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Article *in* Journal of Environmental Engineering · June 1988

DOI: 10.1061/(ASCE)0733-9372(1988)114:3(672)

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Development of Cost Equations for GAC Treatment Systems

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Abstract: The use of granular activated carbon (GAC) as a broad spectrum adsorbant in the treatment of drinking water has been shown to be effective in removing or reducing concentrations of specific organics and total organic carbon (TOC). Much concern has been expressed, however, regarding the cost of GAC systems, and therefore several studies have been conducted to develop cost-estimating equations for system components. Early cost studies are based on design and not on "as-built" plants. A comparison between costs from some recently completed field projects and costs estimated from these conceptual design studies has resulted in a reevaluation of the early estimates. Most estimates are close to the actual costs derived from the field projects. However, by combining data from the field projects and design studies, an updated set of cost estimating equations has been developed for GAC treatment systems. These new equations can be used to estimate capital costs and individual operation and maintenance cost components.

Introduction

The use of granular activated carbon (GAC) as a broad spectrum adsorbant in the treatment of drinking water has been shown to be effective in removing or reducing concentrations of specific organics and total organic carbon (TOC) (Lykins et al. 1984). Many drinking water systems vulnerable to synthetic organic contamination of their raw water supplies have demonstrated interest in modifying existing treatment plants to include GAC adsorption. One large drinking water utility in the process of upgrading its treatment plant to include GAC is the Cincinnati Water Works. The plant conversion includes postfiltration GAC adsorption contactors and on-site carbon reactivation. Granular activated carbon treatment in Cincinnati will be specifically for the control of organic contaminants from surface water.

A number of municipalities have found volatile organic chemicals in their groundwater sources. This concern has renewed interest in the use of GAC as a treatment technique for utilities supplied by groundwater.

Recent amendments to the *Safe drinking water act* (1986) have made the determination that the use of GAC for synthetic organic chemical (SOC) control should be considered as a feasible treatment technique. In this regard, feasible means with the use of the best technology, treatment techniques, and other means available for meeting maximum contaminant

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Note. Discussion open until November 1, 1988. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 13, 1985. This paper is part of the ***Journal of Environmental Engineering***, Vol. 114, No. 3, June, 1988. ©ASCE, ISSN 0733-9372/88/0003-0672/$1.00 + $.15 per page. Paper No. 22509.

levels (MCLs). In setting the MCLs for SOCs, the use of GAC is feasible according to the 1986 amendments. Any other technology, treatment technique, or other means to be the best available for the control of SOCs must be as effective as GAC for this purpose. The administrator of the U.S. Environmental Protection Agency (EPA) must list the technology, treatment technique, and other means that he determines as feasible for meeting the MCL. This does not mean that these treatment techniques *must* be used for meeting the MCL.

A major consideration in making choices among various types of technologies is the problem of cost estimating. Ultimately, at some point in the technological decision-making process, cost will have to be considered. Therefore, the Drinking Water Research Division (DWRD) of the EPA has devoted considerable effort to developing cost-estimating equations that have many applications. This paper presents the results of a current effort that seeks to provide improved cost-estimating equations for GAC.

Original Cost Modeling Efforts

In response to early concerns about impact of cost on drinking water utilities, the Drinking Water Research Division of the EPA initiated a study to develop standardized cost data for 99 water supply unit processes (Gumerman et al. 1979). The approach was to assume a standardized flow pattern for a treatment train and then to cost out the individual unit processes. This approach requires assumptions about such details as common wall construction and amount of interface and yard piping required. After the flow pattern was established, the costs associated with specific unit processes were calculated. "As-built" designs and standard cost reference documents were used to calculate the amount of excavation, framework, and materials such as concrete and steel. Information from existing plants and manufacturers was used to calculate the costs of equipment associated with a unit process. Concrete, steel, and excavation quantities were calculated for various unit processes. Once the base estimates are calculated, capital cost curves were developed.

Derivation of Cost Curves

The construction cost for each unit process considered in this study was presented as a function of the process design parameter that was determined to be the most useful and flexible under varying conditions. Such variables as loading rate, detention time, or other conditions that can vary because of designer's preference or regulatory agency requirements were used. For example, GAC contactor construction costs are presented as a function of the effective GAC volume (cubic feet) in the contactors, an approach that allows various empty-bed contact times to be used. Operation and maintenance (O&M) cost curves for conventional contactors are presented in terms of square feet of surface area. Reactivation facility cost curves are presented in terms of square feet of hearth area for the multiple hearth furnace, but pounds per day of reactivation capacity is used for the other reactivation technologies considered. Such an approach provides much more information than if the costs were related to water flow through the treatment plant.

Construction Cost Components

The costs for eight principal construction components were developed and then aggregated to give the construction cost for each unit process. The eight components are: (1) Excavation and sitework; (2) manufactured equipment; (3) concrete; (4) steel; (5) labor; (6) pipe and valves; (7) electrical and instrumentation; and (8) housing. These categories also provide enough detailed information to permit accurate cost updating (Gumerman et al. 1979).

The construction cost value is not the final capital cost for the unit process because they do not include costs for general contractor overhead and profit, administration, engineering and legal fees, fiscal determinations, and interest during construction. These items are more directly related to the total cost of the project and they are added following summation of the cost of the individual unit processes, if more than one unit process is required.

Operation and Maintenance Cost Components

Operation and maintenance requirements were developed for process fuel and electric, building-related energy, related process energy, maintenance materials, and labor. The separate determination of building energy allows for regional variations. Energy requirements are presented in kilowatt hours per year for electricity, standard cubic feet per year for natural gas, and gallons per year for diesel fuel. Labor is presented in hours per year, allowing local variations to be incorporated into the O&M cost calculations. Maintenance material cost is given in dollars per year, but does not include the cost of chemicals, which must be added separately.

