

SECTION 6.0

CARBON ADSORBERS

This section provides guidance on proper operation and maintenance (O&M) of carbon adsorption systems (CASs) used as air pollution control devices to comply with applicable emission standards. It is also intended to assist Agency personnel responsible for making inspections at facilities that use CASs in the recognition and understanding of the indicators of efficient and reliable equipment operation.

6.1 General Description

Adsorption is a surface phenomenon in which volatile organic compounds (VOCs) are selectively adsorbed on the surface of such materials as activated carbon, silica gel, or alumina. Because it is the most widely used adsorbent, activated carbon is the focus of this section. Adsorption systems using silica gel or alumina are less likely to be found in air pollution control and, thus, are not discussed in this manual.

6.1.1 Principles of Adsorption

It is well established that the molecular forces at the surface of a liquid are in a state of imbalance or unsaturation. The same is true of the surface of a solid where the molecules or ions may not have all their forces satisfied by union with other particles. Because of this unsaturation, solid and liquid surfaces tend to satisfy their residual forces by attracting to and retaining on their surfaces gases or dissolved substances with which they come in contact. This phenomenon of concentration of a substance on the surface of a solid (or liquid) is called adsorption. The substance thus attracted to a surface is said to be the adsorbed phase or adsorbate, and the substance to which it is attached is the adsorbent. "Adsorption" should be carefully

distinguished from "absorption". In the latter process, a substance is not only retained on a surface, but also passes through the surface to become distributed throughout the phase. Where doubt exists as to whether a process is true adsorption or absorption, the noncommittal term "sorption" is sometimes used.

The study of adsorption of various gases (or vapors) on solid surfaces has revealed that the forces operating in adsorption are not the same in all cases. Two types of adsorption are generally recognized, namely, "physical" (van der Waals adsorption) and "chemical" (activated adsorption).

Physical adsorption is the result of the intermolecular forces of attraction between molecules of the solid and of the substance adsorbed. For example, when the intermolecular attractive forces between a solid and a gas (or vapor) are greater than those existing between molecules of the gas itself, the gas will condense on the surface of the solid. The adsorbed substance neither penetrates within the crystal lattice of the solid nor dissolves in it; it remains entirely upon the surface. Should the solid be highly porous and contain many fine capillaries, however, the adsorbed substance will penetrate these interstices if it "wets" the solid. At equilibrium, the partial pressure of the adsorbed substance equals that of the contacting gas phase. Lowering the pressure of the gas phase or raising the temperature will readily remove the adsorbed gas or desorb it in unchanged form. Physical adsorption is characterized by the fact that the adsorption equilibrium is established rapidly and is reversible.

Chemisorption, or activated adsorption, is the result of chemical interaction between the solid and the adsorbed substance. The strength of the chemical bond may vary considerably, and identifiable chemical compounds may not form. Nevertheless, the adhesive force is generally much greater than that found in physical adsorption. The process is frequently irreversible; and, on desorption, the original substance will often be found to have undergone a chemical change.¹

6.1.2 Activated Carbon

Activated carbon is composed largely of neutral carbon atoms with no electrical gradients between molecules. Thus, carbon does not attract polar molecules in

preference to nonpolar molecules. Carbon is effective in adsorbing organic compounds from a humid gas stream because it does not show a higher affinity for the polar water molecules.

Activated carbon is made by a two-step process. In the first, material from various sources (e.g., coconut shells, petroleum products, wood, and coal) is carbonized by heating it in the absence of air until all organic compounds except the carbon are volatilized. High-temperature steam, air, or carbon dioxide is then used to make the carbon porous or activated. Depending on the extent of this process and the original source, the carbon can be made to fit the use for which it is desired.

After activation, the external surface of a carbon particle is a few square meters per gram; however, the available surface area within the pores is hundreds of square meters per gram. The pore structure of activated carbon consists of progressively smaller pore sizes. Diffusion of the adsorbate gas into the larger pores occurs fairly rapidly, but as the pore diameters become smaller, the diffusing molecules strike the walls and stick for short periods of time. This diffusion process continues until the molecules reach a location where they no longer have sufficient energy to escape the forces that hold them to the pore wall. This usually occurs where the pore diameter is not more than twice the diameter of the adsorbate molecule (critical diameter).

The purpose of a carbon adsorber is to transfer the adsorbate from the gas stream to the carbon, where it can more easily be recovered or disposed of. Therefore, at some point the adsorbate must be removed from the carbon. This process is called desorption or regeneration. Desorption is accomplished by shifting or reversing the equilibrium established during the adsorption process. There are three ways to shift the equilibrium: 1) increasing the temperature, which is usually done by the use of steam; 2) reducing the pressure of the atmosphere surrounding the carbon; and 3) reducing the concentration of the adsorbate in the gas stream to a value less than the concentration within the carbon. In most air pollution control applications, desorption is accomplished by increasing the temperature, whether by use of an in situ regeneration system or at a regeneration facility after the carbon has been replaced. After desorption, adsorbate remaining in the carbon is called the "heel." The heel will

reduce the working capacity of the carbon for subsequent use, depending upon the total amount of residual adsorbate.²

6.1.3 Full-Scale Adsorption Systems

Carbon adsorption is used for pollution control and/or solvent recovery in a variety of industries. It is usually a batch operation, and it can involve multiple beds. Five types of adsorption equipment are used in collecting gases: 1) fixed regenerative beds, 2) disposable/rechargeable canisters, 3) traveling-bed adsorbers, 4) fluidized-bed adsorbers, and 5) chromatographic baghouses. Of these five, the first two are the most common.³ In this document, the fixed regenerative bed is discussed in the most detail.

The practical application of the adsorption process to a full-size carbon bed is illustrated in Figure 6-1. In this figure, VOC-laden air (SLA) flows from left to right. As shown, the bed has three zones, labeled saturated, mass transfer, and fresh. The saturated zone, which is located at the entrance to the bed, represents the carbon that has already adsorbed its working capacity of adsorbate. Because the saturated carbon is at thermodynamic equilibrium with the incoming vent stream, no net mass transfer occurs in this zone. The mass transfer zone (MTZ) is the section of the carbon bed where the adsorbate is removed from the carrier stream. The carbon in this zone is at various degrees of saturation, but it is still able to adsorb some adsorbate. In a typical system, the mass transfer occurs within a section approximately 3 inches in depth. The fresh zone is downstream of the mass transfer zone and represents the region of the bed where no new adsorbate has passed since the last regeneration. This zone still has available all its working capacity (i.e., equilibrium capacity minus the heel).

