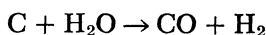


Activated carbon from activated sludge

H. BOSCH, G. J. KLEEREBEZEM, AND P. MARS

ACTIVE CARBON usually is prepared by carbonization and activation of organic substances of primarily biological origin; the usual procedure consists of drying, carbonizing from 200° up to 700°C, and activating. In the last treatment, carbon is partially gasified at 800° to 900°C, mainly according to



by which fine pores are developed.

The problems with handling surplus sludge and the increased application of active carbon in the wastewater treatment led to the idea that active carbon might be prepared from primary or secondary sludge.¹ This type of activated carbon could be useful in polishing the effluent from the secondary settling basin, and/or it could be fed into this basin mixed with the activated sludge. To increase the available amount of carbon, the used carbon may be regenerated.

These investigations are an exploration into the principal question: Is it possible to prepare active carbon with a sufficiently high surface area from sludge? Additional problems directing the preliminary research are

1. Does the active carbon thus prepared have satisfactory adsorption properties?

2. Does the presence of the carbon particles affect the rate and/or degree of the biological oxidation?

3. The mixture of sludge and active carbon must be dewatered before entering the combined pyrolysis and activation furnace. Therefore, does the active carbon act as a filter aid?

EXPERIMENTAL WORK

Activation. Primary and secondary sludges were obtained from some domestic wastewater treatment plants in Twente,

The Netherlands. After centrifugation and drying (16 hr at 105°C), the sludge was carbonized in nitrogen gas; the temperature was slowly increased up to 700°C in about 4 hr.

The activation of the sample (2 to 60 g, particle diam about 1 mm) took place with steam at 800°C and P_{H_2O} about 0.5 atm in a horizontal tube (diam 6 cm, length 60 cm) to imitate a rotating pipe furnace, as well as in a fixed bed of granulated carbon. Some experiments were carried out with a mixture of nitrogen, oxygen, and water vapor. The weight percentage of ash was estimated by heating a sample in the presence of air at 1,000°C. From this result, the burnoff (that is, the weight that is actually gasified with respect to the maximum weight that can be gasified) was calculated from the weight fractions of ash before and after activation (a_0 and a_1 , respectively) by means of the formula

$$\text{Burnoff} = \frac{1 - a_0/a_1}{1 - a_0} \times 100\%$$

Pore structure. The surface area, S_{BET} , according to the adsorption theory of Brunauer, Emmett, and Teller, was calculated from the adsorption isotherm, which was measured at -196°C with argon as the adsorbate. Previously, the samples were dried at 350°C and 10^{-2} mm Hg. From some samples, a pore size distribution was estimated with a mercury porosimeter* up to 1,500 atm, such that the volume of all pores with a radius from 75,000 down to 50 Å could be estimated.

Adsorption capacity. To estimate the adsorption capacity of the activated carbon, 2 g of carbon were added to 100 cu cm of a 0.1 M aqueous solution of phenol.

* Model 70, Carlo Erba, Milan, Italy.

After 24 hr, the concentration of the remaining phenol was measured with an ultraviolet spectrophotometer † between 430 and 500 nm.

The adsorption of both membrane-filtered effluent and a phenolic solution on the experimental carbon were compared with those on commercial carbons.

To point out the influence of the particle size of the carbon on the adsorption capacity, some experiments were carried out by grinding the carbons mentioned above in an agate mortar down to a particle size of $<10\mu$. In this case, the concentration of phenol was 40 mg/l, so that the percentage of organic carbon (TOC) was the same as that of the effluent (TOC = about 27 mg/l).

In accordance with the amount of experimental carbon that could be obtained from an activated sludge installation, 30 mg of this carbon was added to 100 cu cm of the solutions mentioned above.

The specific surface area of the commercial carbons is about five times higher, so 6 mg of the commercial carbon were added to a solution of 100 cu cm. After these solutions were shaken for 24 hr, their percentages of TOC were determined.‡

Influence of active carbon on biological oxidation and floc structure in an activated sludge tank. The influence of active carbon on the waste removal was determined by comparing the floc growth in two identical laboratory activated sludge plants, one with and one without activated carbon. The weight ratio of sludge:active carbon was 4:1. The units were fed with 0.16 g of skim milk powder/l containing the necessary nutrients at a rate of 4.2 l/hr. The aeration time was 2.9 hr, and the sludge concentration averaged 3.5 g/l. Excess sludge was wasted at intervals and the loss of active carbon and water restored. The rate of substrate removal in the two units was measured in batch experiments with 2-l portions of sludge fed every hour with 0.32 g suspended milk

† Model PMQII, Carl Zeiss, Oberkochen/Württ., Germany.