In order to make the cost data more flexible, the construction costs can be easily indexed using, for example, the *Engineering News Record* construction cost index. Material costs are indexed using the producers price index. Operation and maintenance input values include labor wage rates, electrical power rates, chemical costs, etc.

Cost Equations

The cost data base described in the previous section was utilized to develop a set of cost equations for each of the unit processes considered.

Initially, regression estimates were calculated based on the general equation form (Clark and Dorsey 1982):

$$Y = aX_1^b, \ldots, X_n^r \qquad (1)$$

where Y = annual operating or capital cost; $a, b, \ldots, r$ = constants determined from the regression analysis; and $X_1, X_2, \ldots, X_n$ = variables influencing cost, such as design capacity and power cost.

In this effort, all capital costs were calculated on the basis of 8% interest and a 20-yr amortization period. Conversion to another base requires only a simple calculation. Overhead, interest during construction, and engineering fees were calculated from the original curves and, in general, account for approximately 30% of the total cost.

During the same time period that the cost data base and equations were being developed, the DWRD was conducting field studies designed to collect cost and performance data on GAC systems. These studies are discussed in the following section.

GAC Field Studies

In 1976, the EPA's Drinking Water Research Division initiated a series of field studies to evaluate and characterize the performance of GAC. These field-scale systems consisted of units that are close to modular size for a water treatment plant. Eight utilities participated in these studies, including Cincinnati, Ohio; Manchester, New Hampshire; Evansville, Indiana; Jefferson Parish, Louisiana; Miami, Florida; Huntington, West Virginia; Beaver Falls, Pennsylvania; and Passaic, New Jersey. However, only Cincinnati, Manchester, and Jefferson Parish provided large amounts of cost data.

Because of their importance to this cost data base development, the Manchester, Cincinnati, and Jefferson Parish field-scale and pilot-scale systems are described in the following sections. Each full-scale facility involved in the GAC research effort utilized essentially the same treatment scheme: (1) Predisinfection; (2) coagulation/flocculation; (3) settling; (4) filtration; and (5) postdisinfection.

Cincinnati, Ohio

The primary source water for the Cincinnati Water Works is the Ohio River (Miller et al. 1982). Conventional treatment is provided in a 235,000-gallons-per-day plant with a typical demand of about 130 mgd. During the field research study, four of the water treatment plant's 47 sand filters were converted to GAC filters. One other sand filter was used for storage of makeup GAC. Because the "Ten State Standards" require a minimum of 12 in. (30.5 cm) of filter sand for turbidity removal, only 18 in. (45.7 cm) of sand in one of the 30-in.-deep (76.2-cm) filters was removed and replaced with Westvaco 12 × 40 WVG® GAC ("Recommended Standards" 1982). With the concurrence of the Ohio EPA, all of the sand [30 in. (76.2 cm)] in the three other filters was replaced with GAC. Each GAC filter adsorber had an effective area of 1,400 sq ft (130 m^2) with a hydraulic loading of 2.5 gallons per minute (gpm)/sq ft or flow rate of 5 mgd (6.0 m/hr).

The performance of the previously described, conventional-depth, 30-in., (76.2-cm) gravity filters was compared to that of deep-bed contactors. Four contactor tanks were utilized in this study. Each contactor was of cylindrical shell construction made of 3/8-in. (9.55-mm-) thick carbon steel plate. Each contactor was designed to the following specifications: (1) Diameter of 11 ft (3.4 m); (2) GAC depth of 15 ft (4.6 m); (3) design capacity of 1.0 mgd (0.04 m^3/s); (4) hydraulic loading of 7.4 gpm/sq ft (17.8 m/hr); (5) empty bed contact time (EBCT) of 15.3 min; and (6) the GAC used was 12 × 40 WVG®.

On-site reactivation of spent carbon was provided by a 500-lb/hr (227-kg/hr) fluidized-bed furnace. Total volumetric carbon losses incurred during the study were approximately 15–18% (bed to bed); transport and handling accounted for approximately 3–4% of the total losses.

A cost analysis of the field-scale GAC facilities was conducted during the period from 1979 to 1980. Total construction costs were $2,251,300, which included the conversion of two 5-mgd sand filters to GAC filter adsorbers, four 1-mgd postfilter GAC contactors, one 500-lb/hr (227-kg/hr) fluid-bed reactivator, and a building to house facilities. The total annual-

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ized system cost (capital plus operation and maintenance) for the converted GAC filter adsorbers was $319,216/yr, which included on-site reactivation. The total cost for the deep-bed postfilter contactor system was $425,134/yr. On-site reactivation proved to be cost-effective at 23¢/lb (51¢/kg) compared to the replacement of spent carbon with virgin GAC at 50¢/lb (110¢/kg).

Cost estimates for a complete plant conversion to GAC treatment at the Cincinnati Water Works have been made in terms of 1984 year-dollars. Given a 1.0-mg/L TOC treatment goal, the cost estimate for a deep-bed concrete contactor system with an EBCT of 20 min (including fluid-bed on-site reactivation) was 15.8¢/1,000 gal (4.17¢/m^3). For the same type of system with an EBCT of 15 min, the cost estimate was 18.8¢/1,000 gal (4.96¢/m^3). The cost of a sand-converted GAC filter adsorber system with an EBCT of 7.5 min was estimated at 26.9¢/1,000 gal (7.10¢/m^3). The GAC filter adsorber system had an approximately 70% higher cost than the cost of a deep-bed concrete contactor system, despite having lower capital costs because reactivation would be required more frequently with the filter adsorbers.

