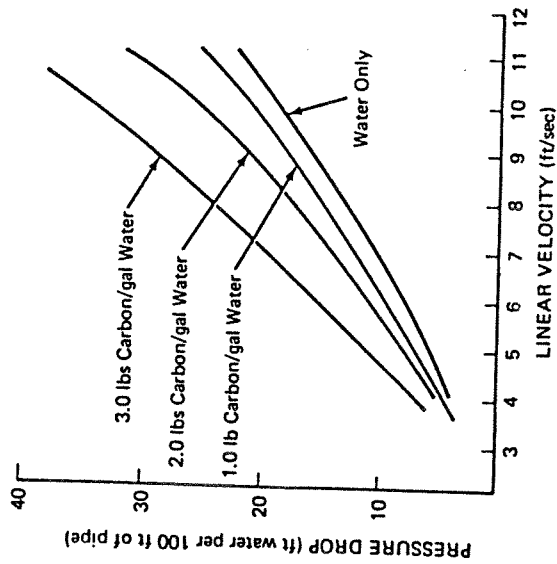


Fig. 12-6. Pressure drop of carbon-water slurries (2-inch pipe).

The removal of trace organics substances at the ng/l to $\mu\text{g/l}$ level and the removal of TOC at the mg/l level were carefully monitored, along with microbial parameters of biological speciation and growth rates. System comparisons were made using estimated total costs of each unit process, as determined by the carbon regeneration rate needed to maintain various effluent criteria.

Conclusions of the Philadelphia study were:

- Enhanced TOC removal before treatment does not appear to increase the adsorptive capacity of the GAC for trace organics of health concern.
- The cost of preozonation is not sufficiently offset by the lowered GAC operating costs associated with less frequent GAC regenerations, when the removal of the halogenated, volatile organic compounds is the controlling criterion. For TOC reductions, preozonation may be cost-effective, depending on the exact criteria chosen.
- Chlorination appears to produce compounds resistant to further oxidation by ozone, and thus should be applied only after ozonation.
- Chlorination and ozonation each affect the adsorptive capacity of the specific organic compounds differently.
- After GAC effluents were effectively disinfected with chlorine, no bacterial regrowth was observed after 5 days.
- Over a 2-year period, there were no operational problems associated

- Variations in the effectiveness of the different types of GAC used during this project were observed for the removal of the lower-molecular-weight volatile substances.
- The 12 × 40 mesh GAC medium in the filter adsorber appeared to remove turbidity as well as, if not better than, the sand medium when equal depths of the media were compared. Thus because the adsorption efficiencies of the two GAC systems (adsorber and filter adsorber) are similar, conversion from sand filtration to GAC filtration (sand replacement) would appear to be advantageous for organic removal and turbidity reduction.

Cincinnati, Ohio

A post-filtration GAC adsorption facility with a capacity of 175 mgd (662.4 MI/d) for treatment of Cincinnati's Ohio River drinking water supply is currently under design by Malcolm Pirnie, Inc., in association with Culp/Wesner/Culp, Consulting Engineers.

The design of the full-scale plant is based upon the results of a cooperative study by the U.S. EPA and the Cincinnati Water Works (CWW). A report of this work entitled *Feasibility Study of GAC Adsorption and On-Site Regeneration* was published in October, 1983.⁶² It was prepared by Richard Miller and David J. Hartman of Cincinnati. Jack DeMarco and Ben J. Lykins, Jr. were EPA project officers.

The abstract of this report follows:

This project determines whether the use of granular activated carbon (GAC) is feasible for removing certain trace organics from Ohio River water while treating it for human consumption. The study used both deep-bed contactors and conventional-depth gravity filters, with on-site GAC regeneration.

The primary objective of the study was to determine if selected organics could be reduced to a pre-designated level without adversely affecting the level of treatment provided by the existing plant and at a cost acceptable to consumers. A secondary objective was to develop plant design and operating parameters for full-scale plant conversion to GAC treatment. The study was unusual because it employed full-sized filters, contactors, and carbon regeneration furnace instead of the pilot-scale components used by most water quality researchers.