‡ Beckman Analyzer Model 915, Fullerton, Calif.

powder. The substrate concentration was estimated in terms of organic carbon (TOC). The structure of the flocs was examined microscopically.

Settling and filtration experiments of sludge-carbon mixtures. The settling characteristics of the sludge and the mixture of sludge and active carbon were measured in a 1-l graduated cylinder. (inside diam ~ 6 cm). During a settling time of 30 min, the volumes of the sludge and the mixture of sludge and active carbon were measured as a function of time.

A few filtration experiments were carried out as described by Gale² with sludge and sludge-carbon (1:1 weight) mixtures at two values of the pressure drop by using a Buchner funnel. The filter medium was a coarse-meshed nylon cloth with negligible resistance. For comparison, the same experiments were carried out with sludge without activated carbon.

RESULTS

Preparation of activated carbon. In the preparation of the activated carbon, the sludge source, agent (steam or molecular oxygen), temperature, and duration of the activation were varied. The results are presented in Table I.

The experiments with molecular oxygen were carried out with emphasis on the application of internal heating in large plants. Activation with molecular oxygen turned out to be unsatisfactory. Steam activation of secondary sludge seemed to be most encouraging. The results of the activation of activated sludge at several degrees of burnoff are shown in Figure 1. With steam at 800°C and a burnoff of approximately 30 percent, a surface area of 200 sq m/g was found. During the activation, more or less equivalent amounts of CO and H₂ always were developed, together with some CO₂ and CH₄. Experiments in a pipe furnace showed that the burnoff rate decreases when the sample is enlarged; obviously, the diffusion of steam and/or CO and H₂ plays a role. After long reaction times, the sample was not uniform, the upper part became gray as a result of the high ash content. Application

TABLE I.—Preparation of Activated Carbon from Various Materials in Packed Bed Reactor

Source Materials			Activation			Results		
Sample	Ash (wt %)	Surface (sq m/g)	Agent (vol %)	Time (hr)	Temperature (°C)	Burnoff* (wt %)	Surface	
							sq m/g Product	sq m/g Carbon
Sludge (Enschede)	32	—	O ₂ 5%	24	450	—	25	—
			O ₂ 1.5%	4	580	—	35	—
			H ₂ O 3%	in 13 hr to	800	86	67	—
Primary carbon from:								
Mixed sludge†	—	—	H ₂ O 50%	1	800	25	155	—
Saccharose	0	7	H ₂ O 3%	1	800	25	1,041‡	—
Protein	0	<5	H ₂ O 3%	1	800	25	427‡	—
Protein-saccharose mixture	0	<5	H ₂ O 3%	1	800	25	378‡	—
Secondary sludge	—	<5	H ₂ O 3%	1	800	25	154	—
Carbon from (primary) sludge (Enschede)	77.1	20	H ₂ O 3%	1	800	13	116	580
				2	800	23	112	640
				1.5	900	24	114	650
				4	900	71	71	1,060
				41	900	95	Nil	—

* Based on original organic content of sludge.

† Pyrolyzed carbon from mixture of primary and secondary sludge.

‡ BET plot was not linear; measurements have been worked up according to Joyner.²¹

