1.9: Activated Carbon

Learning Objectives

- Describe the sources and production of activated carbon
- Describe the organic chemical removal theory
- Describe the types of applications where activated carbon is used
- Outline the disposal methods and regeneration methods for activated carbon

Activated carbon is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment. Adsorption is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases.

Activated carbon filters are used to remove unwanted tastes, odors, radon, and some man-made volatile organic contaminants from drinking water. The efficiency of the unit depends on the type of activated carbon installed, the filter bed depth, the type of contaminants in the water and their concentration, and the contact time between the water and the carbon filter. Activated carbon filters do not adsorb every type of contaminant equally well.

The solid material used in an activated carbon filter is a specialized carbon manufactured for the purpose. Contaminants adhere to the surface of these carbon granules or become trapped in the small pores of the activated carbon. Generally, an activated carbon filter is used with a pre-treatment filter to remove sediment or iron particles that may be present and clog the carbon filter.

Granular activated carbon is an effective filter for removing organic chemicals that may be in drinking water. Although activated carbon is efficient in removing a variety of organic chemicals, a specially formulated synthetic resin may be a better absorber for a specific contaminant.
As surface waters continue to be threatened by industrial contaminants, Groundwaters are increasingly the source of potable and non-potable applications, and it is important to remove these trace organic contaminants. Treatment of such waters for the removal of organic contaminants varies based on the intended uses, however, in most cases, even trace amounts of the contaminants require some level of removal to meet drinking water requirements.

Organic substances are composed of two basic elements, carbon and hydrogen, and are often responsible for taste, odor, and color problems in groundwaters. As such, treatment is used generally to improve aesthetically objectionable water.

Sources of organic compounds (VOC's, taste & odor compounds, disinfection byproducts, and free chlorine) found in groundwaters may include leaking underground gasoline/storage tanks, agricultural runoff containing herbicides or pesticides, solid waste or hazardous waste landfills, and improperly disposed of industrial/chemical waste.

The ability of organic compounds to cause health effects varies greatly from those that are highly toxic to those with no known health effect. The extent and nature of the health effect will depend on many factors including the level of exposure and length of time exposed. Eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment are among the immediate symptoms that some people have experienced soon after exposure to some organics.

The technologies most suitable for organic contaminant removal in process waters are granular activated carbon (GAC) and aeration.

GAC has been designated by the U.S. Environmental Protection Agency (EPA) as the best available technology (BAT) for organic chemical removal. Activated carbon adsorption provides an effective and reliable treatment for removing organic contaminants and is suitable for treating a wide range of organics over a broad range of concentrations. GAC filtration will also remove chlorine.

GAC filtration is recognized by the Water Quality Association as an acceptable method to maintain certain drinking water contaminants within the limits of the EPA National Drinking Water Standards. Organics that are readily adsorbed by activated carbon include:

- Aromatic solvents (benzene, toluene, nitrobenzenes)
- Chlorinated aromatics (PCBs, chlorobenzenes, chloroaphthalene)
- Phenol and chlorophenols
- Polynuclear aromatics (acenaphthene, benzopyrenes)
- Pesticides and herbicides (DDT, aldrin, chlordane, heptachlor)
- Chlorinated aliphatics (carbon tetrachloride, chloroalkyl ethers)
- High molecular weight hydrocarbons (dyes, gasoline, amines, humics)

Various types of GAC are available for removing organics from water, however, the most frequently used carbon in the US. is coal-based carbon due to its hardness, adsorption capacity, and ease of availability.
Coagulation and Flocculation

Particulate impurities in water result from land erosion, dissolved minerals, and the decay of plant material. Additional impurities are added by airborne contamination, industrial discharges, and animal wastes. Surface water sources and reclaimed water, polluted by people and nature, are likely to contain suspended and dissolved organic and inorganic material, as well as biological forms such as bacteria and plankton. With few exceptions, this water requires treatment to remove particulate impurities and color before it is distributed to the consumer.