Manchester, New Hampshire

Lake Massabesic serves as the prinicipal water source for the City of Manchester (Kittredge et al. 1982). This lake supply is of natural origin, having a watershed of 44 sq miles. Water treatment is accomplished in a 40-mgd (1.8-m^3/s) capacity facility with an average demand of 13 mgd (0.58 m^3/s).

In order to evaluate GAC during field-scale application, one of the four GAC filters normally used for taste and odor control was utilized as a test filter. At the beginning of the study, one-half of the filter contained virgin WVG® 8 × 30 mesh GAC and the other half, once reactivated GAC (5-year-old service carbon reactivated at the beginning of the study). A complete separation of the GAC was possible because the GAC filters contained 110 cells spaced at 12-in. (30-cm) centers. The primary objective of the study was to evaluate the cost and performance of a 500-lb/hr (227-kg/hr) fluid-bed reactivator.

The reactivation system was installed in 1979 at a cost of $902,300, which includes the fluid-bed reactivator, building, analytical equipment and supplies, design fees and personnel, and virgin carbon for the test filter. A detailed cost analysis of on-site reactivation was performed during the period of June 1980 through March 1981. During this period, 1,857,176 lb (843,158 kg) of carbon was reactivated, and the system up-time operating factor was about 70%. Total carbon losses incurred as a result of reactivation and handling averaged 11.5% by volume (bed to bed). The cost-effectiveness of on-site reactivation was clearly demonstrated with a unit cost of reactivation of 21.7¢/lb (47.8¢/kg) compared to replacement with virgin GAC at 61.5¢/lb (135.4¢/kg). The largest single cost item was for makeup carbon, which represented approximately 33% of the total reactivation cost. Operation and maintenance (O&M) labor, including overhead, represented about 29% of the total cost. The capital cost made up only about 10% of the total cost, while the fuel oil and electrical power costs represented about 13%, and O&M materials represented about 15% of the total system cost.

In 1981, Manchester Water Works (MWW) conducted an evaluation of regional (off-site) reactivation with three participating water utilities: (1) Connecticut Water Company, in Kelseytown, located 172 miles from MWW; (2) Danvers, Massachusetts, located 41 miles from MWW; and (3) Lowell, Massachusetts, located 33 miles from MWW. Each of the three utilities provided 40,000 lb (18,160 kg) of spent carbon (dry weight) to be reactivated. Transportation of carbon between the utilities and MWW was provided by an open-top trailer dump truck with a capacity of 12,000 cu ft (339.8 m^3). Off-site reactivation proved to be an economical alternative for each of the utilities compared to replacement of spent carbon with virgin GAC. The cost of off-site reactivation for Connecticut was 66.2¢/lb (145.9¢/kg) versus virgin GAC at 104.7¢/lb (230.5¢/kg). For Danvers, Massachusetts, regional reactivation cost was 37.5¢/lb (82.6¢/kg) versus virgin GAC at 67.2¢/lb (148.0¢/kg) and for Lowell, Massachusetts, the cost of off-site reactivation was 44.9¢/lb (99.0¢/kg) versus virgin GAC at 105.7¢/lb (232.8¢/kg).

Jefferson Parish, Louisiana

The Mississippi River serves as the raw water source for the four separate water treatment plants of Jefferson Parish (Koffskey and Lykins 1987). The system has a total capacity of 70 mgd and a typical demand of 55 mgd. At the Permuttit III Plant, a field-scale GAC facility composed of three 1-mgd steel-pressure contactors and one 215-lb/hr (97.5-kg/hr) infrared reactivator, was evaluated for performance and cost. Each contactor was 12 ft (3.65 m) in diameter, contained about 16.5 ft (5.03 m) of GAC, and operated at a hydraulic loading of 6 gpm/sq ft (14.4 m/hr), producing an EBCT of about 20 min. Construction of the facility was completed in January 1985 and operation of the system began in March. The average TOC influent concentration to the GAC contactors was about 3.5 mg/L, and TOC reached steady state in approximately three months with an effluent concentration of about 1.5 mg/L. The average total carbon losses observed were 9% by volume, reactivation contributing about 7% and carbon transport contributing 2%.

The total capital cost for the 3-mgd GAC adsorption and reactivation facility in 1983 dollars was $2,251,552. The general breakdown of costs was as follows: (1) Design and engineering, $343,543; (2) infrared furnace equipment, $682,848; (3) construction of contactors and furnace installation, $1,034,609; (4) initial GAC, $190,552. Based on approximately two years of initial operation, a preliminary cost analysis has been made. The unit cost for the 3-mgd GAC adsorption system (excluding reactivation) was about 17.5¢/1,000 gal (4.6¢/m^3) with the OM portion at 3.9¢/1,000 gal (1.0¢/m^3) and the capital at $13.6¢/1,000 gal (3.6¢/$m^3$). The estimated cost for the infrared reactivation system assuming an up-time operating status of 75% was about 28.4¢/lb (62.6¢/kg) with OM at 20.2¢/lb (44,5¢/kg) and capital at 8.2¢/lb (18.1¢/kg). Assuming a three-month reactivation cycle, the total GAC system cost was about 38.3¢/1,000 gal (10.1¢/m^3).