During operation, the mass transfer zone moves down the bed in the direction of flow. Breakthrough occurs when the mass transfer zone first reaches the bed outlet. The breakthrough point is characterized by the beginning of a sharp increase in the outlet concentration. The available adsorption time for a specific bed before breakthrough occurs is a function of the amount of carbon present, its working capacity, and the concentration and mass flow rate of adsorbate.

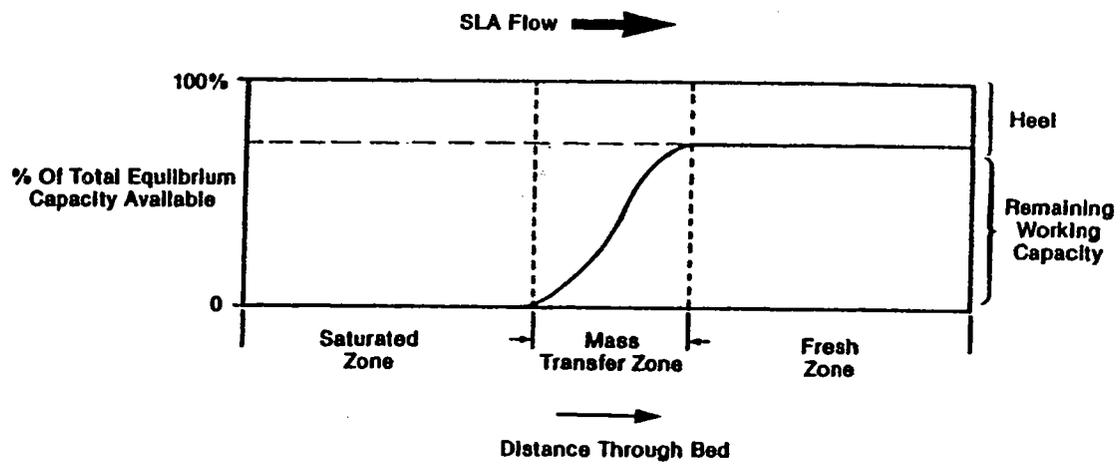


Figure 6-1. Available working capacity in a working bed as a function of distance through bed.²

Theoretically, the concentration in the last zone should be zero; however, a small amount of adsorbate is typically present as a result of two factors:

1. A small amount of SLA may pass through the adsorber without actually contacting the carbon.
2. Because of the low concentration of adsorbate in the vent stream in the last few inches of the bed, the heel remaining from the previous cycle will slowly desorb.

The breakthrough curve, which is the outlet concentration as a function of time, is a mirror image of the concentration profile in the mass transfer zone. As the mass transfer zone reaches the end of the bed, the outlet concentration rises. This will continue until the outlet equals the inlet concentration.²

Fixed Regeneration Bed Systems--

Figure 6-2 presents a process flow diagram for a typical two bed carbon adsorber system. The adsorber system can be broken down into three separate sections: pretreatment, carbon adsorber, and recovery/waste treatment. The vent stream containing the adsorbate enters the adsorption system via the pretreatment section. If the temperature of the vent stream is above the maximum specified in the design, it is reduced within the pretreatment section (usually with a heat exchanger). In addition, a filter is included in the pretreatment section to remove any particulate present in the vent stream.

From the pretreatment section, the vent stream enters the adsorber. Figure 6-2 depicts a two-bed adsorber system. At least two adsorber beds are needed to provide continuous emission control so that one remains on line while the other is regenerated. Adsorber systems with three or more beds are operated similarly. During operation, the organic-laden vent stream passes through the on-line bed for a predetermined time or until breakthrough occurs. The on-line bed is then taken off line for regeneration (desorption) and the other bed is brought on line.

Regeneration of the off-line bed is usually accomplished by passing steam through the bed countercurrent to the direction of vent stream flow. The steam that is

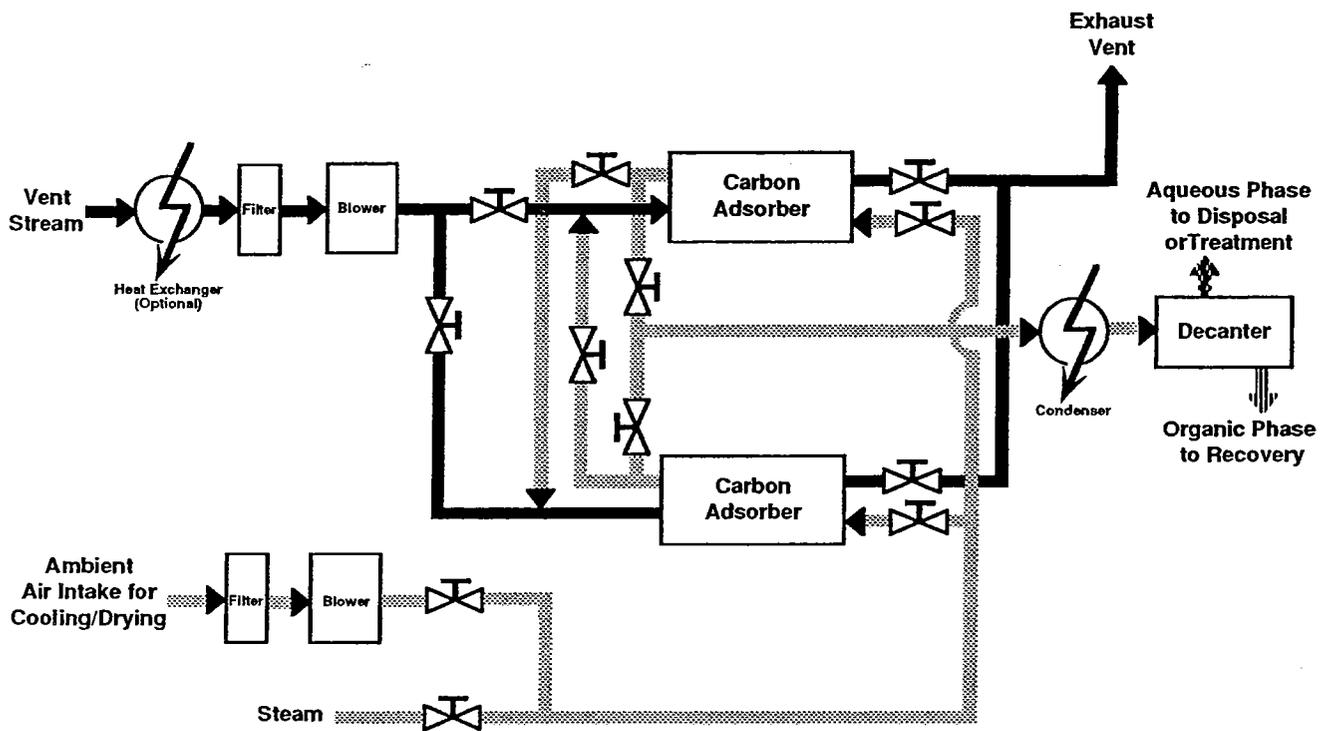


Figure 6-2. Carbon adsorber system process flow diagram.²

injected into the bed serves several purposes: 1) it provides the energy to raise and hold the bed at an elevated temperature, 2) it provides the energy required to desorb the adsorbate from the carbon, and 3) it carries the desorbed adsorbate from the bed. The steam is condensed and then decanted.