Coagulation

The term coagulation describes the effect produced when certain chemicals are added to raw water containing slowly settling or nonsettleable particles. The small particles begin to form larger or heavier floc, which is removed by sedimentation and filtration.

The mixing of the coagulant chemical and the raw water to be treated is commonly referred to as flash mixing. The primary purpose of the flash-mix process is to rapidly mix and equally distribute the coagulant chemical throughout the water column. The entire process occurs in a very short time (several seconds), and the first results are the formation of very small particles.

Coagulants

In practice, chemical coagulants are referred to as primary coagulants or as coagulant aids. Primary coagulants neutralize the electrical charges of the particles, which cause them to begin to clump together. The purpose of coagulant aids is to add density to slow-settling flocs and add toughness so the floc will not break up in the processes that follow.

Metallic salts like aluminum sulfate, ferric sulfate, ferrous sulfate, and synthetic organic polymers are commonly used as coagulation chemicals in water treatment, because they are effective, relatively low in cost, available, and easy to handle, store, and apply.

When metallic salts, such as aluminum sulfate or ferric sulfate, are added to water, a series of reactions occur with the water and with other ions in the water. Sufficient chemical quantities must be added to the water to exceed the solubility limit of the metal hydroxide, resulting in the formation of a precipitate (floc). The resulting floc formed will then adsorb on particles (turbidity) in the water.

The synthetic organic polymers used in water treatment consist of long chains of small subunits, called monomers. The polymer chains can be linear or branched structures, ranging in length from a fraction of a micron to 10 microns. The total number of monomers in a synthetic polymer can be varied to produce materials of different molecular weights, which vary from about 100 to 10,000,000. Cationic polymers have a positive electrical charge, anionic polymers have a negative charge, and nonionic polymers have no electrical charge.

The polymers normally used in water treatment contain ionizable groups on the monomeric units and are referred to as polyelectrolytes. Polymers with positively charged groups on the monomeric units are referred to as cationic polyelectrolytes, while polymers with negatively charged particles are called anionic polyelectrolytes. Polymers without
ionizable groups are referred to as nonionic polymers.

Cationic polymers have the ability to adsorb on negatively charged particles, turbidity, and neutralize their charge. They can also form an interparticle bridge that collects the particles. Anionic and nonionic polymers also form interparticle bridges, which aid in collecting and removing particles from water.

While alum is perhaps the most commonly used coagulant chemical, cationic polymers are used in the water treatment field as a primary coagulant and as a coagulant aid. Anionic and nonionic polymers have also proven to be effective in certain applications as coagulant aids and filter aids.

The theory of coagulation is complex. Coagulation is a physical and chemical reaction occurring between the alkalinity of the water and the coagulant added to the water, which results in the formation of insoluble flocs.

For a specific coagulant, the pH of the water determines which hydrolysis species predominates after mixing the chemical with the water to be treated. Lower pH values tend to favor positively charged species, which are desirable for reacting with negatively charged colloids and particulates, forming insoluble flocs, and removing impurities from the water.

The best pH for coagulation usually falls in the range of pH 5 to 7. The proper pH range must be maintained because coagulants generally react with the alkalinity in the water. Residual alkalinity in the water serves as a buffer to the system preventing the pH from changing, and alkalinity aids in the complete precipitation of the coagulant chemicals. The amount of alkalinity in the source water is generally not a problem unless the alkalinity is very low. Alkalinity may be increased by the addition of lime or soda ash.

Polymers are generally added in the coagulation process to stimulate or improve the formation of insoluble flocs.

Generally, the operator has no control over the pH and alkalinity of the source water. Hence, evaluation of these water quality indicators may play a major role in selecting the type of chemical coagulants to be used at a particular water treatment plant, or in changing the type of coagulant normally used if significant changes in pH and alkalinity occur in the raw water.

In some instances, the natural alkalinity in the raw water may be too low to produce complete precipitation of alum. In these cases, lime is often added to ensure complete precipitation. Care must be used to keep the pH within the desired range.

