

## Design Criteria of an Activated Carbon Bed for Dechlorination of Water

Muna Y. Abdul – Ahad

*Environmental Engineering Department - College of Engineering - University of Baghdad – Iraq*

### Abstract

*Granular carbon can be used after conventional filtration of suspended matter or, as a combination of filtration - adsorption medium. The choice of equipment depends on the severity of the organic removal problem, the availability of existing equipment, and the desired improvement of adsorption condition. Design calculations on dechlorination by granular - carbon filters considering the effects of flow rate, pH, contact time, head loss and bed expansion in backwashing, particle size, and physical characteristics were considered assuming the absence of bacteria or any organic interface.*

**KEY WORDS:** Activated carbon, dechlorination, water purification.

### Introduction

#### THEORY

Granular- activated carbon adsorption is a reliable and effective means of removing most organic impurities found in potable water supplies. Plant operations and pilot column studies have shown carbon filtration to be an effective process for removing detergents (Flentje, 1964), insecticides, (Robeck, 1965), viruses (Robeck, 1964), specific chemical pollutants, (Dostal, 1965), and taste and odor pollutants (Flentje, 1964). These results confirm postulations that carbon bed filtration would remove a high percentage of undesirable organic contaminants from water efficiently over a wide range of impurity concentration conditions.

The utilization of granular- carbon filtration is a relatively simple and economical procedure. It is possible to adopt existing plant filters for a combination filtration - adsorption unit process with minimum alteration, by filling them with granular carbon.

Tests (Joyce, 1966) had shown that, in accordance with adsorption theory, granular carbon in beds is more efficient than pulverized carbon used in slurry form in accordance with conventional water plant procedures.

This advantage compensates for the cost differential of pulverized carbon and granular carbon applied on a single - use basis.

#### Filtration – Adsorption:

The capacity of granular activated carbon for removing viruses has been studied by (Rebeck et al, 1964), who found that in clear water poliovirus was removed much more readily by beds of fresh carbon than by sand beds. Activated carbon, even if its adsorption capacity was exhausted, still removed slightly more virus than did the beds of sand, however. Suitably abrasion- resistant granular activated carbons can serve both as filter media and adsorbent. (Smith and skeel, 1964), have reported that granular carbon beds are serving such a dual role in several locations (ELD, E.F., 1961). Filters with fresh carbon were placed in service along with similar sand medium filters. The carbon beds were (24 in.) deep and were tested for both adsorption and filtration at conventional sand filter rates. The results are summarized in (Table 1) (Smith and skeel, 1964).

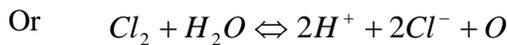
For (60) Days the carbon filters reduced threshold odor from (70 to 4). At the same time, they reduced turbidity to less than (0.07 Jackson units), a performance somewhat superior to that of the sand filters. Super

chlorination preceded the filtration, and free residual chlorine was reduced from ( 1.4-2.8ppm) to less than ( 0.25ppm) .After their odor removal capacity was exhausted , the carbon filters continued to produce water that, in regard to its color and to iron, manganese, chlorine, and turbidity content was of a quality equivalent to or better than that produced by sand filters.

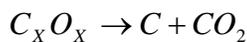
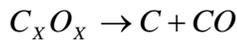
**Chlorine:**

Granular activated carbon has long been used for the removal of residual chlorine from water. As super chlorination finds wider acceptor in the public water supply industry, means of dechlorination are required.

Dechlorination by granular carbon is extremely effective and reliable. Because the granular activated carbon acts principally as a catalyst for the reduction of hypochlorous acid to chloride ion, the capacity of the carbon is determined not by normal adsorption parameters but by other considerations.



The chemisorbed nascent oxygen decomposes in either of the following two ways.



This takes place on the surface of the carbon.

(Magee, 1956), studied the carbon - chloride system in great detail to postulate a relationship between flow rates, bed depth, concentration of influent and effluent chlorine, as well as the granular carbon itself. Also (Gulp, G.L., 1974) gave the following equation.

$$\text{Log} \frac{C_I}{C_B} = \frac{B \times \text{bed depth}(ft)}{\text{filtration rate}(gpm / sq ft)} = \frac{B}{V}$$

Tests (Fairm, Geyerm, and Oukun, 1971), had determined efficiency values for specific carbons available to industrial and municipal treatment operations in the United States. Their results for flow rates, concentration of influent and type of carbon are shown in (Fig.1) (Fairm, Geyerm, and Oukun, 1971).They are based on chlorine breakpoint of (0.01 ppm). The life of the carbon in dechlorination service is extremely long.