Two liquid phases are present in the decanter, the aqueous phase and organic phase. The aqueous phase is either disposed of or, if the level of organics is high, treated prior to disposal. The organic phase is generally recovered for reuse. After the desorption step, heated air is sometimes used to dry the bed. This is not required in most cases, however, because removing water from the carbon usually has little effect on the adsorption process. In fact, the moisture left on the bed can be beneficial because it acts as a heat sink during the adsorption process.

Finally, the regenerated bed is cooled by passing ambient air through it. In a well-designed system, both cooling and drying are performed with the airflow countercurrent to the direction of flow when the adsorber is on line. The air exiting the regenerating bed is directed through the on-line bed to remove any trace adsorbate.

Full Scale System Design Considerations--

Both the physical system design and the system control and operation during adsorption and desorption are important to achieving high removal efficiencies on a continuous basis.

The design of full-scale carbon adsorption systems begins with a determination of the inlet stream characteristics. Characteristics that may be important include:

- Specific compound(s) present
- Flow rate and temperature (range and average)
- Adsorbate concentration (range and average)
- Relative humidity

Any commercial activated carbon should be capable of acceptable performance if the design of the system is based on that particular carbon. Selecting a carbon with

a majority of micropores that are smaller than approximately twice the diameter of the adsorbate molecules will result in the greatest adsorptive forces.² Under certain conditions, however, the carbon adsorption process may not be suitable for some VOCs. Compounds with one or more of the following physical/chemical properties may not readily adsorb or remain adsorbed to carbon especially at low gas stream concentrations, elevated temperatures, or high relative humidities:

- Molecular weight < 50 g/g-mol
- Boiling point, at atmospheric pressure, < 20°C
- Index of refraction (as a measure of the compound's degree of polarity) ≤ 1.40 .

Light-molecular-weight polar compounds with relatively low boiling points may exhibit extremely low adsorption capacities at low concentrations (e.g., vinyl chloride, methylene chloride, ethylene bromide, and formaldehyde). At concentrations in the low parts per million range or less, the mass transfer zone of these compounds can quickly move through the carbon bed and result in hastened breakthrough. In addition, other compounds in the gas stream with a higher affinity for carbon adsorption will often dislodge (desorb) these compounds. As more strongly adsorbed compounds displace the less strongly adsorbed ones, they push them through the bed, which creates a wave front of the lower-molecular-weight compounds at the front of the MTZ. Therefore, rapid breakthrough of these compounds may result in high carbon replacement/regeneration cost.⁴

When the carbon has been selected, the required bed area is calculated based on the desired superficial velocity. For a specified flow rate, the bed area determines the superficial velocity of the vent stream through the bed. The lower limit of superficial velocity is 20 ft/min to insure proper air distribution. The upper limit is usually 100 ft/min. This upper limit is to keep bed pressure drops within the discharge head capacities of the types of fans used in these applications and to avoid excessively high system power costs. Typical superficial velocities are based on vendor experience and the results of pilot-scale testing; they will usually be between 50 and 100 ft/min.

Generally, bed depths of carbon adsorbers range from 1.5 to 3.0 feet. A bed depth of at least 1.5 feet is used to insure that the bed is substantially deeper than the MTZ, which is normally 3 inches deep. If the MTZ is longer than the bed, breakthrough will occur almost immediately. The maximum bed depth of 3 feet is based on keeping system pressure drop within reasonable limits.

Steaming requirements are set as part of the initial system design. The longer the bed steaming time, the greater the amount of adsorbate removed and the smaller the amount of removable heel remaining. As previously discussed, the working capacity of a carbon bed, which is the amount of adsorbate the bed can remove during an adsorption cycle, is the difference between the heel and the equilibrium capacity. Therefore, the longer the bed is steamed, the greater the available working capacity.

In well-designed systems, the bed is steamed countercurrently to the direction of flow during adsorption. This will help minimize the adsorbate emitted at the adsorber outlet prior to breakthrough. After steaming, the concentration of adsorbate (i.e., the amount of heel that remains) is lower at the end of the bed where the steam enters. When the adsorber is brought on line, the lower amount of heel where the SLA exits the bed means less adsorbate is available to desorb. Also, having more working capacity available at the bed exit helps prevent momentary increases in outlet concentration as a result of changes in inlet conditions caused by process upsets.

Another consideration in adsorber design is fouling. Fouling occurs when compounds that will not desorb from the bed are present in the vent stream. These compounds can be solid particles, high-molecular-weight compounds, or compounds that chemically react on the surface of the carbon (such as some ketones). Regardless of the source, bed fouling gradually reduces the carbon adsorption capacity.

Two methods can be used to compensate for fouling. One is to increase the volume of carbon beyond the minimum required to achieve the desired adsorption time. The second is to gradually increase the amount of steam used to regenerate the bed. Increasing the steam used in regeneration reduces the heel, which helps maintain sufficient working capacity. A combination of these methods can also be used.

Figure 6-3 shows a typical adsorption/desorption cycling arrangement for a two-bed adsorber system. For the purpose of discussion, the times shown on the figure correspond to operational aspects of the system. The sequence begins with Bed 1 coming on line as Bed 2 goes off line at t_0 . For the example shown, adsorption lasts 90 minutes, the steaming time is fixed at 30 minutes, and the cooling/drying time is also 30 minutes. The off-line bed is on standby for 30 minutes. In this example, this 30 minutes allows the operator to compensate any daily variations in vent stream conditions and bed fouling without having to leave a bed on line after breakthrough. It is important that a bed not be left on line after breakthrough because that will significantly reduce the overall removal efficiency during that cycle.