In the first phase of the project, three existing rapid sand filters were converted to GAC filter adsorbers. Various GAC bed depths and types were studied to compare organic removal efficiencies, bed lives, general water quality characteristics, the need for a sand underlayer and operational problems.

The second phase involved the use of pilot-scale GAC components to investigate the effects of regeneration on the carbon's adsorptive capability and to determine the reliability of pilot columns as performance indicators for full-scale components. The relative performances of lignite and bituminous-based GAC were also studied.

The last phase of this project studied the relative performance of GAC filters to post-filtration GAC contactors, the most advantageous empty bed contact time for the contactors and the effectiveness of on-site GAC regeneration. Pilot columns were also operated in parallel with the full-sized units to assess the usefulness of pilot columns as predictors of full-scale operation. During this phase, an attempt was made to maximize the use of currently available organic analysis techniques. Additional organic analytical techniques such as acid extract GC/FID profiles, closed loop stripping analyses and carbon-adsorbable organohalides provided a broad data base. Finally, a significant aspect of this project was the development of preliminary cost estimates for full-plant conversion to GAC.

The conclusions stated below are based solely on the governing conditions and findings of this particular project. Although certain findings may well apply at other locations, particularly on the Ohio River, the conclusions are not all-encompassing and may be inappropriate under differing conditions.

1. No turbidity reduction benefit was derived from the requirement of Section 4.2.1.6 in the Recommended Standards for Water Works, commonly referred to as the "Ten State Standards," for a 12-inch (0.305-m) sand underlayer to GAC or from the requirement that replacement media be the same effective size as filter sand.⁴
2. Bacterial growth within the GAC filters and contactors was experienced. Harmful bacteria were eliminated by post-chlorination.
3. Post-chlorination would be an absolute necessity if the entire plant were converted to GAC.
4. Bituminous-based GAC outperformed lignite-based GAC with respect to service life, weight of contaminants adsorbed, and cost per weight of contaminants adsorbed.
5. Pilot columns were reasonably predictive of full-scale GAC systems for organics removal.
6. Floc removal by GAC filters had little effect on the carbon's adsorptive ability.
7. The optimum GAC empty bed contact time (EBCT) would be between 7.0 and 15 minutes during annual average conditions and greater than 15 minutes during critical summer conditions.
8. Regeneration restored the GAC to its virgin adsorptive capacity.
9. GAC regeneration losses averaged 15 percent by volume for ten contactor regenerations and 18.5 percent by volume for six GAC filter regenerations.

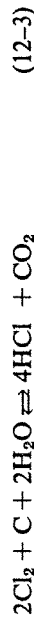
Costs. Cost conclusions [for a 175 mgd (662.4 MI/d) plant] made in the report are based on preliminary estimates using cost curves developed for general application. These cost curves were applied to site-specific design

criteria. Actual costs could be considerably different when determined for this or other sites based on a detailed engineering design.

1. The preliminary cost estimates for full-scale design, construction and operation of a GAC system at the CWWT treatment plant indicate that a capital investment of approximately \$40 million (based on 1981 dollars) may be required to reduce total organic carbon (TOC) concentrations to a specified criterion of 1,000 $\mu\text{g}/\text{l}$ using either GAC filters or contactors.
2. A GAC filter system compared to a contactor system will annually cost (in 1981 dollars) about twice as much for operating and maintenance costs (\$8.0 vs. \$4.0 million) and about 1.5 times as much for total costs, including capital amortization (\$12.4 vs. \$8.5 million).
3. The estimated increase in the unit production costs of water to reduce finished water from an average of about 2,100 $\mu\text{g}/\text{l}$ to a treatment goal of 1,000 $\mu\text{g}/\text{l}$ TOC will be \$0.24/1,000 gal (\$0.06/ m^3) for GAC filters (7.5 min EBCT) and \$0.165/1,000 gal (\$0.04/ m^3) for contactors (15.0 min EBCT), all in 1981 dollars.
4. The cost to regenerate GAC on-site over the life of the project averaged about \$0.21/lb (\$0.46/kg).