**Example:**

Under conditions of sand filter service ( that is 2.5 gpm /sq ft and 2.5 ft bed depth) , granular carbon medium in a ( 1 mgd) filter (700 cu ft ) on dechlorination service alone could process (700 mi1 gal) of ( 4 ppm ) free - chlorine influent water before a breakpoint of (0.01 ppm) chlorine would be reached . A bed processing water containing (2ppm) chlorine under similar conditions would last about (6 years). The effect of mesh size is pronounced. As indicated in ( Fig .1) (Fairm , Geyerm, and Oukun,1971) , a reduction in particle size reflected in the reduction of mesh size from (8x30) to ( 14x40) allows a doubling of flow rate without a sacrifice in efficiency.

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

A rise in temperature and a lowering of (pH) favor dechlorination. (Fig. 2)(Fairm, Geyerm, and Oukun, 1971) indicates the relationship of these factors as they vary from (pH7) and 21°C. Mesh size (8 x 30) and flow rate was (1 gpm / ft3). A break-point of (0.01 ppm) Cl2 and the absence of bacteria or any organic interference were assumed. It is unlikely that a deliberate change in pH or temperature favoring dechlorination alone would be economically feasible, unless existing conditions significantly retard the process. These data are theoretic values determined with chlorine in distilled water. Variance in hydraulic loading, suspended matter, and certain adsorbed organics, as noted above, could adversely affect dechlorination efficiency.

**Design criteria**

Granular carbon can be used after conventional filtration of suspended matter or, as a combination filtration - adsorption medium. The choice of equipment depends on the severity of the organic contaminants (detergents, insecticides, viruses, specific chemical pollutants, and taste and odor pollutants) removal problem, the availability of existing equipment, and the desired improvement of adsorption conditions.

Usually two or more units are used in parallel down flow operation. The start-ups of the units are staggered so that exhaustion of each bed will be in sequence. Blending of the fresh carbon effluent with partially exhausted - carbon

effluent in effect prolongs the life of the bed before reactivation or replacement of the individual beds is necessary.

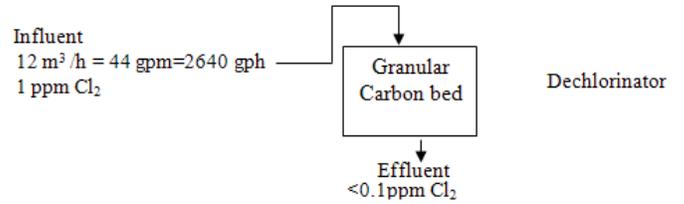
Flow rates are usually (2.5-5gpm/sq.ft), and bed depths are normally (2.5-10 ft) .Varying the combined values of these two factors can be thought of as adjusting the contact time of the water and the granular carbon beds. A direct linear relationship between contact time and carbon bed-performance was found at the Nitro facility in full scale plant tests and concurrent small column tests. During these tests flow rate conditions were (3.7 gpm / sq ft - 10gpm/sq ft) and bed height (5-20 ft). (Fig.3) (Dostal et al, 1965) shows the relationship of contact time and performance. When bed depths at given flow rates are reduced to a contact time function (gpm / cu ft), the performance is directly proportional to this function. When the granular carbon bed is functioning both as a turbidity removal and adsorption unit, there may be reasons to limit the bed depth and flow rate parameters to remove effectively turbidity and to backwash properly the filter. If granular activated carbon is to be effective in turbidity removal, it must be hard enough to withstand vigorous backwash agitation. At the same time, It should be dense enough to expand during the backwash cycle and to settle quickly for immediate resumption of filtration. Backwash expansion data, head loss, and physical characteristics of coal- based granular carbon are presented in (Figs. 4 & 5) and (Table 2) (Magee, 1965).

Particle size of the carbon, in addition to contact time, should be considered carefully as a design factor. Reduction of particle size for a given set of flow conditions is recognized to be a means of increasing adsorption rates and, thereby, improving adsorption performance. This phenomenon has been explored by many authors, including, (Weber and Morris, 1965). Reduction in particle size to improve adsorption must be consistent with other significant factors, such as head loss and backwash expansion. Length of filter run in an adsorption -filtration bed would also be a problem, if too small a particle size were chosen.