Two types of trigger mechanisms are used to control the adsorption/desorption cycles: continuous monitors and timers. Continuous monitors take a bed off line when a specified outlet concentration is reached. Timers cycle the bed at a specified time. A combination of both mechanisms may also be used. One advantage to using continuous monitors is that they allow the beds to remain on line until breakthrough; thus, their full capacity is used during each cycle. This is not the case for a timer-based system because properly guarding against breakthrough requires that allowances be made for variations in the breakthrough time due to changes in the inlet stream characteristics.²

Although continuous monitors allow for the use of more of the available adsorption capacity than timers do, timers can be used as the trigger mechanism in many situations. They are especially appropriate for adsorbates that do not foul the bed or where inlet stream characteristics are very stable. If a timer is used, continuous monitors or a periodic sampling program should be used to adjust the adsorption times as necessary. Deviations in operating conditions do not affect properly designed systems that use timers unless the conditions exceed the range of the design specifications. When this is allowed to occur, a bed may be kept on line after breakthrough. This would significantly reduce removal efficiency.

A final and important consideration in system design is prevention of channeling. Channeling occurs when a portion of the SLA bypasses the bed or a certain section of

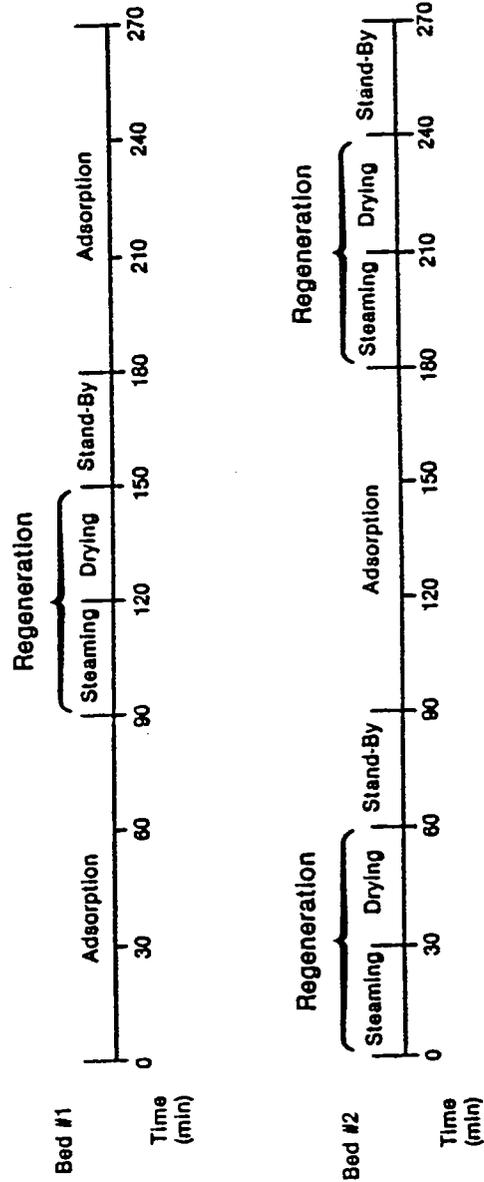


Figure 6-3. Adsorption/desorption cycles in a two-bed system.²

the bed receives a greater portion of the flow than other sections do. The inlet of the vessel must be designed to achieve proper distribution of the SLA so that it does not impinge on a portion of the bed at high velocity. The potential for channeling can be minimized by the use of distribution baffles. It is also important to achieve proper distribution of the regeneration steam. If steam is not well distributed, the steam flow can also cause channels to form in the bed. Poor steam distribution can also result in some portion of the bed not being properly regenerated.

Proper design can minimize the potential for channeling. Maintenance of the distribution baffles and steam distribution system, however, should be performed during scheduled system shutdowns or whenever an increase is detected in the adsorber outlet VOC concentration which is significant enough to result in a removal efficiency below the minimum design level.²

Disposable/Rechargeable Canisters--

For very small vent flows, flows of an intermittent or infrequent nature, and effluents with very low sorbate concentration, utilization of disposable canisters of carbon or other sorbent may be an economical and desirable control approach. Disposable paper and fiber cartridges have been developed that contain the sorbent as a fine powder dispersed in and on an inert carrier of paper, organic or inorganic textiles, and plastic filaments. Paper can contain 50 to 75 percent carbon by weight, and cellulose filters with up to 80 percent activated carbon are available. Such elements, however, are rarely used by industry. A more frequently used element is a replaceable and disposable canister filled with granular sorbent held in a permanent container in the vent line and operated until the sorbent approaches saturation. The canister is then manually removed much like a cartridge filter and disposed of as solid waste (landfill, solid waste incinerator, etc.). Consideration should be given to the disposal method and the possible release of the sorbate as a further environmental pollutant.

For emission control in remote locations, such as breathing losses from a storage tank containing volatile solvents or hydrocarbons, 55-gal steel drums of

granular carbon are available from several sources. These drums are specially fitted with inlet and outlet nozzles. Such a drum installed on the vent of a benzene storage tank continuously venting 0.1 ft³/min of vapor containing 13.5 percent benzene by volume would have a useful life of 2 weeks. When saturated, the spent carbon is replaced with fresh carbon. The spent carbon can be handled as combustible solid waste, but often arrangements can be made to return it to the carbon manufacturer for regeneration.⁵

Traveling Bed Adsorbers--

Continuous countercurrent column adsorbers have been designed and used with limited operation. Both downward-traveling packed-column units and tray units have been used. In both, freshly regenerated adsorbent is elevated and added at the top of the column at a rate that maintains a constant height of solids. A mechanism is provided at the bottom for steady removal of saturated sorbent, which is then regenerated in another vessel before the adsorbent returns to the top. Gas to be treated enters at the bottom and passes up the column being purified and leaves at the top. In a traveling packed-bed unit, all the bed rests on a bottom support grill or grate and the gas passes upward through the voids in the granular bed of solids. With the tray design, solids are fluidized on each tray by the gas rising through sieve-plate holes in the tray. The solids slowly travel across the tray to a downcomer that conducts the solids to the tray below, and the design much resembles that of a plate-type absorption column.⁵

Fluidized-Bed Adsorbers--

Unless bed staging is practiced, a single-stage fluidized bed adsorber would not appear to be a desirable adsorption mechanism at first glance. All sorbent particles in such a bed are well back-mixed, and a typical "adsorption wave" does not occur in the bed. Because all particles are in equilibrium with the outlet gas, low outlet pollutant concentrations can be attained only if all the bed particles are kept relatively unsaturated. This makes the adsorptive capacity of the bed low, and the concept

would be unattractive were it not for the ease with which adsorbent particles can be removed, externally regenerated, and returned to the bed on a continuous basis. An advantage of the fluidized bed is the ability to obtain high heat transfer rates with cooling tubes submerged in the bed to remove the heat of adsorption. It also has merit in a situation where frequent sorbent regeneration is needed. In addition, it might have application for adsorption of organics from a very moist gas stream where frequent carbon regeneration is needed to remove adsorbed water.⁵

