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Activated Carbon Basics

Introduction to Activated Carbon

Understanding the different types of activated carbon products, their specific properties and best practices for use is essential to the design of effective environmental treatment processes

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IN BRIEF

Activated carbon is a type of manufactured carbon material used for a range of adsorptive processes, including drinking water treatment, industrial operations, environmental remediation and many other applications. Reports suggest that crude activated carbons have been used in various ways for millennia, for example by ancient Egyptians and Romans as medicine or for water filtration, but the science of more effective modern activated carbons has been continuously developing over many decades. Today's activated carbon products include cutting-edge manufactured materials that are crucial to society's water and energy infrastructure, as well as modern industry. Activated carbon provides an environmental solution for ensuring clean air and drinking water and contributes to the efficient production of many industrial products. Understanding the different types of activated carbon products, their specific properties, and best practices for use is important to the design of effective treatment processes.

Activated carbon is ubiquitous because it is a versatile adsorbent material with the ability to separate and retain components of many liquids and gases (Figure 1). Within an activated carbon particle, the immense specific surface area facilitates the physical adsorption of molecules onto the carbon surface. In contrast to absorption, where fluids enter the internal area of a material, causing it to expand, adsorption is a phenomenon that describes how molecules physically adhere to a surface. Physical adsorption onto activated carbon occurs through weak intermolecular forces called Van der Waals forces in the internal surface area of carbon, often called the pores of the carbon, which give activated carbon its exceptional ability to adsorb and retain organic compounds. Activated carbon adsorption is non-specific and the adsorbate properties contribute to practical capacity for a given contaminant. The adsorption strength of a compound onto activated carbon increases with molecular weight and aromaticity, and can be influenced by functional groups. This adsorptive capability allows activated carbon to be utilized in a wide range of separation processes. Some common factors that affect adsorption are detailed in Table 1.

How activated carbon is made

Activated carbon is manufactured by carbonizing a carbon-rich material and then generating new internal surface area in a process called activation. The type of activation process used and the selected raw materials will produce finished activated-carbon products with different properties.

There are two types of activation processes used to generate internal surface area: physical activation, which uses a high-temperature gas, such as H_2O or CO_2, to react with carbon to increase surface area; or chemical activation, which produces surface area by reaction of carbon sources with an added chemical, such as HP_3O_4. Physical activation with H_2O vapor is the most common activation process practiced industrially, but chemical activation is

FIGURE 1. Activated carbon is used in treatment processes when manufacturing a wide variety of industrial products, as well as in environmental treatment for water, air and more

used to produce some specialty activated-carbon products.

Worldwide, many raw materials are used to manufacture activated carbon, but the most industrially significant sources of activated carbon are coals, ranging from low-rank coals like lignite, to higher-rank bituminous and anthracite, as well as biomass-based sources, such as wood and coconut shell. The respective raw material used will produce an activated carbon with some properties inherited from the raw material, including adsorptive properties, such as the pore structure (or pore distribution), as well as physical properties like inorganic mineral components, termed ash content, and the hardness of the resulting activated carbon. The selected carbon source influences the physical and adsorptive characteristics of the finished activated carbon product, making different carbons suitable for different applications. Coconut shells and high-rank coals, such as bituminous material, yield denser, harder activated carbons and have low ash content with more microporous pore structures. Wood feedstocks and low-rank coals, such as lignite, yield softer activated carbons with more mesoporous and macroporous structures. The base material can often have a major impact on carbon performance for a given application. For example activated carbons produced from bituminous coal sources adsorb per- and poly-fluoroalkyl substances (PFAS) better than carbons produced to similar specifications from coconut shell sources.

Activated carbon products can be manufactured as granular activated carbon (GAC), in the millimeter particle-size range, as powdered activated carbon (PAC), typically consisting of particles falling below 44 micrometers (µm), or in other forms, such as pellets and cloth. Figure 2 shows the different formats and provides specific properties for each.

Properties and specifications. Specifying the properties for activated carbon is crucial, because specifications ensure that the carbon product will perform as expected for its intended application, and that it is of a consistent quality. Because activated carbon is used in a wide range of industries, including water treatment, air purification and food-and-beverage processing, the specifications that make an optimal carbon product may vary by application. Table 2 describes several typical specifications for activated carbon.

How activated carbon is used

The way activated carbon is used highly depends on the form of carbon chosen. The most common way activated carbon is used is in a packed bed, where GAC is placed in a stationary vessel, and a stream of liquid or gas flows through it. This allows the GAC to adsorb contaminants from the fluid, retaining them within the GAC particles. Packed beds of GAC are widely used in the water-treatment industry to remove organic compounds from drinking water, in wastewater treatment and in liquid chemical processes. Similarly, for air and industrial-gas treatment, packed bed systems are used to remove pollutants, such as volatile organic compounds (VOCs) or H_2S. Packed bed systems allow for relatively simple operations using GAC in both liquid- and vapor-phase applications, and the packed beds themselves are often designed with ease of media installation and removal in mind. Typically, activated carbon is used as a polishing technology for relatively low concentrations in the liquid and gas phase, rather than used in concentrated streams, though there are exceptions.