In a study(Weber and Morris,1965) of the effect of particle size, bed depth, and flow rates on the performance of an ABS system, three sets of three columns in series, containing three mesh size carbons, were examined at bed depths (2.5, 5, & 7.5 ft). The three mesh size carbons were approximately the same in all respects except particle size. (Table 3) (Weber and Morris, 1965) summarizes the results. At shallow bed depths, the smallest particle size demonstrates its rapid adsorption rate. At the deeper bed depths and longer contact periods, however, the difference in performance due to adsorption rate is perhaps significant. A summary

of design criteria is given in (Table 4) (Weber and Morris, 1965).

**Design calculations**



(1) Applying equation

$$\log \frac{C_I}{C_E} = \frac{B \times \text{bed depth}(ft)}{\text{filtration rate}(gpm/ sq ft)} = \frac{B}{V}$$

- (a) Referring to (Fig. 1) and (Table 4), the two carbon mesh sizes used are 8x30 and 14x40.
- (b) Calculation of B using (Fig. 1) For 8x30 mesh size and 2 gpm / ft3 flow rate. Applying

$$\log \frac{C_I}{C_E} = \frac{B}{V}$$

$$\log \frac{1ppm}{0.01ppm} = \frac{B}{2gpm/ ft^3}$$

PH= 7 of water, T = 21°C & a break point = 0.01 of Cl<sub>2</sub> as given by (Fig. 1) .

∴ B = 4 for 8x30 mesh size

- (c) Applying equation again for the actual design flow rate = 44 gpm, influent concentration= 1ppm Cl<sub>2</sub>, effluent = 0.1ppm Cl<sub>2</sub>

$$\log \frac{1.00}{0.10} = \frac{4}{V} , \quad V = 4gpm/ ft^3$$

- (d) Bed volume=  $\frac{44gpm}{4gpm/ ft^3} = 10 ft^3$  for 8x30 mesh size

e) For 14x40 mesh size and using (Fig. 1), for 1 gpm  $lft^3$  applying

$$\log \frac{C_i}{C_E} = \frac{B}{V}, \log \frac{2}{0.01} = \frac{B}{1gpm / ft^3}$$

B = 2.3 for 14x40 mesh size

(f) Applying equation again for the actual design flow rate = 44 gpm

$$\log \frac{1}{0.1} = \frac{2.3}{V} \quad V = 2.3 \text{ gpm } lft^3$$

(g) Bed volume =  $\frac{44 \text{ gpm}}{2.3 \text{ gpm} / ft^3} = 19.13 ft^3$  for 14x40 mesh size

2) Referring to (Table 4), which gives a summary of design criteria for granular carbon filtration for rough calculations of height of carbon bed and diameter (L & D)

(a) Using bed as filtration adsorption from table, flow rate  $\leq 2.5 \text{ gpm} / ft^2$

(a-1) mesh size 8x30

Applying equation

$$\log \frac{C_i}{C_E} = \frac{B \times \text{bed height}(ft)}{\text{superficial flowrate gpm} / ft^2}$$

$$\log \frac{1.0}{0.1} = \frac{4 \times L(ft)}{2.5 \text{ gpm} / ft^2}, L = 0.625 \text{ ft}$$

$$D = \sqrt{\frac{4 \times \text{volume of bed}}{\pi \times L}} = \sqrt{\frac{4 \times 10 ft^3}{(\pi)(0.265) ft}} = 4.6 \text{ ft}$$