Chromatographic Baghouses--

In this approach, granular adsorbent is continuously introduced at a controlled rate into the gas stream to be treated, and the gas stream conveys the suspended adsorbent through a contact area of adequate length and residence time to provide appreciable contact and adsorption before entering a conventional fabric filter. The sorbent is filtered from the gas stream on the surface of the bags and further adsorption may occur as additional gas passes through the collected cake of sorbent. Periodically, the sorbent is removed from the bags in the conventional manner. Because the flow of sorbent and gas is concurrent, the exit concentration of pollutant is controlled by the ratio of sorbent to gas used, and to a lesser extent by the contact time provided. Such a system cannot completely saturate the sorbent and reach extremely low outlet pollutant concentrations. With suitable sorbents, however, the spent solids removed from the baghouse can be regenerated and recirculated.⁵

6.1.4 Auxiliary Equipment

No adsorber system could operate without adequate auxiliary equipment and components to collect, transport, and filter vapor-laden airstreams being delivered to the adsorber. These components must be properly designed to provide proper service to the adsorber. The ducts and piping must be sized properly for required air velocities to optimize the efficiency of the adsorber. If the air velocity is too high, the stationary-bed adsorber may become a fluidized-bed adsorber, or low flows may create severe channeling through the beds. The fan is the catalyst for forcing the gas stream into

and out of the unit, so it is important that careful attention be given to the design and sizing of this equipment.⁶

Because there are several adsorber configurations, the location of a filter can vary. It can be placed before the inlet airstream (in a stationary bed) to reduce possible contamination to the adsorbent, or it can be placed after the fluidized-bed adsorber to reduce particulate emissions. The filter efficiency can be monitored by measuring the pressure drop across the filter with either a manometer or a pressure gauge that will read from 1 to 20 inches water column.

Some adsorber systems require compressed-air systems for valve and damper operation. For best results, the air supply should be kept contaminant-free through the use of a filter installed close to the adsorber. The compressed-air supply should be equipped with an in-line filter, a pressure regulator, and a lubricator.

Following adsorption, several devices are installed in series for recovery of the contaminant after regeneration. Condensers and separators are examples of recovery devices. The condenser is installed just after the system for removal of the heat from the vapors. There are two basic types of condensers: surface condensers and contact condensers. In a surface condenser the coolant does not contact the vapors or condensate. Most surface condensers are of shell-and-tube configurations. Water flows through the tubes and vapors condense on the shell side. In contact condensers, the coolant vapors and condensate are intimately mixed. These condensers are more flexible, simpler, and considerably less expensive to install. Sizing these condensers is also more straightforward.

Separators (decanters) are installed after the condenser to separate the contaminant from the water. Separators work on the principle of gravitational forces, where the heavier material to be separated is removed from the bottom of the canister and the lighter material is removed through a line located at the top of the canister. Water separators are more effective with single solvent applications and when the solvent is immiscible in water.¹

Foul condensate from the decanter or water separator may still contain recoverable solvent or water-soluble compounds. To meet regulatory effluent

standards and/or to further recover solvent may require the use of air- or steam-stripping of the foul condensate. In such cases, the stripping offgases may need to be controlled, typically by carbon adsorbers or by thermal or catalytic incinerators.

6.1.5 Key Operating Parameters

Key operating parameters for carbon adsorbers include:

- Operating temperature
- Inlet and outlet adsorbate concentration
- Gas stream relative humidity
- Gas volumetric flow rate
- Steaming conditions

In addition, changes from the initial design operating conditions should be considered, including adsorbate type(s) and steaming conditions for regenerable carbon adsorbers.

Temperature--

The operating temperature of an adsorber can be affected in three ways: 1) changes in the inlet stream temperature, 2) exothermic chemical reactions taking place inside the adsorber, or 3) failure of the cooling step after regeneration. Changes in the inlet stream's temperature lead to changes in the adsorber operating temperature. Changes in the inlet solvent loading can change the rate of heat generation because of the heat of adsorption. Heat can also be generated within the system by chemical reactions taking place on the bed. Ketones in particular have been identified by several studies as particularly reactive compounds. The problem is usually not serious, however, unless the concentration of adsorbate is extremely high, the gasflow rate through the carbon is relatively low, and the carbon is dry and contains no heel.

Each of these possible scenarios results in a variation in the temperature at which the adsorption process takes place. Therefore, the effect of temperature on

breakthrough must be evaluated. The relationship between carbon capacity and temperature indicates that as the temperature within the bed increases, the adsorptive capacity of the carbon decreases. Thus, as the temperature increases, the working capacity of the carbon also decreases. A shift in this direction has no effect on the achievable removal efficiency, but it does require a change in the cycle time to compensate for the shift.

Changes in operating temperature should not cause an increase in the baseline outlet concentration prior to breakthrough because the outlet concentration at the beginning of the cycle is primarily a function of the heel remaining in the last few inches of the bed. The amount of heel is established by the bed steaming conditions during desorption. Only if the temperature of the carbon in the adsorber rises to values close to those during steaming is there a chance the removable heel will desorb and subsequently decrease the achievable removal efficiency.

Temperature fluctuations in the inlet stream can essentially be eliminated by installation of a heat exchanger upstream of the carbon adsorber. A properly designed system will not permit the inlet temperature to exceed the maximum design temperature.²

Inlet and Outlet Adsorbate Concentration--

The concentration of organics in the inlet stream may vary because of process changes. Short-term variations are those that occur within a given cycle, whereas long-term variations may last over several cycles. Changes can occur as equipment or product lines are either brought on or taken off line.

For the purpose of this discussion, the flow rate through the bed is assumed to remain constant. Therefore, when the concentration increases, the loading rate to the adsorber increases.

Increasing the concentration will increase the working capacity of the carbon. The working capacity increase, however, will not be large enough to offset the increase in mass loading completely. Therefore, the net effect will be a decreased working capacity. The effect of variations in inlet concentration on the outlet concentration prior

to breakthrough should be negligible. As stated previously, the outlet concentration is a function of the heel that remains in the last few inches of the bed after regeneration. Because the inlet stream reaches equilibrium with the carbon within the mass transfer zone, the amount of heel at the adsorber outlet is independent of inlet concentration. Thus, short-term variations in the inlet concentration will not increase the baseline outlet concentration.²

An increase in outlet concentration generally indicates breakthrough and that it is time to regenerate or replace (in nonregenerative systems) the carbon bed. A detected increase of hydrocarbons above a setpoint using a continuous hydrocarbon monitor can be used to start the regeneration cycle.

Gas Stream Relative Humidity--

With relatively high inlet concentrations, relative humidity does not significantly affect working capacity. Because this is generally the case for adsorbate concentrations greater than 1,000 ppm, only a slight change should occur in the breakthrough time associated with variations in relative humidity in this case.