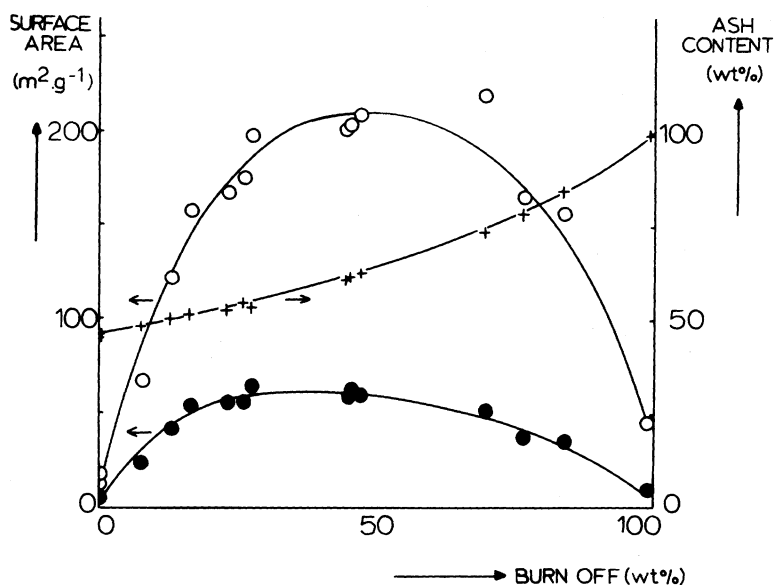


FIGURE 1.—Activated carbon from activated sludge; surface area and ash content as a function of burnoff. ○ Surface area, expressed as square meters per gram of product. ● Surface area, expressed as square meters per gram of dry sludge. + Ash content, weight percent.

of a rotating furnace, of course, will reduce the influence of the diffusion of reactants in the gas phase between the particles.

Surface area and pore structure of prepared activated carbon. The average ash content of the prepared active carbon was very high (77 percent) when primary sludge was used as the starting material (Table I). In this case, secondary sludge was more useful; a BET-surface area of 200 sq m/g is obtainable, whereas the carbon contains 50 percent ash (Figure 1). The ash does not contribute to the surface area, as may be concluded from the low surface area of the ash that remains after activation up to 100 percent burnoff. This means that the specific surface area of the activated carbon itself amounts to 400 sq m/g carbon, which is quite satisfactory in comparison with that of the carbon obtained from protein. From protein, an activated carbon may be prepared with a maximum specific surface area of 400 sq m/g at a burnoff of 25 percent (Table I). One cannot expect to obtain a higher surface area from sludge because it contains much protein. For practical application of these findings, however, the surface area per gram of starting material rather than that per gram of product must be considered; this will be discussed subsequently.

The pore volume distribution of a sample with a surface area of 200 sq m/g was determined; the pore volume of intermediate and macropores seems to be 0.11 cu cm/g. From the densities estimated in mercury and in toluene, a total pore volume of 0.42 cu cm/g was calculated. In view of literature data,³ there is an acceptable relation between the volume of pores with radii between 4 and 100 Å (0.31 cu cm/g) and the volume of pores with radii between 100 and 75,000 Å (0.11 cu cm/g). The average pore radius is approximately 15 Å and lies in the range suitable for activated carbon used in tertiary purification.⁴

Adsorption properties of activated carbon. The discussion of the characteristics of the produced activated carbon above was confined to some adsorption experiments with phenol at 20°C⁵ and with

membrane-filtered effluents. According to Mattson,⁶ it applies to activated carbons for which, in the case of phenol adsorption, up to 50 percent of the BET surface area may be covered. It seems that the produced activated carbon adsorbs 0.65 mmole phenol/g at an equilibrium concentration of 87 mmole phenol/l. With $\sigma_{\text{phenol}} = 28 \text{ sq } \text{Å}$, this means that about 55 percent of the BET-surface area is covered with phenol. The saturation value of R_2 (a commercial activated carbon specially designed for the purification of drinking water) has been determined as 3.2 mmole phenol/g. The ratio of these saturation values is the same as those of their BET-surface areas. The active carbon from sludge contains 50 weight percent ash, which does not contribute to the surface area. Therefore, the effectiveness for phenol adsorption calculated per gram of active carbon without ash (noted subsequently as "per gram C") equals that of the commercial one. Also, some other carbons prepared from sludge, which are compared with the above-mentioned commercial carbon in this particular way, show this result.

The results of the adsorption of membrane-filtered effluent are given in Table II. It is reported⁷ that in adsorption towers granulated carbon will adsorb dissolved TOC up to 20 weight percent. The authors' experiments show an adsorption capacity (mg TOC/sq m active carbon) that is less, but for finely powdered carbon only.