Overdosing as well as under-dosing of coagulants can lead to reduced solids removal efficiency. This condition can be corrected by carefully performing jar tests and verifying process performance after making any changes in the operation of the coagulation process.

**Flocculation**

Flocculation is a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles. The flocculation process provides contact between particles to promote their gathering together into floc for ease of removal by sedimentation and filtration. Generally, these contacts or collisions between particles result from gentle stirring created by a mechanical or hydraulic means of mixing.
An efficient flocculation process involves the selection of the right stirring time, detention time, the proper stirring intensity, a properly shaped basin for uniform mixing, and mechanical equipment or other means of creating the stirring action. Insufficient mixing will result in ineffective collisions and poor floc formation. Excessive mixing may tear apart the flocculated particles after they have clumped together.

### Adsorption

Adsorption is the gathering of a gas, liquid, or dissolved substance on the surface or interface zone of another material. This process removes taste and odor producing compounds because the compounds attach themselves to the material added to the water for that purpose. In water treatment, this material is powdered activated carbon (PAC) or granular activated carbon. PAC is added to the treatment process at the influent, and GAC is used as a filter medium. The material being removed by adsorption is known as the adsorbate and the material responsible for the removal is known as the adsorbent.

The primary adsorbents for water treatment are the two types of activated carbon. These materials are activated by a process involving high temperature and high-pressure steam treatment. The original source of the carbon may be wood, coal, coconut shells, or bones. The purpose of the activation process is to significantly increase the surface area of the particles so that more adsorption can take place per pound of carbon.

The nature of the porous structure of the carbon compound being used will exert a significant effect on the success of the treatment process. If the pores of the carbon are too small, the compounds that are being treated will not be able to enter the structure and only a small portion of the available surface area will be used for treatment. Activation processes produce carbons with different surface areas. Because adsorption is a surface phenomenon, carbons with greater surface area generally provide greater adsorption capacity.

Activated carbon is typically rated on the basis of the phenol number or iodine number. The higher the value, the greater the adsorption capacity of the carbon for phenol or iodine. This strategy is an excellent approach for evaluating the effectiveness of carbon for the removal of phenol or iodine. However, no direct relationship between the compounds causing taste and odor problems and the removal of phenol or iodine exists. Only by testing various carbons for effective removal of objectionable tastes or odors can a good comparison be made for a particular application.

![Activated Carbon](https://workforce.libretexts.org/Bookshelves/Water_Systems_Technology/Water_151%3A_Water_Treatment_Plant_and_Ope…)

**Figure 1**: Activated Carbon – Image by COC OER is licensed under [CC BY](https://creativecommons.org/licenses/by/4.0/)

### Powdered Activated Carbon

Powdered activated carbon adsorption is the most common technique used specifically for taste and odor control at water treatment plants. This widespread use is largely because of its nonspecific action over a broad range of taste and odor-causing compounds. PAC treatment does have limitations, and its effectiveness and required dose rate varies widely from plant to plant.
Powdered activated carbon can be applied to water at any point in the treatment process before filtration. Because carbon must contact the material to be removed for adsorption to occur, it is advantageous to apply PAC at the plant mixing facilities. Powdered activated carbon is often less effective at removing compounds after chlorination, so application upstream from chlorine treatment is desirable. Chlorine will react with carbon and neutralize the effects of the chlorine and the adsorption by the carbon.

Powdered activated carbon is often applied at the plant flash mixer. This location provides high-rate initial mixing and the greatest contact time through the plant. Thorough mixing and long contact time are necessary for the effectiveness of PAC. Another common location for PAC application is the filter influent. While contact time and mixing are drastically reduced compared to flash mix applications, this method ensures that the water passes through a PAC layer before release into the distribution system. This procedure is used with KMnO4 treatment to prevent colored water problems in the distribution system.