Below adsorbate concentrations of 1,000 ppm, water begins to compete with adsorbate for the available adsorption sites, and the bed working capacity for that adsorbate is then affected. In this case, some type of dehumidification system upstream of the bed or dilution with ambient air may be required. Relative humidity has no effect on the amount of heel that is retained within the carbon pores.

High relative humidities are present in most operating systems, regardless of the vent stream conditions because of the water remaining on the bed after steaming. The working capacity gained by reducing the humidity is small. In this case, reducing steam humidity would probably not be cost-effective. In addition, the water content in the bed provides a heat sink valuable in controlling bed temperature.²

Volumetric Flow Rate--

The superficial bed velocity for a system changes as the volumetric flow to the system changes. The primary effect is to change the depth of the mass transfer zone

within the bed. As the superficial velocity increases, the depth of the mass transfer zone also increases, as the individual carbon pellets are exposed to the adsorbate for a shorter period and the quantity removed at a given point decreases. The effect of a deeper mass-transfer zone is that the time prior to breakthrough is shortened by increases in volumetric flow rate.²

Steaming Conditions--

As previously discussed, steaming requirements are determined as part of the initial system design. Variables that must be considered are the steaming temperature, duration, and rate. Because steam temperature is generally fixed for a given plant, the effect of temperature is not discussed. The amount of steam required is determined by the required working capacity. Once the initial design is set, if the amount of steam used per desorption cycle remains constant, the available working capacity will also remain constant, assuming no fouling or other degradation of the carbon bed.

In actual application, however, the carbon's total adsorption capacity gradually decreases over time due to fouling. If the operator desires to maintain the same breakthrough time, steam use per desorption cycle must be gradually increased. At some point the amount of steam required per desorption cycle becomes so great that either insufficient time remains to complete desorption before breakthrough of the on-line bed or the cost of steam becomes too great. At this point the carbon must be replaced.

Although the amount of steam is important in the desorption process, duration is also a consideration. To remove the adsorbate, sufficient time at the steaming temperature is required to allow for diffusion of the adsorbate out of the pores and out of the carbon particles. Without sufficient time, increasing the flow of steam will not remove the adsorbate from deep within the pores of the carbon.²

6.2 Monitoring Carbon Adsorption System Operation

System monitoring may include measurement and recording of key operating parameters as well as discharge monitoring for solvent breakthrough. Monitoring of operating parameters may include:

- Operating temperatures
- Outlet VOC concentrations
- Gas flow rate
- Steaming conditions
- Pressure drop

6.2.1 Monitoring Systems

Instrumentation for measuring any or all of these parameters may range from simple to complex. The most recent plant installations may have the capability to generate daily reports of plant operations, such as overall performance, alarm conditions, efficiency, and energy consumption. In some cases, these data may be transmitted via modem to offsite locations for purposes of troubleshooting or detailed diagnosis.

Operating Temperatures--

Inlet gas temperatures and the temperature of the carbon bed can be measured by simple thermocouples. The thermocouples can be permanently installed in the duct, or they can be portable and inserted during inspections. Permanent thermocouples can be connected to continuous recorders with digital, analog, or strip-chart display.

Outlet VOC Concentration--

Outlet VOC concentration monitoring can demonstrate whether breakthrough occurs. Although not an exact test, it is probable that a system that goes through several cycles of full-load operation without reaching breakthrough is operating at adequate adsorption efficiencies. Determination of the presence or absence of

breakthrough requires continuous measurement of VOC concentrations in the 0- to 500-ppm range. Several types of instruments are currently available for measuring solvents at these low levels, including:

- Flame ionization detectors (FIDs)
- Photoionization detectors (PIDs)
- Diffusion sensors.

These systems each have some advantages and disadvantages. They require calibration for the solvent being measured if exact measurements are required, but they can also be used without calibration to indicate relative concentration levels. If the output of a suitable detector is connected to a recorder, the adsorber discharge concentration can be monitored over several cycles to determine if breakthrough occurs. For a facility operating at normal production rates, the absence of breakthrough may be taken as evidence that the adsorption system is operating satisfactorily. For successful testing, an inspector must become familiar with the use of the instrumentation, the required safety considerations, and its application to carbon adsorption systems.⁷

When these monitors are used, care must be taken to ascertain that all VOC compounds can be detected by the instrument. For example, vinyl chloride exhibits an ionization potential of 9.995 eV. Therefore, if a PID is used to monitor breakthrough, the ultraviolet ionization source (bulb) must be of equal or greater potential. Use of a bulb with lesser potential will not ionize vinyl chloride or other VOCs with ionization potentials equal to or greater than vinyl chloride (i.e., the instrument will be blind to these compounds).

Gas Flow Rate--

Of particular concern are gas flow and distribution. Excessive airflow will reduce carbon efficiencies and allow volatiles to escape to the atmosphere. Inadequate airflow or incorrect damper adjustment may cause uneven airflow distribution to systems with

multiple beds in parallel. This may promote uneven adsorption between beds and eventual premature breakthrough from the bed(s) receiving the greatest airflow.

A pitot tube traverse is normally used to measure total gas volume. Use of the pitot tube method relies upon the procedures specified in U.S. EPA Reference Methods 1 and 2. The pitot tube traverse samples gas velocity and the duct cross-sectional area.

Most facilities do not measure gas volume. Other indicators may be used to estimate the gas volume or to indicate changes from a baseline measurement. The alternate parameters include fan operating voltage or amperage, production rate, or gas condition (e.g., percent O₂, CO₂).

Steaming Conditions--

Steaming conditions can be monitored by measuring steam temperature and pressure with a thermocouple and magnehelic gauge, respectively, and observing the duration of the carbon regeneration cycle. These parameters can be compared to design values to aid in determining if beds are being fully regenerated.

Pressure Drop--

The pressure drop across a carbon adsorber can be used as an indicator of proper gas flow, carbon bed plugging, or carbon bed channeling.

Static pressure gauges such as magnehelic gauge or manometer can be installed at the inlet and outlet of the carbon adsorber to determine the unit's pressure drop. Portable pressure meters can be used as an alternative to differential pressure gauges. Hand-held static pressure gauges inserted through pressure taps provide a simple method of taking pressure readings. This technique is less expensive and reduces potential problems of meter moisture or corrosion damage and clogging; however, the readings are not continuous.

6.3 Routine Inspection and Maintenance Procedures

Effective air pollution control with carbon adsorption must be accompanied by a routine maintenance program. The program should provide for scheduled inspections of all equipment components, as well as all necessary monitoring of operating parameters to ensure correct operation and optimum performance of the control equipment.