It is well known that adsorption on carbon proceeds faster with decreasing grain sizes.^{8,9} The authors have found that, in the case of finely powdered carbon, 80 percent of the total TOC decrease is settled in less than 5 min. For the granulated carbons, only 20 percent of the total TOC decrease is obtained in half an hour. The maximum capacities (mg TOC/sq m) of granulated commercial carbon and powdered activated carbon from sludge, however, are in close agreement (Table II). In spite of those qualities, powdered carbon is not applied by cleaning wastewater because of its high resistance in adsorp-

TABLE II.—Adsorption of Membrane-Filtered Effluent (TOC = 27 mg/l) on Activated Carbons after 24 hr

Parameter	R ₂ *				Carbon from Sludge	
	Granulated 15 mesh		Powdered 1 < d < 10 μ		Grains d ~ 2 mm	Powder 1 < d < 10 μ
	6 mg in 100 cu cm	50 mg in 100 cu cm	6 mg in 100 cu cm	50 mg in 100 cu cm	30 mg in 100 cu cm	
Mg TOC/mg AC	0.025	0.022	0.133	0.036	—	0.007
TOC removal (%)	5	39	28	64	2	7
Mg TOC/sq m AC	0.028	0.024	0.15	0.04	—	0.035

* R₂ is commercial carbon used for water purification and especially suitable for application in wastewater.

tion towers and regeneration problems. This point will be discussed later.

Influence of activated carbon on substrate removal in activated sludge process. The TOC removal in the batch experiments demonstrates that the rate of removal is enhanced by the presence of active carbon (Figure 2). Other experiments with the commercial carbon R₂ instead of activated carbon from sludge show this result.

It is likely that the better ultimate substrate removal after addition of milk powder is not caused by a single adsorption of nutrient solutes on carbon. The background may be related to the microscopic observations, in accordance with Hutton,¹⁰ that the bacterial flocs are growing on the surface of the activated carbon particles.

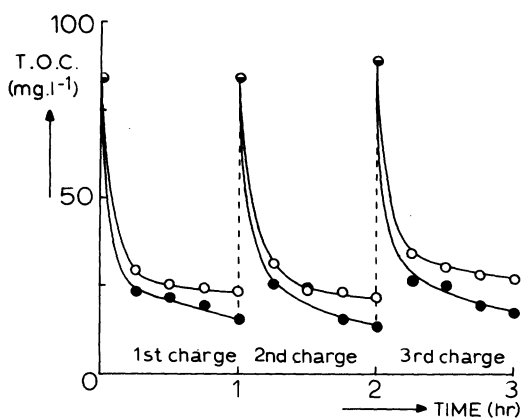


FIGURE 2.—Conversion of total organic carbon in effluent after repeated addition of milk powder. ○ By sludge. ● By a mixture of activated carbon and sludge (1:4).

Settling and filtration characteristics of a mixture of sludge and activated carbon. Settling characteristics of activated sludge and activated sludge-activated carbon mixtures are estimated after sampling from the installation. Some typical settling curves are shown in Figure 3. This figure also gives results obtained after aeration of the activated sludge during 24 hr before activated carbon is added. The addition of only 300 mg activated carbon decreases the sludge volume after a settling time of 2 hr by 30 percent. A higher carbon:sludge ratio results in a greater decrease.

Settling experiments with activated sludge that was both fed and aerated in

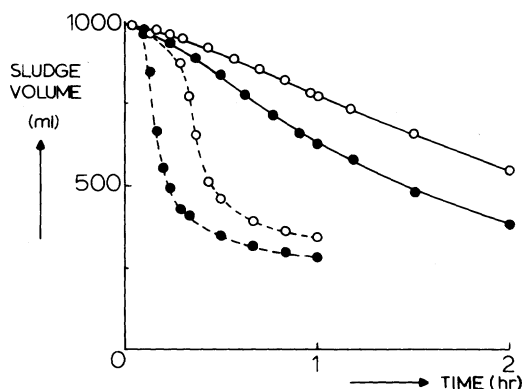


FIGURE 3.—Settling characteristics of activated sludge and a mixture of activated carbon and sludge. ○ Activated sludge (2.24 g/l). ● Mixture of activated sludge and finely ground activated carbon from sludge (7.5:1). — Settling immediately after sampling. - - - Settling after 24 hr aeration of sludge.

the presence of carbon for several days strongly indicate that the supernatant will be much clearer. In this case, however, the difference between the final sludge and sludge-carbon volumes was small.

The filtration experiments did not show any effect of the carbon on the filter resistance and the water:sludge ratio of the cake. This result seems to contradict that obtained by Philips and Rottendorf,¹¹ who observed that grains—perhaps coarser than the authors'—make excellent filter aids. The addition of activated carbon, however, reduced the attachment of the filter cake to the filter cloth.