Additional Data

A recent EPA report presented detailed cost and performance data from the field-scale GAC treatment research facilities at Cincinnati, Ohio, and Manchester, New Hampshire, as well as several other water systems

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(Lykins et al. 1984). The report presented cost estimates for various GAC treatment scenarios, examined the effect of economies of scale inherent in GAC systems, and evaluated the cost trade-offs between off-site and on-site reactivation alternatives. The costs of GAC treatment systems consisting of steel or concrete GAC contactors and on-site reactivation using fluid-bed, infrared, and multihearth technologies were examined. The report showed that the reactivation process may account for up to 50% or more of the total cost of GAC treatment (adsorption contributes to the remaining portion of the total cost). The concept of regional reactivation as a solution to reducing the cost of the reactivation process was studied in Manchester, New Hampshire (Adams et al. 1986).

In addition to the field studies, another report was prepared to reflect costs for technologies that might be most appropriate for small systems application (Gumerman et al. 1985). This cost data base includes "as-built" data wherever possible.

Using data from these and other sources, updated cost equations were developed. The development of these new equations is presented in the following section.

Development of New Cost Equations

In order to generalize the cost equations concept developed earlier, a different functional form was fit to the cost data for both the larger system technologies and the small systems cost data.

The revised functional form of the estimating equations is as follows:

$$Y = a + b\,(USRT)^c(d^z) \quad \text{(2)}$$

where Y = the base cost for capital or operation and maintenance; $USRT$ = process design or operating variable; a, b, c, and d = parameters determined from nonlinear regression; and z = 0 or 1 used to adjust cost function for a range of $USRT$ values.

The revised equation form is an improvement over the earlier functional form given in Eq. 1 because it does not restrict the cost to equal zero at or near $USRT = 0$. Also, Eq. 2 allows some flexibility in the coefficient to the $USRT$ variable. The d^z factor effectively changes the coefficient to the $USRT$ variable over a specified range of values. If the data when plotted on a log-log scale fits a straight line or has a mild bend or curve, it typically does not need a d^z factor. Deciding if the d^z factor is needed is done on a case-by-case analysis.

For example, the following equation gives the construction cost of a small package-plant steel pressure contactor:

$$\text{CC} = 16{,}125 + 7{,}632.0\,(\text{CUFT})^{0.523}(1.102)^z \quad \text{(3)}$$

where CC = construction cost for steel contactor, 1983 dollars; CUFT = effective GAC volume in cubic feet; and z = 0 if CUFT $\leq$ 400, or z = 1 if CUFT $>$ 400.

Fig. 1 presents the cost curve for package pressure GAC contactors generated from Eq. 3 along with the cost observations used in developing the equation from nonlinear regression analysis. The pattern of observations are such that the d^z factor provides a better fit of the data at higher values of the GAC volume.

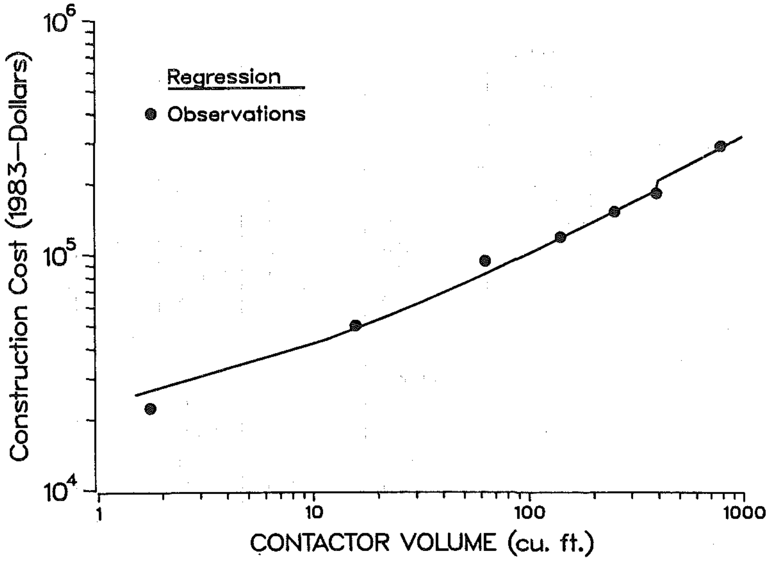

FIG. 1. Construction Cost Curve for Package GAC Pressure Contactors

Revised cost-estimating equations have been developed for a number of technologies used in GAC treatment. Under each treatment technology, the overall cost is broken down into several components. For example, the cost of GAC contactors typically includes capital, process energy and pumping, building energy, maintenance materials, and operation and maintenance (O&M) labor. Table 1 presents the equation parameters applicable to functional form Eq. 2 for the various components of the treatment processes. Also specified are the units of measure for the design and operating variables (*USRT*) used in the equations, and the *USRT* range of values for which $z = 1$ in the d^z factor.

Construction costs (CC) are expressed in terms of 1983 dollars. To convert an estimate to present-day dollars, the *Engineering News Record* (ENR) construction cost index (CCI) can be used: CC $*$ current CCI/4,114.6. The construction cost estimates do not include engineering and design fees, contractor profit and overhead, interest during construction and other overhead, and costs for special site requirements. These costs must be added separately, in order to arrive at a final capital cost estimate. Annual capital costs are estimated by multiplying CC by the capital recovery factor (CRF): CRF $= I(1 + I)^N/[(1 + I)^N - 1]$, where I = period lending interest rate and N = payback period.