Routine maintenance of air pollution control equipment can also be important because equipment failure can be expensive in terms of lost production, lost solvents, degradation of air resources, and potential effects on employee health. Each component must operate properly to ensure steady, efficient output and the desired results from the system.

Establishing an equipment maintenance program need not be elaborate or complicated. The work involved in routine inspection and servicing may largely be performed by shop personnel operating the control equipment. Of course, extensive repairs or rebuilding should be accomplished by skilled and trained maintenance personnel. System components of the carbon adsorber that require routine maintenance fall into four major categories: 1) air handling, 2) adsorbing, 3) stripping, and 4) reclaiming.

The function of the air-handling apparatus is to collect, transport, and deliver particulate-free, solvent-laden air to the adsorber. Any leaks in the ductwork on the suction side of the fan will introduce excessive ambient air into the system and result in a reduction of VOC concentration and poor adsorber efficiency. Air-duct leakage on the pressure side of the fan will discharge unwanted VOC vapors into the work place. Leakage checks should be performed periodically, especially at flexible connections, at joints in the ductwork, on the fan and filter housing, and around the adsorber bed dampers. Accurate collection velocity data should be established by routinely checking the capture velocity at the source with a vane-type velocity meter or a thermal anemometer. Correct operation of flow-indicating devices within the ducts can be verified by mechanically stopping flow to the duct or by turning off the fan motor.

Ventilation system imbalance may also occur from time to time and may require periodic adjustments to dampers to rebalance the system. The particulate filter bag installed in-line ahead of the adsorber beds should be equipped with a differential pressure gauge to indicate dirty or stopped-up filter media. The bag should be changed or cleaned when the differential pressure increases by 1 inch (water) or more.

Maintenance inspections on the adsorption-cycle equipment are somewhat more complex than for the air-handling apparatus. The integrity of the activated carbon must be maintained to ensure efficient removal of VOC vapors from the airstream. As the carbon particles erode with time and the capillaries become plugged with contaminants and polymers, the granules gradually lose their ability to adsorb and retain VOC molecules. Carbon adsorbability and retentivity should be tested regularly by opening up the bed and extracting carbon samples from the top, center, and bottom layers. Laboratory analysis will reveal the effectiveness of the carbon bed. Most manufacturers of activated charcoal will perform adsorbability and retentivity tests for their customers. If the carbon fails these tests, all the adsorbent should be removed from the system and regenerated or replaced.

Maintenance requirements on the desorption-cycle equipment primarily involves the steam supply, valving, and timer controls. Steam pressure on the carbon tanks should be regulated to minimize steam stripping pressure (3 to 10 psi on perchloroethylene [PCE]). Lower steam pressure will require too much run time to strip the beds adequately, whereas pressure that is too high will tend to fluidize the bed and create excessive erosion of the carbon granules. Steam traps must be operative or water will be carried into the carbon beds and retard proper stripping action. Periodically, the steam pressure relief valves located in the supply line and in the main carbon tanks should be checked for correct pressure settings by increasing steam pressure until the valves "pop off." Steam leaks around gaskets and operating dampers should be corrected by replacing the gaskets and seals. Gasket materials that are in contact with the solvent vapors must withstand the chemical properties of that particular solvent. Often the gasket material supplied with the system may not be suitable for the VOC presented to the adsorber, and a substitute material may be

required. Leaks around the carbon tanks may create additional problems of corrosion around the leak. Boiler feedwater treatment may require some modification if "carryover" chemicals are introduced into the carbon beds and create corrosion problems.

The apparatus used to reclaim the VOC requires little maintenance. The automatic cooling-water valve should be checked for proper opening and closing operation. Automatic mechanical valve shafts and other mechanisms should be lightly oiled. The condenser may eventually become inefficient because of excessive buildup of solubles from the cooling water. Acidizing of the water jacket or tubes may be required to renew condenser efficiency. Inadequate separation of water and VOC in the decanter may indicate a plugged vent line. All vent lines and drain lines must be unrestricted for correct operation of the system.

In general, normal maintenance procedures should be followed in routine cleaning of electrical contacts; lubrication of all bearings, compressed-air components, and air cylinder shafts; replacement of obviously broken or worn parts; and housekeeping practices around the adsorber. In the final analysis, common sense is the best maintenance tool available in view of the fact that a large percentage of carbon adsorber equipment failures can be traced to neglect, improper operation, or just plain abuse.¹

Figures 6-4 and 6-5 present example daily and weekly inspection forms for carbon adsorbers. These forms should be tailored to specific carbon adsorption systems and applications. Inspection forms for longer periods (i.e., monthly, quarterly, and annually) are not included because they are highly specific to the carbon adsorption system design and to the process being controlled. Figure 6-6 shows an example maintenance report form.

DAILY CARBON ADSORBER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
Carbon Adsorber ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
System Motors and Fans Operating? Drive Belts OK?	
Visible Liquid Leaks Pumps Carbon Adsorber	
System Gas Leak?	
Outlet VOC concentration _____ ppm Steam Pressure _____ in WG Temperatures: Gas _____ °F Adsorber _____ °F Steam _____ °F Pressures: Inlet _____ in WG Outlet _____ in WG Carbon Regeneration time _____ min. Regeneration set point _____ hrs or _____ VOC ppm	

Figure 6-4. Example daily carbon adsorber inspection form.

WEEKLY CARBON ADSORBER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
Carbon Adsorber ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
Bearings Greased?	
Ductwork Condition? Corrosion Air Leaks	
Check Pressure Gauges for Clogging	
Calibrate VOC Instrument	
Time between regeneration cycles _____ hrs Time for regeneration cycle _____ min VOC concentration after regeneration _____ ppm VOC concentration just before regeneration _____ ppm	

Figure 6-5. Example weekly carbon adsorber inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: _____ Date: _____ Time: _____

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: _____

Foreman: _____ Date: _____

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: _____

Work Done: _____

Supervisor: _____ Completion Date: _____

Materials Used: _____

Labor Requirements: _____

Figure 6-6. Example maintenance report form.

6.4 Equipment Problems and Troubleshooting

6.4.1 Troubleshooting

An overall system material balance, taken over a reasonable time period, is one of the best techniques for determining overall system efficiency and to detect system problems and malfunctions. To use a material balance, the plant must maintain accurate records of VOC-containing materials entering the process and of the recovered solvent. Recovered VOCs returned to the process is considered as part of the VOC entering the system. The VOC concentration of all materials entering the process must be known. Figure 6-7 shows a form for performing a VOC material balance.