DISCUSSION

Preparation and properties of sludge-based carbons. Activation of the dried sludge with oxygen-containing gases proved to be unsatisfactory. The low quality of the carbon prepared from sludge by Beeckmans and Ng¹ (86 to 92 percent ash and low adsorption capacity) was caused by the oxygen present in the gas used by these investigators. From other experiments not mentioned herein, it was found that activation with oxygen (air) is suitable only when the temperature is so high and air is introduced in such a way that the oxygen will react with CO and H₂ before the carbon is reached.

The adsorption property of active carbons is extensively used in wastewater treatment.^{7, 12, 13} In this case, the activation of the activated sludge must be optimized to yield the highest adsorption capacity possible. If the surface area is assumed to be a measure of the adsorption capacity, that means maximizing the surface area per unit weight of starting material, that is, per gram of dry sludge. When γ_s represents the weight fraction of activated carbon produced from the sludge (grams per gram dry sludge) the product $\gamma_s \cdot S_{\text{BET}}$ (sq m/g sludge) should be maximized. When this product is calculated from Figure 1 as a function of burnoff, it seems that the maximum is reached at a surface of 60 sq m/g sludge. Although a higher burnoff would yield some additional surface area per gram product, the burnoff

should be as low as about 25 percent to minimize the ash content, especially when carbon is regenerated. Consequently, these studies were confined to adsorption experiments with carbons of this particular burn-off.

In the adsorption experiments with membrane-filtered ($d = 0.45 \mu$) effluent, the extent of the adsorption was surprisingly low; adsorption on finely powdered carbon does not exceed 15 weight percent (Table II). One might conclude that the values of high adsorption capacity on granular carbon reported in the literature could be caused by mainly biological processes. The anaerobic conditions often noted in adsorption towers may support this view. However, more experimental work must be done to confirm whether adsorption towers are mainly an extension of the biological oxidation in the aeration compartment.

Need to recirculate used activated carbon. In an activated process, 90 percent purification of wastewater with a biochemical oxygen demand (BOD) concentration of 230 mg/l BOD results in the removal of $0.90 \times 230 = 217$ mg/l BOD. According to Imhoff,¹⁴ this BOD removal yields 217 g surplus sludge/cu m effluent. As was mentioned above, the carbon is produced on the basis of 60 sq m/g dry sludge; that is, from each gram of dry surplus sludge, $60/185 = 0.32$ g activated carbon can be obtained. Thus, only $0.32 \times 217 = 69$ g activated carbon/cu m effluent can be produced. In view of the results of the adsorption experiments (Table II), the adsorption on this carbon (in a fixed bed or in the settling tank) may have only a small effect on the BOD of the effluent.

When, after regeneration, the used active carbon is available again, this amount may be increased to a considerable extent. Because of results already mentioned (enhancement of the rate of biological oxidations, better ultimate substrate removal, and smaller sludge volume in the same settling time), it is suggested in Figure 4 that the used activated carbon should be recycled by mixing it with the sludge in the secondary settling basin. One also may use an adsorption bed at the exit of the sec-

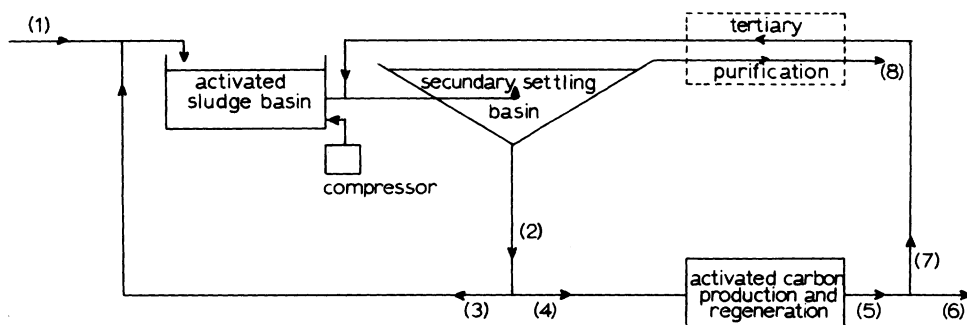


FIGURE 4.—Biological wastewater treatment with (re)generation of activated carbon and effluent polishing. (1) From primary settling tank; (2) sludge: $(C_s/\tau_a + r_{ss})V_a$, active carbon: r_{AC} ; (3) return sludge + active carbon; (4) surplus sludge: $r_{ss}V_a$ + active carbon; (5) active carbon: r_{AC1} ; (6) sludge: xr_{AC1} ; (7) return active carbon: $(1-x)r_{AC1}$; (8) effluent. Mass balances are given in Appendix.