Electrical energy requirements (PE, BE, PUMPE) are given in terms of kilowatt-hours (kwh) per year. Cost estimates are determined by multiplying the requirements (kwh/yr) to the electric rate ($/kwh). Maintenance-material costs (MM) are expressed in terms of 1983 dollars per year. The producers price index for finished goods (PPI) can be used to update an estimate to a present cost base: MM $*$ current PPI/287.1. O&M labor requirements (OL) are given in terms of workhours per year. Cost estimates are determined by multiplying the requirements (hr/yr) to the

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TABLE 1. Construction and OM Cost Function Parameters

Process/function[a] (1)	*USRT* variable (2)	*a* (3)	*b* (4)	*c* (5)	*d* (6)	$z = 1$ range (7)
Package pressure GAC contactors						
CC	cu ft	16,125	7,632.0	0.523	1.102	>400
PE	cu ft	50	0.2	1.075		
BE	cu ft	1,950	829.7	0.456	1.319	>140
MM	cu ft	100	34.2	0.601		
OL	cu ft	190	11.9	0.518		
Package gravity GAC contactors						
CC	cu ft	40,000	664.0	0.867		
PE	cu ft	0	0.4	0.975		
BE	cu ft	4,845	75.2	0.882		
MM	cu ft	625	3.2	0.931		
OL		0	158.0	0.191		
Conventional steel-pressure GAC contactors						
CC	cu ft	100,100	155.6	0.997	0.958	<3,000
PE	sq ft	0	12.0	1.0		
PUMPE	mgd	0	119,620.0	1.0		
BE	sq ft	0	1,000.0	0.813		
MM	sq ft	1,115	7.33	1.0		
OL	sq ft	1,460	12.6	0.698		
Conventional concrete gravity GAC contactors						
CC	cu ft	93,700	1,999.1	0.712	1.027	>5,000
PE	sq ft	0	12.0	1.0		
BE	sq ft	15,150	350.0	0.916		
MM	sq ft	540	23.6	0.753		
OL	sq ft	1,160	0.3	1.068	1.152	<7,000
Backwash pumping						
CC	mgd	47,200	21.8	0.933		
GAC storage						
CC	cu ft	20,400	9.7	1.1		
Infrared reactivation						
CC	lb/day	700,000	148.4	0.933		
PE	lb/day	49,245	346.5	0.988		
BE	lb/day	500	25.0	0.753		
MM	lb/day	0	956.00	0.397		
OL	lb/day	2,920	69.0	0.500		
Fluid-bed reactivation						
CC	lb/day	1,038,000	8,131.7	0.494		
PE	lb/day	0	43.8	1.0		
MM	lb/day	15,600	830.2	0.353		
OL	lb/day	2,920	210.2	0.400		
NG	lb/day	111,110	1,084.0	1.0		

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TABLE 1. *Continued*

Process/function[a] (1)	*USRT* variable (2)	*a* (3)	*b* (4)	*c* (5)	*d* (6)	*z* = 1 range (7)
Multihearth reactivation						
CC	sq ft	144,000	198,300.4	0.434		
PE	sq ft	354,600	6,387.0	0.755		
BE	sq ft	12,250	312.1	0.649		
MM	sq ft	0	4,456.6	0.401		
OL	sq ft	2,920	282.0	0.700		
NG		648,400	287,714.9	0.899		

[a]If "*d*" value is blank, then not applicable.

Note: CC = Construction cost, 1983 $; PE = Process energy, kwh/yr; BE = Building energy, kwh/yr; PUMPE = Pumping energy, kwh/yr; MM = Maintenance material, 1983 $/yr; OL = OM labor, work-hr/yr; NG = Natural gas, scf/yr.

labor rate ($/hr). OL costs do not include labor overhead or administrative costs. These costs must be added separately. Natural gas requirements (NG) are given in units of standard cubic feet per year (scf/yr), which when multiplied by the fuel rate ($/scf) provide an estimate of the annual cost. Where an alternate fuel such as number 2 fuel oil is used, an estimate of the gallons per year required can be determined using a total fuel British thermal unit (BTU) value equal to that of natural gas.

The definitions of the design and operating variables (*USRT*) for each unit process, and the assumptions concerning what cost items are included in the preliminary estimates are discussed in the following sections.

Package Plant GAC Contactors

The construction cost equations for both pressure and gravity-flow package GAC contactor systems utilize a design variable (*USRT*) based on the total effective GAC volume (cu ft) of all contactors combined. These equations should be used when estimating costs for systems with carbon volumes of 1,000 cu ft or less. Preliminary cost estimates are for factory assembled units that are mounted on a steel skid. Conceptual designs include one and two contactors with diameters ranging from about 1 ft (0.3 m) to 12. ft (3.6 m). Carbon contactors are cylindrical steel and down-flow type. Costs include piping, valves, instrumentation and control panel, supply and backwash pumps, initial charge of GAC for contactors, and a building to house the system. Costs for a clearwell and finished water pumping are not included. As mentioned earlier, construction contractor and overhead fees must be added separately.

It was assumed that the carbon columns function as adsorption units, and when filtration is needed, that it precedes the GAC contactors. The user rate (*USRT*) variable for each of the O&M cost components is based on the effective GAC volume (cu ft) of all contactors combined, but is adjusted to reflect the percent utilization of the system. For example, if the system is to operate at 50% design capacity and the design GAC volume is 800 cu ft, then O&M costs are determined using a *USRT* value of 400 cu ft. Process energy requirements are for backwash pumping. Supply and product water pumping are not included. Building energy requirements are for heating, lighting, and ventilation of the facilities. Maintenance material requirements were estimated from anticipated costs of replacement parts and for supplies involved in daily operation of the equipment. The cost of replacement carbon, which is a major operating expense is not included, and must be added separately. Labor requirements were developed assuming that facilities operate nearly unattended. Labor is for backwashing the carbon, performing routine maintenance tasks, and monitoring the performance of the contactors. Overhead, administrative labor, and laboratory labor are not included and must be added separately. Labor for on-site carbon handling and transport is discussed under GAC reactivation.