(a-2) mesh size 14x 40

$$\log \frac{1}{0.1} = \frac{2.3 \times L}{2.5}, L = 1.09 \text{ ft}$$

$$D = \sqrt{\frac{4 \times 19.3 ft^3}{\pi \times 1.09 ft}} = 4.75 \text{ ft}$$

(b) Using bed as adsorption only

From table,

flowrate = 5 gpm /ft<sup>2</sup>

(b. 1) 8x30 mesh size

$$L \frac{1 \times 5 \text{ gpm} / ft^2}{4} = 1.25 \text{ ft}$$

$$D = \sqrt{\frac{4 \times 10 ft^3}{\pi \times 1.25 ft}} = 3.19 \text{ ft}$$

(b-2) 14 x 40 mesh size

$$L = \frac{1 \times 5 \text{ gpm} / ft^2}{2.3} = 2.17 \text{ ft}$$

$$D = \sqrt{\frac{4 \times 19.3 ft^3}{\pi \times 2.17 ft}} = 3.37 \text{ ft}$$

(3) Expansion of granular - carbon bed in back - washing at 22°C

(3-1) Adsorption - filtration bed - flow rate  $\leq 2.5 \text{ gpm} / ft^2$

(a) 8 x 30 mesh size Using 2.5 gpm / ft<sup>2</sup> from (table 4).

% carbon bed expansion  $\approx 1\%$

(b) 14 x 40 mesh size % carbon bed expansion  $\approx 2\%$

(3-2) Absorption only bed flow rate = 5 gpm / ft<sup>2</sup>

(a) 8 x 30 mesh size % carbon bed expansion  $\approx 2\%$

(b) 14x40 mesh size % carbon bed expansion  $\approx 13\%$

(4) Head loss on coal - based granular - carbon bed of 22°C

(4-1) Adsorption - filtration bed - superficial velocity  $< 2.5 \text{ gpm} / ft^2$

a) 8 x 30 mesh size, using (Fig. 5).

Head loss through bed = 1.5 in. / ft.

- (b) 14 x 40 mesh size  
Head loss through bed = 3.5 in. /ft

(4-2) Adsorption - bed only - superficial velocity=5 gpm/ft<sup>3</sup>

- (a) 8 x 30 mesh size  
Head loss through bed = 3 in. / ft.
- (b) 14 x40 mesh size  
Head loss through bed = 6.5 in. /ft

**Experimental laboratory evaluation**

To assess the feasibility of using the AC for this application is to put together a liquid phase adsorption isotherm in the laboratory, which also determines the distribution of chlorine the adsorbed phase, and the solution phase at equilibrium. Data for the isotherm were obtained by treating a fixed volume of the contaminated liquid in a series of known carbon dosages. The carbon liquid mixture is agitated at a constant temperature for 3 hours. During that time the carbon and liquid reach adsorptive equilibrium, the carbon is removed and the residual contamination in the liquid is measured (Degramount 1991, WHO 1984, White, 1972, Water fac. 2000). The adsorption isotherm gives the chlorine contaminant amount remaining in solution. It depicts the ability of graduated amounts of carbon to treat equal volumes of chlorine contaminant solutions under identical conditions, also can be used to compare the relative efficiency of different grades of carbon and to investigate the effects of variables, such as pH and temperature. Results are shown in (Fig. 6) .As shown, a significant benefit is achieved by reducing particle size from 8 x 30 to 14 x 40 meshes.

To estimate the contaminant capacity for calculating the weight of carbon needed for a column, one uses an X I M value that corresponds to the influent concentration (Co = 1 ppm). This value, X I Mco, represents the maximum amount of contaminant adsorbed per unit weight of carbon when the carbon is in equilibrium with the untreated contaminant concentration.

Once (X I Mco is determined = 1.2 mg Ig , for the system from (Fig. 6), the theoretical carbon demand for the given volume of chlorine contaminated liquid can be calculated. For complete removal of the chlorine contaminant:

$$Y = Co I (X I MCo)$$

Where Y = weight of carbon required per unit volume of chlorine contaminated liquid

$$Y = .8333 \text{ gm / l}$$

Table shows the overall calculated design parameters converted to metric system.

Carbon mesh size	Eff. Carb on constant B	Carbon bed volume ft <sup>3</sup>		Flow rate gpm / ft <sup>2</sup>	Carbon bed depth L ft	Carbon bed diameter D ft	% carbon bed expansion in back washing	Head loss in . / ft
8x 30 = [Mean dia.] 1.5mm	4	10 =283m <sup>3</sup>	Filtration adsorption bed	2.5 =7.335 m <sup>3</sup> /m <sup>2</sup> /h	.625 =.1905m	4.6 =1.402m	1	1.5 =12.5cm/m
			Adsorption bed only	5 =14.67 m <sup>3</sup> /m <sup>2</sup> /h	1.25 =.381m	3.19 =.972m	2	3 =25cm/m
14x40 = [Mean dia.] 0.9mm	2.3	19.3 =547m <sup>3</sup>	Filtration adsorption bed	2.5 =7.335 m <sup>3</sup> /m <sup>2</sup> /h	1.09 =.332m	4.75 =1.448m	2	3.5 =29.17cm/m
			Adsorption bed only	5 =14.67 m <sup>3</sup> /m <sup>2</sup> /h	2.17 =.661m	3.37 =1.207m	13	6.5 =54.17cm/m