secondary settling compartment (tertiary purification unit), the carbon used there being fed continuously into this settling compartment. In this design, the activated carbon and the secondary sludge will be drained off together from the secondary settling basin and activated carbon is also introduced into the aeration tank with the return sludge. Part of the recycling sludge-activated carbon mixture is fed into the unit in which sludge is converted into activated carbon and the used activated carbon is regenerated. During the formation of activated carbon from sludge, the regeneration of the used activated carbon takes place. It is assumed that this combined activation and regeneration will not influence the maximum surface area per unit weight of starting material, as mentioned previously. Juhola¹⁵ reported that the adsorbed organics are partly converted into activated carbon. This design leads to two circulating currents: a sludge circulation and a circulation in which activated carbon is formed and regenerated. The optimum mass flows of this system will be discussed in the next sections.

Optimum sludge load to attain maximum amount of activated carbon per volume of effluent. In the stationary situation of the recirculation of activated carbon, the ash content will be much higher than that of a sample formed in a batch experiment because inorganics are taken up and car-

bon is gasified. That is why material still must be sluiced by preference as activated carbon to avoid the disposal of fresh sludge. When only secondary sludge is used as the source of activated carbon, advantage might be taken of mixing the sluiced activated carbon with the influent to improve the settling in the primary settling tank.

The extra waste removal by adsorption depends on the ratio $R_{C:w}$ of active carbon formation available for adsorption (kg C/day) and the wastewater flow (cu m/day). In the Appendix, it has been derived that, in the stationary situation, this ratio is given by

$$R_{C:w} = \frac{(1-x)(\gamma_s - a_s) \cdot r_{ss}\tau_a}{1 - \beta_C(1-x)} \quad (\text{kg C/cu m effluent}) \quad (1)$$

in which

- a_s = weight fraction of inorganics in the recirculation sludge,
- β_C = yield of regeneration of used active carbon,
- γ_s = yield of active carbon from sludge, kg C/kg dry sludge,
- C = activated carbon exclusive of ash,
- r_{ss} = sludge formation rate, kg dry sludge/day/cu m aeration tank,
- x = weight fraction sluiced of the output of the combined activation-regeneration unit, and
- τ_a = aeration time, days.

$R_{C:w}$ reaches a maximum value when the sludge formation per cubic meter of wastewater, $r_{ss}\tau_a$, is maximized, other variables being constant. According to Koot,¹⁶

$$r_{ss}\tau_a = \frac{b}{k\tau_s} = b\epsilon\eta \quad (2)$$

in which

- b = BOD content of the influent, kg BOD/cu m,
- k = sludge load, kg BOD/day/kg sludge,
- τ_s = sludge age, days,
- ϵ = weight of surplus sludge from 1 kg of BOD removal, and
- η = degree of waste removal.

It must be taken into account that at a sludge load $k > 0.5$ kg BOD/day/kg sludge the waste removal decreases. As a consequence of a higher BOD content of the effluent, more activated carbon is needed to obtain the same overall purification. Because the value of b cannot be influenced,

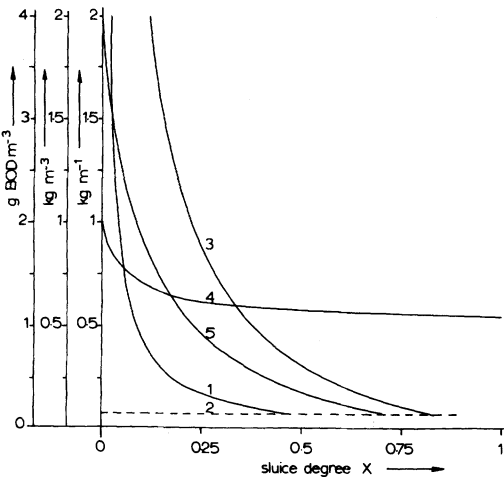


FIGURE 5.—Calculated influence of sludging on carbon:effluent and carbon:sludge ratios. (1) Ratio activated carbon:effluent, kg/cu m; (2) ratio activated carbon:effluent without recirculation of carbon, 0.07 kg/cu m; (3) ratio activated carbon:sludge at exit of secondary settling tank, kg/kg; (4) ash content, kg/kg; (5) extra biochemical oxygen demand removal by adsorption only, g BOD/cu m, taking 0.035 g BOD/sq m (see Table II).