When PAC is used, dosages may range from 1 to 15 mg/L. The literature indicates that as much as 100 mg/L has been required to adequately treat some serious taste and odor problems. At very high doses, treatment costs become prohibitive, and consideration of granular activated carbon treatment in the filter becomes an option.

The use of powdered activated carbon for taste and odor removal can interfere with filter performance at a water treatment plant. Caking of PAC on the surface of filters may cause substantially shorter filter runs than otherwise expected. If this occurs, adjustments to improve PAC removal in the settling process may increase the effective length of filtration. An added advantage of optimizing the settling process is the physical removal of taste and odor compounds with the settled sludge.

### Granular Activated Carbon

Activated carbon is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment. Adsorption is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases. Activated carbon is an effective adsorbent because it is a highly porous material and provides a large surface area to which contaminants may adsorb. The two main types of activated carbon used in water treatment applications are granular activated carbon (GAC) and powdered activated carbon (PAC).

GAC is made from organic materials with high carbon contents such as wood, lignite and coal. The primary characteristic that differentiates GAC to PAC is its particle size. GAC typically has a diameter ranging between 1.2 to 1.6 mm and an apparent density ranging between 25 and 31 lb/ft³, depending on the material used and manufacturing process. The bed density is about 10 percent less than the apparent density and is used to determine the amount of GAC required to fill a given size filter. The uniformity coefficient of GAC is quite large, typically about 1.9, to promote stratification after backwashing and minimize desorption and premature breakthrough that can result from mixing activated carbon particles with adsorbed compounds with activated carbon particles with smaller amounts of adsorbed compounds. Iodine and molasses numbers are typically used to characterize GAC. These numbers describe the quantity of small and large pore volumes in a sample of GAC. A minimum iodine number of 500 is specified for activated carbon by AWWA standards.
The two most common options for locating a GAC treatment unit in water treatment plants are: (1) post-filtration adsorption, where the GAC unit is located after the conventional filtration process (post-filter contactors or adsorbers); and (2) filtration-adsorption, in which some or all of the filter media in a granular media filter is replaced with GAC.

In post-filtration applications, the GAC contactor receives the highest quality water and, thus, has as its only objective the removal of dissolved organic compounds. Backwashing of these adsorbers is usually unnecessary, unless excessive biological growth occurs. This option provides the most flexibility for handling GAC and for designing specific adsorption conditions by providing longer contact times than filter-adsorbers.

In addition to dissolved organics removal, the filter-adsorber configuration uses the GAC for turbidity and solids removal, and biological stabilization. Existing rapid sand filters can frequently be retrofitted for filtration-adsorption by replacing all or a portion of the granular media with GAC. Retrofitting existing high rate granular media filters can significantly reduce capital costs since no additional filter boxes, underdrains and backwashing systems may be required. However, filter-adsorbers have shorter filter run times and must be backwashed more frequently than post-filter adsorbers (filter-adsorber units are backwashed about as frequently as conventional high rate granular filters). In addition, filter-adsorbers may incur greater carbon losses because of increased backwashing and may cost more to operate because carbon usage is less effective.

Primary factors in determining the required GAC contactor volume are the (1) breakthrough, (2) empty bed contact time (EBCT), and (3) design flow rate. The breakthrough time is the time when the concentration of a contaminant in the effluent of the GAC unit exceeds the treatment requirement. As a rule of thumb, if the GAC effluent concentration is greater than the performance standard for over three consecutive days, the GAC is exhausted and must be replaced/regenerated. The EBCT is calculated as the empty bed volume divided by the flow rate through the carbon. Longer EBCTs can be achieved by increasing the bed volume or reducing the flow rate through the filter. The EBCT and the design flow rate define the amount of carbon to be contained in the adsorption units. A longer EBCT can delay breakthrough and reduce the GAC replacement/regeneration frequency. The carbon depth and adsorber volume can be determined once the optimum EBCT is established. Typical EBCTs for water treatment applications range between 5 to 25 minutes.