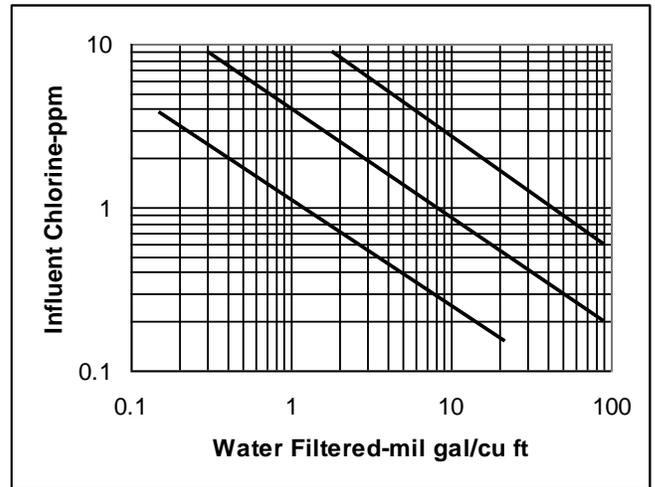


Fig.1: the effect of mass flow rate and mesh size on Dechlorination by Granular-Carbon Filters (Fairm, Geyerm, and Oukun, 1971).

The pH of the water was 7 and the temperature was 21°C. A breakpoint of 0.01 ppm Cl<sub>2</sub> and the absence of bacteria or any organic interference were assumed. Curve A represents an 8x30 mesh size and a 2 gpm/cu ft flow rate; Curve C represents a 14x40 mesh size and a flow rate of 1 gpm/cu ft; Curve B represents mesh sizes of 8x30 and 14x40 at flow rates of 1 and 2 gpm/cu ft respectively, and illustrates that such a reduction in mesh size allows a doubling of the flow rate without any sacrifice of efficiency.

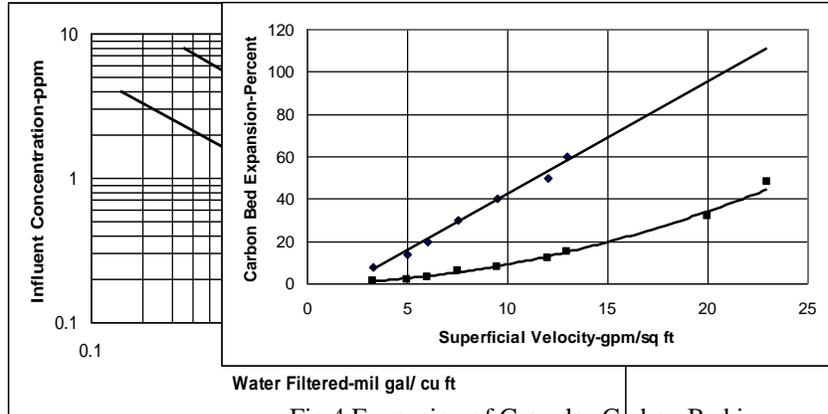
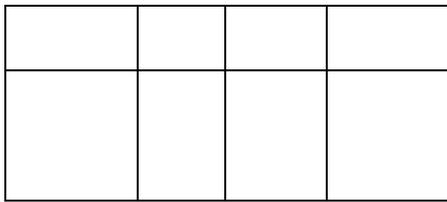


Fig 4 Expansion of Granular-Carbon Bed in Backwashing at 22 °C (Magee, 1956).

Curve **A** represents a 14x40 mesh size; Curve **B**, an 8x 30 mesh size.

Fig. 2: Effect of pH and temperature on Dechlorination by Granular Carbon (Fairm, Geyerm, and Oukun, 1971).

Mesh size was 8 x 30 and flow rate was 1 gpm/cu ft. A breakpoint of 0.01 ppm Cl<sub>2</sub> and the absence of bacteria or any organic interference were assumed.