PAC is too fine to be retained within a packed bed, and instead is typically added to a liquid stream in a batch process, in which the carbon

TABLE 1. COMMON FACTORS THAT AFFECT ADSORPTION			
Property	**Effect on liquid-phase adsorption**	**Property**	**Effect on vapor-phase adsorption**
Solubility	The higher the solubility, the more difficult to adsorb	Concentration	Wt. % loading on carbon increases as inlet species concentration increases
Concentration	Wt. % loading on carbon increases as inlet species concentration increases	Saturation pressure	The closer to saturation pressure, the more strongly adsorbed
Molecular weight	The higher the molecular weight, the better adsorbed	Relative humidity (RH)	RH above 50% interferes with adsorption efficiency — lower adsorption capacity
Functional groups	More complex structures adsorb more strongly	Temperature	Higher temperatures result in lower wt. % loading

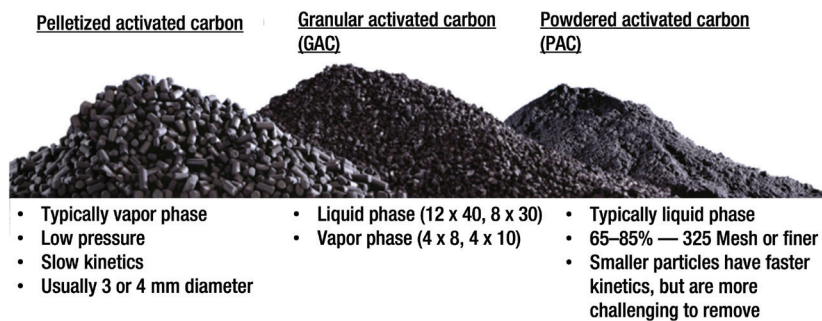| TABLE 2. TYPICAL ACTIVATED CARBON SPECIFICATIONS		
Specification	**Unit**	**Description**
Mesh size	Mesh	The size of the carbon particles, measured in the percentage of particles existing between the U.S. mesh sizes denoted, such as 8x30 or 12x40
Iodine number	mg/g	A surrogate measure of the surface area of the carbon, with higher numbers indicating greater surface area available for adsorption
Hardness	%	A measure of the carbon's resistance to breakage or abrasion, with higher percentages indicating greater durability
Ash content	%	The amount of inorganic material present in the carbon, which can affect its performance in certain applications
Moisture content	%	The amount of water present in the carbon, which can affect its performance and handling characteristics
Apparent density	g/cm^3	The weight of packed carbon per unit of volume, which can affect its handling and transportation costs

Pelletized activated carbon	Granular activated carbon (GAC)	Powdered activated carbon (PAC)
• Typically vapor phase • Low pressure • Slow kinetics • Usually 3 or 4 mm diameter	• Liquid phase (12 x 40, 8 x 30) • Vapor phase (4 x 8, 4 x 10)	• Typically liquid phase • 65–85% — 325 Mesh or finer • Smaller particles have faster kinetics, but are more challenging to remove

FIGURE 2. There are multiple formats for activated carbon products, each with a unique set of properties

particles are dispersed into the fluid and allowed to adsorb the contaminants. After the adsorption process, the PAC particles are filtered out of the fluid, typically using a mechanical filtration system. PAC can also be injected into vapor streams and removed in particulate capture devices, such as baghouses, a practice used for the removal of VOCs and dioxins, furan and mercury from fluegases.

While PAC particles have larger external surface area than GAC, there is no significant difference in specific surface area between GAC and PAC, because the majority of activated carbon's surface area is internal. Adsorption kinetics onto activated carbon are dependent on particle size, and the small particle size of PAC results in rapid adsorption kinetics, allowing PAC to adsorb compounds at a faster rate than larger particles of carbon.However, there is no difference in the equilibrium loading of GAC and a corresponding PAC produced to an equivalent adsorption specification. Indeed, packed beds of GAC often result in better carbon usage rates than PAC. Practically, GAC used in a packed bed system often loads to a higher degree than PAC, adsorbing more contaminants per mass of carbon used.