Conventional GAC Contactors

The construction cost equations for conventional concrete gravity contactor systems and steel pressurized contactor systems utilize as their design variable (*USRT*), the total effective GAC volume (cu ft) of all contactors combined in the given system. The *USRT* value should include planned excess capacity for the system. These equations should be used when estimating costs for systems with carbon volumes greater than 1,000 cu ft. Concrete gravity contactors were rectangular in shape, having various dimensions, and were similar in design to gravity filtration structures except for having deeper beds and carbon-removal troughs and piping. Steel pressure contactors were cylindrical, having diameters of 10 ft (3 m) or 12 ft (3.6 m). A hydraulic loading rate of 5 gpm/sq ft (12 m/hr) was assumed, and GAC depth varied depending on the desired EBCT.

Construction costs include contactor structure, liquid- and carbon-handling pipe with headers in a pipe gallery, cylinder-operated butterfly valves, flow measurement and other instrumentation, master operations control panel, and building to house the system. Not included in the cost estimate for carbon contactors are backwash pumping, initial GAC charge for contactors, makeup carbon storage, spent and reactivated carbon handling outside of contactor pipe gallery, construction overhead, contractor and engineering fees, and GAC reactivation facilities. Separate equations are given for GAC reactivation, backwash pumps, and additional carbon storage.

The construction cost for backwash pumping is based on pump capacity (gpm) and assumes a maximum design rate of 18 gpm/sq ft (43.3 m/hr) and pumping dynamic head of 50 ft (15.2 m). One standby pump was included in the cost estimate. The construction cost for additional carbon storage, other than the spent and regenerated carbon storage tanks with on-site reactivation facilities, can be estimated using the parameters given in Table 1. The design variable (*USRT*) is the carbon storage capacity (cu ft).

The operations and maintenance cost equations for PE, BE, MM, and OL utilize a *USRT* variable that specifies the total GAC filter area (sq ft) of all contactors combined, and adjusted for percent plant utilization. A hydraulic loading rate of 5 gpm/sq ft (12 m/hr) is assumed. If another rate is contemplated, for cost-estimating purposes, determine the effective total filter area as if the rate were 5 gpm/sq ft with the given contactor flow rate. The electrical energy cost for pumping water to the pressurized contactors (PUMPE) is based on the total average production flow rate (mgd) of all contactors combined.

Process energy requirements are for backwash pumping and carbon slurry pumping. Building energy includes heating, ventilation, and lighting. Maintenance material costs include general supplies, pump maintenance, instrumentation repairs, and replacement parts. The cost of replacement carbon is not included and must be added separately. Labor requirements are for operating and monitoring the contactors, backwash pumps, and carbon slurry pumps, as well as performing routine maintenance tasks. Labor overhead, administrative labor, and laboratory efforts are not included.

Infrared Reactivation

Construction and O&M costs for infrared reactivators were developed as a function of furnace capacity in pounds of carbon per day for a single reactivator. Conceptual designs for a single reactivator ranged in size from 100 lb/hr (45.4 kg/hr) to 60,000 lb/day (27,216 kg/day). Infrared furnaces are factory constructed in modules of various lengths, which allows assemblage of a furnace with a wide range of reactivation capacities. Another advantage of infrared furnaces is that the furnace design permits start-stop operation without furnace damage or excessive operating cost. The costs include the premanufactured furnace modules (drying, pyrolysis, and activation), carbon holding tank, dewatering feed screws, quench tank, afterburner, wet scrubber, exhaust gas blower, all duct work, scrubber water piping and valving within process limits, and process electrical equipment and controls. The equipment is entirely housed in a prefabricated metal building erected on a slab foundation. Open sidewall construction was assumed for the furnace area to facilitate heat removal.

Operation and maintenance costs are based on 100% utilization of the reactivator. If it is operated part of the time, then the cost estimate should be adjusted according to its utilization. Process energy requirements are related to operation of the infrared heating units, cooling and exhaust blowers, and the scrubbing water system. Building energy is for lighting and ventilation only. Maintenance material includes the replacement costs of the heating units, replacement of small moving parts associated with dewatered carbon hauling and the scrubbing system, and general equipment maintenance. Makeup carbon costs are not included and must be added separately. Labor requirements are for operation and maintenance of the equipment. Operating attention is required to oversee performance of the equipment and make occasional process adjustments. Maintenance attention is required on an infrequent basis, principally to service moving parts. Labor overhead and administrative labor are not included and must be added separately.

Additional estimated costs not covered by the equations specified in Table 1 are as follows:

1. Water for reactivation process = 21–27 gal/lb of GAC.
2. Water for on-site carbon transport = 2–7 gal/lb of GAC.
3. Labor for on-site carbon transport = 0.4 work-hr/1,000 lb of GAC.

Fluid-Bed Reactivation

Construction and O&M costs for fluidized-bed reactivation were developed as a function of the capacity (lb/day) for a single reactivator.

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Construction cost estimates include spent and reactivated carbon storage, carbon dewatering system, the fluid-bed reactor, fluidizing air blower, quench tank, particulate scrubber, interconnecting piping and electrical equipment within process area limits, controls and instrumentation, and a steel building to house the system.

Continuous operation is assumed, and O&M costs should be adjusted according to percent utilization. The PE equation includes both process electrical and building electrical requirements. Maintenance material costs include replacement parts for electrical drive machinery, damaged refractory materials, and other general maintenance items. Makeup carbon costs are not included and must be added separately. Water for the reactivation process and carbon transport must also be added separately as described under the infrared reactivation section. Labor requirements are for operation and maintenance of the equipment and do not include administrative labor or overhead. Labor for on-site carbon transport is estimated at 0.4 work-hr per 1,000/lb of carbon, and must be added separately. Natural gas (NG) was used to provide regenerating steam.