ACTIVATED CARBON FOR DECHLORINATION OF WATERS

Carbon has been used for over half a century to dechlorinate water, the early systems using granular coal and coke.⁶⁸ The proposed mechanism was originally considered as:



However, this reaction describes the summation of the reactions taking place on the surface of the carbon. The actual reaction according to Kovach is:⁶⁷



The chemisorbed nascent oxygen (last term on right) decomposes in either of the following two ways:



An empirically derived equation to describe the process is:

$$\log \frac{C_0}{C} = k \frac{L^{1/2}}{V} \quad (12-7)$$

where:

C_0 = inlet chlorine concentration, mg/l

C = outlet chlorine concentration, mg/l

L = bed length, ft (m)

K = a constant

V = flow rate, mgd (ML/d)

The process of chlorine removal from water is not a pure adsorption process but also involves a chemical reaction between the chlorine and the water. The initial step is the adsorption of chlorine in the form of hypochlorous acid on the carbon surface. The subsequent step is decomposition of the hypochlorous acid and nascent oxygen.

The hydrochloric acid is not readily adsorbed and is released into solution, while the chemisorbed oxygen builds up to form an oxide complex on the carbon surface. This surface oxide, which reduces the efficiency of the dechlorination process, is fairly stable at low reaction rates. At high inlet chlorine concentrations (1,000 mg/l), free carbon monoxide and carbon dioxide can be found in the effluent water. Removal of the surface oxide is incomplete below 752°F (400°C), making in situ regeneration uneconomical. It is postulated that even under conditions of industrial dechlorination (below 30 mg/l chlorine), some carbon dioxide is generated; however, the quantity is too low to be detectable against the background carbon dioxide content. Several investigators also postulated the formation of HClO_2 above 2,660 mg/l chlorine concentration, but recent work shows that the thermodynamics of this reaction, at least in static systems, is unfavorable.

The basic design parameters related to the operation of an activated carbon dechlorinator are:

- Chemical state of the free chlorine, including pH
- Inlet chlorine concentration
- Flow rate through the carbon bed
- Particle size of the carbon
- Type of carbon
- Temperature
- Manner of operation (continuous or interrupted)
- Impurities present

It has also been proposed that the dechlorination process is controlled by the slow chemical reaction on the surface, that is, decomposition of HOCl , in which case equation (12-7) above can be modified to:

$$\log \frac{C_0}{C} = k_1 \frac{L}{V} \quad (12-8)$$



Based on current data, the use of either equation can be justified, depending on the conditions of the experiment. Because k_1 is less than k , the latter equation contains a built-in safety factor.

While the establishment of a design based on either equation can be performed easily, expected variations in process conditions are rarely taken into account. The equations show the importance of using the actual chlorine concentrations expected in the influent water; acceleration of the test by using artificially high chlorine concentrations for rapid carbon evaluation leads to faulty conclusions.

The chemical state of the chlorine strongly influences the dechlorination process. For example, chloramines considerably reduce dechlorination efficiency. Unfortunately, no quantitative evaluation was available to the authors on the effects of chloramines. In some instances where chlorine dioxide is used, the effect of pH becomes important because the NaClO_2 formed is more stable than HOCl ; thus, any evaluation of activated carbon should be subjected to the same chlorine forms, or the pH should be adjusted.

Dechlorination efficiency for any activated carbon is also strongly dependent on particle size, and the smallest mean particle size should be selected for any carbon grade. Of course, the limiting factor in such a selection is the maximum allowable pressure drop. The micro- and macroporosity of the carbon also influence dechlorination efficiency. Because the dechlorination process is related to the surface area of the carbon, macropores are necessary to make the high surface areas accessible for the adsorption reaction. The raw material from which the carbon is made generally does not have any effect on dechlorination efficiency.