Liquid-phase best practices
GAC liquid adsorbers can be used with single vessels, but designs commonly include multiple adsorber vessels operating in series flow, lead-lag configuration, to allow for the greatest utilization of GAC capacity. In this configuration, when the lead vessel has reached its capacity, the lag vessel is moved into the lead position and a fresh carbon bed is put online in the lag position. Typically, at least ten minutes of empty bed contact time (EBCT) per vessel are required to account for the kinetics of adsorption and provide for an adequate bed life, depending on contaminant inlet concentrations and treatment objectives. In general, longer contact times are required as the carbon particle size increases

and as the fluid viscosity increases. Decreasing the flowrate through a given vessel will reduce and sharpen the mass transfer zone (MTZ) of the bed, increasing carbon loading. Additionally, pretreatment and operational maintenance (such as backwashing) may be warranted in some applications, some of which are detailed in Table 3.

Vapor-phase best practices
Vapor-phase adsorption applications with activated carbon differ significantly from liquid-phase applications in that the required contact time is often much less in the vapor phase, due to the kinetic advantages associated with gas adsorption. For high removal across a vapor-phase carbon bed, typically three or more seconds of contact time are required. Because adsorption is an exothermic process, and in vapor-phase applications there is not excess water present to dissipate heat, there are some guidelines for

TABLE 3. TYPICAL LIQUID PRETREATMENT AND OPERATIONAL GUIDELINES FOR GAC SYSTEMS	
Parameter	**Pretreatment recommendations and operational considerations**
Total organic carbon (TOC)	• Adsorbable TOC consumes carbon capacity, so lower TOC results in lower carbon usage rates. GAC can tolerate greater than 1,000+ parts per million (ppm) TOC, depending on application
Total suspended solids (TSS)	• TSS will foul beds and block access to carbon pores • Upstream filtration of 5–10 µm is recommended • Backwashing may be required for TSS in the 3–5 mg/L range, otherwise solids can cause increased ΔP
Total dissolved solids (TDS)	• Application-dependent, though typical hardness < 100 mg/L for water treatment
Manganese	• <0.5 ppm
Iron	• <1 ppm
Chlorine (or other oxidizers)	• <5 mg/L
Oil and grease	• If not fully dissolved or in solution, remove upstream of GAC • Do not use GAC to directly treat two-phase systems or free product containing water
Langelier Saturation Index (LSI)	• Avoid corrosive or saturated conditions • Neutral or negative LSI desired to avoid Ca or Mg buildup
Bacteria	• Backwashing can help mitigate biofouling; caustic solution disinfection recommended for inoculated carbon beds
Linear velocity	• The superficial velocity of the liquid stream as it passes through the carbon bed is calculated as the volumetric flow rate of the stream divided by the cross-sectional area of the carbon bed • The linear velocity should be carefully controlled to prevent channeling (velocity too low) or excessive pressure drop (velocity too high). Guidelines for linear velocity in liquid-phase applications typically range from 2 to 9 gal/min/ft².

TABLE 4. TYPICAL VAPOR-PHASE GUIDELINES AND OPERATING CONDITIONS	
Design requirement/parameter	Description
Particulate matter and aerosols	• As in liquid-phase applications, GAC will physically filter some particulate matter, but since backwashing is not typically possible in vapor-phase applications, it is recommended to remove particulate matter prior to the carbon bed to prevent their buildup and associated issues, such as channeling • GAC will not adsorb aerosols in the same way it adsorbs gases
Linear velocity	• The superficial velocity of the airstream as it passes through the carbon bed is calculated as the volumetric flowrate of the airstream divided by the cross-sectional area of the carbon bed • The linear velocity should be carefully controlled to prevent channeling (velocity too low) or carbon fluidization and vibration (velocity too high). Guidelines for linear velocity in vapor-phase applications typically range from 15 to 90 ft/min
Length/diameter (L/D) ratio	• The ratio of the bed length (depth) to the bed diameter. L/D is important because it affects the flow distribution of the air stream through the carbon bed, which in turn affects the efficiency of the adsorption process • In general, a higher L/D ratio leads to better flow distribution and more efficient adsorption, but also increases pressure drop and energy requirements • L/D ratio of 3 to 5 is typically recommended to balance efficiency and pressure drop considerations. Typically, at least several feet of bed depth are used
Humidity	• The moisture content of the vapor stream being treated must be considered. This parameter is important because moisture can compete with the target species for adsorption sites on the carbon • Relative humidity (RH) above 50% can negatively impact VOC adsorption
Pressure drop (ΔP)	• Pressure drop is the decrease in pressure that occurs as the vapor stream passes through the carbon bed. This parameter is a function of the flowrate of the vapor stream, bed design, carbon type and the gas properties • Smaller-sized carbon particles will cause higher pressure drop and require greater energy to overcome the pressure drop across the bed

reducing thermal risk in these applications. Typically, inlet concentrations of VOCs exceeding 1,000 ppmv in air are not recommended. Additionally, some compounds, such as ketones and aldehydes, can oxidize on the carbon by atmospheric oxygen, generating additional heat, and so their inlet concentrations should be limited. Additional vapor-phase design and operating considerations are included in Table 4.