Multihearth Reactivation

Construction and O&M costs for multihearth reactivation were developed as a function of the total effective hearth area (sq ft) of a single reactivator. The construction cost includes the basic furnace, center shaft drive, furnace and cooling fans, spent carbon storage and dewatering equipment, auxiliary fuel system, exhaust scrubbing system, reactivated carbon handling system, quench tank, steam boiler, control panel, instrumentation, and building to house the system.

Operating and maintenance costs assume operation 100% of the time and should be adjusted according to percent utilization. Process electrical energy and natural gas requirements were determined using a hearth carbon loading of 40–50 lb/sq ft per day (195.4–244.3 $kg/m^2/day$). Building energy requirements are for lighting and ventilation. Maintenance material costs were related to repair of electrical drive machinery, replacement of rabble arms, and damaged refractory materials. Makeup carbon must be added separately, as well as water, for the reactivation process and carbon transport. Labor requirements are for the operation and maintenance of the equipment. Labor for on-site carbon transport is estimated at 0.4 work-hr per 1,000 lb of carbon, and must be added separately. Administrative labor and overhead must be added separately.

Off-Site GAC Transport

Operation and maintenance cost estimates for transporting GAC to and from off-site reactivation facilities were developed as a function of the amount of GAC hauled (lb/yr) and one-way distance traveled (miles). Capital costs for trucks were not addressed. The cost equations for diesel fuel (DF), maintenance materials (MM), and O&M labor (OL) are as follows:

$$DF = 10 + 0.000037\,(AMT)(MILES)^{1.01} \quad (4)$$

$$MM = 30 + 0.000063\,(AMT)(MILES)^{0.9989} \quad (5)$$

$$OL = 20 + 0.000338\,(AMT)^{1.03}(MILES)^{0.1311}(0.729)^{z} \quad (6)$$

where DF = diesel fuel requirement (gal/yr); AMT = amount of carbon hauled (lb/yr); MILES = distance traveled, one-way (miles); MM = maintenance material cost (1983 dollars/yr); OL = operating labor (work-hr/yr); $z = 1$ if MILES < 25, or else $z = 0$.

Requirements are for loading wet-drained carbon from plant storage tanks or contactors to semidump trailers, hauling to the reactivation facility, unloading, reloading carbon, the return to treatment plant, and discharging the GAC. The estimates do not include the cost of reactivation at the off-site facility.

Comparison of Preliminary Cost Estimates and Actual Field Experience

Comparisons have been made between cost data obtained from constructed and operating field-scale GAC systems, and preliminary estimates generated from the cost equations. Several of the original cost equations of the form given in Eq. 1 required modifications. The construction cost functions for GAC contactors and reactivators were adjusted to account for additional equipment related to the systems. Process energy requirements for fluid-bed and multihearth systems were increased to account for energy consumption during reactivation start-ups and shut-downs. Building energy requirements for fluid-bed reactivators had previously been excluded but have now been included. The earlier reactivation O&M labor estimates were low compared to actual field-scale experience but have been redeveloped. Not included in the original cost estimates were requirements for reactivation process water, on-site transport water, and transport labor.

The revised equations provide much better preliminary cost estimates for GAC systems than the original functions. Tables 2–5 present comparisons between field-scale system costs and cost estimates generated from the equations.

A comparison of fluid-bed reactivation costs experienced at Cincinnati Water Works (CWW) and estimates generated from the original and revised cost equations is presented in Table 2. The capital, O&M, and total

TABLE 2. Reactivation Costs Experienced at Cincinnati (CWW) Compared to Original and Revised Cost Functions

Cost function (1)	Capital ($/yr) (2)	OM ($/yr) (3)	Total ($/yr) (4)	Total (¢/yr) (5)
CWW experienced	121,000	300,000	421,000	23.4
Revised functions	150,000	281,500	431,500	24.0
Original functions	103,000	221,500	324,500	18.0

Note: 500-lb/hr fluid-bed reactivator; 1,800,000 lb GAC reactivated (1979–1980); OM based on 75% up-time, makeup GAC at 50 ¢/lb, and 17% losses; to convert ¢/lb to ¢/kg, divide by 0.454.

TABLE 3. GAC System Costs at Cincinnati (CWW) Compared to Cost Functions

Cost function (1)	Pressure contactor construction cost (1978 $) (2)	Capital ($/yr) (3)	OM ($/yr) (4)	SUM Contactors ($/yr) (5)	SUM Contactors (¢/1,000 gal) (6)	Reactivation (¢/1,000 gal) (7)	Total system (¢/1,000 gal) (8)
CWW experienced	1,190,000	140,000	58,000	198,000	16.5	14.4	30.9
Revised equations	1,083,000	127,000	45,000	172,000	14.3	15.1	29.4
Original equations	546,500	65,000	19,000	84,000	7.0	11.3	18.3

Note: Four 1-mgd pressure contactors, 1,200 MG/yr; 753,600 lb//yr GAC reactivated; capital based on 10% interest, 20 yrs; to determine ¢/m^3 , multiply ¢/1,000 gal values by 0.2642.