Most of the information can be assembled from shipping data and from component data available from raw-material suppliers. The information needed to complete the material balance is the quantity of recovered VOC. This information is only available directly from the source through the use of totalizing flowmeters that measure VOC from the recovery systems. Nonregenerative installations do not have these flowmeters installed; therefore, the material balance procedure will not be applicable to every carbon bed installation.

A third efficiency evaluation procedure can be used for systems that use instruments (such as flowmeters) to provide data that can be used to calculate steam-to-recovered-VOC ratios. If one assumes a constant VOC input into the system and a constant length of adsorption cycles, a decrease in the ratio of VOC to steam is indicative of a decrease in collection efficiency. This technique is readily used on systems recovering immiscible VOCs and having flowmeters on both the VOC and water streams following the decanter. Although the techniques will alert maintenance/inspection personnel to a malfunction of some type in the carbon-bed system, it is unfortunately of little aid in diagnosing the problem.

Several types of visual inspections can also be used to help evaluate or troubleshoot a carbon adsorption system. The first visual check that can be made is to

CARBON BED ADSORPTION SYSTEM MATERIAL BALANCE

Inventory Period: From _____ to _____.

INPUT

(a) Solvent containing materials:

of materials x (# solvent/# material) = # solvent.

1.

2.

3.

4.

5.

6. Total solvent in raw materials (in #)
(=1 + 2 + 3 + 4 + 5)

(b) Purchased solvent

7.

8.

9.

10.

11. Total purchased solvent (in #)
(=7 + 8 + 9 + 10)

RECOVERED SOLVENT

12. Total solvent from recovery system

13. Solvent sold

14. Recycled solvent (=12-13)

% OVERALL EFFICIENCY

$$100 \times \frac{(12)}{(6) + (11) + (14)} = \quad \%$$

Note: If the solvent-recovery system returns more than one solvent stream, a separate sheet should be prepared for each solvent stream. Overall efficiency is the average of the efficiencies for each stream.

Figure 6-7. Overall material balance for facilities using solvent recovery systems.²

determine if the proper bed is on the adsorption or desorption cycle according to the mode selection of the control panel.

If the system operates on timed cycles, a check should be made to determine if the bed actually changes at the predetermined time (the cycle duration). At this time, the inspector may also inquire as to the rationale for the cycle duration. Sometimes operating conditions no longer coincide with design specifications and cycle times have not been adjusted accordingly to insure adequate system performance.

The concentration setting of the organic analyzer being used to monitor the carbon adsorber outlet concentrations should be checked to see if it is within reasonable limits. If possible, the zero setting of the device (as described in the operating manual) should also be checked.

6.4.2 Equipment Problems

Bed Fouling--

Bed fouling gradually decreases working capacity by tying up the active adsorption sites in the micropores or blocking the pores that allow adsorbate molecules to enter. Because the capacity of the system is decreased, the time prior to breakthrough is shortened. This has no effect on an adsorber's removal efficiency until the shortened length of the adsorption cycle begins to conflict with the regeneration time. At this point the carbon should be replaced.

Fouling will not affect the outlet concentration prior to breakthrough because fouling has no effect on the amount of heel left in the bed.

Fouling gradually reduces bed working capacity. In some cases, the steam flow and/or temperature can be increased to reduce the heel and thus increase the working capacity as the bed ages. At some point, however, increasing the steam flow will have little beneficial effect on working capacity. Therefore, even if the system is well designed and operated, eventually insufficient time will remain to regenerate the off-line bed before the on-line bed reaches breakthrough. At this point, the carbon must be replaced.

Though fouling of the carbon bed has no effect on the efficiency of an adsorber system, it does reduce bed life, which in turn increases the annual operating cost of the system. The fouling rate is affected by numerous factors, but the adsorbate characteristics can be considered the most important (e.g., particulates and adsorbates that polymerize on the carbon).²

Channeling--

A carbon adsorber system should be designed with adequate flow baffles and proper steam distribution to prevent channeling. If channeling does occur, it will cause elevation of the outlet concentration over a cycle or a gradual increase during the cycle. In systems with VOC monitors, these increases will be readily apparent. If the amount of channeling is small, the system still may be able to retain the required removal efficiency. If significant channeling occurs, adsorber removal efficiency will be significantly degraded.

In a well-designed system, channeling need not occur. From the perspective of the ability of a carbon adsorber to meet a specific regulatory removal requirement, channeling is actually a malfunction of the system rather than a factor causing inherent variability in short-term efficiency.²

Changes in the Adsorbate--

The concentration and type of organic are key factors in the design of a carbon adsorption system. The adsorption characteristics of each compound are assessed by using data on their physical properties such as polarity, refractive index, boiling point, molecular weight, and solubility in water. Nonpolar compounds (compounds with high refractive indices) tend to be adsorbed more readily. High vapor pressure/low boiling point adsorbates and low-molecular-weight compounds adsorb less readily. Compounds with molecular weights greater than 142 adsorb readily but are difficult to desorb.

If the adsorbate is water-soluble, water left as condensate in the bed after steaming and cooling can contain adsorbate. When the adsorber is brought on line,

the water and adsorbate will evaporate from the bed during the first part of the adsorption cycle, which will slightly increase the initial outlet concentration for a brief time until the concentration rapidly falls to a normal baseline value.

The properties and adsorption characteristics affect both the design and operating conditions. If the feed stream is changed, the adsorber system must be reevaluated. If it can accommodate the new feed, achievable removal efficiency will not be affected even though on-line adsorption time and steaming requirements may need to be changed. If timers are used as the trigger mechanisms, the new working capacity of the beds must be determined. Based on this working capacity and a maximum inlet loading, the appropriate new adsorption time can be determined so that the timers can be reset for the new operating conditions.²

6.5 Operator Training

Similar to any piece of equipment, a carbon adsorption system will not receive proper maintenance without facility management support and the willingness to provide its employees with proper training. Efficient operation of a carbon adsorber, promoted by adequate inspection and maintenance procedures, is as important as the productive operation of any piece of process equipment. Management and employees must take a proactive approach to operation to prevent production-stopping equipment malfunctions or failures.

The training and motivation of employees assigned to monitor and maintain the system are critical factors. These duties should not be assigned to inexperienced personnel that do not understand how a carbon adsorption system works or the purpose behind assigned maintenance tasks.

System training should be provided by the manufacturer when a new system is commissioned. The manufacturer's startup services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in methods for ensuring proper assembly and operation of the system components, checking and resetting

system instrumentation and controls, checking for the proper operation of any continuous emission monitoring system, and performing simple troubleshooting.

After startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new installation will include manufacturer-recommended maintenance procedures. Annual in-house training should, at a minimum, include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping.

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