Spent media and reactivation
After activated carbon has reached its capacity and will no longer adsorb the target chemical species, it often must be removed from service. In packed beds using GAC, the spent GAC is removed from the adsorber vessel by vacuum or by slurry method, depending on the vessel design and utilities. Spent GAC is moved by truck and can be disposed of by landfill or incineration. A more environmentally friendly and cost-effective approach is to reactivate the spent activated carbon.

Carbon reactivation is a process where spent, contaminant-loaded GAC is returned to a facility with a suitable reactivation furnace, which operates under similar high-temperature conditions to physical carbon-activation furnaces. In the carbon reactivation furnace, contaminants are desorbed from the GAC and destroyed, and the furnace atmosphere facilitates the generation of new surface area in the GAC. A downstream abatement process ensures adequate destruction, control of acid-gas generation, and particulate-matter removal. Thus, the carbon reactivation process removes and destroys contaminants from GAC, allowing for the GAC to be re-used in the same or other processes. Reactivation is typically only practiced on granular materials with sufficient hardness and density to resist physical degradation in the aggressive furnace atmosphere.

To be eligible for carbon reactivation, the material must undergo a "Carbon Acceptance" process, where the composition of the carbon and contaminants are verified as acceptable. Carbon reactivation has proven to be effective at removing and destroying even robust compounds, such as PFAS. Ref. 1 describes a peer-reviewed study demonstrating >99.99% destruction of total PFAS compounds across a carbon reactivation furnace.

System design and scaleup
System design and performance of GAC adsorbers is dependent on several factors, but key details include targeted adsorbate species, stream composition, inlet concentrations and outlet concentration goals. There are several methods that can be used to inform the design and determine the expected performance of a larger GAC system, and they are ranked in the order of increasing accuracy. ***Computational models.*** Technical industry experts can use computational models to estimate the performance of carbon in various applications, inputting key factors, such as stream properties and composition, selected model sorbents and so on. These can be effective for some target species and applications, but have less value than empirical data generated using source waters and chosen sorbents.
Isotherms. Isotherm testing measures the adsorption capacity of a sorbent by plotting the mass of adsorbate loaded on carbon against its concentration at a constant temperature and is often performed at bench scale with selected sorbent products and source waters. An isotherm can inform the theoretical maximum capacity of a sorbent for a selected adsorbate. While isotherms are useful at determining feasibility for an application, they do not accurately model full-scale adsorber systems and cannot determine component breakthrough order or time.

Laboratory column testing. Small column testing can be performed at bench scale to simulate the longer-term performance of a full-scale system. Two common methods include the Rapid Small-Scale Column Test (RSSCT) and Accelerated Column Test (ACT), where GAC is carefully resized to a determined smaller particle size, allowing for the simulation of months of full-scale system run time in just days. Laboratory column testing can be more reliable than isotherms and can provide better details about component breakthrough order and estimated days until breakthrough.

Pilot systems. Pilot systems consist of small vessels located onsite at the application, treating a slipstream or representative sample of the target source stream. Pilots can be designed to more closely replicate the conditions of a full-scale system and, coupled with representative pretreatment, are the most reliable method for determining full-scale system performance.

Some GAC and equipment vendors offer rental equipment, which includes carbon-exchange services, including removal of spent GAC from the vessel, disposal and replacement with fresh GAC. Rental units can be particularly good options for pilot systems, and some rental equipment units are designed so that the entire unit can be returned to the provider for carbon reactivation or disposal, simplifying media exchange.

Safety

Activated carbon is generally a safe technology, especially when used in well-designed systems. However, there are a few safety considerations that are worth highlighting.

Wet activated carbon preferentially removes oxygen from air. In closed or partially closed containers and vessels, oxygen depletion may reach hazardous levels. If workers are to enter a vessel containing carbon, appropriate sampling and work procedures for potentially low-oxygen spaces should be followed, including all applicable federal and state requirements.

In vapor-phase applications, high concentrations of VOCs and some reactive components can cause the temperature within a carbon bed to increase. Heating may be controlled by diluting the inlet air with nitrogen or by pre-wetting the carbon. Concentrations of gases should be kept to below 25% of the lower explosive limit (LEL). Seeking input and advice from an activated carbon supplier for applications involving high concentrations of organic compounds or potentially reactive species (certain ketones, aldehydes and carboxylic acids) is highly recommended. ■

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Reference

1. DiStefano, R., others, Thermal destruction of PFAS during full-scale reactivation of PFAS-laden granular activated carbon, *Remediation*, Vol. 32, Issue 4, September 2022.

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