$R_{C:w}$ is maximized when the sludge load is chosen in such a way that $\epsilon\eta$ reaches a maximum value, on the condition that η does not fall below 0.9.

If the dependence of ϵ and η on the sludge load as given by Imhoff¹⁴ is assumed, the optimum sludge load seems to be 0.3 kg BOD/day/kg sludge. At such a sludge load, the sludge age turns out to be 4 days, so that the optimum value of $k\tau_s$ amounts to 1.2 kg BOD/kg sludge.

The sludge concentration C_s now may still be chosen on the condition that the aeration time is sufficient to guarantee the maximum attainable waste removal. Choose $C_s = 4$ kg/cu m; $b = 0.23$ kg BOD/cu m (Imhoff¹⁴) also is a practical value; then the remaining parameters are fixed. It follows that, for the aeration time $\tau_a = b/kC_s = 0.19$ days, the amount of excess sludge $r_{ss} = C_s/\tau_s = 1$ kg/day/cu m and, on each passage through the aeration tank, the sludge grows with a factor $r_{ss} \cdot \tau_s/C_s + 1 = 1.05$. In this case the degree of biological waste removal remains high, that is, about 0.9.

Amount of activated carbon per volume of effluent in the case of carbon recycling. Now the optimum sludge may be calculated (see Appendix for details). With $a_s = 0.175$ and $\beta_c = 0.9$, as reported by Slechta,¹² Velten,¹⁷ and Hager,¹⁸ one may calculate the following quantities as a function of the degree of sludging: x , the ash content (Equation A6), $R_{C:w}$ (Equation 1), and, from these results, the total amount of solid matter $R_{AC:w}$, expressed as kilograms of carbon including ash per cubic meter of effluent (Equation A10). The results are presented in Figure 5.

A sludge degree of 0.1 to 0.2 is permissible and is therefore the optimum situation. In this case, the ash contents amount to approximately 65 percent. Thus, a carbon:sludge ratio of about 1:1 may be obtained, which exceeds the experimental ratios to a considerable extent. The results mentioned in Figures 2 and 3 may be improved.

In calculating the amount of active carbon per volume of effluent, data from existing plants were used.¹⁴ The normal plant operation, however, is not scheduled

for a maximum production of surplus sludge per volume of effluent. It is conceivable that a modified operation scheme may increase the value used above.

From experiments on a semitechnical scale, it must be decided whether the proposed process is feasible. That is why at this stage no attention has been paid to cost aspects.

It is obvious that the yield of active carbon per volume of effluent is marginal in the proposed process. In the authors' opinion, a meaningful application might be possible when the wastewater has a high fraction of biologically decomposable material, for instance, when the wastewater of certain industries such as potato-flour mills, strawboard factories, or slaughter houses forms a considerable amount of the flow.

CONCLUSION

At this stage, it has not yet been determined whether other activation conditions could lead to a higher adsorption capacity. Because the proposed process facilitates the regeneration of powdered carbon, it may be rewarding to add commercially obtainable powdered carbon with a higher adsorption capacity. The adsorption (faster and more effective) may be shown to full advantage, and in this case an extra separator for the carbon used in the tertiary purification is not necessary. No effort was made to investigate the adsorption of ions of heavy metals. By the regeneration procedure the salts will be made partly insoluble; mercury salts will condense in the cooled flue gas.¹⁹ It seems that the restriction of the regeneration by distinct salts¹⁹ plays no role in this case. Perhaps this depends on the compounds to be pyrolyzed, and protein might be comparatively favorable as a carbon source.

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APPENDIX—Mass Balances in the Stationary Situation when Activated Carbon Is Recirculated

The procedure of Figure 4 is detailed below. In the diagram a stream of surplus sludge, r_{ss} (kg dry sludge/day/cu m aeration tank), and a stream of activated carbon (kg activated carbon/day) are inserted, both including a distinct weight fraction of inorganics denoted, respectively, by a_s and a_{AC} .

If the weight fraction of inorganics, a_s , in the recirculation sludge is assumed to be independent of the sludge growth, the uptake of inorganics from the influent into the sludge, r_a (kg/day), varies with that sludge growth.