Curve A represents pH 9 and 21°C; Curve B, pH 7 and 21°C; Curve C, both pH and 21°C and pH 7 and 30 °C



Fig.3: Relationship of Contact Time to Reduction of Threshold Odor at (Nitro, W. Va) (Dostal et al, 1965).

The influent threshold odor during the tests averaged 150. The data points represent the following: **A**, a 10 gpm/sq ft flow rate at a depth of 5 ft; **B**, 10 gpm/sq ft flow rate at 10 ft; **C**, 5 gpm/sq ft at 5 ft; **D**, 4 gpm/sq ft at 5 ft; **E**, 10 gpm/sq ft at 15 ft; **F**, 3.6 gpm/sq ft at 5 ft; and **G**, 10 gpm/sq ft at 20 ft.

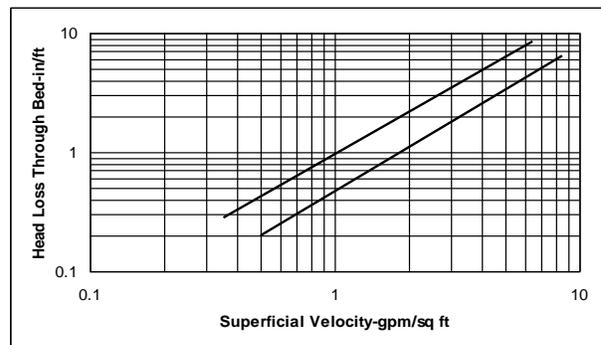


Fig. 5: Head Loss on Coal-Based Granular Bed at 22 °C (Magee, 1956).

Curve **A** represents a 14x40 mesh size; Curve **B**, an 8x30 mesh size.

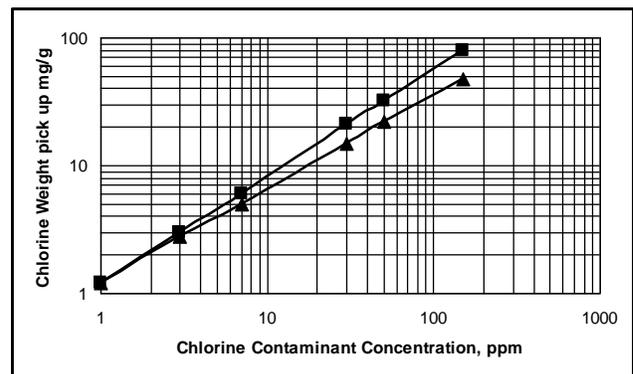


Fig.6: Activated Carbon Adsorption Isotherms.

Curve **A** represents a 14x40 mesh size; Curve **B**, an 8x30 mesh size

Table 1. Impurity Removal by Adsorption-Filtration Carbon Beds\* and by Sand Medium (Smith and Skeel, 1964).

Impurity	Impurity in influent	Impurity in Carbon Bed Effluent	Impurity in Sand Medium Effluent
Threshold odor No.	35-140	0-4#	35-70#
Color units	4-14	0-2	1-2
Mn-ppm	0.066-0.15	0.008-0.017	0.008-0.017
Fe-ppm	0.2-0.37	0.006-0.025	0.012-0.087 0.10-
Turbidity-ppm	0.45-1.4	0.07-0.15	0.25
Chlorine-ppm	1.4-2.8	0-0.25	1.4-2.8

\*24 in. deep, with flow rate of 2 gpm/sq ft.  
# Odor samples taken over a 60-day period; other samples, over a 150-day period

Table 2. Physical Properties of Coal-Based Granular Carbon\*(Magee, 1956).

	8x30 Mesh size	14x40 Mesh size
Total surface area # sq m/g	800-900	800-900
Bed density <sup>®</sup> lb/cu ft	30	30
Particle density <sup>^</sup> g/cu cm	1.4-1.5	1.4-1.5
Effective size mm	0.80-0.90	0.55-0.6
Uniformity coefficient	1.9 ≤	≤ 1.7

\*Type MWT: manufactured by the Pittsburgh Activated Carbon Co. Pittsburgh, Pa.

\*Measured by the N<sub>2</sub>, BET method.

<sup>®</sup>Backwashed and drained

<sup>^</sup>Wetted in water.