The surface loading rate for GAC filters is the flow rate through a given area of GAC filter bed and is expressed in units of gpm/ft². Surface loading rates for GAC filters typically range between 2 to 10 gpm/ft². High surface loading rates can be used when highly adsorbable compounds (such as SOCs) are targeted for removal. The surface loading rate is not important when mass transfer is controlled by the rate of adsorption as is the case for less-adsorbable compounds.

The carbon usage rate (CUR) determines the rate at which carbon will be exhausted and how often carbon must be replaced/regenerated. Carbon treatment effectiveness improves with increasing contact times. Deeper beds will increase the percentage of carbon that is exhausted at breakthrough. The optimum bed depth and volume are typically selected after carefully evaluating capital and operating costs associated with reactivation frequency and contactor regeneration.
construction costs.

GAC contactors can be configured as either (1) downflow fixed beds, (2) up-flow fixed or expanded beds, or (3) pulsed beds; with single or multiple adsorbers operated in series or in parallel. In down-flow fixed beds in series, each unit is connected in series with the first adsorber receiving the highest contaminant loading and the last unit receiving the lightest contaminant load. Carbon is removed for reactivation from the first unit, with the next adsorber becoming the lead unit. For down-flow fixed beds in parallel, each unit receives the same flow and contaminant load. To maximize carbon usage, multiple contactors are frequently operated in parallel-staggered mode in which each contactor is at a different stage of carbon exhaustion. Since the effluent from each contactor is blended, individual contactors can be operated beyond breakthrough such that the blended flow still meets the treatment goal. Upflow expanded beds permit removal of suspended solids by periodic bed expansion and allow using smaller carbon particles without significantly increasing head loss. In pulsed bed adsorbers, removal of spent carbon occurs from the bottom of the bed while fresh carbon is added at the top without system shutdown. A pulsed bed cannot be completely exhausted, which prevents contaminant breakthrough in the effluent.

Depending on the economics, facilities may have on-site or off-site regeneration systems or may waste spent carbon and replace it with new. Spent GAC must be disposed of recognizing that contaminants can be desorbed, which can potentially result in leaching of contaminants from the spent GAC when exposed to percolating water, contaminating soils or groundwater. Due to contamination concerns, spent GAC regeneration is typically favored over disposal. The three most common GAC regeneration methods are steam, thermal, and chemical; of which thermal regeneration is the most common method used. Available thermal regeneration technologies used to remove adsorbed organics from activated carbon include: (1) electric infrared ovens, (2) fluidized bed furnaces, (3) multiple hearth furnaces, and (4) rotary kilns.

Review Questions

1. Describe the sources and production of activated carbon.
2. Describe the organic chemical removal theory.
3. Describe the types of applications where activated carbon is used.
4. Outline the disposal methods and regeneration methods for activated carbon.

Test Questions

1. ______ is the physical and chemical process of accumulating a substance at the interface between liquid and solids phases.
   1. Absorption
   2. Adsorption
   3. Oxidation
   4. Stabilization

2. The technologies most suitable for organic contaminant removal in process waters are ______ and ______.
   1. Oxidation, reduction
2. Coagulation, flocculation
3. Adsorption, absorption
4. Granular activated carbon, aeration

3. _______ is the gathering of a gas, liquid, or dissolved substance on the surface or interface zone of another material.

4. Absorption
5. Adsorption
6. Oxidation
7. Stabilization

8. Activated carbon is typically rated on the basis of the _______. The higher the value, the greater the adsorption capacity of the carbon for phenol or iodine.
   1. Adsorption number
   2. Absorption number
   3. Taste and odor number
   4. Phenol number or iodine number

9. _______ is commonly used to adsorb natural organic compounds, taste and odor compounds, and synthetic organic chemicals in drinking water treatment.
   1. Oxidation
   2. Coagulation
   3. Absorption
   4. Activated carbon

10. The two primary types of activated carbon used in water treatment applications are _______ and _______.
    1. Oxidation, reduction
    2. Coagulation, flocculation
    3. Adsorption, absorption
    4. GAC, PAC