It may be seen from Figure 4 that the following mass balances are valid:

For activated carbon:

Across the secondary settling compartment:

$$r_{AC} = \frac{C_s/\tau_a}{C_s/\tau_a + r_{ss}} \cdot r_{AC} + (1 - x)r_{AC1} \quad (A1)$$

Across the combined activation-regeneration unit:

$$r_{AC1} = \gamma_s r_{ss} V_a + \frac{r_{ss}}{C_s/\tau_a + r_{ss}} \cdot \beta_{AC} r_{AC} \quad (A2)$$

For the inorganics:

Across the installation:

$$r_a = x a_{AC} r_{AC1} \quad (A3)$$

Across the aeration tank:

$$r_a = a_s r_{ss} V_a \quad (A4)$$

in which

- a_{AC} = activated carbon inclusive of ash,
- β_{AC} = yield of regeneration of used activated carbon,
- γ_s = yield of active carbon from sludge, kg AC/kg dry sludge,
- C_s = sludge concentration in entrance of aeration tank, kg dry sludge/cu m,
- r_{AC} = active carbon from secondary settling compartment, kg AC/day,
- r_{AC1} = active carbon from activation unit, kg AC/day,
- V_a = volume of aeration tank, cu m,
- ϕ_v = influent, cu m/day,
- $\tau_a = V_a/\phi_v$ = aeration time, days, and
- x = weight fraction of r_{AC1} that is sluiced (degree of sluicing).

The ash content, a_{AC} , of the active carbon varies with the degree of sluicing and so does β_{AC} . If the yield, β_c , of the organic fraction of the active carbon is independent of the degree of sluicing,

$$\beta_c = \frac{\beta_{AC} - a_{AC}}{1 - a_{AC}} \text{ or } \beta_{AC} = a_{AC}(1 - \beta_c) + \beta_c \quad (A5)$$

with the restriction that $\beta_{AC} \geq a_{AC}$. The subscript c means activated carbon without ash.

Now there are five independent equations and six unknown variables; hence, by the choice of the degree of sluicing, x , the remaining parameters are fixed.

From Equations 3 through 7 the following relationship may be derived:

$$a_{AC} = \frac{1 - \beta_c(1 - x)}{\frac{\gamma_s x}{a_s} + (1 - \beta_c)(1 - x)} \quad (A6)$$

For both carbon streams it follows that

$$r_{AC} = \frac{1 - x}{x} \cdot \frac{a_s}{a_{AC}} \left(\frac{C_s}{\tau_a} + r_{ss} \right) V_a, \quad \text{kg AC/day} \quad (A7)$$

$$r_{AC1} = \frac{a_s \cdot r_{ss} V_a}{x \cdot a_{AC}}, \quad \text{kg AC/day} \quad (A8)$$

Of principal interest is the amount of activated carbon that is available for ad-

sorption per cubic meter of effluent.

$$R_{AC:w} = \frac{(1-x)r_{AC1}}{\phi_v}, \text{ kg AC/cu m} \quad (A9)$$

This amount consists partly of inorganics, which have no adsorption capacity; hence, the effective quantity of adsorbents amounts to

$$R_{C:w} = (1 - a_{AC}) \cdot R_{AC:w} \\ = \frac{(1-x)(\gamma_s - a_s)}{1 - \beta_C(1-x)} \cdot r_{ss}\tau_a, \\ \text{kg C/cu m} \quad (A10)$$

In terms of amounts to be recirculated, there is one more process characteristic of interest, the ratio of activated carbon: sludge $R_{AC:s}$ in the secondary settling

basin.

$$R_{AC:s} = \frac{r_{AC}}{(C_s/\tau_a + r_{ss})V_a}, \\ \text{kg AC/kg dry sludge} \quad (A11)$$

a_{AC} , $R_{AC:w}$ and $R_{AC:s}$ are calculated as a function of the degree of sluicing by inserting the values calculated previously. ($a_s = 0.175$, $\beta_C = 0.9$, $C_s = 4$ kg/cu m, $r_{ss}\tau_a = 0.19$ kg/cu m). A suitable value for γ_s is selected ($\gamma_s = 0.32$). The results are given in Figure 4.

Also given in this figure is the extra BOD decrease obtainable by adsorption only. From Equation A10, the surface area available for adsorption is calculated; the adsorption capacity is taken from Table II. The experimental conditions of Table II are satisfied at a degree of sluicing of about 0.13.