Table 3. Effect of Mesh Size and Bed Depth on Detergent (ABS) Removal\*(Weber and Morris, 1965).

Mesh Size	Bed Depth (Contact Time)		
	2.5ft (1gpm/cu ft)	5.0ft (0.5gpm/cu ft)	7.5ft (0.3 gpm/cu ft)
	ABS Removal Capacity- percent <sup>^</sup>		
8x30 <sup>#</sup>	3.8	7.6	10.9
12x40 <sup>@</sup>	5.6	9.0	11.5

\*Under the following conditions:

Concentration of ABS in influent, 10 ppm; flow rate, 2.5ppm/sq ft; Break point, 0.5ppm ABS; type of carbon, MWT grade.

<sup>#</sup>Mean particle # Mean particle diameter is 1.5mm.

<sup>@</sup>Mean par @ Mean particle diameter is 0.9 mm.

Weight <sup>^</sup> Weight of ABS/ weight of carbon

Table 4. Summary of Design for Granular-Carbon Filtration (Weber and Morris, 1965).

System Factor	Filtration Adsorption	Adsorption only
Flow rate-gpm/sq ft	2.5 ≤	2.5-5.0
Bed depth-ft	2.5-5.0	5-10
Backwash-gpm/sq ft	5-15	5-15
Minimum free-board-percent	30	30
Mesh size	8x30 or 14x40	8x30 or 14x40

## CONCLUSIONS

From the results obtained above, it is clear that the greater the size of the activated carbon granules used, for a constant flow rate of water, the carbon bed volume, carbon bed depth, carbon bed diameter, % carbon bed expansion in backwashing, and head loss, are of lower percentages assuming chlorine removal only, as shown below.

Flow rate gpm / ft <sup>2</sup>	% decrease when using 8x30 mesh size carbon bed granules					
	Filtration adsorption bed	Carbon bed volume ft <sup>3</sup>	Carbon bed depth L ft	Carbon bed diameter D ft	% carbon bed expansion in back washing	Head loss in. / ft
2.5 =7.335 m <sup>3</sup> /m <sup>2</sup> /h		2.5%	42.7%	3.2%	50%	57.1%
5 =14.67 m <sup>3</sup> /m <sup>2</sup> /h	Adsorption bed only	2.5%	42.4%	5.3%	84.6%	53.8%

Furthermore additional design calculation studies are required taking into account the presence of organic impurities to calculate the actual design parameters that affect the purification process.

**Nomenclature**

- ABS : Adsorption beds system
- $B$  : The efficiency constant for each carbon.
- $C_B$  : The concentration of  $Cl_2$  in the effluent (ppm)
- $C_E$  : The breakpoint of 0.01 ppm  $Cl_2$  and the absence of bacteria or any organic interference were assumed.
- $C_I$  : The concentration of  $Cl_2$  in the influent (ppm).
- $C_B$  : The concentration of  $Cl_2$  in the effluent (ppm).
- D : Diameter of the carbon bed (ft).
- L : Length of carbon bed (ft).
- V : Filtration rate ( *gpm/ cu ft* ).

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## الافكار التصحيحية لعمود الكربون المنشط المستخدم في ازالة الكلور من الماء

### الخلاصة

ان حبيبات الكربون يمكن ان تستعمل تقليديا للفلترية وذلك لازالة المواد العالقة او كواسطة او اداة للفلترية والامتصاص . ان اختيار الجهاز المناسب لهذه العملية يعتمد على مدى شدة او المدى لازالة مشكلة المواد العضوية , امكانية توفر الجهاز المناسب , وكذلك على الرغبة في مدى زيادة التحسن لظروف الامتصاص للكربون المستخدم.

ان هذه الدراسة قد تم اجراؤها لحساب القيم التصميمية لازالة الكلور فقط من الماء باستخدام حبيبات الكربون المنشط اخذين بنظر الاعتبار تأثيرات معدل الجريان , درجة الحمضية , الوقت الذي يستغرقه السائل بالتماس مع الكربون , الخسارة بالضغط , مقدار تمدد الكربون اثناء عملية الغسل العكسي , قياس اقطار الحبيبات , اخذين الخواص الفيزيائية بنظر الاعتبار وعلى فرض عدم وجود اي بكتريا او تماس عضوي في الماء المستخدم مع حبيبات الكربون المنشط المستعملة .