The presence of colloidal impurities or high organic concentrations can substantially reduce the carbon's useful life as a dechlorinator. The colloids may plug the pores of the carbon, reducing the surface area available for dechlorination. Organics can form an adsorbate film on the carbon, causing the same end result. If pretreatment steps are adequate to remove these impurities, beds of activated carbon will have a long useful life as dechlorinators.

If the experimental conditions are carefully selected so that they match the expected operating conditions, then it is fairly straightforward to evaluate activated carbon in dechlorination and to size the adsorber.

Recent tests have determined efficiency values for specific carbons available to industrial and municipal treatment operations in the United States. The results for flow rates, concentration of influent, and type of carbon are shown in Fig. 12-7. They are based on a chlorine breakpoint of 0.01 mg/l. The pH of the water was 7 and the temperature was 73.4°F (23°C). The absence of bacteria or any organic interference was assumed.

The life of the carbon in dechlorination service is extremely long. For example, with 2.5 feet (0.76 m) of carbon in a 1 mgd (3.785 MI/d) sand

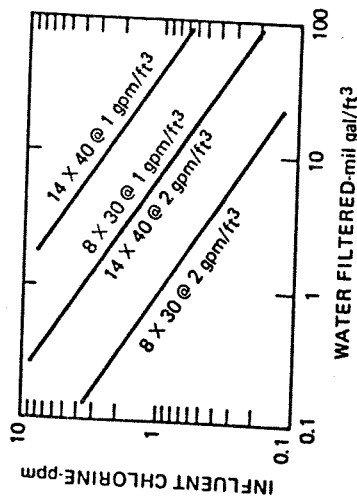


Fig. 12-7. Effect of flow rate and mesh size on dechlorination by granular carbon filters.

filter operated at 2.5 gpm/sq ft (6.1 m/h), the carbon volume is 700 cu ft (19.6 m³), and it could process 700 MG (2,650 MI) of 4 mg/l free-chlorine influent water before a breakpoint of 0.01 mg/l chlorine would be reached. A bed processing water containing 2 mg/l chlorine under similar conditions would last about 6 years. The effect of mesh size is pronounced. As indicated in Fig. 12-7, a reduction in particle size reflected in the reduction of mesh size from 8 X 30 to 14 X 40 allows a doubling of flow rate without a sacrifice in efficiency.

Dechlorination will proceed concurrently with adsorption of organic contaminants. Long-chain organic molecules such as those of detergents will reduce dechlorination efficiency somewhat, but many common water impurities such as phenol have little apparent effect upon the dechlorination reaction.

A rise in temperature and a lowering of pH favor dechlorination. Figure 12-8 indicates the relationship of these factors as they vary from pH 7 and

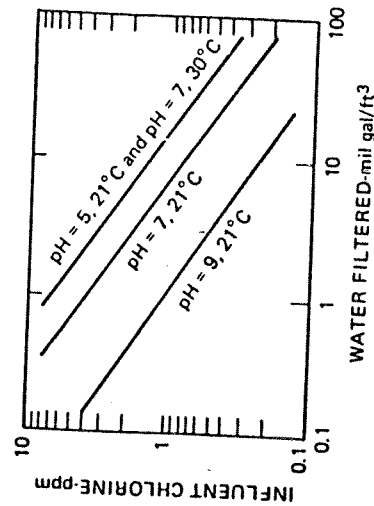


Fig. 12-8. Effect of pH and temperature on dechlorination by granular carbon (8 X 30 mesh at 1 gpm/ft³).



70°F (21°C). Mesh size was 8×30 , and flow rate was 1 gpm/cu ft carbon ($8.03 \text{ m}^3/\text{h}/\text{m}^3$ carbon). A breakpoint of 0.01 mg/Cl₂ and the absence of bacteria or any organic interference were assumed. It is unlikely that a deliberate change in pH or temperature favoring dechlorination alone would be economically feasible, unless existing conditions significantly retarded the process. These data are values determined with chlorine in distilled water. Variance in hydraulic loading, suspended matter, and certain adsorbed organics, as noted above, could adversely affect dechlorination efficiency.

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