TABLE 4. Reactivation Costs Experienced at Jefferson Parish (JP) Compared to Cost Functions

Cost functions (1)	Capital (¢/lb) (2)	OM (¢/lb) (3)	Total (¢/lb) (4)
JP experienced	8.2	20.2	28.4
Revised equations	9.4	19.6	29.0

Note: 215-lb/hr infrared reactivator; 75% up-time; 1,412,500 lb/yr GAC reactivated; capital based on 1985 $, 10% interest over 20 yr; makeup GAC at 75 ¢/lb, 9% losses; to convert from ¢/lb to ¢/kg, divide by 0.454.

cost values associated with the actual field-scale experience and the revised equations match up fairly well, but estimates from the original equations are much lower. Table 3 shows the costs related to the steel pressure contactor system and fluid-bed reactivation system at CWW compared to cost estimates generated from the original and revised equations. Overall, the field-scale costs and revised function costs compare relatively close, but the original function costs are significantly lower in value.

Tables 4 and 5 present field-scale costs for infrared reactivation and steel pressure contactors at Jefferson Parish (JP), Louisiana, compared to cost estimates determined from the set of revised equations. Again, the itemized cost values match up relatively closely, with the equation estimates being more on the conservative side.

TABLE 5. GAC System Costs at Jefferson Parish (JP) Compared to Cost Functions

Cost functions (1)	Contactor capital (¢/1,000 gal) (2)	Contactor OM (¢/1,000 gal) (3)	Reactivated capital (¢/1,000 gal) (4)	Reactivation OM (¢/1,000 gal) (5)	Total cost (¢/1,000 gal) (6)
JP experienced	13.6	2.8	10.6	11.3	38.3
Revised equations	15.0	5.5	12.1	10.9	43.5

Note: Three 1-mgd pressure contactors; GAC reactivation every 3 mo, 609,768 lb/yr; capital based on 1985 $, 10% interest over 20 yr; OM for 1986 prices; to determine ¢/m^3 , multiply ¢/1,000 gal values by 0.2642.

Summary and Conclusions

Granular activated carbon offers the opportunity to provide broad spectrum capability for removing organics from drinking water. Most of the concerns that have been voiced regarding GAC usage are related to the cost of implementation. This report uses data from field-scale research and design studies in order to develop cost equations for the various cost components associated with GAC. Originally developed cost equations have been tested and modified using actual costs from the granular activated carbon systems constructed in Cincinnati, Ohio; Manchester, New Hampshire; and Jefferson Parish, Louisiana. The effort demonstrates the need to verify cost equations with "as-built" experience.

Acknowledgments

The writers would like to thank Benjamin W. Lykins, Jr., for the many contributions he made related to obtaining data from the Cincinnati Water Works, Manchester Water Works, and Jefferson Parish Water Utility. The writers also thank Patricia Pierson for typing the manuscript.

Appendix I. References

Adams, J. Q. et al. (1986). "Regional reactivation of granular activated carbon." *J. Amer. Water Works Assoc.*, 38–41.

Clark, R. M., and Dorsey, P. (1982). "A model of costs for treating drinking water." *J. Amer. Water Works Assoc.*, 74(12), 618–627.

Culp, R., Faist, T., and Smith, C. (1981). "Granular activated carbon installations." *EPA-600/2-81-177*, U.S. EPA, Cincinnati, Ohio.

Gumerman, R. C., Burris, B. E., and Hansen, S. P. (1985). "Estimation of small system water treatment costs." *EPA-600/S2-84-184*, U.S. EPA, Cincinnati, Ohio.

Gumerman, R., Culp, R. L., and Hansen, S. P. (1979). "Estimating water treatment cost." II, *Cost curves applicable to 1 to 200 mgd treatment plants*, EPA-600/2-79-162b, U.S. EPA, Cincinnati, Ohio.

Kittredge, D. et al. (1982). "Granular activated carbon adsorption and fluid-bed reactivation at Manchester, New Hampshire." *EPA 600/2-83-104*, U.S. EPA, Cincinnati, Ohio.

Koffskey, W., and Lykins, B. (1987). "Experiences with granular activated carbon filtration and on-site reactivation at Jefferson Parish, Louisiana." presented at the 1987 AWWA Annual Conf. and Exposition, held at Kansas City, Mo.

Lykins, B. et al. (1984). "Field scale granular activated carbon studies for removal of organic contaminants other than trihalomethanes from drinking water." *EPA-600/2-84-165*, U.S. EPA, Cincinnati, Ohio.

Miller, R. et al. (1982). "Feasibility study of granular activated carbon and on-site regeneration." *EPA-600/2-82-087A*, U.S. EPA, Cincinnati, Ohio.

"Recommended standards for water works." (1982). *Policies for the review and approval of plans and specifications for public water supplies*, Health Education Service, Albany, N.Y.

Safe drinking water act 1986 amendments. (1986). EPA 570/9-86-002, U.S. EPA, Office of Drinking Water, Washington, D.C.

Appendix II. Notation

The following symbols are used in this paper:

AMT = amount of GAC hauled, lb/yr;

a, b, c, d = parameters determined from nonlinear regression analysis;

BE	=	building energy, kwh/yr;
CC	=	construction cost, $ (1983);
CCI	=	ENR construction cost index (base year 1913);
CRF	=	capital recovery factor;
CUFT	=	effective GAC volume;
DF	=	diesel fuel, gal/yr;
I	=	payback interest rate on capital;
MILES	=	distance traveled, one-way miles;
MM	=	maintenance materials, 1983 $/yr;
N	=	capital payback, yr;
NG	=	natural gas, scf/yr;
OL	=	OM labor, work-hr/yr;
PE	=	process energy, kwh/yr;
PPI	=	producers price index for finished goods;
PUMPE	=	pumping energy, kwh/yr;
$USRT$	=	process design or operating variable;
Y	=	base capital or OM cost; and
z	=	0 or 1, used to adjust cost function for a range of $USRT$ values.